Volume 70, Nos. 2 and 3

CR SPECIAL 33, 2016

Published October 27, 2016

Drought in Central Europe— from drought response to preparedness

Editors: Donald A. Wilhite, Rudolf Brázdil, Ulf Büntgen, Michael Hayes, Miroslav Trnka

Photos: Jan Vopravil (left); Petr Hlavinka (right)

SPECIALS of Climate Research (CR) present important new information on climate phenomena, measured and assessed by closely coordinated group efforts. They concentrate on specific research themes or geographic areas.

CR SPECIAL 33 highlights some of the main findings from the interdisciplinary drought research (InterSucho) project (sucho: Czech for drought). The aim of the InterSucho project was to understand drought as multifaceted extreme events at a regional scale with focus on the Czech Republic and Central Europe, and across various time scales. Some of the topics covered in this Special are:

- *Characteristics of historical and more recent drought events derived from documentary data*
- *Observed drought trends, including observed trends in drought impacts*
- *Response of agriculture to drought on seasonal and long-term scales*
- *Expected changes and challenges arising with ongoing climate change*
- *Methods to increase drought resilience starting from spatially explicit estimation of drought related hazards to drought planning*

Contributions to this CR SPECIAL provide—for the first time—a comprehensive overview of drought and its impacts, as well as possible measures to increase resilience in the region, which is considered to be one of Europe's climate change hot spots.

We are pleased to make the online version of this CR SPECIAL available with Open Access.

Inter-Research

Inter-Research

Nordbünte 23 (+3, 5, 28, 30), 21385 Oldendorf/Luhe, Germany

Tel: (+49) (0)4132 7127, Fax: (+49) (0)4132 8883

Email: ir@int-res.com, Internet: www.int-res.com

Contents

Vol. 70: 99–102, 2016
doi: 10.3354/cr01430

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

Introduction

Managing drought risk in a changing climate

Donald A. Wilhite

University of Nebraska, Lincoln, NE 68583, USA

ABSTRACT: There is an increasing concern worldwide regarding the ineffectiveness of current drought management practices that are based largely on crisis management. These practices are reactive and, therefore, only treat the symptoms (impacts) of drought rather than the underlying causes of the vulnerabilities associated with impacts. More effective drought management requires a shift in the paradigm from drought response to a drought risk management approach.

KEY WORDS: Drought management · Drought risk reduction · Drought policy · Drought early warning systems

Drought impact and responses

Drought is a naturally occurring event that occurs in virtually all of the world's climatic regimes. Drought results in significant economic, social, and environmental impacts in both developing and developed countries (Wilhite 2000, WMO 2006). Characteristics of drought impacts differ markedly from country to country and even within a country, depending on the primary economic activities and the vulnerability of the population to extended periods of water shortage (Sivakumar et al. 2014). Societal vulnerability to drought changes in response to increasing population, regional shifts of population, changes in land use, urbanization, and applications of new technology (Wilhite & Buchanan-Smith 2005). Changes in the frequency, severity, and duration of drought will also affect drought impacts, not only by increasing the magnitude of drought impacts, but also by potentially shortening recovery time between severe drought episodes.

People most closely associate the impacts of drought with the agricultural sector because of its direct effects on plant growth, water availability and food supplies. Certainly, the agricultural sector remains one of the most vulnerable to an extended period of precipitation deficiency in Central Europe and for most other drought-prone regions (Sivakumar et al. 2011). Rain-fed agriculture is particularly at risk to drought. However, irrigated agriculture also experiences significant impacts if drought conditions extend over a longer period of time through reduction of available water supplies from both surface and ground water sources (Sivakumar et al. 2011). Higher temperatures, often occurring during drought episodes (Wilhite & Glantz 1985), increase evaporative demand for water which can exceed the capacity of agricultural irrigation systems to meet this demand. In developing countries, droughts can be especially devastating since reduced agricultural productivity may raise serious food security and other public health concerns (Wilhite et al. 2014). However, the impact of today's droughts both in Central Europe and globally are more complex and often also affect many other sectors besides agriculture. Most notable are drought impacts on transportation, energy production, tourism and recreation, ecosystem services, and health, as well as broader environmental and social impacts. Drought often results in an increased level of conflict between the various water use sectors (e.g. agriculture, recreation and tourism, transportation, energy production, ecosystems) (Wilhite & Buchanan-Smith 2005). These drought impacts occur in many countries each year, although how each country is affected by drought depends on the severity of the drought, its duration

*Corresponding author: dwilhite2@unl.edu

Publisher: Inter-Research · www.int-res.com

and spatial extent, the level of vulnerability of key sectors and the institutional capacity of each nation in terms of both their level of preparedness and response capability (WMO & GWP 2014). Thus, it is critical for all countries to develop national drought policies that focus on managing the risks associated with drought rather than the traditional approach of managing the disaster (i.e. crisis management). Drought risk reduction builds institutional capacity that will reduce the impacts of future drought episodes.

Moving towards drought risk management

Globally, there are serious concerns about the spiraling impacts of drought on a growing number of sectors (e.g. energy, agriculture, transportation, recreation and tourism), especially given current increases in drought incidences for many regions, and projected further increases in drought and other extreme climatic events as a result of climate change (Peterson et al. 2013, Herring et al. 2014, IPCC 2014, Melillo et al. 2014, Trenberth et al. 2015). These concerns have resulted in increased attention to the need for risk-based national drought policies and preparedness plans as an instrument to implement those policies. The need for a more proactive approach to drought management was a motivating factor that led the World Meteorological Organization's (WMO) Congress at its Sixteenth Session (held in Geneva in 2011) to recommend the organization of a 'High-level Meeting on National Drought Policy (HMNDP)'. Accordingly, the WMO, the Secretariat of the United Nations Convention to Combat Desertification (UNCCD), and the Food and Agriculture Organization of the United Nations (FAO), in collaboration with a number of UN agencies, international and regional organizations, and key national agencies, organized the HMNDP in Geneva in March 2013 (Sivakumar et al. 2014, Wilhite et al. 2014). The theme of HMNDP was 'Reducing societal vulnerability—helping society (communities and sectors)' (WMO 2013). This meeting aimed to encourage all countries to adopt national drought policies that focus on risk reduction by providing a framework for policy development and adoption. The meeting concluded with the unanimous approval of a declaration by the 87 attending countries that promotes the development of national drought management policies for all countries (WMO 2013).

National drought policies will establish a clear set of principles or operating guidelines to govern the management of drought and its impacts (WMO & GWP 2014). The overriding principle of drought policies is an emphasis on risk management through the application of preparedness and mitigation measures. These policies should be directed toward reducing risks by developing more awareness and better understanding of drought hazards and the underlying causes of societal vulnerability. The objectives associated with national drought policies will vary from country to country but, in principle, will likely reflect some common themes. The intent of the HMNDP was not to be prescriptive to countries on the specific process and elements for the development of a national drought policy, but rather to provide guidelines that would assist them in the policy development process. The 3 objectives to consider as part of a national drought policy are: (1) encourage vulnerable economic sectors and population groups to adopt self-reliant measures that promote risk management; (2) promote sustainable use of the agricultural and natural resources; and (3) facilitate early recovery from drought through actions consistent with the national drought policy objectives, i.e. risk reduction.

One of the important outcomes of the HMNDP is the continued collaboration between WMO, FAO, UNCCD and UN-Water on drought risk reduction, and agreement between these agencies on a common approach for improving drought management at the national level. This approach requires attention to 3 key pillars for drought management as part of a national drought policy development process: (1) monitoring, early warning and information delivery; (2) assessment of risk, vulnerability and impacts; and (3) mitigation and response (WMO & GWP 2014). The crisis management approach that has historically characterized responses to drought throughout the world has not emphasized this overarching concept of drought management policy. As a result, the crisis management approach has been characterized by untimely, poorly coordinated, ineffective and costly response actions by governments and donor organizations (Wilhite et al. 2005, WMO & GWP 2014).

Drought risk management: the 3 pillars

Drought is a slow-onset, creeping phenomenon. Thus, in the absence of a comprehensive, integrated early warning system that gathers and assesses the status of the water supplies in the hydrologic system on a regular basis, the severity of droughts often goes undetected until the water shortage reaches crisis stage for many sectors. Once a region has reached a state of crisis, there are few alternatives other than providing relief (e.g. forage for livestock, food aid, water) to the most drought-affected sectors. Nations need to establish an integrated drought monitoring and early warning system (pillar 1) that compiles information on the status of all segments of the hydrologic cycle and delivers that information to decision makers at all levels in a timely fashion so risks can be mitigated and reduced. This integrated monitoring system would include not only information on precipitation deficiencies and temperature anomalies but also the status of ground and surface water supplies, soil moisture, snowpack, and vegetation status among other variables. Long-term climate forecasts, although not highly reliable for many regions, may provide usable information for decision makers as well, especially for those areas where there are strong connections to phenomena such as El Niño and La Niña that result in significant climatic anomalies for many regions of the world (National Drought Mitigation Center 2016) as we have seen in 2015 and 2016. Documenting drought impacts at the local level is important to verify the severity of droughts and to identify those individuals, sectors, and communities most at risk. This information is a critical and integral component of the second and third pillars for drought management and risk reduction.

The second pillar focuses on the completion of an assessment of drought vulnerability or risk to the different sectors, population groups and regions. Vulnerability refers to the degree of resilience to drought in a society or its ability to withstand the effects of a drought episode. It is associated with the diminished capacity of an individual or group to anticipate, cope with, resist, and recover from the impacts of drought. It is also important to note that vulnerability is dynamic — as society changes, so does vulnerability to drought. The purpose of a drought vulnerability or risk assessment is to determine who and what is at risk and why (Wilhite et al. 2005, WMO & GWP 2014).

The third and final pillar in the development of a risk-based drought management policy is the development of mitigation and response measures and options. Mitigation refers to proactive measures that are identified and implemented that increase the resilience of an individual, population group, community or nation and, thus, reduce or eliminate the negative impacts of drought. Nations cannot be 'drought-proofed' since drought is a naturally occurring phenomenon. However, the impacts of drought can be reduced or even eliminated with careful planning at all levels. The identification of mitigation measures is derived from the risk/vulnerability assessment process (pillar 2). Once identified, these mitigation measures are prioritized and implemented during this stage of the drought preparedness plan development. Response measures must support the principles of risk reduction.

Drought in Central Europe — from drought response to preparedness

I have had the pleasure of working with Mirek Trnka and his colleagues from the Czech Republic and other Central European countries for more than a decade on drought and drought management in the region. This CR Special is the culmination of much of this work, and incorporates some of the collaborative activities with the National Drought Mitigation Center at the University of Nebraska and elsewhere in the United States. Brázdil and colleagues explore incidences and causes of droughts in the Czech Republic and the Central European region over a >500 yr record in order to better understand the drought history of the region (Brázdil et al. 2016a). Brázdil et al. (2016b) and Trnka et al. (2016a) investigate more recent trends in drought occurrence whereas Štěpánek et al. (2016) analyze the future of drought under a changing climate. This CR Special contribution presents projections of drought-inducing climate conditions in the Czech Republic, providing a glimpse into the future and a basis for future drought management efforts (Štěpánek et al. 2016). Other contributions in this CR Special examine the relationships between drought and tree growth (Dobrovolný et al. 2016), its impact on grapes (Možný et al. 2016), and winter wheat and spring barley (Anderson et al. 2016). The interrelationships between drought, soil erosion and local flooding on agricultural lands in the Czech Republic provides yet another and important description of the complexities of drought and its impacts on agriculture (Trnka et al. 2016b). Trnka et al. (2016c) explore the changing regional weather–crop yield relationships across Europe in recent decades. This contribution gives the reader an improved understanding of the relationships between climate variability and crop yields, and provides a window for interpreting how these relationships may change in a changing climate (Trnka et al. 2016b). The contribution of Finnessey et al. (2016) is especially important given its focus on drought preparedness and the importance of timely and reliable information for decision makers at all levels as they seek to improve drought management.

This CR Special is focused on understanding the drought hazard for Central Europe (past, present and future) and the steps necessary to improve drought assessment, response and preparedness. Drought has been and continues to be a serious threat to Central Europe and is projected to become a greater problem in future decades as a result of climate change. Coupled with the projected increase in frequency of drought episodes in the future is the increase in societal vulnerability to drought and other natural hazards, as competition for finite water supplies between different sectors continues to increase.

The contributions to this CR Special provide the underpinnings for understanding drought occurrence, its impacts and risks, and how climate information can be applied in drought planning in Central Europe. This understanding can provide the basis for further research and institutional capacity building at the national or sub-national level within the region to increase the resilience of the region to future drought episodes. In light of documented changes in climate to date and future projected changes, the time to create more drought resilient societies is now.

LITERATURE CITED

Anderson MC, Hain CR, Jurecka F, Trnka M and others (2016) Relationships between the evaporative stress index and winter wheat and spring barley yield anomalies in the Czech Republic. Clim Res 70:215–230

Brázdil R, Dobrovonlý P, Trnka M, Büntgen U and others (2016a) Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501. Clim Res 70:103–117

Brázdil R, Raška P, Trnka M, Zahradníček P and others (2016b) The Central European drought of 1947: causes and consequences, with particular reference to the Czech Lands. Clim Res 70:161–178

Dobrovolný P, Rybníček M, Büntgen U, Trnka M and others (2016) Recent growth coherence in long-term oak (*Quercus* spp.) ring width chronologies in the Czech Republic. Clim Res 70:133–141

Finnessey T, Hayes M, Lukas J, Svoboda M (2016) Using climate information for drought planning. Clim Res 70: 251–263

Herring SC, Hoerling MP, Peterson TC, Stott PA (eds) (2014) Explaining extreme events of 2013 from a climate perspective. Bull Am Meteorol Soc 95:S1–S96

IPCC (Intergovernmental Panel on Climate Change) (2014) Summary for policymakers. In: Climate change 2014: mitigation of climate change. Contribution of Working Group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Melillo JM, Richmond TC, Yohe GW (eds) (2014) Climate change impacts in the United States: the third national climate assessment. U.S. Global Change Research Program, Washington, DC

Možný M, Brázdil R, Dobrovolný P, Trnka M and others (2016) Drought reconstruction based on grape harvest dates for the Czech Lands, 1499–2012. Clim Res 70: 119–132

National Drought Mitigation Center (2016) ENSO and drought forecasting. http://drought.unl.edu/droughtbasics/ensoandforecasting.aspx (accessed 31 August 2016)

Peterson TC, Stott PA, Herring S (2013) Explaining extreme events of 2012 from a climate perspective. Bull Am Meteorol Soc 94:S1–14

Sivakumar MKV, Motha R, Wilhite D, Wood D (eds) (2011) Proceedings of an expert meeting on agricultural drought indices (Murcia, Spain, June 2010). World Meteorological Organization, Geneva

Sivakumar MVK, Stefanski R, Bazza M, Zelaya S, Wilhite D, Rocha Magalhaes A (2014) High-level meeting on national drought policy: summary and major outcomes. Weather Clim Extrem 3:126–132

Štěpánek P, Zahradníček P, Farda A, Skalák P, Trnka M, Meitner J, Rajdl K (2016) Projection of drought-inducing climate conditions in the Czech Republic according to Euro-CORDEX models. Clim Res 70:179–193

Trenberth KE, Fasullo JT, Shepherd TG (2015) Attribution of climate extreme events. Nat Clim Change 5:725–730

Trnka M, Balek J, Štěpánek P, Zahradníček P and others (2016a) Drought trends over part of Central Europe between 1961 and 2014. Clim Res 70:143–160

Trnka M, Semerádová D, Novotný I, Dumbrovský M and others (2016b) Assessing the combined hazards of drought, soil erosion and local flooding on agricultural land: a Czech case study. Clim Res 70:231–249

Trnka M, Olesen JE, Kersebaum KC, Rötter RP and others (2016c) Changing regional weather–crop yield relationships across Europe between 1901 and 2012. Clim Res 70:195–214

Wilhite DA (ed) (2000) Drought: a global assessment. Vol 2. In: Keller AZ (ed) Hazards and disasters: a series of definitive major works. Routledge, London

Wilhite DA, Buchanan-Smith M (2005) Drought as hazard: understanding the natural and social context. In: Wilhite DA (ed) Drought and water crises: science, technology, and management issues. CRC Press, Boca Raton, FL, p 3–29

Wilhite DA, Glantz MH (1985) Understanding the drought phenomenon: the role of definitions. Water Int 10: 111–120

Wilhite DA, Hayes MJ, Knutson CL (2005) Drought preparedness planning: building institutional capacity. In: Wilhite DA (ed) Drought and water crises: science, technology, and management issues. CRC Press, Boca Raton, FL, p 93–135

Wilhite DA, Sivakumar MVK, Pulwarty RS (2014) Managing drought risk in a changing climate: the role of national drought policy. Weather Clim Extrem 3:4–13

WMO (2013) High-level meeting on national drought policy. www.wmo.int/pages/prog/wcp/drought/hmndp/index.php. (accessed 31 August 2016)

WMO (World Meteorological Organization) (2006) Drought monitoring and early warning: concepts, progress and future challenges. No. 1006. Geneva

WMO (World Meteorological Organization) & GWP (Global Water Partnership) (2014) National drought policy guidelines: a template for action (D. A. Wilhite). Integrated Drought Management Programme (IDMP) tools and guidelines series 1. WMO, Geneva and GWP, Stockholm

Vol. 70: 103–117, 2016
doi: 10.3354/cr01380

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501

Rudolf Brázdil[1,2,*], Petr Dobrovolný[1,2], Miroslav Trnka[2,3], Ulf Büntgen[2,4,5], Ladislava Řezníčková[1,2], Oldřich Kotyza[6], Hubert Valášek[1,7], Petr Štěpánek[2,8]

[1]Institute of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
[2]Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic
[3]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[4]Swiss Federal Research Institute for Forest, Snow and Landscape WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland
[5]Oeschger Centre for Climate Change Research, Falkenplatz 16, 3012 Bern, Switzerland
[6]Regional Museum, Dlouhá 173, 412 01 Litoměřice, Czech Republic
[7]Moravian Land Archives, Palackého nám. 1, 625 00 Brno, Czech Republic
[8]Czech Hydrometeorological Institute, Kroftova 43, 616 67 Brno, Czech Republic

ABSTRACT: This study addresses the reconstruction of 4 slightly different drought indices in the Czech Lands (now the Czech Republic) back to 1501 AD. Reconstructed monthly temperatures for Central Europe that are representative for the Czech territory, together with reconstructed seasonal precipitation totals from the same area, are used to calculate monthly, seasonal and annual drought indices (SPI, SPEI, Z-index, and scPDSI). The resulting time series reflect interannual to multi-decadal drought variability. The driest episodes cluster around the beginning and end of the 18th century, while 1540 emerges as a particularly dry extreme year. The temperature-driven dryness of the past 3 decades is well captured by SPEI, Z-index and scPDSI, whereas precipitation totals show no significant trend during this period (as reflected in SPI). Data and methodological uncertainty associated with Czech drought indices, as well as their position in a greater European context, are critically outlined. Comparison with fir tree-rings from southern Moravia and a spatial subset of the 'Old World Drought Atlas' (OWDA) reveals statistically significant correlation coefficients, of around 0.40 and 0.50, respectively. This study introduces a new documentary-based approach for the robust extension of standardised drought indices back into pre-instrumental times, which we also believe has great potential in other parts of the world where high-resolution paleoclimatic insight remains limited.

KEY WORDS: Documentary evidence · Climate reconstruction · Drought variability · Extreme years · Central Europe

1. INTRODUCTION

Although the fifth IPCC report (Stocker et al. 2013) indicates the Mediterranean region is one of the most drought-prone areas of Europe, based on recent global warming projections, drought indices also indicate an important increase in drought in Central Europe from the year 2000, as has been shown, for example, for the territory of the Czech Republic (e.g. Brázdil et al. 2009, 2013a, 2015b, Brázdil & Trnka 2015, Trnka et al. 2015a,b, Zahradníček et al. 2015). The distinctiveness of this phenomenon can only be evaluated on the basis of long-term drought reconstructions in which documentary data are combined with either instrumental records (Brázdil et al. 2013a) or with dendrochronological analyses of the

*Corresponding author: brazdil@sci.muni.cz

Publisher: Inter-Research · www.int-res.com

rings of trees sensitive to hydroclimatic patterns in their area of growth (Brázdil et al. 2002, Büntgen et al. 2010, 2011a, Cook et al. 2015, Dobrovolný et al. 2015b).

Several drought indices have been developed for the detection, monitoring and evaluation of drought episodes (for overviews, see e.g. Byun & Wilhite 1999, Heim 2000, 2002, Vogt & Somma 2000, Wu et al. 2007, Niemeyer 2008). Instrumentally derived data related to meteorological variables (particularly temperature and precipitation) or hydrological variables (discharge, groundwater level) are employed in their calculation. Although the indices thus created are able to describe various aspects of meteorological, agricultural, hydrological and groundwater droughts (Heim 2002, Mishra & Singh 2010, Dai 2011), none of them can be used across the board. The differences among them arise out of the input data used, the intervals for which the values of the indices are integrated and the ways in which each individual index is calculated. Such indices are thus usually selected with respect to the aims of any given study, or aspects under particular investigation.

Although documentary data sources for Central Europe are particularly rich (Brázdil et al. 2005, 2010), the reliable documentary drought proxies provided by formal religious supplications for rain (rogations), so marked in the Mediterranean areas, for example (Piervitali & Colacino 2001, Barriendos 2005, Domínguez-Castro et al. 2008, 2010, Diodato & Bellocchi 2011) are absent. The creation of drought indices for the former area must therefore rely upon combined descriptions of temperature and precipitation patterns derived from a range of documentary sources that may provide series of temperature and/or precipitation indices, as has been done, for example, for Switzerland (Pfister 1988, 1999), Germany (Glaser 2001, 2008) and the Czech Lands (Dobrovolný et al. 2009). Temperature indices for all 3 of these territories have been used, together with instrumental measurements, to create a temperature series for Central Europe (Dobrovolný et al. 2010). Similarly, precipitation indices combined with precipitation measurements have been used to calculate precipitation series for the Czech Lands (Dobrovolný et al. 2015a). Despite their considerable potential for the study of long-term drought fluctuations, to date their only direct use for this purpose has been for the creation of a 512-yr drought frequency chronology for the Czech Lands (Brázdil et al. 2013a). However, in this case, only simple sums of negative precipitation indices on a decadal scale were used to express the measure of drought severity.

More recently, Wetter et al. (2014) coined the term ‘megadrought’ for the extremely dry year that occurred in Europe in 1540. Büntgen et al. (2015) expressed some doubts about the use of this term because no clear sign of such an extreme appeared in many existing tree-ring chronologies for that particular year. However, Pfister et al. (2015) provided support for the original results from documentary data, citing inconsistencies in the identification of extreme years in tree-ring data derived from different tree species, regions and periods analysed. In making such comparisons, it should be borne in mind that, documentary data are not restricted to a particular time of year. On the other hand, tree-rings may be used to reconstruct drought indices far beyond the period covered by documentary data (e.g. Büntgen et al. 2011b, Dobrovolný et al. 2015b). More recently, Cook et al. (2015) developed the ‘Old World Drought Atlas’ (OWDA), in which they produced year-to-year maps of summer wetness and dryness in Europe and the Mediterranean during the Common Era, expressed in terms of self-calibrated Palmer Drought Severity Index (scPDSI) values reconstructed from 106 tree-ring series. In this context, reconstruction of drought indices based on documentary data may provide an important contribution to the study of past and recent droughts, comparable with other existing drought reconstructions.

This study aims to fill a gap in existing pre-instrumental drought reconstructions for Europe. It provides a 515 yr series of drought indices for the Czech Lands based on combined temperature and precipitation reconstructions derived from documentary and instrumental data.

2. DATA AND METHODS

Four slightly different drought indices are employed in this contribution: the Standardised Precipitation Index (SPI, McKee et al. 1993), the Standardised Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al. 2010), Palmer’s Z-index, and the self-calibrated version of the Palmer Drought Severity Index (PDSI) (Palmer 1965). Calculations of these were based on ~500-yr temperature and precipitation reconstructions, as described below. The selected indices are those used the most frequently in drought studies and express various aspects of drought. The SPI, calculated from monthly precipitation totals, can be interpreted as the number of standard deviations by which the observed precipitation anomaly deviates from the long-term mean. The SPEI is analogue of the SPI, but instead of precipitation only it is based on monthly differences between precipitation and potential evapotranspiration. Therefore it represents anomaly of the climatological water balance. The Z-index is principally used to express soil moisture anomaly, depending on the difference between precipitation and potential evapotranspiration, i.e. it evaluates the deviation from climatological optimum, which reflects prevailing patterns at the assessed site in the particular month (Palmer 1965). Compared to more frequently used PDSI it represents only the current state of the water balance, without considering the antecedent soil moisture status.

Temperature series for Central Europe were created by means of reconstructions at the monthly level by Dobrovolný et al. (2010). Included in this calculation were index series for Switzerland (Pfister 1988), Germany (Glaser 2001) and the Czech Lands from 1501 to 1854, combined with homogenised mean temperature series from eleven central European stations (including Czech Prague-Klementinum) covering the period 1760–2007. The application of simple linear regression, calibration and verification interval enabled the 1760–1854 period to be included, with a high share of explained variance (between 86% in January and 56% in September). This series for AD 1500–2007 has proven quite representative for Central Europe and the Czech Lands due to high spatial temperature correlations in this region. It was impossible to extend the central European temperature series (Dobrovolný et al. 2010) beyond 2007 using the original instrumental data from the 11 stations, so the series was taken to December 2010 by means of linear regression with the mean Czech Land temperature series (see Brázdil et al. 2012a, 2012b) and subsequently extended to cover the period January 2011–August 2015. Statistically significant correlation coefficients between the 2 series fluctuated from 0.90 (September) to 0.96 (February) in the 1800–2007 common period. In general, higher correlation coefficients were typical of winter, while lower values emerged in summer. This is due to the fact that winter temperature patterns are mainly related to strongly expressed macro-scale circulation patterns, while the influence of meso- or micro-scale effects related to sunshine duration or cloudiness increases in summer.

Precipitation series, of greater spatial variability than temperature series in Central Europe, were used for reconstruction only for the Czech Lands (Dobrovolný et al. 2015a). The limited available documentary data meant that it was only possible to create precipitation indices at seasonal level (DJF, MAM, JJA, SON) for the 1501–1854 period. While instrumentally-based mean precipitation series for the Czech Lands exist from 1804 (Brázdil et al. 2012a, 2012b), the overlap between documentary and instrumental data is limited to the 1804–1854 period (explained variance between 35% in JJA and 26% in DJF). Nevertheless, the reconstruction obtained adequately represents precipitation in the Czech Lands in AD 1501–2010. The precipitation series for the Czech Lands up to 2010 (Brázdil et al. 2012a, 2012b) was further extended to January 2011–August 2015.

The calculation of SPI requires monthly precipitation totals, while SPEI, Z-index and PDSI need monthly temperature means as well. While temperature data were estimated from documentary data for each month (Dobrovolný et al. 2010), the documentary sources for precipitation provided only seasonally-resolved data between 1501 and 1803 (Dobrovolný et al. 2015a). In order to estimate the likely distribution of seasonal precipitation totals among individual months and to create proxy monthly records, the Czech mean monthly series from the 1875–1974 instrumental period were employed, i.e. from the period with a sufficiently dense observational network. The proportions of precipitation for individual months of the season for each year between 1875 and 1974 were calculated on the basis of the observed monthly precipitation totals. For example, in the spring of 1875, March achieved 29% of the MAM total, April 25% and May 46%; in the spring of 1876, these figures were 35% in March, 32% in April and 33% in May; etc. The next step was to create a 100-member ensemble of monthly precipitation totals for each season and year between 1501 and 1803, dividing the seasonal precipitation according to the recorded monthly precipitation in individual years during the 1875–1974 period. Monthly precipitation totals for 1804–2015 were then added to every 100-series for 1501–1803.

SPI, SPEI, Z-index and scPDSI were then calculated by standard procedure with distribution calibrated to 1875–2014; however, this was done separately for each of the 100 realisations. Median and 5th and 95th percentiles from the 100-series were further estimated and used for 1501–1803, while after 1804 the calculated drought indices for all 100-series were identical. Only aggregations of SPI and SPEI for periods of 3 mo and longer were used for further analysis, significantly reducing the noise introduced by monthly precipitation estimated from seasonal totals. In all cases, the variation in water balance was aggregated and evaluated for seasons and years individually and examined carefully. It must be noted that all the major drought/wet episodes are present in the record regardless of ensemble membership. For all analyses in this study, series of drought indices calculated as median for 1501–1803 were extended further from 1804 to 2015 by indices derived from instrumental data.

The series of drought indices calculated were further divided into 3 groups, categorising the various types of drought:

(1) Short-term drought: seasonal series (DJF, MAM, JJA, SON) in terms of SPI-3, SPEI-3 and Z-index

(2) Medium-term drought: summer half-year (April–September) series in terms of SPI-6, SPEI-6 and Z-index

(3) Long-term drought: annual series in terms of SPI-12, SPEI-12 and scPDSI

Short-term drought (particularly for MAM and JJA) is used to represent agricultural drought (e.g. Brázdil et al. 2009, Hlavinka et al. 2009) affecting cereal and fodder crops in the region. Medium-term drought (April–September) has impacts on forests (e.g. Rybníček et al. 2015) and perennial cultures, including grapevines (e.g. Možný et al. 2016 this Special). Long-term drought indicators indicate hydrological drought with likely impacts on rivers and overall water availability. This division follows, to some degree, suggestions made by Heim (2002), who argued that each type of drought (meteorological, agricultural, hydrological and socio-economic) requires its own specific set of indicators. As each of these represents a different facet of drought, the most notable drought episodes will differ somewhat, as will — to some degree — the most/least drought affected periods.

The series of drought indices were further used for basic statistical analyses. Their temporal fluctuations were smoothed by 20 yr Gaussian filter, by calculation of linear trends and by selection of extremely dry years. For the pre-instrumental period, the grey area in Figs. 1–3 (see Section 3.1) expresses the interval between 5th and 95th percentiles of reconstructed values, thus identifying the confidence interval of 90% for reconstructed values. Comparison of drought index series with other reconstructions was based on 30 yr running correlation coefficients.

3. RESULTS

3.1. Drought variability

Fig. 1 shows fluctuations in the reconstructed Czech seasonal SPI-3, SPEI-3 and Z-index describing short-term (seasonal) droughts in the Czech Lands. These 3 indices correlate best in summer (between 0.97 for SPEI-3 with Z-index and 0.94 for SPI-3 with Z-index), while the lowest correlations appear in winter (0.67 and 0.71 for Z-index with SPI-3 and SPEI-3, respectively; but 0.96 for SPI-3 with SPEI-3). Inter-annual and inter-decadal variability is well-expressed in all series, while any statistically significant linear long-term trend is absent. Series smoothed by 20 yr Gaussian filter are very similar in the character of fluctuations and in alternation of relatively drier and wetter periods. The driest 30-yr periods for seasonal SPI-3 and SPEI-3 are more or less identical, although occurring in different sections of the period studied: 1680–1709 for DJF, 1774–1803 for MAM (1773–1802 for Z-index), 1700–1729 for JJA (also for Z-index) and 1605–1634 for SON. The driest 30 yr periods in terms of the Z-index occur in 1702–1731 in DJF and for 1699–1728 in SON. Although the final decades of the late 20th and early 21st centuries show a clear tendency towards increasing dryness in terms of SPEI-3 and the Z-index in all seasons except winter, they are less dry than the driest 30 yr periods, which concentrate markedly around the decades at the beginning and end of the 18th century.

The reconstructed series for the summer half-year (April–September), i.e. the SPI-6, SPEI-6 and Z-indices that characterise medium-term droughts (Fig. 2), do not differ much from the fluctuations in short-term droughts. The driest 30 yr periods are also very similar: 1773–1802 for SPI-6 and SPEI-6 and 1700–1729 for Z-index. This indicates that severe droughts in MAM and JJA significantly influence the character of drought for the whole summer half-year. The slightly increasing dryness of past decades is not expressed in SPI-6 values. All 3 drought indices correlate to a high degree: 0.98 for SPEI-6 with Z-index and 0.93 for the 2 remaining combinations of indices.

Fig. 3 shows fluctuations in reconstructed series of annual Czech drought indices, i.e. in terms of SPI-12, SPEI-12 and scPDSI. SPI-12 correlates closely with SPEI-12 (0.92); the correlations with scPDSI are 0.85 for SPEI-12 and 0.78 for SPI-12. Although SPI-12 and scPDSI indicate that the driest decades and 30-yr periods fell in the early 18th century (1704–1733), SPEI-12 shows more dryness in recent decades (1986–2015). This index captures the effect of increasing temperature means while precipitation totals remain more or less stable (see SPI-12). The steep decrease in fluctuations of annual scPDSI in 1727–1729 is particularly remarkable, and without parallel in the past 515 yr. This is a cumulative result of years with dry episodes occurring between 1724 and 1728 (compare with Brázdil et al. 2013a; for a description of the extremely dry year of 1726, see Brázdil & Trnka 2015).

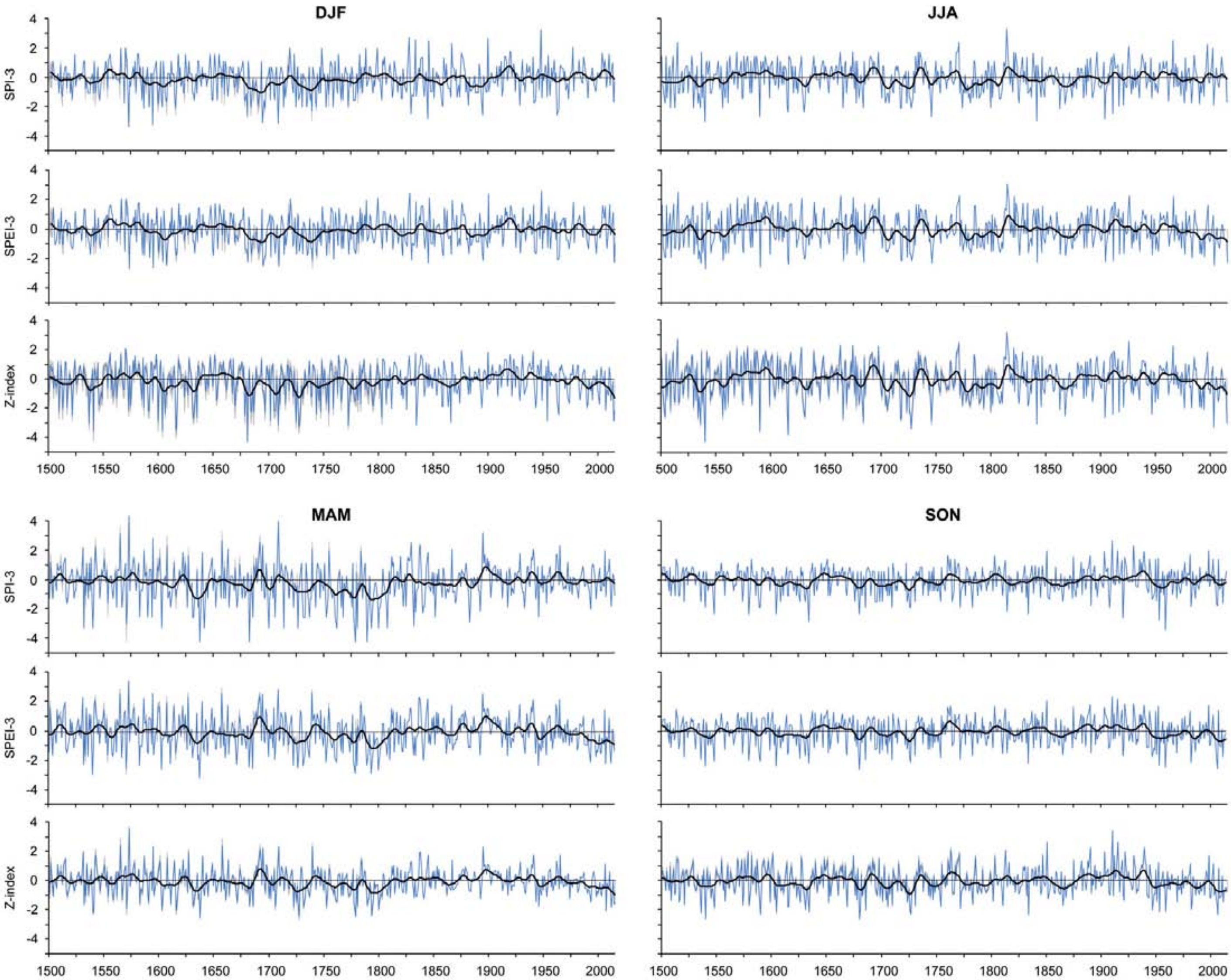

Fig. 1. Fluctuations in reconstructed series of Czech seasonal drought indices (SPI-3, SPEI-3 and Z-index as indicators of short-term drought) in the 1501–2015 period (SON: to 2014) smoothed by 20-yr Gaussian filter. For the pre-instrumental period (1501–1803), 5th and 95th percentiles approximate to 90 % confidence intervals (in grey)

3.2. Drought extremes

Using the reconstructed series of Czech drought indices, it was possible to identify the driest years in the entire 1501–2015 period. The 10 driest years were selected from each series used. For every group of drought indices, these 10 extreme years were then weighted in order of severity for all 3 indices (e.g. SPI-3, SPEI-3 and Z-index for JJA) to obtain their total weight, allowing the creation of a final order for the whole group. The 5 most important events in terms of short-term, medium-term and long-term droughts could then be identified.

The results, shown in Table 1, highlight the severity of the 1540 drought, which figures prominently in all cases except DJF, and was the most extreme drought in JJA and the summer half-year. It was identified by one or more indices as the most severe drought in JJA (SPI-3, SPEI-3, Z-index), SON (Z-index), the summer half-year (SPI-6, SPEI-6, Z-index) and annual series (SPI-12, SPEI-12) (Table 2). This event, which had particularly significant manifestations and impacts in western and Central Europe, has been described as a 'megadrought' on the European scale by Wetter et al. (2014). Detailed documentary testimony exists as to its effects in the

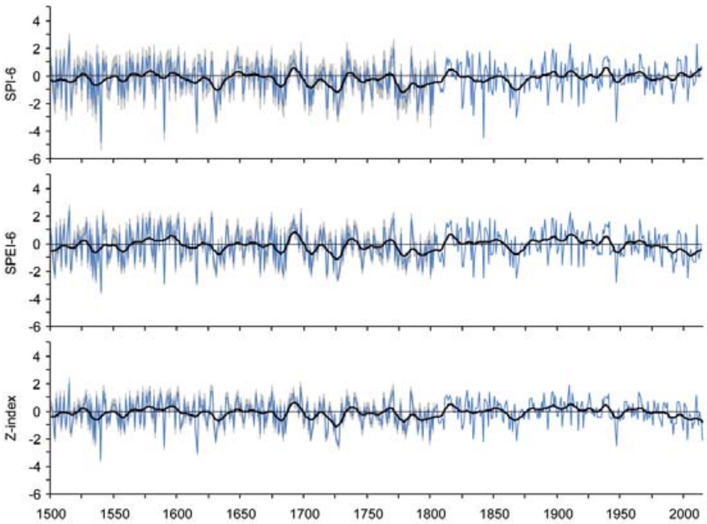

Fig. 2. Fluctuations in reconstructed series of Czech summer half-year drought indices (SPI-6, SPEI-6 and Z-index as indicators of medium-term drought) in the 1501–2015 period, smoothed by 20 yr Gaussian filter. For the pre-instrumental period, 5th and 95th percentiles approximate to 90% confidence intervals (in grey)

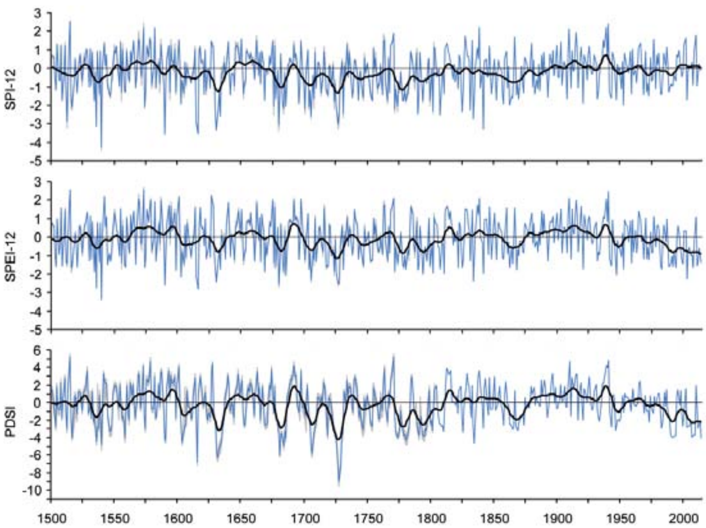

Fig. 3. Fluctuations in reconstructed series of Czech annual drought indices (SPI-12, SPEI-12 and scPDSI as indicators of long-term drought) in the 1501–2014 period, smoothed by 20 yr Gaussian filter. For the pre-instrumental period, the 5th and 95th percentiles approximate to 90% confidence intervals (in grey)

Czech Lands (Brázdil et al. 2013a, 2013b). For further discussion of the 1540 'megadrought' in Europe see more recent papers by Büntgen et al. (2015) and Pfister et al. (2015).

The severe drought of 1540 in JJA, summer half-year and annual indices in the Czech Lands was followed by two further droughts of significance in 1590

Table 1. The 5 driest seasonal, summer half-year and annual droughts in the 1501–2015 period, based on reconstructed series of Czech drought indices. STD: short-term drought (3 mo); MTD: medium-term drought (6 mo); LTD: long-term drought (1 yr)

Order	STD				MTD	LTD
	DJF	MAM	JJA	SON	Apr–Sep	Annual
1	1572–73	1638	1540	1680	1540	1616
2	1594–95	1779	1590	1959	1590	1540
3	1708–09	1540	1616	2006	1616	1590
4	1680–81	1794	1842	1540	1947	1631
5	1694–95	1603	2003	1605 and 1634	1727 and 1842	1727

and 1616 (for detailed descriptions, see Brázdil et al. 2013a,b). As Table 1 shows, together with the drought of 1540, these constitute the 3 most severe drought events in the entire 1501–2015 period. The list of most extreme droughts in JJA and the summer half-year is made up by droughts from the instrumental period, in 1842, 1947 and 2003 (for detailed descriptions, see Brázdil & Trnka 2015, Brázdil et al. 2016 this Special). The most severe droughts in the remaining 3 seasons occurred in 1572–73 (DJF), 1638 (MAM) and 1680 (SON). The MAM event of 1638 was identified as the most severe spring drought by all 3 drought indices (SPI-3, SPEI-3, Z-index). In DJF and MAM, no event among the 5 driest years occurred within the instrumental period. In SON, droughts in the years 1959 and 2006 were the next most serious after that occurring in 1680. Further, scPDSI indicated no drought from the instrumental period occurring among the 5 most extreme years.

Details of the driest periods at regular annual, decadal, 30 yr and 50 yr time scales are shown for the respective indices in Table 2. There is consistency among all three indices in identification of the driest decades for MAM (1791–1800), JJA (1531–1540) and annual drought indices (1721–1730). The decade 1721–1730 is also the driest in terms of the Z-index for DJF, SON, and the summer half-year and SPEI for SON and the summer half-year. For regular 30 yr periods, 1771–1800 is identified as the driest period by 10 indices, while 1981–2010 and 1681–1710 are each identified as driest by 4 indices. The driest 50 yr period is identified as occurring in 1701–1750 by 13 indices. 1751–1800 is identified as the driest 50 yr period for MAM by 3 indices and by SPI-6 for the summer half-year, while 1951–2000 was the driest according to SPEI-3 for SON. Among the centuries, the 18th century was identified as the driest in all drought indices.

Table 2. Driest annual, decadal, 30 yr and 50 yr periods in the 1501–2015 period according to reconstructed series of individual Czech drought indices. STD: short-term drought; MTD: medium-term drought; LTD: long-term drought; SPI: Standardised Precipitation Index; SPEI: Standardised Precipitation Evapotranspiration Index; scPDSI: self-calibrated Palmer Drought Severity Index

Period	STD: DJF			STD: MAM			STD: JJA		
	SPI-3	SPEI-3	Z-index	SPI-3	SPEI-3	Z-index	SPI-3	SPEI-3	Z-index
1 yr	1573	1573	1681	1638	1638	1638	1540	1540	1540
10 yr	1691–1700	1731–1740	1721–1730	1791–1800	1791–1800	1791–1800	1531–1540	1531–1540	1531–1540
30 yr	1681–1710	1681–1710	1681–1710	1771–1800	1771–1800	1771–1800	1771–1800	1981–2010	1771–1800
50 yr	1701–1750	1701–1750	1701–1750	1751–1800	1751–1800	1751–1800	1701–1750	1701–1750	1701–1750
Period	STD: SON			MTD: summer half-year			LTD: full year		
	SPI-3	SPEI-3	Z-index	SPI-6	SPEI-6	Z-index	SPI-12	SPEI-12	scPDSI
1 yr	1959	1680	1540	1540	1540	1540	1540	1540	1728
10 yr	1951–1960	1721–1730	1721–1730	1861–1870	1721–1730	1721–1730	1721–1730	1721–1730	1721–1730
30 yr	1681–1710	1981–2010	1981–2010	1771–1800	1771–1800	1771–1800	1771–1800	1981–2010	1771–1800
50 yr	1701–1750	1951–2000	1701–1750	1751–1800	1701–1750	1701–1750	1701–1750	1701–1750	1701–1750

4. DISCUSSION

4.1. Spatial significance

In the overall evaluation of reconstructed series of drought indices in the Czech Lands, it is important to consider their spatial interrelationships with other parts of Europe. Certain gridded seasonal drought indices for Europe are available that correlate with Czech series in the 1901–2012 period. Fig. 4 shows seasonal fields of correlation coefficients between Czech SPEI-3 and the Global SPEI Database (http://sac.csic.es/spei/index.html, accessed 25 October 2015). Except for summer, the long belt of positive correlations extends laterally from France to Russia, north- or northeastwards from the Black Sea. In the summer the area of positive correlations tends to focus around Czech territory, with a small extension to the east. By contrast, negative correlations are apparent in the northwestern part of Norway. Different fields of correlation coefficients appear for seasonal scPDSI, when compared with values from the CRU database (van der Schrier et al. 2006) (Fig. 5). The areas with positive correlations are much smaller and extend from the Czech territory to the southeast, almost as far as Greece. Other areas with positive correlation coefficients have a somewhat patchy and random distribution. Regions with negative correlations are mainly present over northern Europe (from the southern side of the Baltic Sea to the north).

It follows from Figs. 4 and 5 that it would be unreasonable to expect correlations between the indices used in this study and reconstructed series of precipitation totals for other areas, even close to the Czech territory, or drought indices for more distant areas. However, some significant correlation coefficients (however, only around the 0.20 level) were found in comparisons of SPI, SPEI and Z-index series with a multiproxy precipitation reconstruction for Central Europe (Pauling et al. 2006), and tree-ring width reconstructions from Norway spruce *Picea abies* for the Bavarian Forest (Wilson et al. 2005) and from black pine *Pinus nigra* for the Vienna region (R. Wimmer pers. comm.).

4.2. Multi-proxy comparison

Reconstructed Czech drought indices show correlations of between 0.30 and 0.40 with reconstructions of March–July precipitation totals derived from the tree-ring widths of fir *Abies alba* Mill. in southern Moravia (Brázdil et al. 2002) and with the May–June Z-index (Büntgen et al. 2011a). Statistically significant correlation coefficients with the May–June Z-index fluctuate between 0.37 (SPI, SPEI) and 0.39 (Z-index), while correlation coefficients for March–July precipitation totals vary from 0.34 (SPI, Z-index) to 0.35 (SPEI). The use of 30 yr running correlation coefficients between the series compared generally generates an unstable signal over time (Fig. 6). This is typical of comparisons between temperature and precipitation reconstructions based on documentary data or natural proxies (see e.g. Brázdil et al. 2010, Dobrovolný et al. 2010, 2015a). Both tree-ring reconstructions exhibit a marked drop in correlation with Czech drought indices in ~1560–1600 and March–July totals with SPI in the first half of the 18th century. High positive correlations occur particularly in the first half of the 17th century and for Z-index in the

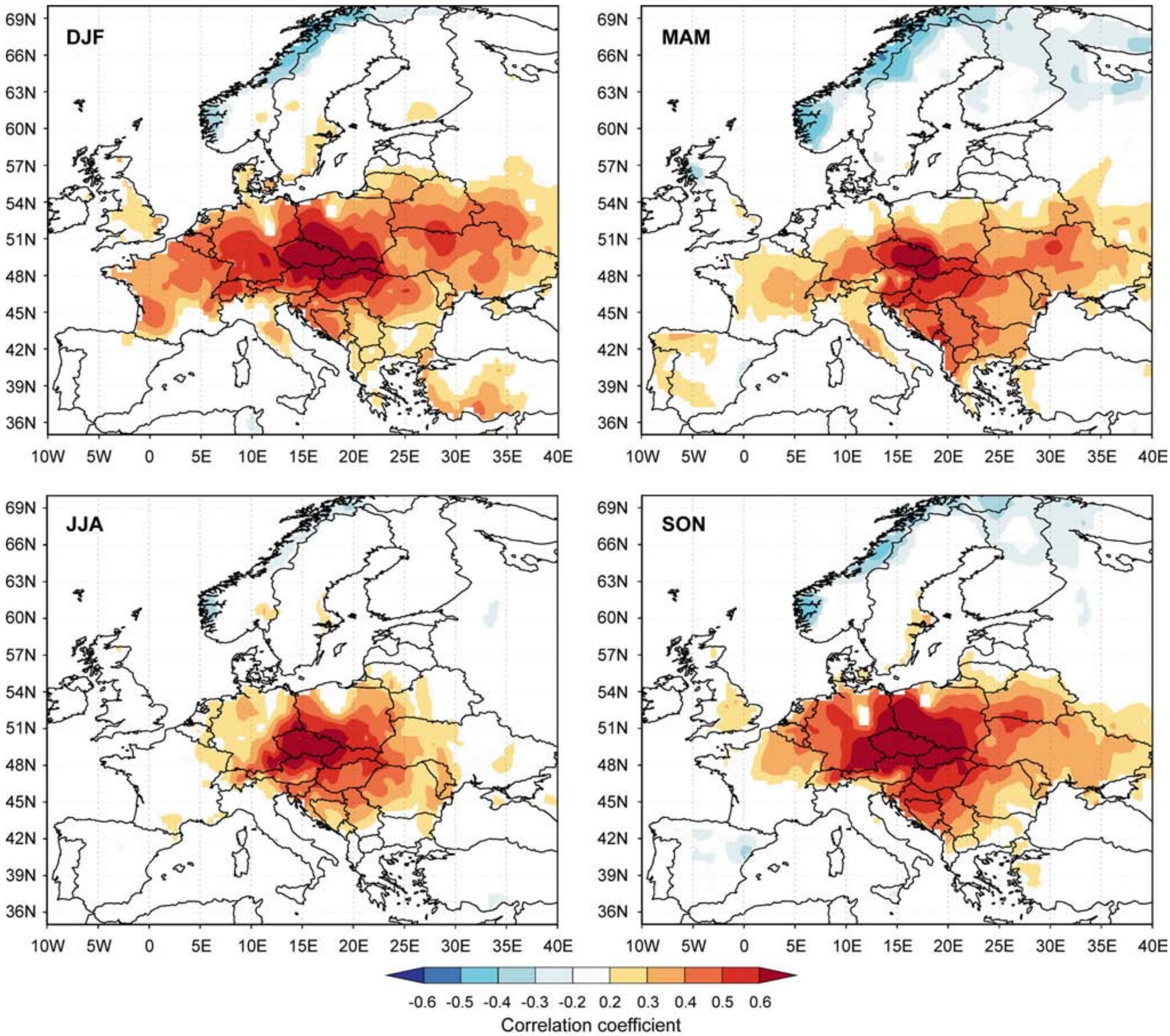

Fig. 4. Spatial correlations of seasonal Czech SPEI-3 series with SPEI-3 gridded series from the Global SPEI Database (http://sac.csic.es/spei/index.html, accessed 25 October 2015) in the 1901–2012 period

years ~1750–1875, after which a considerable decrease in correlation coefficient values is again apparent. Correlation coefficients of drought indices with precipitation totals in this second period are clearly below those with Z-index. The highest correlations of drought indices with March–July precipitation totals centred around 1925 give way to a steep decrease in correlation coefficients up to the second half of the 20th century, the result of a lost relationship between tree-rings and precipitation totals, as addressed by Brázdil et al. (2002).

The fluctuation of reconstructed series of Czech drought indices can also be compared with the 512 yr Czech chronology of drought frequency for the summer half-year created by Brázdil et al. (2013a). Cases in which at least 2 consecutive months were classified as dry, very dry or extremely dry were defined as dry episodes in the pre-instrumental period, while for the instrumental period, cases in which both SPEI-1 and Z-index had a return period of $N \geq 2$ yr were used. On the decadal scale, 8 yr with such dry episodes were recorded in 1801–1810 and 7 yr in 1701–1710, 1861–1870, 1941–1950, 1991–2000 and 2001–2010. However, only 2 of these decades appeared among the 5 driest in reconstructed SPI-6, SPEI-6 and Z-index series for the summer half-year: in order of severity, these were 1721–1730, 1861–1870, 1531–1540, 1791–1800 and 1701–1710; the remaining decades, with

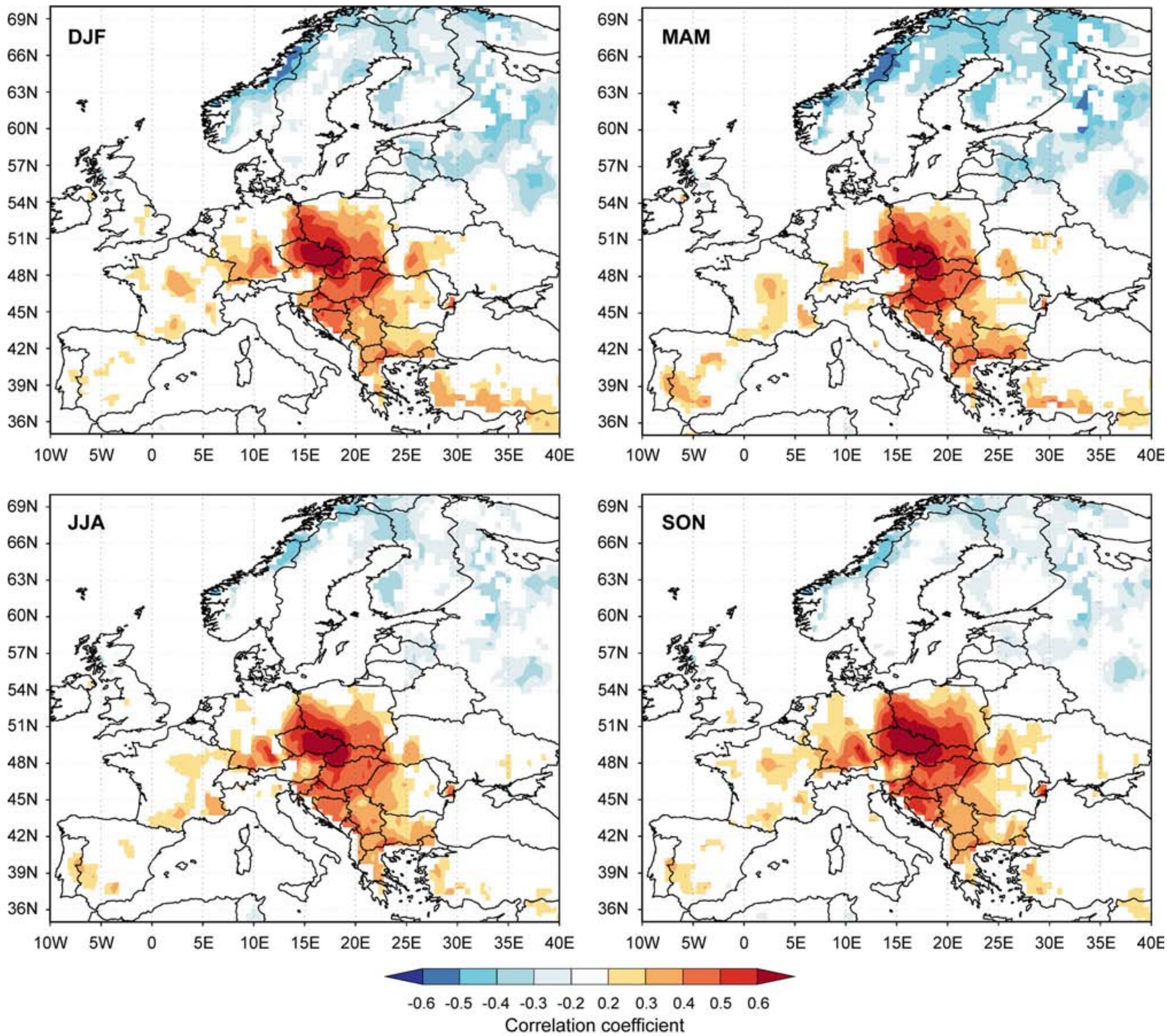

Fig. 5. Spatial correlations of seasonal Czech scPDSI series with seasonal scPDSI 3.21 gridded series from the CRU database (van der Schrier et al. 2006) in the 1901–2012 period

the exception of 1941–1950, appear in the list of the 10 driest decades for the summer half-year. Within 50 yr periods (Table 2) there is a high frequency of dry episodes in 1751–1800 (25 yr) and 1701–1750 (24 yr), while 1951–2000, with 26 dry years, is among the driest periods if only SON is considered. A total of 49 yr with episodes of drought in the 18th century render it the driest century in terms of Czech drought indices.

Significant correlation coefficients exist between drought indices and JJA scPDSI series reconstructed from tree rings in the European OWDA by Cook et al. (2015). Gridded data for the Czech Lands (CZs, 91 grids) and Central Europe (CEs, 421 grids) were used for calculation of 2 scPDSI series for comparison with reconstructed JJA SPEI-3 and Z-index, summer half-year SPEI-6 and Z-index, and finally with annual scPDSI. Fluctuations in 30 yr running correlation coefficients of reconstructed drought indices with CZs are shown in Fig. 7 and with CEs in Fig. 8 for the 1501–2012 period. Statistically significant correlation coefficients with CZs are slightly higher than those with CEs. Correlations with CZs fluctuate between 0.54 for the summer half-year Z-index and 0.47 for annual scPDSI, compared to a range of correlations with CEs between 0.51 for JJA Z-index and 0.41 for scPDSI. It follows from these comparisons that the best agreement between Czech drought indices with

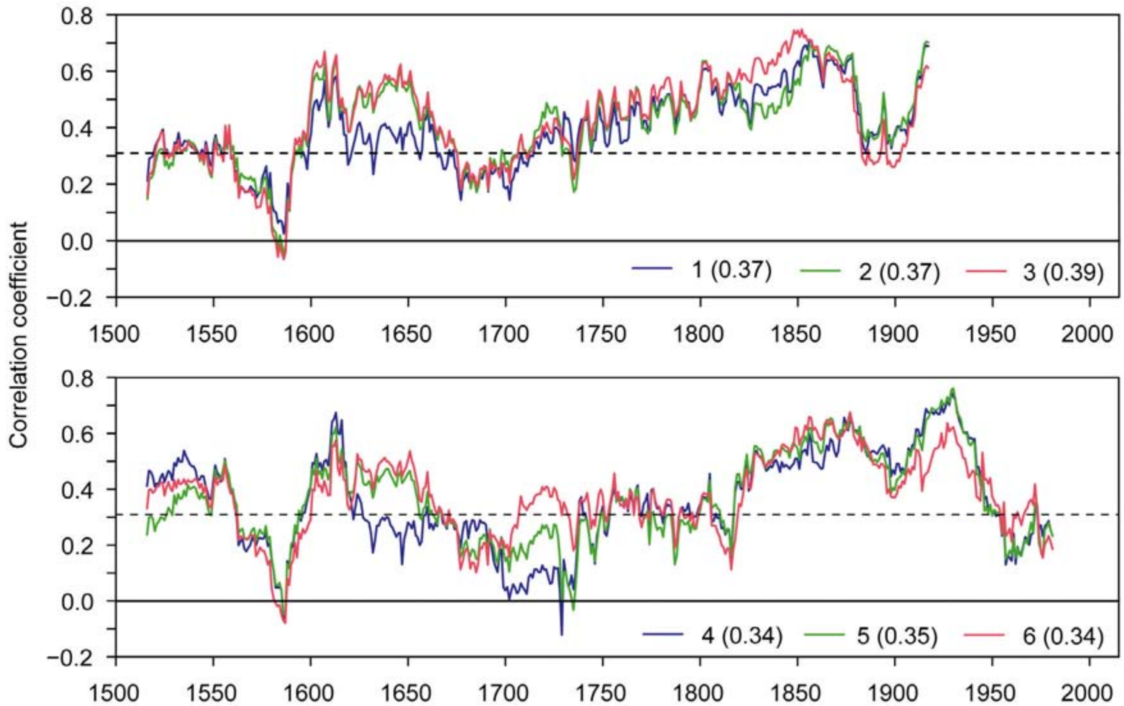

Fig. 6. Running 30 yr correlation coefficients of selected Czech drought index series with the May–June Z-index (1: SPI; 2: SPEI; 3: Z-index) and March–July precipitation totals (4: SPI; 5: SPEI; 6: Z-index) in southern Moravia derived from tree-ring widths of fir *Abies alba* Mill. (Brázdil et al. 2002, Büntgen et al. 2011a). Significant positive correlations appear above the broken horizontal line; correlation coefficients between corresponding series are indicated in parentheses

CZs and CEs occurs in the first half of the 16th century, during the 17th century, in the late 19th and early 20th centuries, and finally in ~1950–1980. Several important decreases in correlation values, even below the level of statistical significance, are apparent in the latter half of the 16th century, around 1700, mid-18th century and at its end. Despite this, the comparison clearly demonstrates the similarity between the Czech drought reconstructions based on documentary data and OWDA JJA scPDSI reconstructions based on tree-rings.

4.3. Uncertainties in data and methods

This study employs 4 separate drought indices, calculated from precipitation data or from a combination of temperature and precipitation, with the added possibility of including the influence of soil water-holding capacity. Indices including both temperature and precipitation not only allow the capture of drought driven by lack of rain, but also consideration of increased evaporative demand from the atmosphere. Such drought-stress reinforcement by higher temperatures is sometimes termed 'global-change-type drought' (Breshears et al. 2005). On the other hand, precipitation-based drought indices (including SPI) assume that variability of precipitation is much higher than that of other variables, and that the latter are stationary, i.e. their influence is negligible, and droughts are responses to temporal variability in precipitation totals. Each of the drought indices used herein differs not only in basic concept, but also in individual spectral characteristics (e.g. Heim 2002). It is therefore considered preferable to use a whole suite of drought indices to account for the different behaviours of each index across a range of frequency domains. A number of studies (e.g. Trnka et al. 2009, Paulo et al. 2012) have demonstrated that, while most common drought indices (including those used in this study) show considerable capability in drought identification, differences exist that are significant enough to justify the use of several types of drought index. Combining the use of indices with those driven by precipitation facilitates better attribution of droughts and drought trends in terms of their main driving factors. Paulo et al. (2012) also showed that differences in formulation and spectral characteristics impact upon the number of severe and extreme droughts determined (with scPDSI showing higher drought frequency). Further, PDSI, in this study representing non-normalised indices, is negatively biased; this

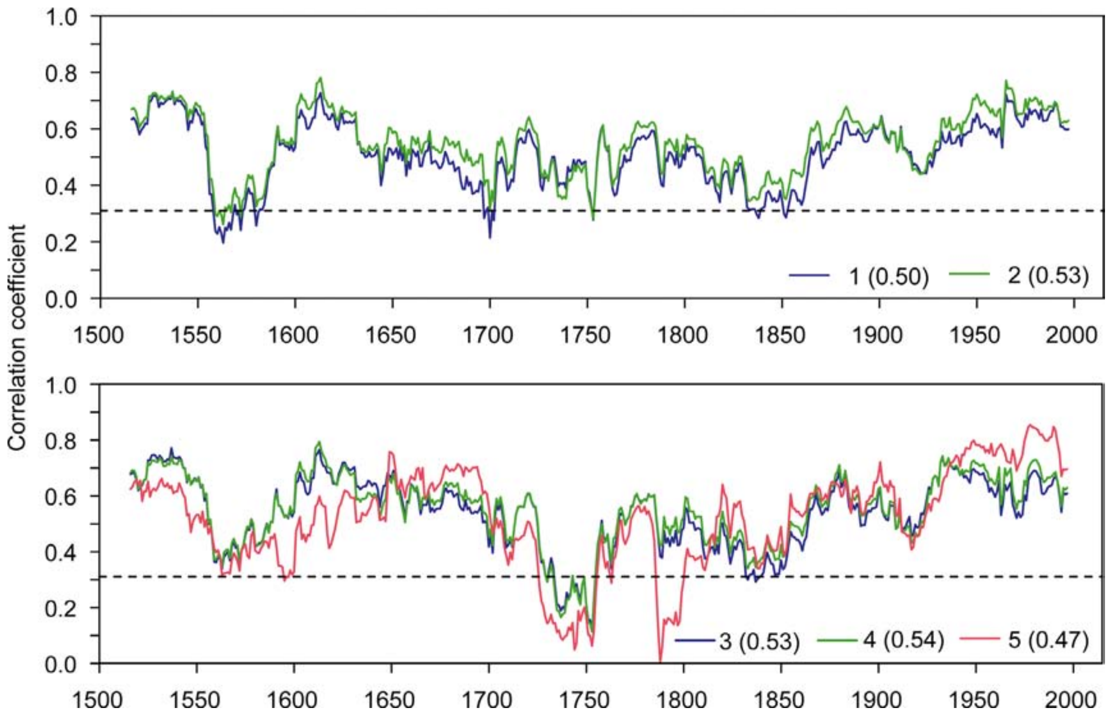

Fig. 7. Running 30 yr correlation coefficients of selected Czech drought indices series (1: JJA SPEI-3; 2: JJA Z-index; 3: summer half-year SPEI-6; 4: summer half-year Z-index; 5: annual scPDSI) with the Czech Lands JJA scPDSI series (CZs), after Cook et al. (2015). Significant positive correlations appear above the broken horizontal line; correlation coefficients between corresponding series are indicated in parentheses

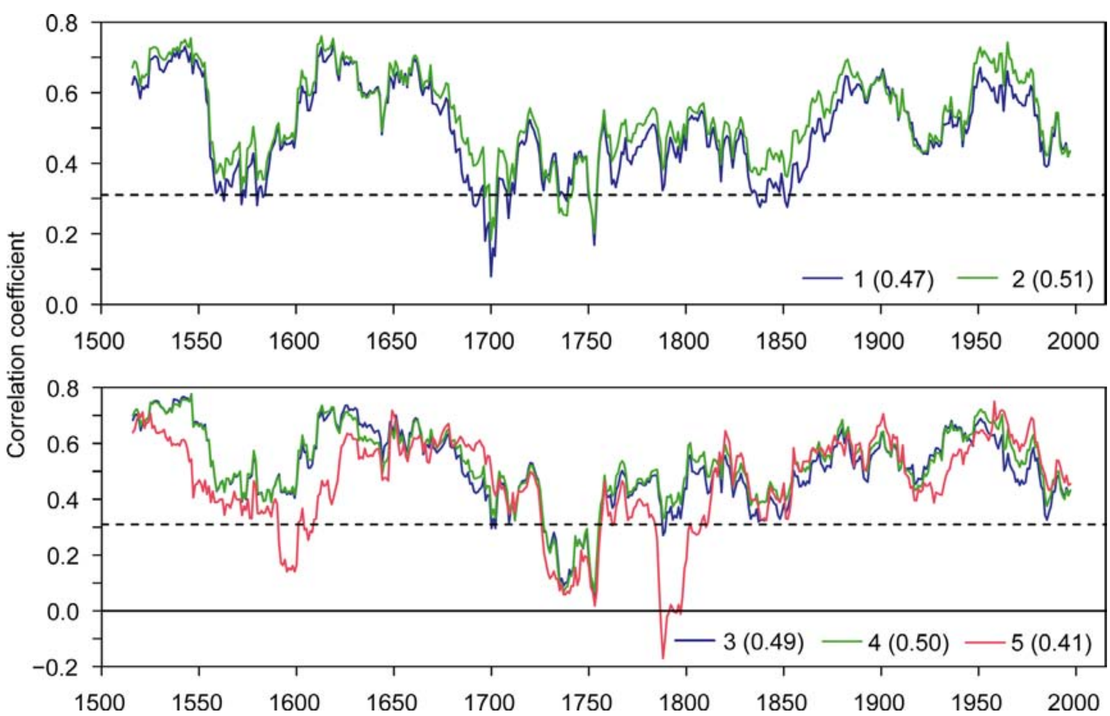

Fig. 8. Running 30 yr correlation coefficients of selected Czech drought indices series (1: JJA SPEI-3; 2: JJA Z-index; 3: summer half-year SPEI-6; 4: summer half-year Z-index; 5: annual scPDSI) with the central European lands JJA scPDSI series (CEs), after Cook et al. (2015). Significant positive correlations appear above the broken horizontal line; correlation coefficients between corresponding series are indicated in parentheses

relates to its calibration using data from extremely dry and wet events and not seeking a probabilistic balance between dry and wet events.

Four drought indices were calculated from reconstructions of central European temperature and Czech precipitation series by Dobrovolný et al. (2010, 2015a, respectively); the uncertainties within them are discussed in detail in both papers. The use of central European temperature data rather than data for the Czech Lands is not a source of bias, since there is a high degree of similarity between this series and mean Czech temperatures series (Brázdil et al. 2012a,b), as shown by the high correlation coefficients for the 2 series in the 1800–2007 period (see Section 2). More problematical is the use of the Czech seasonal precipitation reconstruction (Dobrovolný et al. 2015a), a situation arising out of its lesser explained variance in the 1804–1854 verification period, and its use of seasonal precipitation totals when monthly values are necessary for the calculation of drought indices. The way in which this problem was overcome in the calculation process is described in Section 2. Obviously, the monthly values for each index in the 1501–1803 period may be affected by the lack of monthly-resolved precipitation values. The value of such data would in any case be limited, as they could only consist of statistical extrapolation based on observed distribution over a long period. Aggregation of all drought indices to seasons and longer periods was therefore employed to minimise influences from the calculation procedure. As Figs. 1–3 show, the confidence intervals of all indices track the index values closely, showing a minimum influence of uncertainty, and demonstrating the robustness of the method used.

The use of both documentary and instrumental data for drought reconstructions raises the question of how the 2 types of data, and the method used for calculation of drought indices, might change the relative distribution of indices from the pre-instrumental (1501–1759) and the instrumental (1804–2015) periods. The 1760–1803 period, with its mixture of instrumental (temperature) and documentary (precipitation) data was excluded from this comparison. Fig. 9 shows examples of this comparison for JJA SPI-3, JJA Z-index, summer half-year SPEI-6 and annual scPDSI. The relative distribution of drought indices for the pre-instrumental and instrumental datasets is very similar. This distribution does not deviate significantly from normal distribution, since the Q-Q plots in Fig. 9 approximate closely to straight lines. The variability of indices in the pre-instrumental and instrumental periods was compared using the *F*-test. Data from the pre-instrumental period show higher variability compared with instrumental data for all index series. However, they are significantly higher (significance level $\alpha = 0.05$) only for JJA Z-index and annual scPDSI.

5. CONCLUSIONS

This study takes a completely new direction in the study of the long-term fluctuations of droughts, in that it calculates drought indices from series of quantitatively reconstructed mean air temperatures and precipitation totals derived from documentary data dating back to AD 1501. The drought indices calculated for the pre-instrumental period are then used at the same level as those derived from temperature and precipitation measurements in the instrumental period to create a 515 yr series in order to investigate long-term drought variability in the Czech Lands and Central Europe.

Despite great inter-annual and inter-decadal variability, no long-term trends are detectable in the series of Czech drought indices. The prevalence of extreme droughts in the pre-instrumental period is notable, with the most extreme drought occurring 1540, followed by 1590 and 1616, and the driest 30 yr periods occurring in the 3 decades at the beginning of the 18th century and at its end. In the longer-term context, a clear tendency of increasing dryness appears in the late 20th and early 21st centuries according to drought indices that combine the effects of temperature and precipitation, such as SPEI, Z-index and scPDSI. This is an indication of the influence of rising air temperatures on increasing potential evapotranspiration in the context of recent global warming (Trnka et al. 2015a) and decreasing soil moisture (Trnka et al. 2015b).

The reconstructed 515 yr series of drought indices for the Czech Lands provided only weak correlations with other European precipitation series, but compared well with precipitation and drought indices reconstructed from hydric-sensitive fir tree-ring series in southern Moravia (Brázdil et al. 2002, Büntgen et al. 2011a) as well as with a European OWDA JJA scPDSI reconstruction (Cook et al. 2015), thus facilitating cross-checking of the 2 methods of reconstruction. The methodological approach here applied has great potential for use in the creation of new drought series for Europe. Moreover, the reconstructed series of Czech drought indices will prove useful for comparisons with other European drought reconstructions.

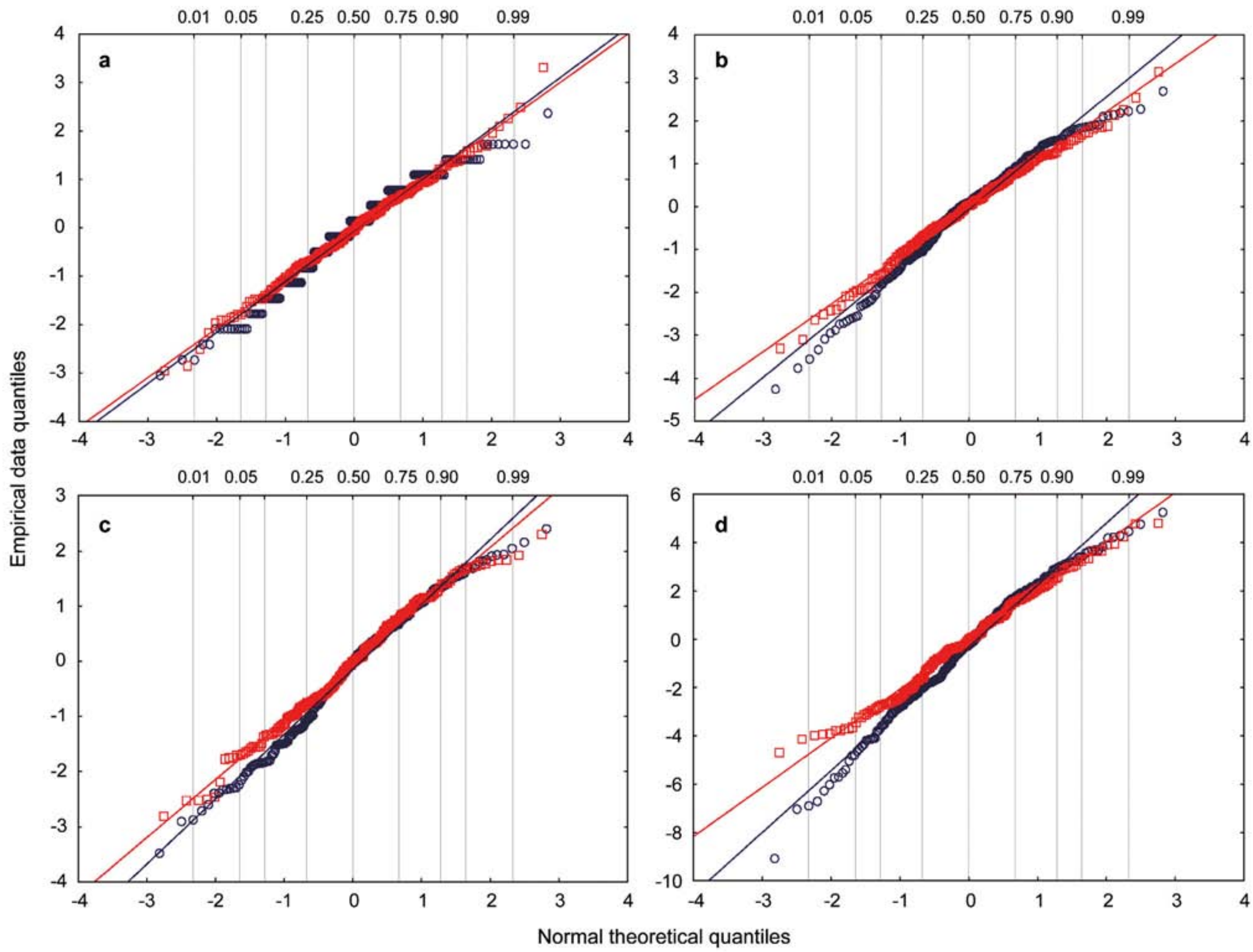

Fig. 9. Q-Q plots comparing distribution of reconstructed drought indices for the pre-instrumental (1501–1759, blue) and instrumental (1804–2015, red) periods in the Czech Lands: (a) JJA SPI-3, (b) JJA Z-index, (c) summer half-year SPEI-6, (d) annual scPDSI. Vertical straight lines indicate a comparison of distribution of indices against theoretical normal distribution

Acknowledgements. R.B. and P.D. acknowledge the support of the Grant Agency of the Czech Republic for project no. P209/11/0956, L.Ř. and H.V. for project no. 13-19831S and M.T. for project no. 13-04291S. R.B., P.D., M.T., U.B., L.Ř. and P.Š. also acknowledge funding from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I). Tony Long (Svinošice) helped improve the English.

LITERATURE CITED

Barriendos M (2005) Climate and culture in Spain: religious responses to extreme climatic events in the Hispanic Kingdoms (16th–19th century). In: Behringer W, Lehmann H, Pfister C (eds) Kulturelle Konsequenzen der 'Kleine Eiszeit' — Cultural consequences of the 'Little Ice Age'. Vandenhoeck & Ruprecht, Göttingen, p 379–414

Brázdil R, Trnka M (eds) (2015) Sucho v českých zemích: minulost, současnost, budoucnost (Drought in the Czech Lands: past, present and future). Centrum výzkumu globální změny Akademie věd České republiky, v.v.i., Brno

Brázdil R, Štěpánková P, Kyncl T, Kyncl J (2002) Fir tree-ring reconstruction of March–July precipitation in southern Moravia (Czech Republic), 1376–1996. Clim Res 20: 223–239

Brázdil R, Pfister C, Wanner H, von Storch H, Luterbacher J (2005) Historical climatology in Europe — the state of the art. Clim Change 70:363–430

Brázdil R, Trnka M, Dobrovolný P, Chromá K, Hlavinka P, Žalud Z (2009) Variability of droughts in the Czech Republic, 1881–2006. Theor Appl Climatol 97:297–315

Brázdil R, Dobrovolný P, Luterbacher J, Moberg A, Pfister C, Wheeler D, Zorita E (2010) European climate of the past 500 years: new challenges for historical climatology. Clim Change 101:7–40

Brázdil R, Bělínová M, Dobrovolný P, Mikšovský J and others (2012a) Temperature and precipitation fluctuations in the Czech Lands during the instrumental period. Masaryk University, Brno

Brázdil R, Zahradníček P, Pišoft P, Štěpánek P, Bělínová M, Dobrovolný P (2012b) Temperature and precipitation fluctuations in the Czech Lands during the period of instrumental measurements. Theor Appl Climatol 110:17–34

Brázdil R, Dobrovolný P, Trnka M, Kotyza O and others

(2013a) Droughts in the Czech Lands, 1090–2012 AD. Clim Past 9:1985–2002

Brázdil R, Kotyza O, Dobrovolný P, Řezníčková L, Valášek H (2013b) Climate of the sixteenth century in the Czech Lands. Masaryk University, Brno

Brázdil R, Trnka M, Mikšovský J, Řezníčková L, Dobrovolný P (2015) Spring-summer droughts in the Czech Land in 1805–2012 and their forcings. Int J Climatol 35:1405–1421

Brázdil R, Raška P, Trnka M, Zahradníček P and others (2016) The Central European drought of 1947: causes and consequences with particular reference to the Czech Lands. Clim Res 70:161–178

Breshears DD, Cobb NS, Rich PM, Price KP and others (2005) Regional vegetation die-off in response to global-change-type drought. Proc Natl Acad Sci USA 102:15144–15148

Büntgen U, Brázdil R, Frank D, Esper J (2010) Three centuries of Slovakian drought dynamics. Clim Dyn 35:315–329

Büntgen U, Brázdil R, Dobrovolný P, Trnka M, Kyncl T (2011a) Five centuries of Southern Moravian drought variations revealed from living and historic tree rings. Theor Appl Climatol 105:167–180

Büntgen U, Brázdil R, Heussner KU, Hofmann J and others (2011b) Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium. Quat Sci Rev 30:3947–3959

Büntgen U, Tegel W, Career M, Krusic PJ, Hayes M, Esper J (2015) Commentary to Wetter et al. (2014): Limited tree-ring evidence for a 1540 European 'Megadrought'. Clim Change 131:183–190

Byun H, Wilhite DA (1999) Objective quantification of drought severity and duration. J Clim 12:2747–2756

Cook ER, Seager R, Kushnir Y, Briffa KR and others (2015) Old World megadroughts and pluvials during the Common Era. Sci Adv 1:e1500561

Dai A (2011) Drought under global warming: a review. WIREs Clim Change 2:45–65

Diodato N, Bellocchi G (2011) Historical perspective of drought response in central-southern Italy. Clim Res 49: 189–200

Dobrovolný P, Brázdil R, Valášek H, Kotyza O, Macková J, Halíčková M (2009) A standard paleoclimatological approach to temperature reconstruction in historical climatology: an example from the Czech Republic, AD 1718–2007. Int J Climatol 29:1478–1492

Dobrovolný P, Moberg A, Brázdil R, Pfister C and others (2010) Monthly and seasonal temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500. Clim Change 101:69–107

Dobrovolný P, Brázdil R, Trnka M, Kotyza O, Valášek H (2015a) Precipitation reconstruction for the Czech Lands, AD 1501–2010. Int J Climatol 35:1–14

Dobrovolný P, Rybníček M, Kolář T, Brázdil R, Trnka M, Büntgen U (2015b) A tree-ring perspective on temporal changes in the frequency and intensity of hydroclimatic extremes in the territory of the Czech Republic since 761 AD. Clim Past 11:1453–1466

Domínguez-Castro F, Santisteban JI, Barriendos M, Mediavilla R (2008) Reconstruction of drought episodes for central Spain from rogation ceremonies recorded at the Toledo Cathedral from 1506 to 1900: a methodological approach. Global Planet Change 63:230–242

Domínguez-Castro F, Garcia-Herrera R, Ribera P, Barriendos M (2010) A shift in the spatial patterns of Iberian droughts during the 17th century. Clim Past 6:553–563

Glaser R (2001) Klimageschichte Mitteleuropas. 1000 Jahre Wetter, Klima, Katastrophen. Primus Verlag, Darmstadt

Glaser R (2008) Klimageschichte Mitteleuropas. 1200 Jahre Wetter, Klima, Katastrophen. Primus Verlag, Darmstadt

Heim RR (2000) Drought indices: a review. In: Wilhite DA (ed) Drought: a global assessment. Hazards and disasters series, Vol. 1. Routledge, New York, NY, p 159–167

Heim RR (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165

Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Zalud Z, Mozný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric For Meteorol 149: 431–442

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time steps. In: Preprints, 8th Conference on Applied Climatology, January 17–22. Anaheim, CA, 17–22 January 1993. American Meteorological Society, Boston, MA, p 179–184

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol (Amst) 391:202–216

Možný M, Brázdil R, Dobrovolný P, Trnka M and others (2016) Drought reconstruction based on grape harvest dates for the Czech Lands in AD 1499–2012. Clim Res 70: 119–132

Niemeyer S (2008) New drought indices. In: López-Francos A (ed) Drought management: scientific and technological innovations. CIHEAM, Zaragoza, p 267–274

Palmer WC (1965) Meteorological drought. Office of Climatology Research Paper 45, US Weather Bureau, Washington, DC

Pauling A, Luterbacher J, Casty C, Wanner H (2006) Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Clim Dyn 26:387–405

Paulo AA, Rosa RD, Pereira LS (2012) Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. Nat Hazards Earth Syst Sci 12:1481–1491

Pfister C (1988) Klimageschichte der Schweiz 1525–1860. Das Klima der Schweiz von 1525–1860 und seine Bedeutung in der Geschichte von Bevölkerung und Landwirtschaft, Band 1–2. Paul Haupt, Bern

Pfister C (1999) Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen (1496–1995). Paul Haupt, Bern

Pfister C, Wetter O, Brázdil R, Dobrovolný P and others (2015) Tree-rings and people — different views on the 1540 Megadrought. Reply to Büntgen et al. 2015. Clim Change 131: 191–198

Piervitali E, Colacino M (2001) Evidence of drought in western Sicily during the period 1565–1915 from liturgical offices. Clim Change 49:225–238

Rybníček M, Čermák P, Prokop O, Žid T, Trnka M, Kolář T (2015) Oak (*Quercus* spp.) response to climate differs more among sites than among species in central Czech Republic. Dendrobiology (Pozn) 75:55–65

Stocker TF, Qin D, Plattner GK, Tignor M and others (eds) (2013) Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Trnka M, Dubrovský M, Svoboda M, Semerádová D, Hayes M, Žalud Z, Wilhite D (2009) Developing a regional drought climatology for the Czech Republic. Int J

Climatol 29:863−883
Trnka M, Brázdil R, Balek J, Semerádová D and others (2015a) Drivers of soil drying in the Czech Republic between 1961 and 2012. Int J Climatol 35:2664−2675
Trnka M, Brázdil R, Možný M, Štěpánek P and others (2015b) Soil moisture trends in the Czech Republic between 1961 and 2012. Int J Climatol 35:3733−3747
van der Schrier G, Briffa KR, Jones PD, Osborn TJ (2006) Summer moisture variability across Europe. J Clim 19: 2818−2834
Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multi-scalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J Clim 23:1696−1718
Vogt JV, Somma F (eds) (2000) Drought and drought mitigation in Europe: advances in natural and technological hazards research. Kluwer, Dordrecht
Wetter O, Pfister C, Werner JP, Zorita E and others (2014) The year-long unprecedented European heat and drought of 1540 — a worst case. Clim Change 125:349−363
Wilson RJS, Luckman BH, Esper J (2005) A 500 year dendroclimatic reconstruction of spring–summer precipitation from the lower Bavarian Forest region, Germany. Int J Climatol 25:611−630
Wu H, Svoboda MD, Hayes MJ, Wilhite DA, Wen F (2007) Appropriate application of the standardized precipitation index in arid locations and dry seasons. Int J Climatol 27: 65−79
Zahradníček P, Trnka M, Brázdil R, Možný M and others (2015) The extreme drought episode of August 2011– May 2012 in the Czech Republic. Int J Climatol 35: 3335−3352

Editorial responsibility: Donald Wilhite (Guest Editor), Lincoln, Nebraska, USA

Submitted: December 15, 2015; Accepted: February 28, 2016
Proofs received from author(s): June 1, 2016

Vol. 70: 119–132, 2016
doi: 10.3354/cr01423

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

Drought reconstruction based on grape harvest dates for the Czech Lands, 1499–2012

M. Možný[1], R. Brázdil[2,3], P. Dobrovolný[2,3], M. Trnka[2,6], V. Potopová[4], P. Hlavinka[6,2], L. Bartošová[6,2], P. Zahradníček[2,5], P. Štěpánek[2,5], Z. Žalud[6,2]

[1]Czech Hydrometeorological Institute, Doksany Observatory, 411 82 Doksany, Czech Republic
[2]Global Change Research Institute AS CR, Bělidla 986/4a, 603 00 Brno, Czech Republic
[3]Institute of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
[4]Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 165 21 Prague 6, Czech Republic
[5]Czech Hydrometeorological Institute, Regional Office Brno, Kroftova 43, 616 67 Brno, Czech Republic
[6]Faculty of Agronomy, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic

ABSTRACT: The timing of maturity of grapes depends on the weather conditions during the growing season. This study relies on the dependence of harvest dates on the air temperature and dry/wet conditions. Recorded observations show that increases in air temperature and dryness are associated with earlier grape harvests. Documentary data of grape harvests from the Bohemian wine-growing region (mainly northwest of Prague) were combined with mean Standardized Precipitation Evapotranspiration Index (SPEI) series starting in 1841 and ordinary least square regression with subsequent scaling to reconstruct the mean SPEI values for this area for April to August from 1499 to 2012. The reconstructed SPEI series explains 75% of the drought variability since 1841. All dry years that were detected by the reconstructed April–August SPEI values correlate well with years of excellent and good red wine of vintage quality for 1499–1840. A comparison of the reconstructed series with other SPEI reconstructions from the Czech Lands (the recent Czech Republic) based on documentary and instrumental data shows good agreement. The results demonstrate that grape harvest series may be used as a proxy for drought reconstruction in the central European region.

KEY WORDS: Climate reconstruction · Drought · Grape harvest dates · SPEI · Bohemian wine-growing region

1. INTRODUCTION

Documentary data are important proxies that can be used to study climate before the instrumental period (Brázdil et al. 2005, 2010, Jones et al. 2005). Grape harvest dates (GHDs) have been successfully used for several temperature reconstructions, mainly for spring/summer temperatures. GHD is mainly influenced by the local temperature during the stages before the bloom and veraison (Chuine et al. 2004, García de Cortázar-Atauri et al. 2010). GHD series have been used for temperature reconstruction over large parts of Europe, e.g. in Austria (Strömmer 2003, Maurer et al. 2009), Czech Republic (Možný et al. 2016), France (Le Roy Ladurie & Baulant 1980, Chuine et al. 2004, Le Roy Ladurie 2005, Menzel 2005, Etien et al. 2008, Garnier et al. 2011), Germany (Glaser & Hagedorn 1991), Italy (Mariani et al. 2009), Switzerland (Pfister 1981, 1984, Burkhardt & Hense 1985, Meier et al. 2007) and Hungary (Kiss et al. 2011). An open-access dataset of GHD data from different parts of Europe has been compiled (Daux et al. 2012).

Temperature increases are accompanied by both an earlier onset of phenological phases, such as the

*Corresponding author: m.mozny@seznam.cz

Publisher: Inter-Research · www.int-res.com

beginning of the growing season, and a shortening of the intervals between successive phenological phases (Mozny et al. 2009, Možný et al. 2012). Harvests take place earlier with warmer temperatures and drought, and are delayed by wet conditions; however, enhanced warming from anthropogenic greenhouse gases can generate the high temperatures needed for early harvest without drought (Cook & Wolkovich 2016).

Advances in maturation dates of approximately 4 to 8 d per decade have been detected in the major wine-growing regions of Australia, France and Germany (Jones et al. 2005). Other climate variables also likely affect the ripening of grapes. For example, Webb et al. (2012) attributed the earlier ripening in Australian wine regions to temperature increases, soil drying, and/or changes in vineyard management techniques.

Several studies have reflected the growing risk of drought in the Czech Republic (e.g. Brázdil et al. 2009, 2015, 2016a this Special) and Central Europe (Spinoni et al. 2015). For example, a trend towards increased drought occurrence was recorded at most meteorological stations in the Czech Republic during 1961–2012; the greatest decreases in water reserves occurred in May and June (Trnka et al. 2015). Recent studies have also demonstrated the impact of soil moisture on extreme maximum temperatures in Europe (Hirschi et al. 2011, Whan et al. 2015). Occurrences of recent mega-heatwave temperatures have been argued to be due to the combination of soil desiccation and atmospheric heat accumulation (Miralles et al. 2014), and evapotranspiration has been shown to amplify the European summer drought (Teuling et al. 2013).

A drought may be defined as a negative deviation from the climatic water balance in a specific area over a given time interval (Brázdil et al. 2015). While the principal cause of all droughts is a deficit in precipitation over time, higher air temperatures, intense global radiation, lower relative humidity and higher wind speeds increase evapotranspiration and subsequently cause droughts (Allen et al. 1998). The Standardised Precipitation Evapotranspiration Index (SPEI), which was proposed by Vicente-Serrano et al. (2010), is often used to quantify droughts. This index uses the monthly differences between precipitation and potential evapotranspiration. The SPEI has been applied extensively in recent climatological and hydrological studies (e.g. Potop 2011, Heim & Brewer 2012, Li et al. 2012, Paulo et al. 2012, Potop et al. 2012, Brázdil et al. 2013a, 2015, Beguería et al. 2014, Yu et al. 2014, Potopová et al. 2016).

The main objective of this paper was to use GHDs for the reconstruction of drought series expressed by the SPEI for the Bohemian wine-growing region for 1499–2012, applying standard palaeoclimatological methods. Present results show the relationships between the GHDs and the air temperature, effective rainfall and potential evapotranspiration (including their trends), the long-term reconstructions of SPEI from GHDs and the relationship between the SPEI and vintage quality.

2. DATA AND METHODS

2.1. Study area

Wine production in the Czech Republic is limited to 2 wine-growing regions: southern Moravia and northwestern Bohemia. Wine-growing has been a tradition in these regions for more than 1000 yr. The Bohemian wine-growing region, which is the focus of this paper, is a small historical wine region located near Prague in the northwest part of the country near the Vltava, Ohře and Elbe rivers. Wine grapes are grown on south, southwest and southeast protected slopes at elevations from 170 to 260 m a.s.l. The vineyards are located around the city of Prague and 7 towns (Kutná Hora, Karlštejn, Mělník, Slaný, Roudnice nad Labem, Litoměřice and Most; Fig. 1a). This region specializes in the cultivation of traditional grape varieties that are suited to the northerly climate and which are particularly frost-resistant and have an early harvest date.

The Czech Republic is characterized by a moderate, humid climate and 4 distinct seasons (Tolasz et al. 2007). The leaf bud burst begins on average between 20 April and 8 May, the beginning of flowering occurs between 5 and 15 June, the end of flowering occurs between 15 and 26 June, and the softening of berries occurs between 1 and 29 August (Hájková et al. 2012). Average annual air temperature in the Bohemian wine-growing region area was 8.7–8.9°C (15–15.3°C for April–August) and the mean annual precipitation was 480–540 mm (255–280 mm for April–August) from 1961 to 2000 (Tolasz et al. 2007). The entire Czech wine region falls into Region I according to the standard growing degree-days, representing the climate type 'Cool' according to the Huglin Index and cool climate maturity according to the average growing season temperature index.

The area of investigation is one of the driest regions in the Czech Republic (cf. Brázdil et al. 2015).

Fig. 1. The Bohemian wine-growing region extends around the places identified on the map

For example, the April–September SPEI data indicate probabilities of the occurrence of dry months greater than 40% between 1961 and 2012 (Potopová et al. 2016).

2.2. GHDs and vintage quality data

GHDs were taken from the PHENODATA database of the Czech Hydrometeorological Institute (CHMI). These data contain systematic phenological observations from several hundred sites in the recent Czech Republic since 1845 (Svitáková et al. 2005). For the period prior to 1845, GHDs were obtained from several documentary sources such as chronicles, town documents, aristocratic documents, ecclesiastical materials, farming calendars, personal diaries, farming records and reports. GHD observations for the Bohemian wine-growing region were compiled for the period from 1499 to 2012. A total of 5363 harvest dates were collected from 61 sites. While a greater part of the data was related to the systematic observations starting after 1921, fewer data were available before 1700. There are no temporal gaps in the data; at least one entry was found for each year. The mean GHD series for 1499–2012 used the median values of the data from all of the sites in the corresponding year.

Vintage quality data, which were expressed as the sugar content at ripeness of *Vitis vinifera* L. cv. Pinot Noir by the Czech-Slovak standards (°NM), were obtained for the period from 1980 to 2015 from the Czech Statistical Office. The data from 1841 to 1980 were obtained from the database of CHMI, data from before 1841 are from the same sources as those described previously for the GHDs. Four classes were used for the vintage quality assessment: 2, excellent; 1, good; 0, average; and −1, poor.

2.3. Meteorological data

The meteorological data were taken from the CHMI CLIDATA database. Seven climatological and 33 rain-gauge stations were used to calculate representative mean meteorological time series for the entire Bohemian wine-growing region for the period 1841–2015. The ProClimDB and AnClim software (Štěpánek 2010) was used to homogenize the series using Alexandesson's standard normal homogeneity test, the bivariate test of Maronna and Yohai, the Easterling and Peterson test, and the Vincent method (for additional details, see Štěpánek et al. 2011). We calculated the effective precipitation using the Soil Conservation Service runoff curve-number method (USDA Soil Conservation Service 1972), which uses the daily precipitation, the modeled soil water content in the root zone, the wilting-point water and the field capacity water content (Williams et al. 2012). The Penman-Monteith equation (Allen et al. 1998) was used to estimate the potential evapotranspiration for the period from 1961 to 2015. The soil type and available water capacity were taken from the CHMI database, and the SoilClim model (Hlavinka et al. 2011) was used to estimate the soil water saturation.

2.4. Calculation of SPEI

Using representative meteorological time series (cf. Section 2.3), SPEI values were calculated for the period from 1841 to 2012. The following steps were applied to calculate the SPEI (Potop et al. 2012, Potopová et al. 2016):

(1) parameterization of the potential evapotranspiration based on the monthly minimum and maximum air temperatures and extra-terrestrial radiation (Hargreaves model; Hargreaves & Allen 2003);

(2) a simple monthly water balance that was calculated as the difference between the monthly effective precipitation and potential evapotranspiration;

(3) normalization of the climatic water balance into a log-logistic probability distribution to transform the original values to standardized units that are comparable in space and time and to the various SPEI time scales that were utilized in the study area.

2.5. Reconstruction of SPEI

The mean GHD series for 1499–2012 was also used as a predictor to reconstruct the SPEI for the Bohemian wine-growing region. A linear regression model (LRM) was used to calibrate the GHDs to the target SPEI values. LRMs are commonly used in paleoclimatology for climate reconstruction (Cook et al. 1994), and this model was recently applied in historical climatology for series of documentary data of (bio)physical series and temperature indices (e.g. Leijonhufvud et al. 2008, 2010, Dobrovolný et al. 2009, 2010, Brázdil et al. 2010). The quality of the LRM calibration was evaluated with the square of Pearson's correlation coefficient (r^2), the standard error of estimate (SE), and the Durbin-Watson test (DW). While r^2 and SE evaluate the quality of the regression model, the DW diagnoses the first-order autocorrelation within the regression residuals (von Storch & Zwiers 1999). DW values between 1.5 and 2.5 are generally acceptable, while those outside this range indicate problems with reconstructing multi-decadal fluctuations.

Verification was based on several measures of reconstruction skill, including r^2, reduction of error (RE) and the coefficient of efficiency (CE, Cook et al. 1994). While r^2 quantifies the amount of SPEI variability that is explained by the reconstruction, RE indicates whether a reconstruction provides a better estimate of the SPEI variability than simply using the mean value of the target SPEI in the calibration period ($\bar{x}_c$). RE is calculated as:

$$RE = 1 - \left[\frac{\sum_{i=1}^{n} (x_i - \hat{x}_i)^2}{\sum_{i=1}^{n} (x_i - \bar{x}_c)^2} \right] \quad (1)$$

where x_i and $\hat{x}_i$ are the target and reconstructed SPEI values for the verification period, i.e. the mean value of target SPEI in the calibration period $\bar{x}_c$. CE is similar to RE, but it tests the reconstruction skill against the mean value of the target SPEI in the verification period ($\bar{x}_v$):

$$CE = 1 - \left[\frac{\sum_{i=1}^{n} (x_i - \hat{x}_i)^2}{\sum_{i=1}^{n} (x_i - \bar{x}_v)^2} \right] \quad (2)$$

Both RE and CE can have values between 1 and minus infinity. Positive RE and CE values indicate that the linear regression model has some potential for reconstruction, and the result is better than simply using the mean of a given calibration–verification period as a 'reconstruction'.

3. RESULTS

3.1. GHDs and meteorological variables in 1961–2012

The beginning of the grape harvest depends on the weather patterns of the preceding months. We found a statistically significant correlation ($r^2 = 0.72$, $p < 0.001$) between the GHDs and the mean April–August temperatures for 1961–2012 (Fig. 2a). Statistically significant relationships were also found between the GHDs and the total potential evapotranspiration for April–August (Fig. 2b; $r^2 = 0.64$, $p < 0.001$) and the total effective precipitation for April–August (Fig. 2c; $r^2 = 0.30$, $p < 0.01$).

The GHD changes in the Bohemian wine-growing region are illustrated by the example of the mean GHDs for 1961–2012 (Fig. 3a). A statistically significant trend toward earlier harvests was found during this period (0.33 d yr^{-1}; $r^2 = 0.30$, $p < 0.001$). The earliest harvests were recorded in the past 20 yr (1993–2012). The latest harvest dates occurred during 1972–1981, while the earliest dates occurred during 2000–2009. The earliest GHDs were recorded in 2000 (13 September) and 2003 (18 September), and

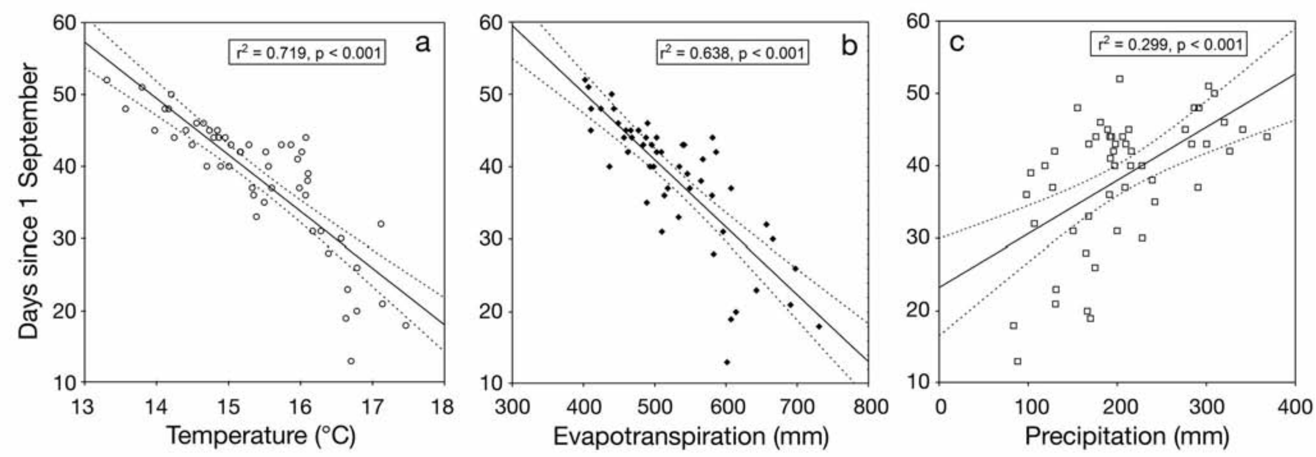

Fig. 2. Relationships between grape harvest dates (days since 1 September) and meteorological variables in the Bohemian wine-growing region for April–August 1961–2012: (a) mean air temperature; (b) total potential evapotranspiration; (c) total effective precipitation. Dotted lines show 95 % confidence level

the latest occurred in 1980 (22 October) and 1965 (21 October).

The climate variability in the Bohemian wine-growing region during 1961–2012 was illustrated by variations of 3 annual series of meteorological variables in the summer half-year (April–August). Statistically significant trends towards higher total potential evapotranspiration and mean temperature were detected (2.7 mm yr^{-1}, $r^2 = 0.57$, $p < 0.01$ and 0.044°C yr^{-1}, $r^2 = 0.46$, $p < 0.01$, respectively; Fig. 3b,c). The highest mean April–August temperature and potential evapotranspiration were recorded in 2003 (17.5°C and 731 mm, respectively), while the lowest mean April–August temperature and evapotranspiration occurred in 1980 (3.3°C and 411 mm). The April–August precipitation totals did not show any significant long-term trends (Fig. 3d). Changes in precipitation that coincided with increases in temperature and evapotranspiration did not increase the risk of drought in the vine-growing season. A statisti-

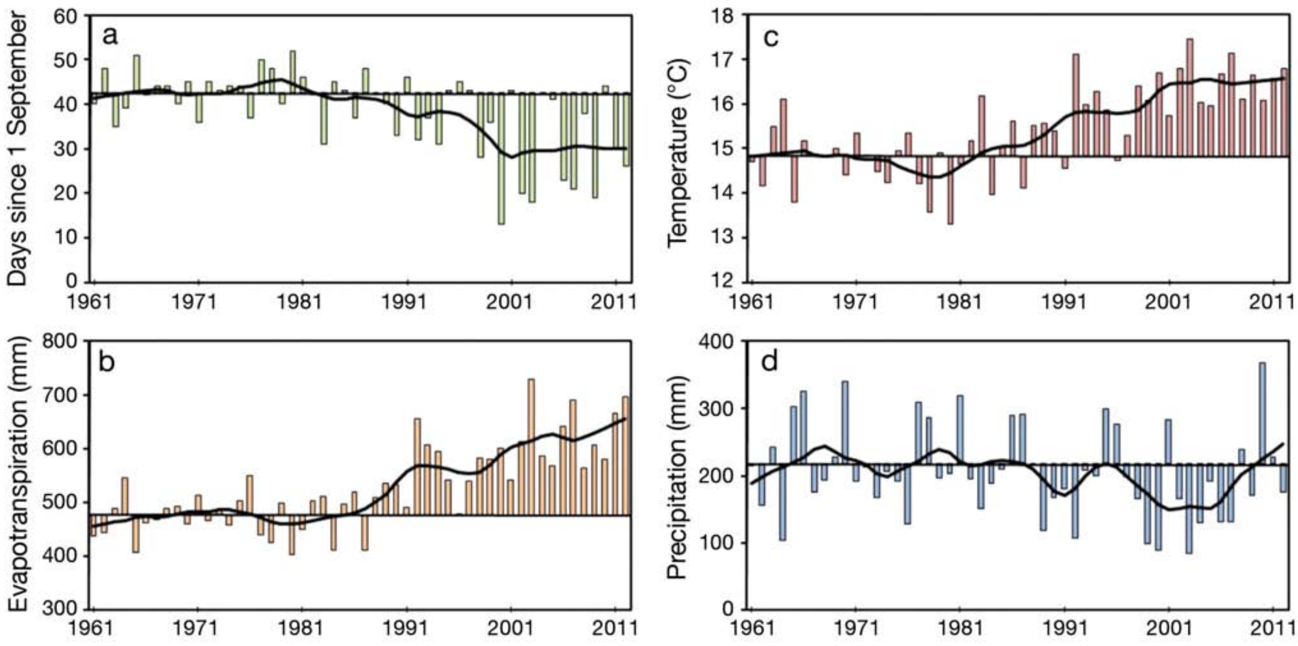

Fig. 3. Fluctuations in grape harvest dates and meteorological variables in the Bohemian wine-growing region for April–August 1961–2012: (a) grape harvest dates (days since 1 September), (b) total potential evapotranspiration, (c) mean air temperature, (d) total effective precipitation. Bars indicate deviations from the 1961–1990 means (horizontal lines). Data are smoothed by a 10 yr Gaussian filter (black line)

Table 1. Summary of the calibration and verification statistics that were used for the SPEI reconstruction based on the grape harvest dates in the Bohemian wine-growing region for 2 sub-periods. r^2: variance; SE: standard error of estimate; DW: Durbin-Watson test; RMSE: root mean square error; RE: reduction of error; CE: coefficient of efficiency

Sub-period	Calibration statistic			Verification statistic			
	r^2	SE	DW	r^2	RMSE	RE	CE
Early calibration (1841–1925)/late verification (1926–2010)	0.70	0.48	2.20	0.77	0.48	0.79	0.76
Early verification (1841–1925)/late calibration (1926–2010)	0.77	0.48	2.07	0.70	0.47	0.74	0.70

cally significant trend toward earlier grape harvests and statistically significant relationships between the GHDs and the air temperatures, total potential evapotranspiration and total effective precipitation were observed in the study period.

3.2. SPEI reconstruction based on GHDs

Overlapping periods of GHDs and calculated SPEI values for 1841–2010 and the linear regression model were used to reconstruct the April–August SPEI for the Bohemian wine-growing region from 1499 to 2012. The calibration and verification were performed twice for early (1841–1925) and late (1926–2010) sub-periods, and the statistical measures described in Section 2.5 were used to evaluate the reconstruction skill. The entire process was performed for the early calibration and late verification sub-periods, and it was then repeated by switching the calibration and verification sub-periods. The final calibration was performed for the full overlapping period of 1841–2010.

Statistical measures were applied to both sub-periods to confirm the high reconstruction skill of the GHDs (Table 1). The results of the Durbin-Watson test indicate that there were no problems with the autocorrelation in the residuals. The RE and CE values were highly positive and indicated that the GHDs had a high potential for SPEI reconstruction. Fig. 4 shows comparisons of the measured and reconstructed SPEI values for the 2 exercises. The final calibration was performed for the full overlap period; the results indicate that the GHDs explain 75 % of the April–August SPEI variance in the period from 1841 to 2010. A change of 8.9 d in the GHDs approximately corresponds to a unit change in the April–August SPEI.

The SPEI values that were reconstructed through linear regression were adjusted further to have the same mean and variance over the overlapping period of 1841–2010. Uncertainty estimates were expressed as a 95 % confidence interval, which was defined as 2SE from the regression relationship between the GHDs and the calculated SPEI values within the full calibration period (Fig. 5). These intervals represent what is known as the 'regression error' and evaluate the quality of proxy data for only the calibration period.

The reconstructed series show that several irregular variations of drier and wetter periods occurred between 1499 and 2012. Significantly drier periods (based on unsmoothed data) were found for 1532–1556 and 1983–2012 (Fig. 5). The early GHDs indicate that the first half of the 16th century was exceptionally dry. Four significantly wetter periods, which occurred in approximately 1650, 1740, 1805 and 1913 and were separated by slightly drier intervals, were detected in the reconstruction. The driest 30 yr periods occurred from 1983 to 2012 (mean SPEI of −0.9), and the wettest occurred from 1900 to 1929 (0.13). The lowest April–August SPEI was recorded in 1540 (−3.4), and the highest was recorded in 1919 (1.9). The fluctuations of the April–August SPEI values show large inter-annual and inter-decadal variabilities and decreasing trends for the 19th century and particularly dramatic decreases since the late 1970s.

3.3. April–August SPEI and vintage quality

Vintage quality depends on the weather patterns of the preceding months. We found a statistically significant correlation (Spearman's rho = −0.79, $p < 0.01$) between the sugar content at ripeness of *Vitis vinifera* L. cv. Pinot Noir and the calculated April–September SPEI in the Bohemian wine-growing region in the period from 1980 to 2015 (Fig. 6a). Decreases of the April–September SPEI during previous years were reflected in higher sugar contents of the grapes. Therefore, the SPEI can be considered to be an important factor for the red wine vintage quality in this region. Poor quality vintages correspond to wet patterns, such as in 1980 (SPEI = 1.2) and 1984

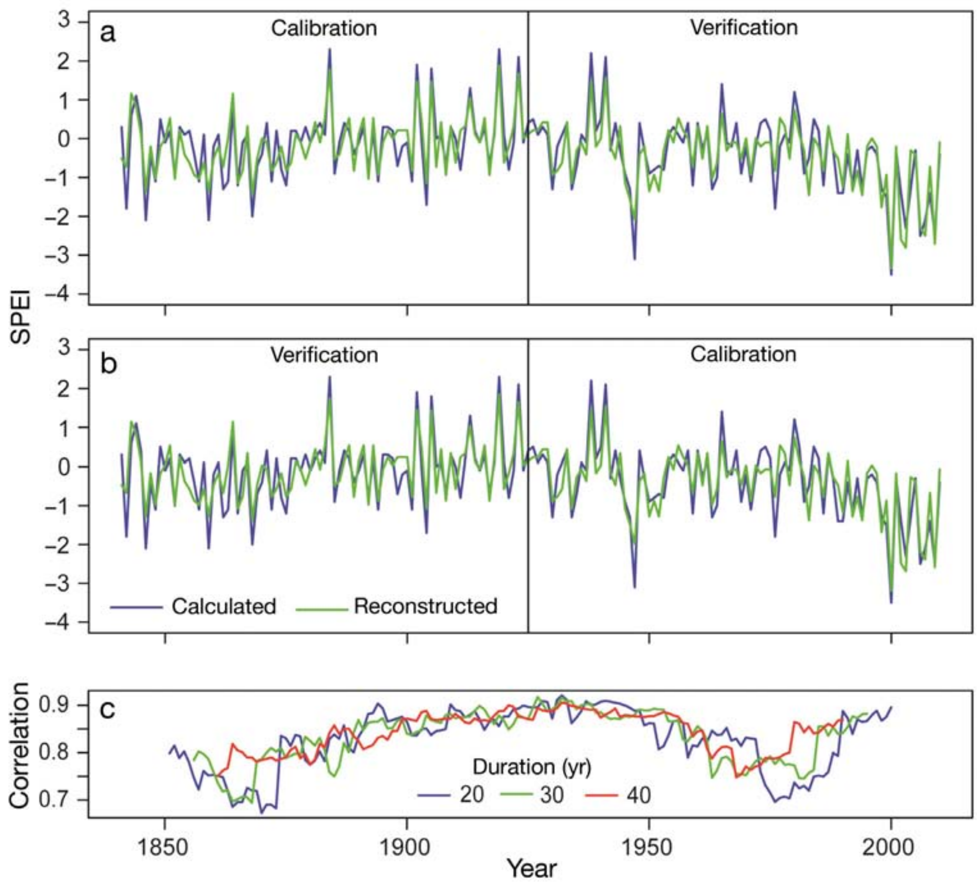

Fig. 4. (a,b) Comparison of the calculated and reconstructed April–August SPEI values for the Bohemian wine-growing region. Reconstructions were performed for (a) early (1841–1925) and (b) late (1926–2010) periods. (c) Running correlations for windows of 3 different durations (20, 30 and 40 yr) between the April–August SPEI and the grape harvest dates for 1841–2010

(SPEI = 0.5). In contrast, water deficit stress corresponds to very good or excellent vintages in 2015 (SPEI = −3.7), 2000 (SPEI = −3.5) and 2006 (SPEI = −2.6). A statistically significant trend towards higher sugar content was found during the period from 1980 to 2015 (0.13°NM yr^{-1}, $r^2 = 0.91$, $p < 0.01$; Fig. 6b). The decade 1981–1990 had the lowest mean sugar content (17.9°NM), while the highest was recorded from 2006 to 2015 (21.2°NM). The highest sugar contents occurred in 2006, 2013 and 2015 (23°NM), and the lowest occurred in 1984 (16.8°NM) and 1980 (17.2°NM).

A statistically significant correlation (Kendall's tau = −0.68, $p < 0.01$) also exists between the reconstructed April–August SPEI and the vintage quality in the Bohemian wine-growing region from 1499 to 1840 (Fig. 6c). As expected, poor vintage quality corresponded to wet periods, and good vintage quality corresponded to dry patterns. The vintage quality series does not show any strong long-term trends during 1499–1840 (Fig. 6d).

4. DISCUSSION

4.1. Relationship between grape harvest dates and meteorological variables

Although the strong dependence between the GHDs and the air temperature of the growing season is widely accepted and has also been used to test the quality of GHDs (Daux et al. 2012), relationships with other meteorological variables are not commonly used. We found statistically significant correlation coefficients between the GHDs and other meteorological variables (temperature, potential evapotranspiration and precipitation) in the Bohemian wine-growing region in the period from 1961 to 2012. We detected a statistically significant trend towards earlier GHDs, higher total potential evapotranspiration and mean temperatures. A trend towards earlier maturity of wine grapes has been observed in several countries as a result of recent climate change (Webb et al. 2011, Malheiro et al. 2013, Vršič et al. 2014).

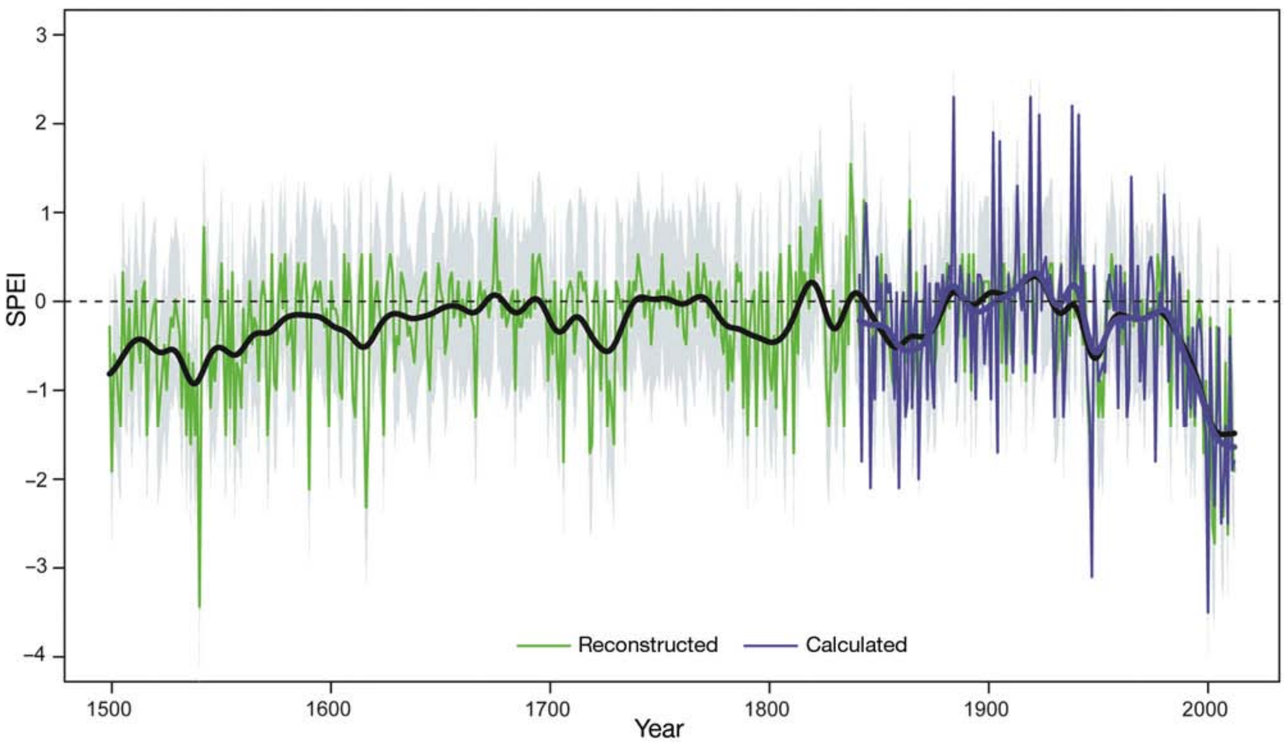

Fig. 5. Reconstructed April–August SPEI for the Bohemian wine-growing region calculated from grape harvest days for 1499–2012 and smoothed by a 30 yr Gaussian filter (black line). The light gray area shows the approximate 95% confidence interval based on the SE of the estimate. The reconstructed SPEI values are compared with the calculated SPEI values that were smoothed by a 30-year Gaussian filter for 1841–2012

Earlier maturity of wine grapes has been associated with increasing temperature and decreasing soil water content during the growing season in Australia (Webb et al. 2012), but this conclusion was apparently inconsistent with long-term trends of annual rainfall (White 2013). According to Urhausen et al. (2011), who analyzed the relationship between various climatic parameters and phenological stages in viticulture, only temperature-based predictors showed sufficient skill. In contrast, Ramos et al. (2015) found high correlations between the veraison date and temperature variables as well as with precipitation–evapotranspiration data that were recorded during the bloom–veraison period. The interaction of temperature with other meteorological variables must be taken into account; for example, the warm season is often a time of higher solar radiation, lower total rainfall and higher vapor pressure deficits (Sadras et al. 2012). Zahradníček (2009) found high correlations of selected phenophases (e.g. leaf bud burst, beginning and end of flowering, softening of berries) of vines (*Vitis vinifera* L. cv. Lemberger) with the air temperature and potential evapotranspiration in the Moravian wine-growing region for 1984–2007; the relationship with the total precipitation was statistically significant. We found statistically significant correlations between the GHD and temperature as well as with precipitation and potential evapotranspiration (calculated by the Penman-Monteith equation) for the period from 1961 to 2015. We used the GHD series to reconstruct the drought index SPEI. The SPEI uses the basic water balance calculation (monthly differences between precipitation and potential evapotranspiration). The inclusion of temperature (the monthly minimum and maximum air temperatures) along with precipitation data allows SPEI to account for the impact of temperature on a drought situation. The output is applicable for all climate regimes, with the results being comparable because they are standardized. With the use of temperature data, SPEI is an ideal index when looking at the impact of climate change in model output under various future scenarios (WMO & GWP 2016).

Cook & Wolkovich (2016) investigated the climate controls of GHD from 1600–2007 in France using historical harvest and climate data. Early harvest occured with warmer temperatures (−6 d $°C^{-1}$) and were delayed by wet conditions (+0.07 d mm^{-1}; +1.68 d $PDSI^{-1}$) during spring and summer. In recent decades (1981–2007), however, the relationship

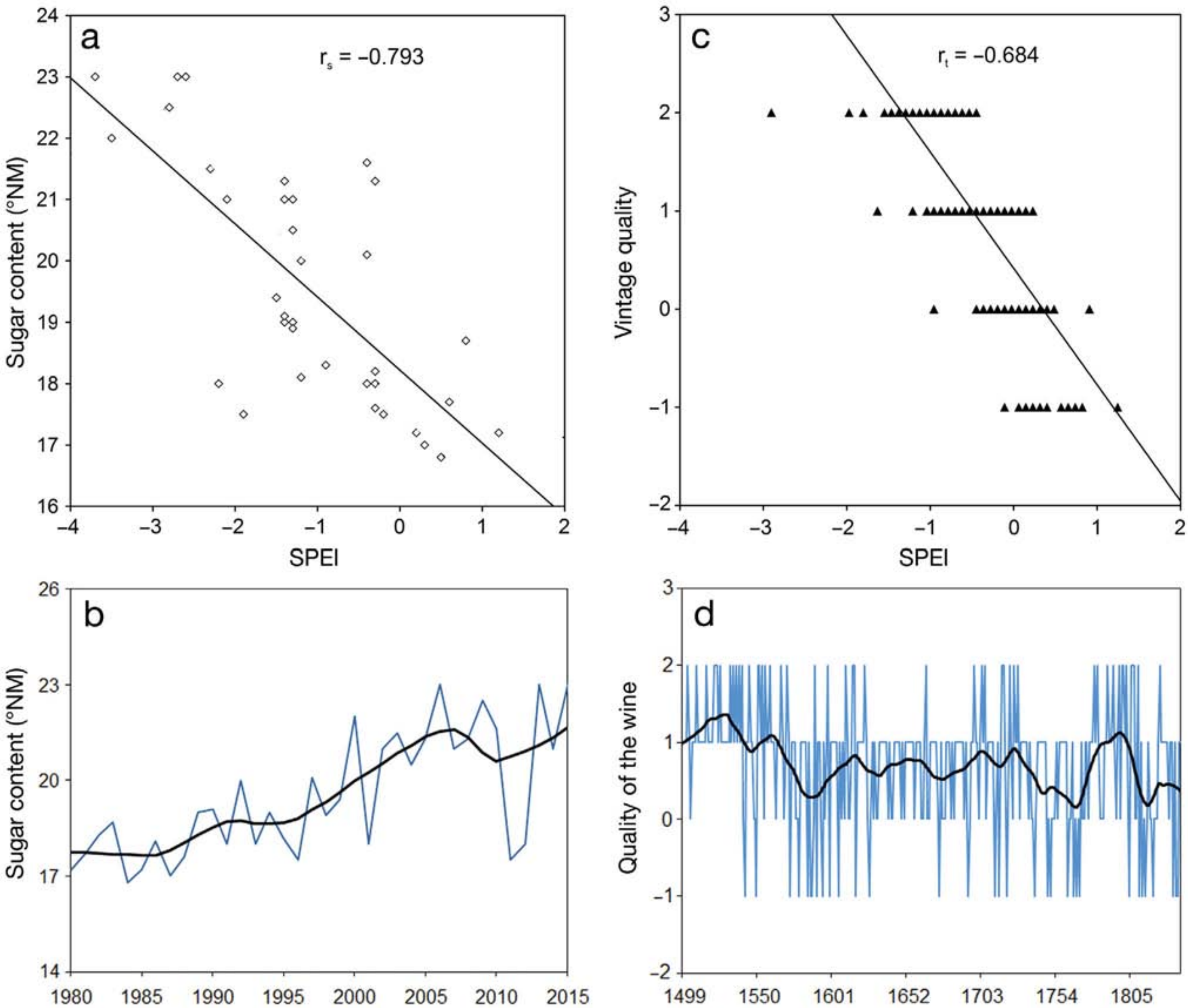

Fig. 6. Relationships between the calculated April–August SPEI values and (a) sugar content at ripeness of *Vitis vinifera* L. cv. Pinot Noir and (b) variation in sugar content in the Bohemian wine-growing region from 1980–2015, and (c) the relationships between reconstructed April–August SPEI values and vintage-quality (*Vitis vinifera* L. cv. Pinot Noir) and (d) the variation of vintage quality 1499–1840. Lines in (a) and (c) show regressions. The series in (b) and (d) are smoothed by a 10 yr Gaussian filter. Vintage quality: 2, excellent, 1, good; 0, average; −1, poor

between harvest timing and drought has broken down. The Palmer drought severity index (PDSI) is calculated using monthly temperature and precipitation data along with information on the water-holding capacity of soils (WMO & GWP 2016). Brázdil et al. (2015) analyzed of long-term drought fluctuations (1805–2012) in the Czech Republic. The drying trends have been driven by a major air temperature increase, leading to higher potential evapotranspiration (and therefore to a major shift in the climatological water balance). We have not seen any change in the relationship between GDH and drought in the recent period. Our results show that it is necessary to analyze the effective precipitation, which significantly affects the water reserves in the soil. In recent years, a greater proportion of the precipitation has fallen in the form of intense one-day events, and the loss of snow cover in the winter has negatively influenced the soil water saturation in the first part of the growing season (Potopová et al. 2016). An average of 44 % of the total precipitation in April–August in the Bohemian wine-growing region occurred during days with total rainfall ≥10 mm in the period from 1961 to 2000, while in 2001–2015, this proportion was 51 %. Low infiltration capacity of soils and slope vineyards cause a significant proportion of the precipita-

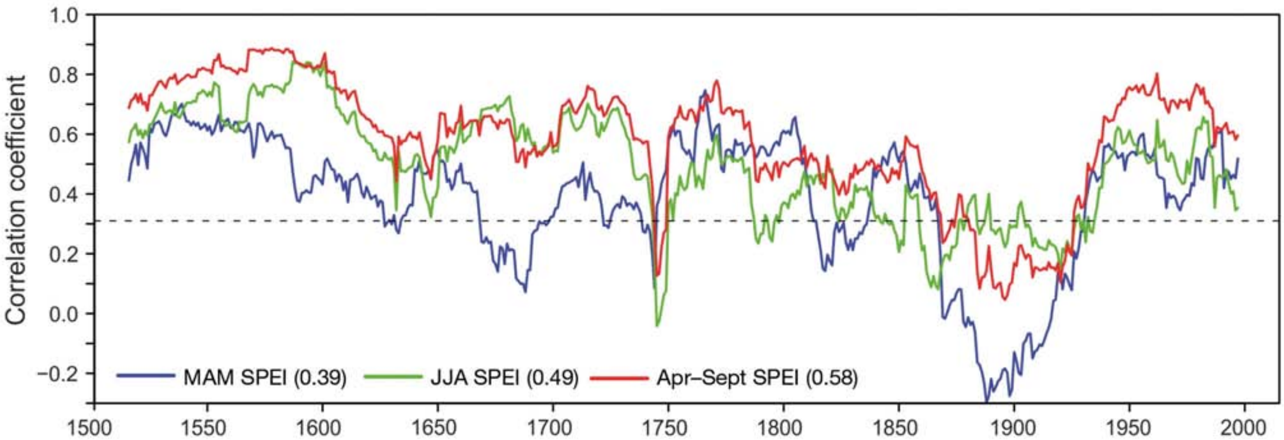

Fig. 7. Running 31 yr correlation coefficients of the GHD-based April–August SPEI of the Bohemian wine-growing region with the March–May (MAM), June–August (JJA) and April–September SPEIs of the Czech Lands derived from documentary and instrumental data (Brázdil et al. 2016a). Significant positive correlations appear above the dashed horizontal line; the overall correlation coefficients between corresponding series are indicated in parentheses

tion to be lost by surface runoff. Therefore, it is more appropriate to use the effective total precipitation than the standard total precipitation.

4.2. Comparison of SPEI reconstructions

The GHD-based April–August SPEI reconstruction for the Bohemian wine-growing region may be compared with the SPEI reconstructions based on documentary and instrumental data for the Czech Lands in the 1500–2015 period published by Brázdil et al. (2016a). These employed 2 series for SPEI calculations: (i) a central European temperature reconstruction (Dobrovolný et al. 2010) combining temperature indices derived from documentary data from Germany, the Czech Lands and Switzerland (1500–1854) with homogenised series from 11 central European stations (1760–2007); this series is fully representative of the territory of the Czech Lands; (ii) a precipitation reconstruction for the Czech Lands (Dobrovolný et al. 2015) combining precipitation indices derived from documentary data (1501–1854) and mean Czech areal precipitation series from instrumental measurements (1805–2015). Further, our SPEI reconstruction is compared with the March–May (MAM) SPEI, the June–August (JJA) SPEI and the April–September SPEI series for the Czech Lands compiled by Brázdil et al. (2016a) for the 1501–2012 period.

As shown in Fig. 7, the highest statistically significant correlation coefficient (0.58) was with the April–September SPEI, which differs from the highest correlation with the reconstructed GHD-based April–August SPEI by only one month (September). The correlations with the JJA and MAM SPEI are lower (0.49 and 0.39, respectively), which partially reflects the absence of March data in the reconstructed series as well as the stronger influence of the summer on the drought/precipitation patterns in the Czech Lands. All 3 SPEI series from Brázdil et al. (2016a) have relatively similar fluctuations with the GHD-based April–August SPEI, including a period of higher significant correlations up to the early 1850s followed by significant declines in the correlations until ca. 1925 (even negative correlations with the MAM SPEI) and then higher statistically significant correlation coefficients. The decrease in the correlation coefficients may be attributed to the some problems in the quality of the GHD series for these periods. Warmer and wetter weather in August–September in the mid-19th century led to a higher incidence of fungal diseases on hops and vines, which influenced timing (early harvest) and yields (Možný et al. in press). Effective synthetic pesticides and fungicides were not available until the early 1920s. The approach to vine growing and fermenting grapes changed in the late 19th century, affecting later harvest dates (Kilián 2012). Vine growers experimented for several years with harvesting a few days later, since sunny weather in October may have helped augment sugar content. Additional deeper declines in correlations were detected between 1650 and 1700 (only with the MAM SPEI) and in the late 1740s (all 3 SPEI series). Despite these fluctuations in the 31 yr running correlations, this comparison of 2 independent SPEI reconstructions confirms the high reconstruction skill of documentary data (represented by grape harvest dates as well as the combination of documentary evidence with instrumental data) to describe long-term fluctuations of droughts.

The 2 independent SPEI reconstructions from the Czech Lands indicate that 1540 was the driest year in both the 1499–2012 and 1501–2015 periods. As documented by rich documentary evidence from the Czech Lands (using only the GHD, or the combination of documentary evidence with instrumental data), 1540 was warm and dry and was associated with crop failure, lack of water, frequent fires and shortages but also with excellent wine quality (for additional details see Brázdil et al. 2013b). Similar weather characteristics and their impacts as in 1540 in the Czech Lands have been documented for many other locations in Europe, which led Wetter et al. (2014) to use the term 'megadrought' to describe an unprecedented 11 mo long drought in large parts of Europe. Although Büntgen et al. (2015) argued that 1540 does not appear to be significant in many European tree-ring width chronologies, Pfister et al. (2015) supported the original concept using other arguments. Moreover, Wetter & Pfister (2013) classified 1540 as the warmest year based on records of grape harvest dates in Switzerland.

In addition to 1540, other important droughts in the pre-instrumental period were identified in the reconstructed GHD-based April–August SPEI for the Bohemian wine-growing region in 1590 (SPEI = –2.1) and 1616 (–2.3); these droughts are well-documented in available documentary evidence. Comparable or higher SPEI values occurred more than 3 centuries later in 1947 (–2.0) and particularly in the 2000s. Reconstructed SPEI values similar to that of 1540 were found for 2000 (–3.4), which was followed by 5 other dry years in 2002 (–2.5), 2003 (–2.7), 2006 (–2.2), 2007 (–2.4) and 2009 (–2.6). These years have been reported and described in many studies of the area of the recent Czech Republic (e.g. Brázdil et al. 2013a,b, 2015, 2016b this Special).

All of the dry years that were identified in the reconstructed April–August SPEI values also agreed with excellent and good vintage qualities in the Bohemian wine-growing region (Pejml 1966, Možný et al. in press). Water-deficit stress resulted in shoot growth slackening, limited berry weight and enhanced berry anthocyanin content. These results are consistent with those of Brázdil et al. (2008), who found a correlation between high-quality wine and warmer and drier periods in the Moravian wine-growing region for 1800–1912. Moreover, in French Bordeaux, the intensity of regional water deficit stress was more important than the temperatures (Van Leeuwen et al. 2009).

5. CONCLUSIONS

GHD series have primarily been used for temperature reconstructions and have shown that prior warm weather patterns result in earlier vintage beginnings and that cooler patterns cause delayed vintage beginnings. A compilation of GHD series of *Vitis vinifera* L. cv. Pinot Noir for the Bohemian wine-growing region from documentary data demonstrated its potential not only for temperature reconstructions (Možný et al. 2016) but also for drought reconstructions. Statistically significant correlations of GHDs with the April–August mean temperature, potential evapotranspiration and effective precipitation allowed droughts to be reconstructed using the SPEI. Standard paleoclimatological reconstruction approaches were used to obtain SPEI series for 1499–2012. The advantages of this reconstruction include the relatively long overlap period of 1841–2010 for the calibration/verification procedures and the high variance, which was stable during this period. The reconstructed series is also significantly correlated with the vintage quality; excellent and good wine quality corresponds to dry years.

The long-term April–August SPEI variations include 2 particularly important periods of high dryness: the first half of the 16th century, which included an extremely dry 1540, and the years since the late 1970s, which included a sharp increase in the dry patterns. These results demonstrate the significant influence of increasing temperatures, high total evapotranspiration and generally stable total precipitation. They also may indicate that Central Europe may be endangered by future droughts due to the continuation of global warming.

The good representativeness of the presented reconstruction is confirmed by a comparison with independent SPEI reconstructions that are based on documentary and instrumental data from the Czech Lands (Brázdil et al. 2016a). Reconstructed series that are based on GHDs can contribute to a better understanding of drought variability in Central Europe and will be used for comparisons in future studies of this topic.

Acknowledgements. We acknowledge the support of the project CzechAdapt – System for Exchange of Information on Climate Change Impacts, Vulnerability and Adaptation Measures on the Territory of the Czech Republic (EHP-CZ02-OV-1-014-2014), which was supported by a grant from Iceland, Liechtenstein and Norway, and the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant number LO1415. R.B. was supported by the Grant Agency of the Czech Republic for project no. 13-19831S, and P.D. was supported by project no. 13-04291S.

LITERATURE CITED

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and drainage paper 56, FAO, Rome

Beguería S, Vicente-Serrano SM, Reig F, Latorre B (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int J Climatol 34:3001–3023

Brázdil R, Pfister C, Wanner H, von Storch H, Luterbacher J (2005) Historical climatology in Europe — the state of the art. Clim Change 70:363–430

Brázdil R, Zahradníček P, Dobrovolný P, Kotyza O, Valášek H (2008) Historical and recent viticulture as a source of climatological knowledge in the Czech Republic. Geografie 113:351–371

Brázdil R, Trnka M, Dobrovolný P, Chromá K, Hlavinka P, Žalud Z (2009) Variability of droughts in the Czech Republic, 1881–2006. Theor Appl Climatol 97:297–315

Brázdil R, Dobrovolný P, Luterbacher J, Moberg A, Pfister C, Wheeler D, Zorita E (2010) European climate of the past 500 years: new challenges for historical climatology. Clim Change 101:7–40

Brázdil R, Bělínová M, Dobrovolný P, Mikšovský J and others (2012a) Temperature and precipitation fluctuations in the Czech Lands during the instrumental period. Masaryk University, Brno

Brázdil R, Zahradníček P, Pišoft P, Štěpánek P, Bělínová M, Dobrovolný P (2012b) Temperature and precipitation fluctuations in the Czech Lands during the period of instrumental measurements. Theor Appl Climatol 110:17–34

Brázdil R, Dobrovolný P, Trnka M, Kotyza O and others (2013a) Droughts in the Czech Lands, 1090–2012 AD. Clim Past 9:1985–2002

Brázdil R, Kotyza O, Dobrovolný P, Řezníčková L, Valášek H (2013b) Climate of the sixteenth century in the Czech Lands. Masaryk University, Brno (abstract in English)

Brázdil R, Trnka M, Řezníčková L, Balek J and others (2015) Sucho v českých zemích: minulost, sou asnost, budoucnost (Drought in the Czech Lands: past, present, future). Centrum výzkumu globální změny Akademie věd České republiky, v.v.i., Brno

Brázdil R, Dobrovolný P, Trnka M, Büntgen U, Řezníčková L, Kotyza O, Valášek H (2016a) Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501. Clim Res 70:103–117

Brázdil R, Raška P, Trnka M, Zahradníček P and others (2016b) The Central European drought of 1947: causes and consequences, with particular reference to the Czech Lands. Clim Res 70:161–178

Büntgen U, Tegel W, Career M, Krusic PJ, Hayes M, Esper J (2015) Commentary to Wetter et al. (2014): Limited tree-ring evidence for a 1540 European 'megadrought'. Clim Change 131:183–190

Burkhardt T, Hense A (1985) On the reconstruction of temperature records from proxy data in mid Europe. Arch Meteorol Geophys Bioklimatol B 35:341–359

Chuine I, Yiou P, Viovy N, Seguin B, Daux V, Le Roy Ladurie E (2004) Historical phenology: grape ripening as a past climate indicator. Nature 432:289–290

Cook BI, Wolkovich EM (2016) Climate change decouples drought from early winegrape harvests in France. Nat Clim Change 6:715–719

Cook ER, Briffa KR, Jones PD (1994) Spatial regression methods in dendroclimatology: a review and comparison of two techniques. Int J Climatol 14:379–402

Daux V, Garcia de Cortazar-Atauri I, Yiou P, Chuine I and others (2012) An open-access database of grape harvest dates for climate research: data description and quality assessment. Clim Past 8:1403–1418

Dobrovolný P, Brázdil R, Valášek H, Kotyza O, Macková J, Halíčková M (2009) A standard paleoclimatological approach to temperature reconstruction in historical climatology: an example from the Czech Republic, AD 1718–2007. Int J Climatol 29:1478–1492

Dobrovolný P, Moberg A, Brázdil R, Pfister C and others (2010) Monthly and seasonal temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500. Clim Change 101:69–107

Dobrovolný P, Brázdil R, Trnka M, Kotyza O, Valášek H (2015) Precipitation reconstruction for the Czech Lands, AD 1501–2010. Int J Climatol 35:1–14

Etien N, Daux V, Masson-Delmotte V, Stievenard M and others (2008) A bi-proxy reconstruction of Fontainebleau (France) growing season temperature from AD 1596 to 2000. Clim Past 4:91–106

García de Cortázar-Atauri I, Daux V, Garnier E, Yiou P and others (2010) Climate reconstructions from grape harvest dates: methodology and uncertainties. Holocene 20: 599–608

Garnier E, Daux V, Yiou P, García de Cortázar-Atauri I (2011) Grapevine harvest dates in Besançon (France) between 1525 and 1847: social outcomes or climatic evidence? Clim Change 104:703–727

Glaser R, Hagedorn H (1991) The climate of Lower Franconia since 1500. Theor Appl Climatol 43:101–104

Hájková L, Voženílek V, Tolasz R, Kohut M, Možný M and others (2012) Atlas fenologických poměrů Česka (Atlas of phenological conditions in Czechia). Český hydrometeorologický ústav, Univerzita Palackého v Olomouci, Prague (abstract in English)

Hargreaves GH, Allen RG (2003) History and evaluation of Hargreaves evapotranspiration equation. J Irrig Drain Eng 129:53–63

Heim R, Brewer M (2012) The global drought monitor portal: the foundation for a global drought information system. Earth Interact 16:1–28

Hirschi M, Seneviratne SI, Alexandrov V, Boberg F and others (2011) Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. Nat Geosci 4:17–21

Hlavinka P, Trnka M, Balek J, Semerádová D and others (2011) Development and evaluation of the SoilClim model for water balance and soil climate estimates. Agric Water Manage 98:1249–1261

Jones GV, White MA, Cooper OR, Storchmann K (2005) Climate change and global wine quality. Clim Change 73:319–343

Kilián J (2012) Nástin vývoje mělnického vinařství v 19. a 20. století (Outline of the development of Mělník viticulture during the 19th and 20th centuries). In: Babíková P (ed) Víno a vinařství v českých zemích po roce 1800. Regionální museum, Mělník, p 44–53

Kiss A, Wilson R, Bariska I (2011) An experimental 392-year documentary-based multi-proxy (vine and grain) reconstruction of May–July temperatures for Köszeg, West-

Hungary. Int J Biometeorol 55:595–611
Le Roy Ladurie E (2005) Canicules, fraîcheurs, vendanges (France 15–19 siècles). C R Biol 328:213–222
Le Roy Ladurie E, Baulant M (1980) Grape harvests from the fifteenth through the nineteenth centuries. J Interdiscip Hist 10:839–849
Leijonhufvud L, Wilson R, Moberg A (2008) Documentary data as proxy variables for Stockholm late winter to early spring temperatures in the 18th and 19th centuries. Holocene 18:333–343
Leijonhufvud L, Wilson R, Moberg A, Söderberg J, Retsö D, Söderlind U (2010) Five centuries of Stockholm winter/spring temperatures reconstructed from documentary evidence and instrumental observations. Clim Change 101:109–141
Li W, Hou M, Chen H, Chen X (2012) Study on drought trend in south China based on standardized precipitation evapotranspiration index. J Nat Disasters 21:84–90
Malheiro AC, Campos R, Fraga H, Eiras-Dias J, Silvestre J, Santos JA (2013) Wine grape phenology and temperature relationships in the Lisbon wine region, Portugal. J Int Sci Vigne Vin 47:287–299
Mariani L, Parisi S, Cola FO, Zoia G, Bonardi L (2009) Tirani (1624–1930): a long time series of harvest dates for grapevine. Ital J Agrometeorol 1:7–16
Maurer C, Koch E, Hammerl C, Hammerl T, Pokorny E (2009) BACCHUS temperature reconstruction for the period 16th to 18th centuries from Viennese and Klosterneuburg grape harvest dates. J Geophys Res 114:D22106
Meier N, Rutishauser T, Pfister C, Wanner H, Luterbacher J (2007) Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. Geophys Res Lett 34:L20705
Menzel A (2005) A 500 year pheno-climatological view on the 2003 heatwave in Europe assessed by grape harvest dates. Meteorol Z 14:75–77
Miralles DG, Teuling AJ, van Heerwaarden CC, Vila-Guerau de Arellano J (2014) Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nat Geosci 7:345–349
Mozny M, Tolasz R, Nekovar J, Sparks T, Trnka M, Zalud Z (2009) The impact of climate change on the yield and quality of Saaz hops in the Czech Republic. Agric Meteorol 149:913–919
Možný M, Brázdil R, Dobrovolný P, Trnka M (2012) Cereal harvest dates in the Czech Republic between 1501 and 2008 as a proxy for March–June temperature reconstruction. Clim Change 110:801–821
Možný M, Brázdil R, Dobrovolný P, Trnka M (2016) April–August temperatures in the Czech Lands, 1499–2012, reconstructed from grape harvest dates. Clim Past 12:1421–1435
Možný M, Hájková L, Vráblík T, Novák J, Reitschläger J, Bareš D (in press) Počasí a výnosy zemědělských plodin v České republice (Weather and crop yields in the Czech Republic). Český hydrometeorologický ústav, Prague
Paulo AA, Rosa RD, Pereira LS (2012) Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. Nat Hazards Earth Syst Sci 12:1481–1491
Pejml K (1966) Příspěvek ke kolísání klimatu v severočeské vinařské a chmelařské oblasti od r. 1500–1900 (Contribution to climate fluctuations in the North Bohemian wine- and hop-growing region from 1500–1900). Český hydrometeorologický ústav, Prague (abstract in English)
Pfister C (1981) Die Fluktuationen der Weinmosterträge im schweizerischen Weinland vom 16. bis ins frühe 19. Jahrhundert: klimatische Ursachen und sozioökonomische Bedeutung. Schweiz Z Gesch 31:445–491
Pfister C (1984) Klimageschichte der Schweiz 1525–1860, das Klima der Schweiz vom 1525–1860 und seine Bedeutung in der Geschichte von Bevölkerung und Landwirtschaft. Verlag Paul Haupt, Bern
Pfister C, Wetter O, Brázdil R, Dobrovolný P and others (2015) Tree-rings and people — different views on the 1540 megadrought. Reply to Büntgen et al. 2015. Clim Change 131:191–198
Potop V (2011) Evolution of drought severity and its impact of corn in the Republic of Moldova. Theor Appl Climatol 105:469–483
Potop V, Možný M, Soukup J (2012) Drought at various time scales in the lowland regions and their impact on vegetable crops in the Czech Republic. Agric Meteorol 156:121–133
Potopová V, Boroneant C, Možný M, Soukup J (2016) Driving role of snow cover on soil moisture and drought development during the growing season in the Czech Republic. Int J Climatol 36:3741–3758
Ramos MC, Jones GV, Yuste J (2015) Spatial and temporal variability of cv. Tempranillo phenology and grape quality within the Ribera del Duero DO (Spain) and relationships with climate. Int J Biometeorol 59:1849–1860
Sadras VO, Bubner R, Moran MA (2012) A large-scale, open-top system to increase temperature in realistic vineyard conditions. Agric Meteorol 154–155:187–194
Spinoni J, Naumann G, Vogt J, Barbosa P (2015) European drought climatologies and trends based on a multi-indicator approach. Global Planet Change 127:50–57
Štěpánek P (2010) ProClimDB – Software for Processing Climatological Datasets. CHMI, Brno. www.climahom.eu/ProcData.html
Štěpánek P, Zahradníček P, Brázdil R, Tolasz R (2011) Metodologie kontroly a homogenizace časových řad v klimatologii (Methodology of quality control and homogenisation of time series in climatology). Český hydrometeorologický ústav, Prague (abstract in English)
Strömmer E (2003) Klima-Geschichte. Methoden der Rekonstruktion und historische Perspektive. Ostösterreich 1700 bis 1830. Franz Deuticke, Vienna
Svitáková Z, Kott I, Nekovář J (2005) Fenologická data za posledních 150 let (Phenological data in recent 150 year period). In: Bioclimatology present and future. Křtiny, 12–14 September 2005
Teuling AJ, Van Loon AF, Seneviratne SI, Lehner I and others (2013) Evapotranspiration amplifies European summer drought. Geophys Res Lett 40:2071–2075
Tolasz R, Míková T, Valeriánová A, Voženílek V (eds) (2007) Climate atlas of Czechia. Czech Hydrometeorological Institute and Palacký University, Prague
Trnka M, Brázdil R, Možný M, Štěpánek P and others (2015) Soil moisture trends in the Czech Republic between 1961 and 2012. Int J Climatol 35:3733–3747
Urhausen S, Brienen S, Kapala A, Simmer C (2011) Climatic conditions and their impact on viticulture in the upper Moselle region. Clim Change 109:349–373
USDA Soil Conservation Service (1972) National engineering handbook, Section 4: Hydrology, Chapters 4–10, Washington, DC, 15-7–15-11
Van Leeuwen C, Tregoat O, Chone X, Bois B, Pernet D,

Gaudillere JP (2009) Vine water status is a key factor in grape ripening and vintage quality for red bordeaux wine. How can it be assessed for vineyard management purposes? J Int Sci Vigne Vin 43:121–134
Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index — SPEI. J Clim 23:1696–1718
von Storch H, Zwiers FW (1999) Statistical analysis in climate research. Cambridge University Press, Cambridge
Vršič S, Šuštar V, Pulko B, Šumenjak TK (2014) Trends in climate parameters affecting wine grape ripening in northeastern Slovenia. Clim Res 58:257–266
Webb LB, Whetton PH, Barlow EWR (2011) Observed trends in wine grape maturity in Australia. Glob Change Biol 17:2707–2719
Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR (2012) Earlier wine-grape ripening driven by climatic warming and drying and management practices. Nat Clim Change 2:259–264
Wetter O, Pfister C (2013) An underestimated record breaking event — why summer 1540 was likely warmer than 2003. Clim Past 9:41–56
Wetter O, Pfister C, Werner JP, Zorita E and others (2014) The year-long unprecedented European heat and drought of 1540 — a worst case. Clim Change 125:349–363
Whan K, Zscheischler J, Orth R, Shongwe M, Rahimi M, Asare EO, Seneviratne SI (2015) Impact of soil moisture on extreme maximum temperatures in Europe. Weather Clim Extremes 9:57–67
White RE (2013) Has soil drying contributed to earlier grape ripening in wine regions of southern Australia? Aust J Grape Wine Res 19:123–127
Williams J, Kannan N, Wang X, Santhi C, Arnold J (2012) Evolution of the SCS runoff curve number method and its application to continuous runoff simulation. J Hydrol Eng 17:1221–1229
WMO, GWP (World Meteorological Organization and Global Water Partnership) (2016) Handbook of drought indicators and indices (M. Svoboda and B. A. Fuchs). Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2, Geneva
Yu M, Li G, Hayes MJ, Svoboda M, Heim RR (2014) Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? Int J Climatol 34:545–558
Zahradníček P (2009) Změna nástupu fenologických fází révy vinné a její závislost na meteorologických prvcích (The change in the phenophases onset of grapevine and its dependence on meteorological elements). In: Fyzickogeografický sborník 7, Fyzická geografie a krajinná ekologie. Masarykova univerzita, Brno, 199–205 (abstract in English)

Editorial responsibility: Ulf Buentgen (Guest Editor), Birmensdorf, Switzerland

Submitted: February 1, 2016; Accepted: August 16, 2016
Proofs received from author(s): October 19, 2016

Vol. 70: 133–141, 2016
doi: 10.3354/cr01402

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

Recent growth coherence in long-term oak (*Quercus* spp.) ring width chronologies in the Czech Republic

Petr Dobrovolný[1,2,*], Michal Rybníček[2,3], Ulf Büntgen[2,4,5], Miroslav Trnka[2,6], Rudolf Brázdil[1,2], Zdeněk Stachoň[1], Ondřej Prokop[3], Tomáš Kolář[2,3]

[1]Department of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
[2]Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic
[3]Department of Wood Science, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[4]Swiss Federal Research Institute for Forest, Snow and Landscape WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland
[5]Oeschger Centre for Climate Change Research, Falkenplatz 16, 3012 Bern, Switzerland
[6]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic

ABSTRACT: Oak ring width measurements compiled from 44 sampling sites throughout the territory of the Czech Republic are analysed for the 1655–2013 period. Measurements taken at all these sites are sorted into 10 sub-chronologies on the basis of 5 environmental factors: soil moisture (dry/wet), elevation (low/high), age (young/old), species (*Quercus robur* or *Q. petraea*), and geographical position (east/west). Several statistical tests are applied to investigate existing significant differences between chronologies during 1920–2013. Further, the sensitivities of individual sub-chronologies to precipitation are compared. Three tests indicate 5 pairs of very similar sub-chronologies. Moreover, the growth-response to May–July precipitation totals is very much the same in these sub-chronologies. This analysis demonstrates that, even in the absence of certainty about age structure, species composition and some environmental factors in the earlier parts of oak ring width chronologies, the internal homogeneity of the chronology remains essentially unaffected, and the lack of such information does not preclude their use in dendroclimatology.

KEY WORDS: Tree-ring width chronology · Oak species · Tree-age structure · Site-specific conditions · Hydroclimate sensitivity · Czech Republic

1. INTRODUCTION

Several millennium-long composite oak tree-ring width (TRW) chronologies exist for Europe: Ireland (Pilcher et al. 1984), Poland (Krąpiec 2001), Germany (Friedrich et al. 2004), and France (Tegel et al. 2010) among them. A number of recent studies have also highlighted the great palaeoclimatic potential of oak data for reconstruction of precipitation/drought characteristics: Čufar et al. (2008) for Slovenia, Friedrichs et al. (2009a,b) for Germany, Kern et al. (2009) for Hungary; Büntgen et al. (2010, 2011b) for central and western Europe, Cooper et al. (2013) for East Anglia (UK), Wilson et al. (2012) for southern-central England and Sohar et al. (2014) for Estonia.

Long oak TRW chronologies are invaluable sources of information for dating purposes, especially in archaeology (Kolář & Rybníček 2011, Čufar et al. 2015). However, their use for climate reconstruction may be complicated by the fact that they sometimes

*Corresponding author: *dobro@sci.muni.cz

Publisher: Inter-Research · www.int-res.com

convey climate signals that appear ambiguous (Büntgen et al. 2008, 2010). Tegel et al. (2010) have indicated certain problems in the use of long oak TRW chronologies for late-Holocene climate reconstructions. These include insufficient knowledge on site-specific conditions of historical and sub-fossil woods, fluctuations in sample size, and inadequate coverage of tree-age structure. Severe problems for the strength of climate signal may also arise out of exceptional environmental changes over time, among them high concentrations of atmospheric greenhouse gases in recent decades, levels of biospheric fertilization, changes in forest management and variations in degree of habitat alteration and clearance (Kaplan et al. 2009).

An oak TRW chronology for the territory of the Czech Republic has been constructed and systematically updated in the course of recent decades (Kolář et al. 2012). The current version of this chronology provides continuous cover, in adequate sample depth, for the period from AD 761 to the present. It has been used in palaeoclimatology for the analysis of the temporal distribution of wet and dry years (Dobrovolný et al. 2015). Two widespread species, the English oak *Quercus robur* L. and the sessile oak *Q. petraea* (Matt.) Liebl., predominate in Czech (CZ) oak TRW measurements. In terms of their wood anatomy, the species are far from distinguishable (Schoch et al. 2004). However, the natural habitat of the English oak consists primarily of river valleys at lower altitudes (below 500 m) whereas sessile oak tends towards higher elevations. As these species often occupy quite different natural habitats, one may assume that their responses to climate conditions differ accordingly.

This may present a serious problem, since it is common in palaeoclimatology that the relative proportions of oak species numbers, and sufficient knowledge of site conditions, may only exist in precise form for living trees, and only the recent parts of chronologies. The roles of these factors are unknown in the more distant parts of chronologies derived from historical and sub-fossil woods. This introduces additional uncertainties to proxy-based quantitative climate reconstructions and may even preclude the use of such chronologies in palaeoclimatology altogether.

This contribution employs the more recent part of the CZ oak TRW chronology as a benchmark for testing ‘internal homogeneity’. The samples from all sites are divided into 10 specific sub-chronologies based on 5 environmental factors: soil moisture conditions (dry/wet), elevation (low/high), age (young/old), species (*Q. robur*/*Q. petraea*), and geographical position (east/west). The main objective of this study is to test whether there are obvious differences between the sub-chronologies.

We hypothesize that the existence of no significant differences between west/east, dry/wet or low/high sub-chronologies demonstrates an ‘internal homogeneity’ in CZ oak TRW chronology and suggest that the full chronology can be employed as a single dataset to represent the past hydroclimate variability on the CZ territory. Further, this analysis addresses the issue of tree-age structure and may also provide an answer to the question as to the degree of significance of problems arising out of the combination of the 2 oak species in the chronology.

2. DATA AND METHODS

The recent part of the CZ oak TRW chronology is used herein, covering the period 1655–2013. It consists of annually resolved and absolutely dated TRW measurements from 1283 randomly sampled living oaks of various ages (22–359 yr), taken at 44 sampling sites in the Czech Republic (area ~79 000 km^2) between 1998 and 2014, especially during 2012–2014 (Fig. 1).

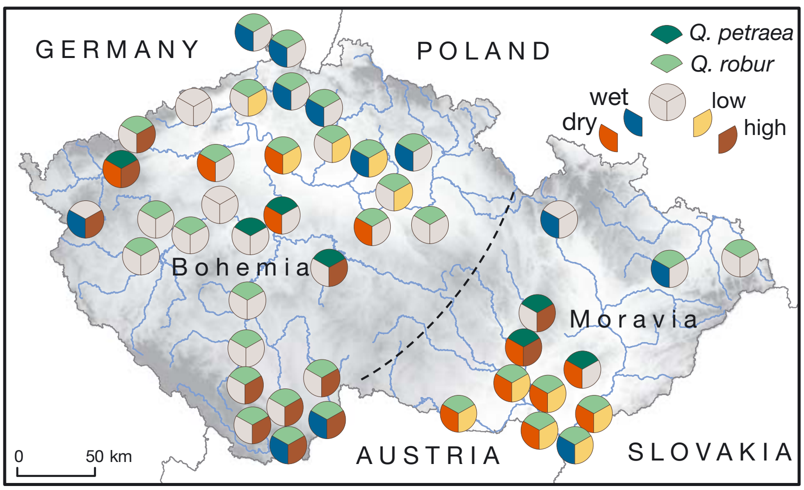

Fig. 1. Spatial distribution of 44 sampling sites and their distribution in terms of west/east, *Querus robur*/*Q. petraea*, dry/wet and high/low-altitude oak TRW sub-chronologies over the territory of the Czech Republic; dashed line marks boundary between west and east chronologies; grey indicates that data from the corresponding sampling site was not used for sub-chronology compilation (see Section 2 for further details)

Most of the samples come from 2 lowland regions: Bohemia (western Czech Republic) and Moravia-Silesia (eastern Czech Republic), regions of natural oak forest occurrence. The 2 regions are characterized by relatively warm (mean annual temperature 9–10°C) and dry (annual precipitation 450–500 mm, maximum in summer) climate conditions. Precipitation totals in these regions are significantly lower than evapotranspiration (Dobrovolný et al. 2015). Thus oak growth is mainly limited by water shortage and therefore sensitive to hydroclimate changes. From the point of view of moisture regime, the CZ territory is quite homogeneous as follows from spatial correlation analysis comparing CZ May–July precipitation totals and the May–July standardised precipitation-evapotranspiration index for 1 mo (SPEI-1) with those characteristics from European gridded databases (Fig. 2). The 2 maps indicate that mean CZ series of precipitation and SPEI are significantly representative for the whole CZ territory.

In order to investigate individual environmental factors, the whole dataset was first divided into 2 sub-chronologies. One was compiled from samples collected at localities where the English oak predominates, while the other came from sites where the sessile oak is in the clear majority. A detailed map of the CZ distribution of the 2 species in 2014 was used for discrimination. Site chronologies from the areas in which the species co-exist equally were not further considered. Thus 2 species-based series (*Quercus robur* and *Q. petraea*) were obtained and their differences tested for mean segment length (MSL), average growth rate (AGR), mean sensitivity and autocorrelation structure. Mean sensitivity indicates if the series is useful for cross-dating or responsive to climate (Bunn et al. 2013). A similar approach was adopted for soil moisture, geography (east/west) and altitude (Fig. 1).

Sub-chronologies were compiled for Bohemia ('west') and Moravia-Silesia ('east'). The Bohemian-Moravian Highlands were considered the boundary limit, since oak occurs only sparsely in them. Moreover, from the phytogeographical perspective, the western part of CZ is part of the Hercynian Region while the eastern part is related to the Pannonian Basin (Chytrý et al. 2001). Based on the relative availability of soil water, on mean elevation and on mean tree-age data, the sampling sites were ranked in ascending order. Only site chronologies belonging to the lower and upper quartiles were used for compilation of specific chronologies: 'wet' and 'dry' according to soil water content (<62 mm and >74 mm for lower and upper quartiles respectively); 'high' and 'low' by altitude (<245 m and >430 m for the lower and upper quartiles respectively); and finally 'young' and 'old' according to mean age (<80 years and >118 years for lower and upper quartiles respectively). The remaining site chronologies, belonging to the second and third quartiles, were excluded from further analysis.

A total of 11 specific sub-chronologies for raw oak TRW measurements were thus obtained — 5 pairs according to specific factors (above) and 1 from all data in addition. The expressed population signal (EPS; Wigley et al. 1984) and inter-series correlation (Rbar) were calculated to assess the quality of each chronology. Moreover, the degree of similarity between the sub-chronologies was addressed by the

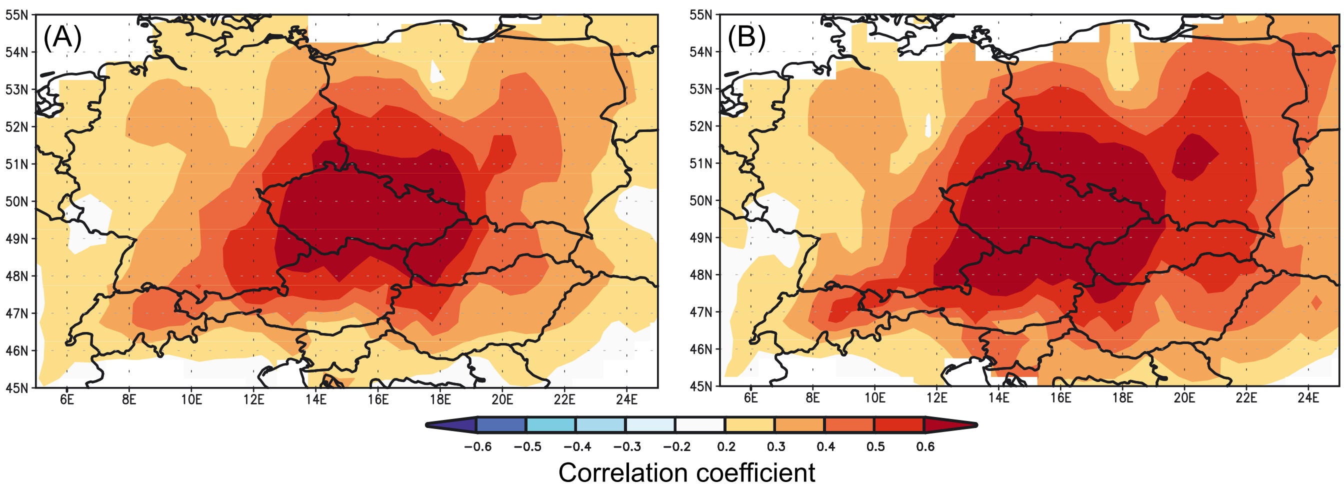

Fig. 2. Spatial correlations between (A) May–July mean Czech precipitation series (Brázdil et al. 2012) and CRU TS3.23 gridded precipitation (Harris et al. 2014) and (B) May–July mean Czech SPEI-1 (Brázdil et al. 2015) and gridded CSIC SPEI drought index (Vicente-Serrano et al. 2010) for the period 1901–2000

statistical metrics frequently used in dendrochronological dating, the T-test after Baillie & Pilcher (1973) (TBP), and the T-test after Hollstein (1980) (THO), coefficient of agreement ('Gleichläufigkeit'; Eckstein & Bauch 1969) and Date index 1 (Knibbe 2004). When the tree-ring series overlap by ≥60 yr, the critical value of Student's *t*-distribution, at p = 0.001 level of significance, is 3.460 (Šmelko & Wolf 1977). As well as direct comparison between individual pairs of sub-chronologies, possible differences in sensitivity to precipitation were also examined. For that purpose, sub-chronologies of raw oak TRW measurement series were first standardized in order to suppress non-climatic factors, as below.

Negative exponential curves together with cubic smoothing splines with a 50% frequency response cut-off at 60 and 120 yr were used for detrending to remove age-related growth trends. TRW indices were calculated as residuals from estimated growth curves after applying an adaptive power transformation to the raw measurement series (Cook & Peters 1997). The final oak TRW chronologies from each of the 3 detrending techniques were calculated using robust bi-weighted means. All 3 chronology versions (standard, residual and ARSTAN) generated from ARSTAN software (Cook & Krusic 2005) were considered. The first-order autocorrelation (AC1) was calculated for all 9, slightly different, variants of each sub-chronology and for the mean CZ precipitation series (Brázdil et al. 2012) that was used as a target. A suitable detrending technique was chosen, based on the highest similarity of autocorrelation structure between proxy and climate data. Very low values of precipitation AC1 correspond to a residual chronology generated from detrending by 120-year spline function.

Residual index tree-ring chronology (TRWI) was used to calculate any correlation between radial increments and precipitation in DendroClim2002 software (Biondi & Waikul 2004) for the period 1920–2013. In this period, all 10 specific sub-chronologies provided a sufficient number of samples and their quality evaluated by EPS also proved acceptable (EPS >0.85). Pearson's correlation coefficients were calculated for the seasonal window from April of the previous year until September of the year of tree-ring formation ('the given year'), i.e. for a period of 18 mo. The climate in this interval has the greatest influence on the radial increment of oak in central Europe (Horáček et al. 2003; Gričar 2010; Rybníček et al. 2015, 2016).

3. RESULTS

The basic characteristics of 10 oak TRW sub-chronologies and the chronology for all data are summarized in Table 1. All the chronologies are well replicated by at least 296 TRW series ('wet' chronology). Cambial age expressed by MSL of all TRW records varies from 64 yr ('young') to 136 yr ('old'). AGR ranges from 1.478 ('old') to 2.207 mm yr^{-1} ('young'). MSL and AGR parameters show high similarities between western and eastern chronologies. However, statistically significant differences were disclosed between the remainder of the TRW sub-chronologies, with the highest of them between 'old' and 'young' chronologies (MSL t = 44.61, p <0.01; AGR t = 14.16, p <0.01). The least, but still statistically significant, difference appeared between AGRs for 'low' and 'high' chronologies (t = 2.01, p <0.05). Compared to the *Quercus petraea* chronology, the

Table 1. Characteristics of raw TRW chronologies: SR: number of sapwood rings; MSL: mean segment length; AGR: average growth rate; SD: standard deviation; MS: mean sensitivity; AC1: first-order autocorrelation; Rbar: mean inter-series correlation (calculated in COFECHA; Grissino-Mayer 2001); EPS: mean expressed population signal

TRW chronology	Start year	End year	Series	SR	MSL (yr)	AGR (mm yr^{-1})	SD	MS	AC1	Rbar	EPS
Dry	1655	2013	401	14	107	1.625	0.671	0.239	0.683	0.527	0.93
Wet	1826	2014	296	15	88	1.869	0.795	0.255	0.643	0.434	0.95
High	1655	2013	416	14	109	1.745	0.722	0.239	0.684	0.485	0.86
Low	1841	2013	428	15	101	1.837	0.801	0.244	0.683	0.429	0.98
Old	1655	2014	347	14	136	1.478	0.686	0.239	0.716	0.455	0.88
Young	1919	2014	311	15	64	2.207	0.832	0.255	0.585	0.416	0.98
Querus petraea	1655	2013	351	14	117	1.493	0.644	0.243	0.684	0.524	0.93
Q. robur	1750	2014	839	15	97	1.949	0.823	0.244	0.671	0.412	0.85
West	1655	2013	721	15	102	1.797	0.788	0.252	0.665	0.448	0.88
East	1826	2014	562	13	100	1.776	0.716	0.236	0.675	0.494	0.98
All	1655	2014	1283	15	101	1.788	0.757	0.245	0.670	0.436	0.89

Q. robur chronology displays lower MSL, higher AGR and especially higher variability expressed as standard deviation. Mean sensitivity is comparable for all sub-chronologies, as are first-order autocorrelations, except for 'young/old' TRW series. The 'old' chronology has considerably higher values, and the 'young' chronology lower, compared with AC1 of the chronology compiled from all TRW series. The Rbar and the EPS indicate robust signal strength. Mean Rbar and mean EPS values are at least 0.41 and 0.85, respectively, for the full length of all sub-chronologies. High similarity among TRW sub-chronologies also was proven by the number of sapwood rings which ranges from 13 to 15.

Direct comparison of the raw TRW measurements in all 10 sub-chronologies, containing data of similar quality and quantity, was made for 1920–2013. The period was also chosen because the TBP and THO test statistics employed were influenced by an overlap of tree-ring series. T-test (both TBP and THO) values ranged from 9.0 to 15.0 (Table 2). The T-tests were markedly below their α-level ($\alpha = 0.05$), which demonstrates a high degree of similarity between sub-chronologies. The coefficient of agreement (GL) also gives a significant relationship between all pairs. Date index 1, calculated as a combination of all 3 previous statistical metrics, displays the highest similarity between *Q. petraea* and *Q. robur* chronologies (511). On the other hand, the lowest correlations appeared between the 'dry/wet' and 'high/low' pairs (335).

Fig. 3 shows a direct comparison of all pairs of indexed TRW sub-chronologies in the study period, while their common variability is expressed as running correlations. The latter are statistically significant for all pairs and for the whole study period. While common variability is quite stable over time for the series differentiated by altitude, age and species, there is a distinct period of lower coherence spanning approximately from the mid-1940s to the mid-1960s for 'dry/wet' and for 'east/west'. The overall correlations between all 5 pairs of raw oak TRW sub-chronologies in the 1920–2013 period are highly significant, varying from 0.705 ('west/east') to 0.821 ('old/young').

Table 2. Coherence of raw TRW sub-chronologies over a common period (1920–2013). TBP: T-value after Baillie & Pilcher (1973); THO: T-value after Hollstein (1980); GL: Gleichläufigkeit ('coefficient of agreement') (Eckstein & Bauch 1969); DI1: Date index 1 (Knibbe 2004); *p = 0.1; **p = 0.001

TRW chronologies	1920–2013 TBP	THO	GL	DI1
Dry/wet	9.1**	10.2**	83.0*	335.0
High/low	11.8**	11.3**	79.8*	335.0
Old/young	14.9**	15.0**	80.9*	463.0
Quercus petraea/ Q. robur	9.9**	15.0**	84.0*	511.0
West/east	11.9**	11.3**	80.9*	347.0

Potential differences between specific TRW chronologies were also explored in terms of their ability to simulate hydroclimate variability. All the indexed TRW sub-chronologies and the chronology from all data were correlated against CZ precipitation totals to reveal possible differences. Precipitation totals in the previous year were not significantly reflected in our data and are therefore not presented.

Correlation analysis demonstrated that all TRW chronologies respond consistently and correlate best for May–July precipitation totals in the 1920–2013 period. Correlation coefficients in individual months (May, June, July) are around the level of significance but the May–July period exceeds the threshold considerably, varying from 0.288 for 'dry' and 'west' chronologies to 0.428 for the 'young' chronology (Fig. 4a). The greatest difference was observed between correlations of 'old' (0.332) and 'young' (0.428) chronologies. The remainder of the pairs responded to precipitation totals in very similar fashion. However, 31 yr running correlations exhibited temporal instability within the relationship. Correlation coefficients were quite stable and around the significance level until the 1960s. A slow decrease of all TRW chronology correlations culminated in a significant decline in the early 1980s, persisting to the present (Fig. 4b). Recalculation of the relationship for a shorter period (1920–1980) shows the same response of all chronologies and increased correlation values in comparison with the full common period. Correlations for the most important May–July precipitation totals vary from 0.381 for 'dry' and 'west' chronologies to 0.538 for the 'young' chronology. Possible sources of this temporal instability are discussed in the next section.

4. DISCUSSION

Some important outcomes arise out of our analysis. (1) All CZ oak sub-chronologies are well replicated, their quality is high and mean sensitivities are similar. (2) The sub-chronologies exhibit significant differences in some of their descriptive characteristics, such as MSL and AGR. The latter is, however, a result that may be anticipated, given the design of the study, since the TRW sub-chronologies were defined to max-

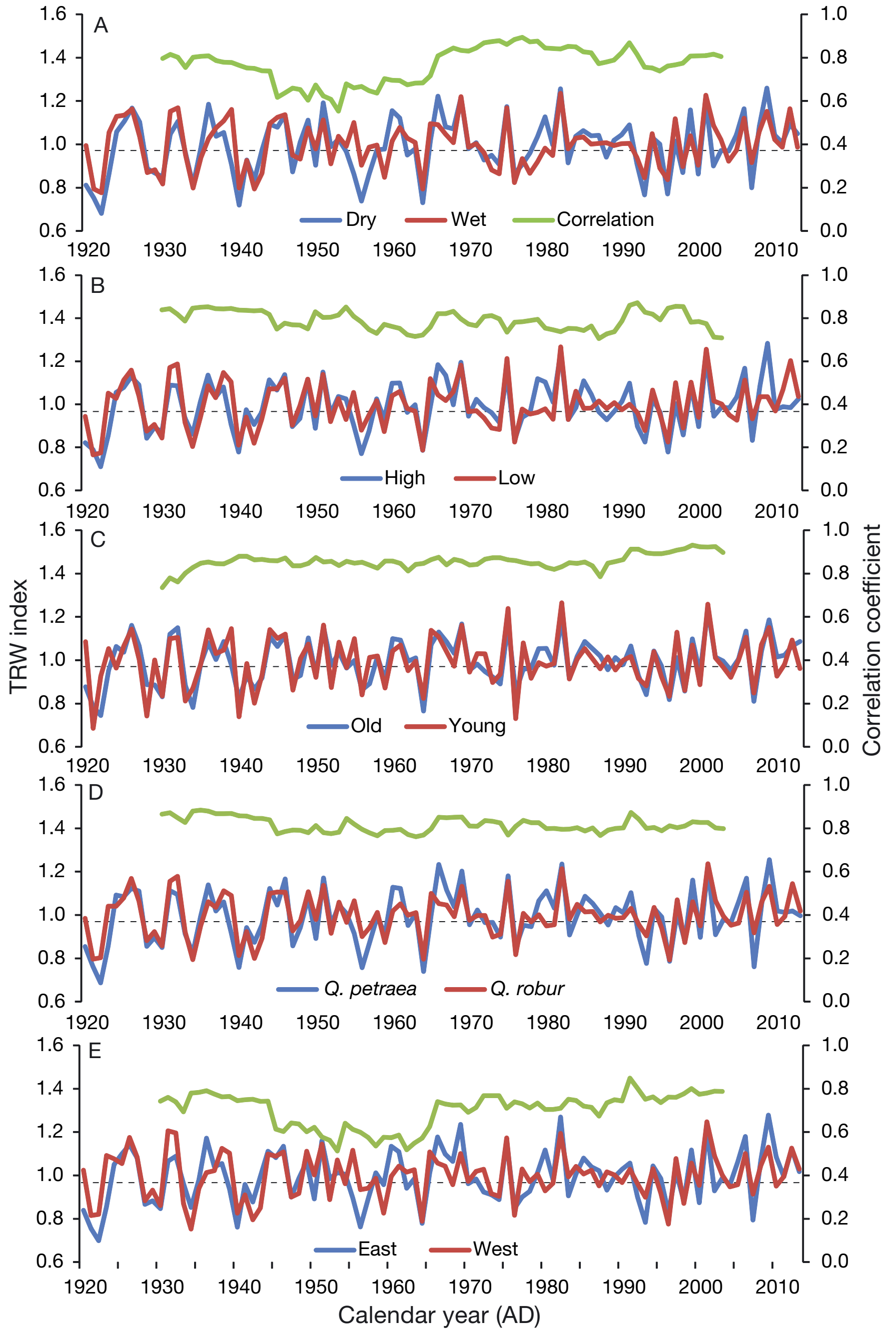

Fig. 3. Running correlations (green, 21 yr window) and (A) differences between dry/wet, (B) low/high-altitude, (C) young/old, (D) *Quercus robur*/*Q. petraea*, and (E) east/west oak TRW chronologies in the period 1920–2013. Dashed line: level of significant positive correlation (α = 0.05)

imise differences between one another in terms of the parameter examined. (3) Despite (2), it transpired that all 5 pairs of sub-chronologies are highly similar in the light of 3 different tests. (4) Moreover, the sub-chronologies are very much the same in their growth response to May–July precipitation totals. These findings are discussed in more detail below.

In general, species and soil moisture conditions had greater influences on TRW growth than elevation gradient. In addition, higher values of MSL corresponded to lower AGR values, resulting from the impact of age trend in particular. Differences between old and young chronologies were rendered especially clear by the relative proportions of juvenile wood, since younger trees contain a higher proportion of it than older ones. This may also account for differences between other specific chronologies. However, the statistical differences between 'dry' and 'wet' TRW chronologies may be influenced by water availability; tree-ring widths may be narrower at sites stressed by drought.

There were distinct differences between the selected characteristics in species-specific chronologies, such as AGR and mean variability. For instance, narrower tree-ring widths accompanied by lower variability occurred in sessile oak, in agreement with other studies conducted in the Czech Republic (Vavrčík & Gryc 2012). However, such differences may arise out of site-specific conditions for both species (Rybníček et al. 2016). Our analysis demonstrated that the hydroclimate sensitivity of the 2 oak species is similar in the Czech Republic, in line with several other European studies (Friedrichs et al. 2009a,b, Büntgen et al. 2010, 2011c, Tegel et al. 2010). Moreover, significant spatial correlations have been observed between different oak chronologies from various locations in Central Europe. These correlations, however, decrease with increasing geographical distance (Pilcher et al. 1984, Ważny & Eckstein 1991, Haneca et al. 2009, Kolář et al. 2012).

CZ oak TRW chronologies responded most strongly to changes in May–July precipitation totals, and young trees exhibited the response that was most sensitive to precipitation. This has been demonstrated by CZ oaks before (Doležal et al. 2010), and positive response to summer precipitation has also been shown

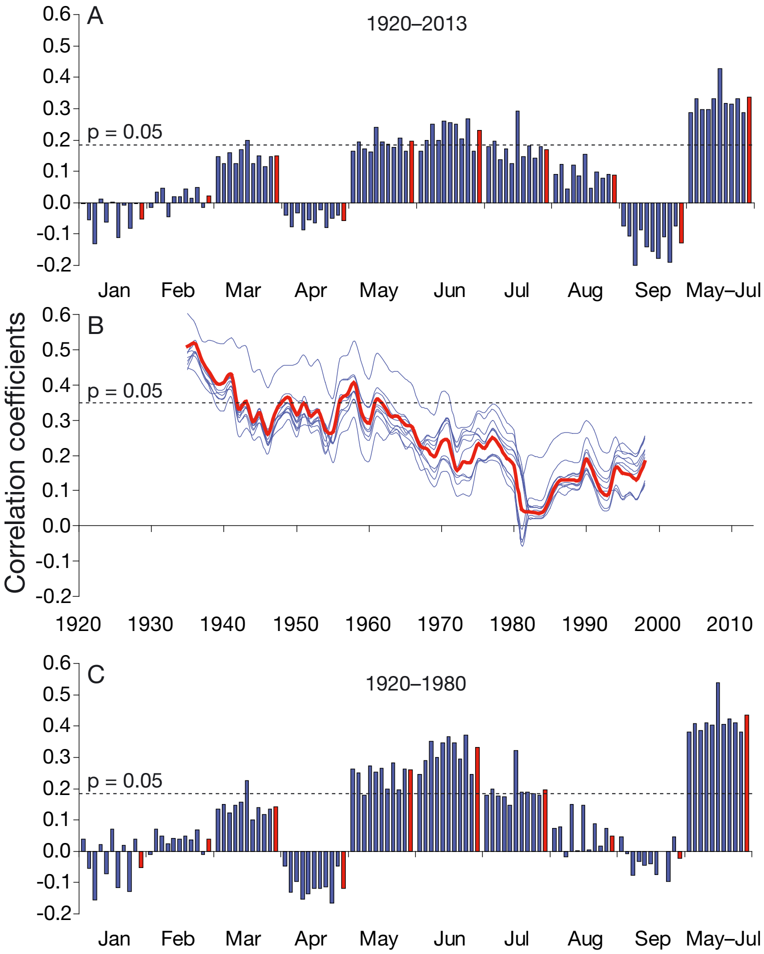

Fig. 4. Correlations of individual TRW sub-chronologies (blue) and chronology from all data (red) with monthly precipitation totals (A) for the common period 1920–2013 and (C) for the shorter 1920–1980 period. (B) 31 yr running correlations of TRW indices with May–July precipitation totals

for oak chronologies from France (Mérian et al. 2011), Romania (Popa et al. 2013), Germany (Friedrichs et al. 2009a), Slovakia (Petráš & Mecko 2011), and Poland (Bronisz et al. 2012). However, responses to hydroclimate in the Czech Republic were quite weak and unstable over time. The most dramatic drop in the hydroclimate sensitivity of CZ oak TRW chronologies takes place between the 1960s and the present. This may be associated with recent global warming; the physiological thresholds of tree growth may also have influenced this result (Rozas 2005, Geßler et al. 2007, Friedrichs et al. 2009a). Although CZ oak TRW chronologies demonstrate no direct relation to air temperature, rising temperatures and changes in precipitation distribution during the growing season are obviously associated with a higher risk of drought occurrence. For example, a precipitation decrease in the first half of the growing season and an increase in the second half have been reported for some parts of the Czech Republic and for central Europe in the past 2 decades (Bauer et al. 2010, Možný et al. 2012, Brázdil et al. 2015). Consequently, a higher intensity of drought, together with a higher variability of precipitation regime, has a potential for negative effects on tree growth.

Reduced sensitivity of CZ TRW chronologies to hydroclimate has already been discussed by Büntgen et al. (2011a) for fir *Abies alba* TRWs in southern Moravia. Authors mentioned air pollution as a possible factor bearing upon the temporal instability of the growth–climate relationship. Further, a significant tree growth reduction in conifers due to high SO_2 concentrations and air pollution in northern Bohemia has already been demonstrated (Rydval & Wilson 2012, Kolář et al. 2015). If global warming and air pollution lie behind the reduced sensitivity of trees to climate, then the modern loss of coherence is exceptional and may not pose a serious problem in earlier parts of TRW chronologies.

5. CONCLUSIONS

Our analysis aimed to evaluate a possible 'extreme' data model, since the study was designed to examine possible differences between 5 specific pairs of chronologies as far as possible from one another in terms of the factor in question. This is because the chronologies are derived from samples representing data of lower and upper quartiles. The mode of data collection for sub-fossil woods, and historical woods in particular, for the earlier parts of chronologies lies close to 'random sampling', which then splices samples from the whole range of values of environmental factors examined here to the resulting chronology. Thus our results, indicating no significant differences between specific sub-chronologies, should be generally valid for the entire CZ oak TRW chronology.

Moreover, results from this analysis of the influence of site, species, age, elevation, and soil moisture on oak TRW are of great importance to hydroclimate reconstructions of the past millennium in a central European context. We have demonstrated that even if the above parameters are not perfectly known for the earlier parts of oak TRW chronologies, the resulting reconstructions may not be significantly biased by such a deficiency.

Acknowledgements. This study was supported by the Czech Science Foundation project no. 13–04291S 'Spring-summer hydroclimate reconstruction of the past millennium for the Czech Republic using oak standard chronology', by the 'Establishment of International Scientific Team Focused on Drought Research' (no. OP VK CZ.1.07/2.3.00/20.0248) project, and by the Ministry of Education, Youth and Sports of CZ within the National Sustainability Program I (NPU I), grant number LO1415. Tony Long (Svinošice) helped improve the English.

LITERATURE CITED

Baillie MGL, Pilcher JR (1973) A simple cross-dating program for tree-ring research. Tree-Ring Bull 33:7–14

Bauer Z, Trnka M, Bauerová J, Možný M, Štěpánek P, Bartošová L, Žalud Z (2010) Changing climate and the phenological response of great tit and collared flycatcher populations in floodplain forest ecosystems in Central Europe. Int J Biometeorol 54:99–111

Biondi F, Waikul K (2004) DendroClim2002: AC++ program for statistical calibration of climate signals in tree ring chronologies. Comput Geosci 30:303–311

Brázdil R, Bělínová M, Dobrovolný P, Mikšovský J and others (2012) Temperature and precipitation fluctuations in the Czech Lands during the instrumental period. Masaryk University, Brno

Brázdil R, Trnka M, Mikšovský J, Řezníčková L, Dobrovolný P (2015) Spring-summer droughts in the Czech Land in 1805–2012 and their forcings. Int J Climatol 35: 1405–1421

Bronisz A, Bijak S, Bronisz K, Zasada M (2012) Climate influence on radial increment of oak (Quercus SP.) in central Poland. Geochronometria 39:276–284

Bunn AG, Jansma E, Korpela M, Westfall RD, Baldwin J (2013) Using simulations and data to evaluate mean sensitivity (ζ) as a useful statistic in dendrochronology. Dendrochronologia 31:250–254

Büntgen U, Frank DC, Wilson R, Career M, Urbinati C, Esper J (2008) Testing for tree-ring divergence in the European Alps. Glob Change Biol 14:2443–2453

Büntgen U, Trouet V, Frank D, Leuschner HH, Friedrichs D, Luterbacher J, Esper J (2010) Tree-ring indicators of German summer drought over the last millennium. Quat Sci Rev 29:1005–1016

Büntgen U, Brázdil R, Dobrovolný P, Trnka M, Kyncl T (2011a) Five centuries of Southern Moravian drought variations revealed from living and historic tree rings. Theor Appl Climatol 105:167–180

Büntgen U, Brázdil R, Heussner KU, Hofmann J and others (2011b) Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium. Quat Sci Rev 30:3947–3959

Büntgen U, Tegel W, Nicolussi K, McCormick M and others (2011c) 2500 years of European climate variability and human susceptibility. Science 331:578–582

Chytrý M, Kučera T, Kočí M (2001) Katalog biotopů České republiky (Catalogue of biotopes of the Czech Republic). Agentura ochrany přírody a krajiny ČR, Prague

Cook ER, Krusic PJ (2005) ARSTAN v. 41d: A Tree-ring standardization program based on detrending and autoregressive time series modeling, with interactive graphics. Tree ring laboratory, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, NY. www.ldeo.columbia.edu/tree-ring-laboratory/resources/software (accessed 29 August 2016)

Cook ER, Peters K (1997) Calculating unbiased tree-ring indices for the study of climatic and environmental change. Holocene 7:361–370

Cooper RJ, Melvin TM, Tyers I, Wilson RJS, Briffa KR (2013) A tree-ring reconstruction of East Anglian (UK) hydroclimate variability over the last millennium. Clim Dyn 40: 1019–1039

Čufar K, Luis MD, Zupančič M, Eckstein D (2008) A 548-year tree-ring chronology of oak (*Quercus* spp.) for Southeast Slovenia and its significance as a dating tool and climate archive. Tree-Ring Res 64:3–15

Čufar K, Tegel W, Merela M, Kromer B, Velušček A (2015) Eneolithic pile dwellings south of the Alps precisely dated with tree-ring chronologies from the north. Dendrochronologia 35:91–98

Dobrovolný P, Rybníček M, Kolář T, Brázdil R, Trnka M, Büntgen U (2015) A tree-ring perspective on temporal changes in the frequency and intensity of hydroclimatic extremes in the territory of the Czech Republic since 761 AD. Clim Past 11:1453–1466

Doležal J, Mazůrek P, Klimešová J (2010) Oak decline in southern Moravia: the association between climate change and early and late wood formation in oaks. Preslia 82:289–306

Eckstein D, Bauch J (1969) Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. Forstwiss Centralblatt 88: 230–250

Friedrich M, Remmele S, Kromer B, Hofmann J and others (2004) The 12 460-year Hohenheim oak and pine tree-ring chronology from Central Europe — a unique annual record for radiocarbon calibration and palaeoenvironment reconstruction. Radiocarbon 46:1111–1122

Friedrichs DA, Büntgen U, Frank DC, Esper J, Neuwirth B, Löffler J (2009a) Complex climate controls on 20th century oak growth in Central-West Germany. Tree Physiol 29:39–51

Friedrichs DA, Trouet V, Büntgen U, Frank DC, Esper J, Neuwirth B, Löffler J (2009b) Twentieth century climate sensitivity of Central European tree species. Trees Struct Funct 23:729–739

Geßler A, Keitel C, Kreuzwieser J, Matyssek R, Seiler W, Rennenberg H (2007) Potential risks for European beech (*Fagus sylvatica* L.) in a changing climate. Trees (Berl) 21:1–11

Gričar J (2010) Xylem and phloem formation in sessile oak from Slovenia in 2007. Wood Res 55:15–22

Grissino-Mayer HD (2001) Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Res 57:205–221

Haneca K, Čufar K, Beeckman H (2009) Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. J Archaeol Sci 36:1–11

Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations — the CRU TS3.10 dataset. Int J Climatol 34:623–642

Hollstein E (1980) Mitteleuropäische Eichenchronologie. Trierer dendrochronologische Forschungen zur Archäologie und Kunstgeschichte. Trierer Grabungen und Forschungen, Mainz

Horáček P, Šlezingerová J, Gandelová L (2003) Analysis of cambial activity and formation of wood in *Quercus robur*

L. under conditions of a floodplain forest. J For Sci 49: 412–418

Kaplan JO, Krumhardt KM, Zimmermann N (2009) The prehistoric and preindustrial deforestation of Europe. Quat Sci Rev 28:3016–3034

Kern Z, Grynaeus A, Morgos A (2009) Reconstructed precipitation for southern Bakony Mountains (Transdanubia, Hungary) back to 1746 AD based on ring widths of oak trees. Idöjárás 113:299–314

Knibbe B (2004) Personal Analysis System for Treering Research – Instruction Manual (Version 4). SCIEM, Brunn am Gebirge

Kolář T, Rybníček M (2011) Dendochronological and radiocarbon dating of subfossil wood from the Morava River basin. Geochronometria 38:155–161

Kolář T, Kyncl T, Rybníček M (2012) Oak chronology development in the Czech Republic and its teleconnection on a European scale. Dendrochronologia 30:243–248

Kolář T, Čermák P, Oulehle F, Trnka M and others (2015) Pollution control in the 1980s contributed to unprecedented spruce growth in the 'Black Triangle', the Czech-Polish border region. Sci Total Environ 538:703–711

Krąpiec M (2001) Holocene dendrochronological standards for subfossil oaks from the area of Southern Poland. Studia Quaternaria 18:47–63

Mérian P, Bontemps JD, Bergès L, Lebourgeois F (2011) Spatial variation and temporal instability in climate-growth relationships of sessile oak (*Quercus petraea* [Matt.] Liebl.) under temperate conditions. Plant Ecol 212:1855–1871

Možný M, Brázdil R, Dobrovolný P, Trnka M (2012) Cereal harvest dates in the Czech Republic between 1501 and 2008 as a proxy for March–June temperature reconstruction. Clim Change 110:801–821

Petráš R, Mecko J (2011) Effect of climatic factors on the dynamics of radial increments of Norway spruce, European beech and Sessile oak. J Sci 57:293–302

Pilcher JR, Baillie MGL, Schmidt B, Becker B (1984) A 7272 year tree-ring chronology for Western Europe. Nature 312:150–152

Popa I, Leca S, Crăciunescu A, Sidor C, Badea O (2013) Dendroclimatic response variability of *Quercus* species in the Romanian Intensive Forest Monitoring Network. Not Bot Horti Agrobot Cluj-Napoca 41:326–332

Rozas V (2005) Dendrochronology of pedunculate oak (*Quercus robur* L.) in an old-growth pollarded woodland in northern Spain: tree-ring growth responses to climate. Ann Sci 62:209–218

Rybníček M, Čermák P, Žid T, Kolář T, Trnka M, Büntgen U (2015) Exploring growth variability and crown vitality of sessile oak (*Quercus petraea*) in the Czech Republic. Geochronometria 42:17–27

Rybníček M, Čermák P, Prokop O, Žid T, Trnka M, Kolář T (2016) Oak (*Quercus* spp.) response to climate differs more among sites than among species in central Czech Republic. Dendrobiology (Pozn) 75:55–65

Rydval M, Wilson R (2012) The impact of industrial SO_2 pollution on North Bohemia conifers. Water Air Soil Pollut 223:5727–5744

Schoch W, Heller I, Schweingruber FH, Kienast F (2004) Wood anatomy of central European species. www.woodanatomy.ch

Šmelko Š, Wolf J (1977) Štatistické metódy v lesníctve (Statistical Methods in Forestry). Príroda, Bratislava

Sohar K, Läänelaid A, Eckstein D, Helama S, Jaagus J (2014) Dendroclimatic signals of pedunculate oak (*Quercus robur* L.) in Estonia. Eur J For Res 133:535–549

Tegel W, Vanmoerkerke J, Büntgen U (2010) Updating historical tree-ring records for climate reconstruction. Quat Sci Rev 29:1957–1959

Vavrčík H, Gryc V (2012) Analysis of the annual ring structure and wood density relations in English oak and sessile oak. Wood Res 57:573–580

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718

Ważny T, Eckstein D (1991) The dendrochronological signal of oak (*Quercus* spp.) in Poland. Dendrochronologia 9: 35–49

Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J Clim Appl Meteorol 23:201–213

Wilson R, Miles D, Loader NJ, Melvin T, Cunningham L, Cooper R, Briffa K (2013) A millennial long March–July precipitation reconstruction for southern-central England. Clim Dyn 40:997–1017

Editorial responsibility: Michael Hayes (Guest Editor), Lincoln, Nebraska, USA

Submitted: January 25, 2016; Accepted: May 9, 2016
Proofs received from author(s): August 30, 2016

Vol. 70: 143–160, 2016
doi: 10.3354/cr01420

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe — from drought response to preparedness'

Drought trends over part of Central Europe between 1961 and 2014

Miroslav Trnka[1,2,*], Jan Balek[1,2], Petr Štěpánek[1,3], Pavel Zahradníček[1,3], Martin Možný[2,4], Josef Eitzinger[5], Zdeněk Žalud[1,2], Herbert Formayer[5], Maroš Turňa[6], Pavol Nejedlík[7], Daniela Semerádová[1], Petr Hlavinka[1,2], Rudolf Brázdil[1,8]

[1]Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic
[2]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[3]Czech Hydrometeorological Institute, Brno Regional Office, Kroftova 2578/43, 616 67 Brno, Czech Republic
[4]Czech Hydrometeorological Institute, Doksany Observatory, Doksany 105, 411 85 Doksany, Czech Republic
[5]University of Natural Resources and Life Sciences, Institute of Meteorology, Peter-Jordan Strasse 82, 1190 Vienna, Austria
[6]Slovak Hydrometeorological Institute, Jeséniova 17, 833 15 Bratislava, Slovakia
[7]Earth Science Institute, Slovak Academy of Science, Dúbravská cesta 9, 845 28 Bratislava, Slovakia
[8]Institute of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

ABSTRACT: An increase in drought frequency, duration and severity is expected for the Central European region as a direct consequence of climate change. This will have profound effects on a number of key sectors (e.g. agriculture, forestry, energy production and tourism) and also affect water resources, biodiversity and the landscape as a whole. However, global circulation models significantly differ in their projections for Central Europe with respect to the magnitude and timing of these changes. Therefore, analysis of changes in drought characteristics during the last 54 yr in relation to prevailing climate trends might significantly enhance our understanding of present and future drought risks. This study is based on a set of drought indices, including the Standardized Precipitation Index (SPI), the Palmer Drought Severity Index (PDSI), the Palmer Z-index (Z-index) and the Standardized Precipitation–Evapotranspiration Index (SPEI), in their most advanced formulations. The time series of the drought indices were calculated for 411 climatological stations across Austria (excluding the Alps), the Czech Republic and Slovakia. Up to 45% of the evaluated stations (depending on the index) became significantly drier during the 1961–2014 period except for areas in the west and north of the studied region. In addition to identifying the regions with the most pronounced drying trends, a drying trend consistency across the station network of 3 independent national weather services was shown. The main driver behind this development was an increase in the evaporative demand of the atmosphere, driven by higher temperatures and global radiation with limited changes in precipitation totals. The observed drying trends were most pronounced during the April–September period and in lower elevations. Conversely, the majority of stations above 1000 m exhibited a significant wetting trend for both the summer and winter (October–March) half-years.

KEY WORDS: SPI · PDSI · SPEI · Z-index · ICDI · Drought climatology · Climate trends

1. INTRODUCTION

Drought is referred to as the most complex and least understood of all natural hazards, affecting more people than any other extreme event (Wilhite 2000). Any realistic definition of drought must be region- and application-specific. Four interrelated categories of drought are usually distinguished based on the time scale and impact: meteorological, agricultural, hydrological and socioeconomic (Heim 2002). Agricultural drought impacts are mostly associated with timescales from weeks to 6–9 mo, while

*Corresponding author: mirek_trnka@yahoo.com

Publisher: Inter-Research · www.int-res.com

hydrological and socioeconomic impacts usually become apparent following longer time lags. The individual drought categories and their timescales obviously overlap. The occurrence of meteorological drought, however, precedes the onset of specific impacts and thus it is extremely important to understand the regional characteristics of meteorological drought before studying its specific impacts. For this purpose, different drought indices are frequently used to examine meteorological drought, because they are convenient and relatively simple to calculate (Wardlow et al. 2012).

The importance of systematic research on drought climatology has been recognized across the world (Wilhite 2005) and particularly in countries/regions where water supply depends on seasonal precipitation patterns or snow accumulation as the main water source (e.g. the Colorado River basin; Christensen et al. 2004). Incorrectly estimating drought risk or omitting drought-related issues in the process of strategic planning can have serious consequences, not only for the stability of remaining natural ecosystems but also for the economy and society as a whole. A prolonged dry spell may not only inflict severe economic losses, but it can potentially paralyze agricultural production over several seasons and restrain other segments of the economy as well (White et al. 2003, Horridge et al. 2005). Global (Dai 2013) as well as regional studies (Calanca 2007, Trnka et al. 2013, Hänsel et al. 2014) indicate that increased drought probability is to be expected during the 21st century as a direct impact of ongoing climate change.

The high vulnerability and devastating effects of droughts that are commonly associated with specific climatic regions (e.g. African Sahel or recently Australia) are rarely experienced in Central Europe. This region is instead faced with so-called 'green droughts', i.e. droughts associated with relatively ample annual precipitation totals (compared to arid regions) but reduced agricultural productivity due to poorly timed rains. However, even here, drought episodes have played an important role since the early Neolithic Age, when relatively short drought periods significantly influenced the location of early settlements (Kalis et al. 2003). The dendroclimatic data and documentary sources indicate several cases of droughts with intensity not recorded during the instrumental period (Büntgen et al. 2011a, Brázdil et al. 2013, Cook et al. 2015, Dobrovolný et al. 2015). However, even the relatively short instrumental records provide a clear indication of the occurrence of persistent drought periods (e.g. van der Schrier et al. 2006) in this region. The most severe of these events in the last 100 yr was recorded in 1947 (Brázdil et al. 2016b this Special) with less pronounced episodes since then in 1953–1954, 1959, 1992, 2000, 2003, 2007 (Brázdil et al. 2015b) and most recently in 2011–2012 (Zahradníček et al. 2015) and 2015. Recent drought episodes after 2000 led to increased research efforts focusing on drought climatology, causes and impacts (Hlavinka et al. 2009, Škvarenina et al. 2009, Trnka et al. 2009, Brázdil et al. 2013, 2015b, Potop et al. 2014, Bochníček et al. 2015). In the case of Austria, drought studies have focused on alpine hydrology, drought impacts on agriculture and hydrological factors such as runoff and groundwater tables (Blaschke et al. 2011, Thaler et al. 2012, van Loon et al. 2015) but have not assessed the trends in drought indicators. In the Czech Republic, however, drought trends between 1961 and 2000 or 2010 have been evaluated in several studies (e.g. Trnka et al. 2009, Potop et al. 2014). By contrast, comprehensive studies of this type have not been conducted for Slovakia or Austria, and comparisons have not been made with neighboring countries using station data. Although large-scale studies covered the region in the past, they relied on a considerably smaller number of stations, and therefore have far lower resolution (Dai 2013, van der Schrier et al. 2013, Spinoni et al. 2014). This is the first drought-focused study that uses homogenized station data and the whole range of drought indices.

The main objectives of this study were to evaluate the trends in drought occurrence indicated by 4 drought indices during the 1961–2014 period, and to identify differences among individual areas, environmental zones and elevations in a selected part of Central Europe (the Czech Republic, Slovakia and northern Austria). First, an analysis of drought episodes between 1961 and 2014 was carried out together with a determination of the most drought-prone areas. This was followed by analysis of the trends toward increased dryness/wetness, and a comparison of differences in drought occurrence between the 1961–1990 and 1991–2014 periods. Finally, the regionalization of drought characteristics was analyzed.

2. AREA STUDIED AND DATA

The area studied consists of the territory of the Czech Republic, Slovakia and northern Austria. When the climate-driven environmental classification of Europe according to Metzger et al. (2005) is used, the study area is dominated by the Continental (CON) classification. Parts of this zone, and in particular

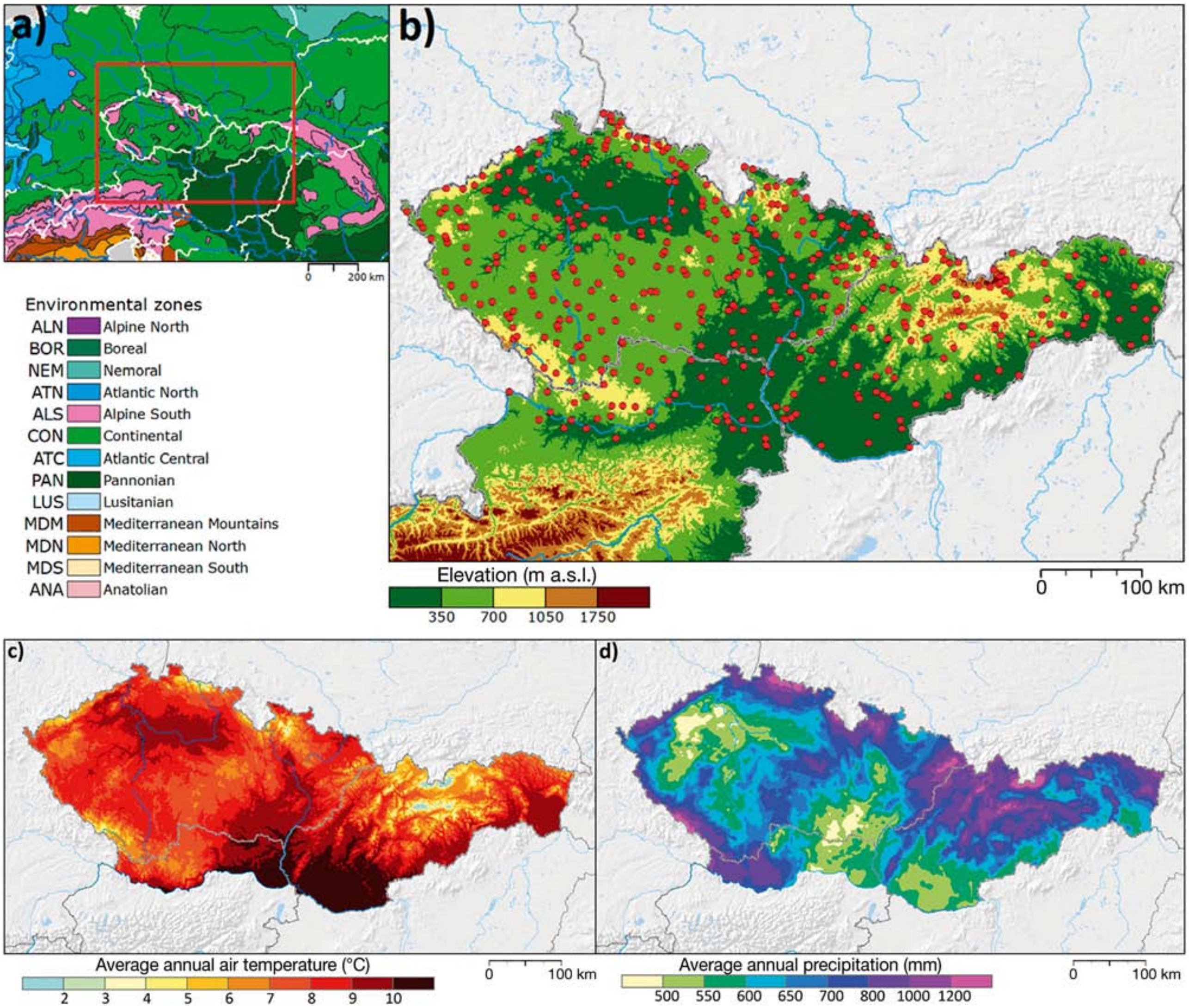

Fig. 1. (a) Overview of the study area with delimitation of environmental zones according to Metzger et al. (2005); (b) location of the climatological stations used in the study for Austria, Czech Republic and Slovakia; (c) mean annual temperature (°C) and (d) mean annual precipitation total (mm) for the study region during the 1981–2010 period

those in Pannonian environmental zone (PAN), are the most susceptible (in the study region) to drought. Higher elevations belong to the Alpine South zone (ALS) (Fig. 1a). The basic climatic patterns are documented in Fig. 1c–d, which shows mean annual temperatures and precipitation totals for the 1981–2010 period. Mean monthly temperatures are usually highest in July and lowest in January or February, with some changes in the temperature pattern in a west–east direction; summer has the highest and winter has the lowest seasonal precipitation totals.

The study area is well covered by climatological stations (Fig. 1b), representing various environmental zones (Fig. 1a), with elevations between 100 m (Somotor, Slovakia) and 2634 m (Lomnický štít, Slovakia). The mean elevation of the stations is 457 m, which is close to the mean elevation of the region (452 m). A database of meteorological variables was produced by the Czech Hydrometeorological Institute, Slovak Hydrometeorological Institute in Bratislava, Central Institute for Meteorology and Geodynamics in Vienna, the Global Change Research Institute in Brno, University of Natural Resources and Life Sciences in Vienna and Mendel University in Brno as a part of the CECILIA FP6 project, followed by several national activities (www.drought.cz, https://ada.boku.ac.at/). The database covers 411 climatological stations and includes daily minimum and maximum temperatures, sums of global radiation, precipitation totals, mean wind speeds and air humidity. The global radiation measurements, as a key input parameter in evapotranspiration calculations, were based partly on direct measurements by pyranometers (10 stations recording measurments from 1983 in the Czech Republic) and over 100 stations recording sunshine duration using heliographs during the 1961–2014 period. Based on previous studies (e.g. Trnka et al. 2005), the Angström-Prescott formula (Prescott 1940) was used to estimate daily global radiation.

All meteorological data were homogenized and checked for consistency using AnClim and ProClim software (Štěpánek et al. 2009, Brázdil et al. 2012). For calculation of areal means on a daily time step, maps were obtained using universal linear kriging interpolation, taking into account the influence of elevation (Šercl & Lett 2002). Local linear regression was applied; a diameter of 40 km was used for air temperature, global radiation, wind speed and air humidity, and a diameter of 20 km was used for precipitation. The so-called technical series of climatic variables (quality controlled, homogeneous and with filled gaps) were used as input for the interpolation (for more details see Štěpánek et al. 2011).

The Standardized Precipitation Index (SPI), Standardized Precipitation–Evapotranspiration Index (SPEI) and Palmer Drought Severity Index (PDSI) including its component Palmer Z-index (Z-index) were applied in this study as the most frequently used drought indicators. Algorithms for the calculation of the last 3 indices were upgraded to address their known caveats.

2.1. Standardized Precipitation Index (SPI)

The SPI is one of the most recent and widely accepted indicators used for drought evaluation at multiple time scales with either monthly or weekly precipitation data. Its calculation is based on the cumulative probability of a given precipitation event occurring at a given station (McKee et al. 1993).

When we analyze regions with different precipitation totals at individual stations but with similar annual patterns of rainfall distribution, then the McKee et al. (1993) SPI (further self-calibrated SPI, or scSPI) results will inevitably indicate a similar number of dry episodes. Although scSPI is of particular value in drought monitoring, its definition of drought as a deviation from the local mean restricts its use as a tool for regional classification in the climatology of drought. This intrinsic property of the scSPI could be partially bypassed through evaluating those scSPI parameters that preserve their variability in space (e.g. Lloyd-Hughes & Saunders 2002, Sönmez et al. 2005). However, this approach comes up short in distinguishing subtle differences between various types of climatic regions over relatively small areas (or regions), as is the case in this study, and this is not very suitable for communication with stakeholders. Therefore, we used the 'relative SPI' (rSPI; Trnka et al. 2009). The rSPI calculation defines the parameters of the gamma distribution based on the dataset created by aggregating all monthly precipitation totals from the 411 stations in the 1961–1990 period. In the following step, the values of the rSPI relative to the reference distribution function were derived for each site (for the use of relative indices, see Dubrovský et al. 2009 and Trnka et al. 2009).

2.2. Palmer Drought Severity Index (PDSI) and Palmer Z-index

The PDSI is one of the most frequently used indices for quantifying drought throughout the world (van der Schrier et al. 2006, Büntgen et al. 2011b, Dai 2013, Cook et al. 2015, Feng et al. 2016). A comprehensive overview of the necessary calculation procedures for PDSI is given by Palmer (1965), Alley (1984) and van der Schrier et al. (2006, 2007). This study uses the self-calibrated version of the index (scPDSI) according to Wells et al. (2004). In general, the index is based on the supply-and-demand concept of a water balance equation, and thus incorporates antecedent precipitation, moisture supply and demand at the surface as calculated according to the Thornthwaite (1948) potential evapotranspiration (PET) method. This empirical PET method is very sensitive to temperature changes and may lead to greater negative PDSI values (Sheffield et al. 2012). Therefore, we estimated PET using the Penman-Monteith method (Allen et al. 1998), which accounts for the impacts of temperature, solar radiation, wind speed and relative humidity on PET. To address other frequently listed shortcomings of the PDSI, such as the lack of a snow cover module, we employed a daily snow cover model to account for the form of precipitation (Trnka et al. 2010).

According to Trnka et al. (2009), the 'relative PDSI' (rPDSI) and 'relative Z-index' (rZ-index) better describe the drought climatology of the region by estimating drought intensity through modeled soil moisture status. The empirical coefficients of both indices

(*K* value) were based on 12 330 yr of data (i.e. set of all monthly observed values from 411 stations covering the whole region of interest for the 1961–1990 period). In the first step, departures from normal soil moisture levels were calculated for each station, and the resulting rZ-index value enabled identification of differences between individual sites. Subsequently, the rPDSI value was determined using the same procedure as used for the PDSI. This approach allowed a comparison of the soil moisture anomaly of each month with the distribution that served as a representation of the overall country climatic conditions. According to the rZ-index (rPDSI), a drought episode was defined as a continuous period of index values below −0.25 (−1.0 for PDSI) that drop below −1.25 (−2.0 for PDSI) at least once during the episode; individual categories were assessed according to Table 1.

The maximum soil water holding capacity (MSWC) is needed to calculate the PDSI. For this study, a constant MSWC of 260 mm m^{-1} depth was used as this represents good quality soil. While such a value is not realistic at higher elevations or for sandy soils in lowlands, the effect on the overall PDSI values in this region is relatively small (e.g. Büntgen et al. 2011a).

2.3. Standardized Precipitation-Evapotranspiration Index (SPEI)

The multi-scalar character of the SPEI enables its use in different scientific disciplines to detect, monitor and analyze droughts (Vicente-Serrano et al. 2010). Similar to the scPDSI and the scSPI, the SPEI can measure drought severity according to its intensity and duration and can identify the onset and the end of drought episodes. The SPEI uses the monthly differences between precipitation and PET as a measure of a simple climatic water balance. The calculation of PET in this paper was performed using the Penman-Monteith method (Allen et al. 1998) and accounted for the snow cover influence using the Trnka et al. (2010) approach. Similar to previous indices, the 'relative SPEI' (rSPEI) was calculated for purposes of spatial analysis. The dataset created by aggregating all monthly precipitation and evapotranspiration totals from the 411 stations in the 1961–1990 period was used to parameterize a single reference distribution function for the whole territory.

2.4. Integrated Climatological Drought Indicator (ICDI)

An Integrated Climatological Drought Indicator (ICDI), conceptually proposed by Trnka et al. (2009), can be used to better communicate results to stakeholders and policy makers. Its main purpose is to provide a relatively simple but robust measure of the relative dryness of a given site in relation to the region of interest. This indicator accounts for the percentage of months that fall in a drought spell according to rSPI, rZ-index, rPDSI and rSPEI during the evaluated time period. Combining both the number of drought events and their duration, ICDI allows visualization of drought risk over the area utilizing a single map. The major shortfall of this approach is that it does not fully account for the intensity of the individual drought events. However, this was dealt with by evaluating individual time series in a separate exercise (see Fig. 2). The ICDI was based on the mean percentage of months in a drought spell as defined in Table 1. We used the 1, 3 and 12 mo rSPI, 1, 3 and 12 mo rSPEI, rZ-index, Z-index and PDSI. All indicators had the same weights. The ICDI takes into account not only indicators based on precipitation deficit (i.e. rSPI) but also includes the effect of evaporation demand (rSPEI, rZ-index and rPDSI) and soil properties (rZ-index or rPDSI).

In drought trend studies, many researchers prefer monthly data for various reasons, including better availability (Lloyd-Hughes & Saunders 2002, Dai et al. 2004, van der Schrier et al. 2007, Feng et al. 2016) and lower sensitivity to observational errors (Viney & Bates 2004). This study addresses drought in time scales ranging from 1 to 12 mo, although we are aware of the fact that shorter time steps would be needed to study certain as-

Table 1. Standardized Precipitation Index (SPI), Standardized Precipitation–Evapotranspiration Index (SPEI), Palmer Z-index (Z-index) and Palmer Drought Severity Index (PDSI) categories according to Heim (2002) and Vicente-Serrano et al. (2010)

SPI	SPEI	Z-index	PDSI	Drought index category
≥2.00	≥2.00	≥3.50	≥4.00	Extremely moist
1.50 to 1.99	1.50 to 1.99	2.5 to 3.49	3.00 to 3.99	Very moist
1.00 to 1.49	1.00 to 1.49	1.00 to 2.49	2.00 to 2.99	Moderately moist
−0.99 to 0.99	−0.99 to 0.99	−1.24 to 0.99	−1.99 to 1.99	Normal range
−1.00 to −1.49	−1.00 to −1.49	−1.25 to −1.99	−2.00 to −2.99	Moderately dry
−1.50 to −1.99	−1.50 to −1.99	−2.00 to −2.74	−3.00 to −3.99	Severely dry
≤−2.00	≤−2.00	≤−2.75	≤−4.00	Extremely dry

pects of drought impacts on agriculture, and longer time steps should be used when hydrological droughts are analyzed. The 1 mo SPI, SPEI and Z-index values are referred to as short-term drought indicators, the 3 mo SPI and SPEI as medium-term drought indicators and the 12 mo SPI, SPEI and PDSI as long-term drought indicators. Tables 1 & 2 show the drought categories indicated by the indices as well as the definition of a drought episode used in this study.

Monthly series of the 1, 3, 6 and 12 mo SPI, SPEI and the PDSI, and Z-index from 1961–2014 were tested for significant trends. We applied the non-parametric Mann-Kendall trend test (Kendall 1990) and considered a trend as significant if the confidence level was 95% or higher. In the case of the trend analysis, the self-calibrated methods of index calculations (rather than their relative versions) were used. To avoid any existing autocorrelation between consecutive drought indices, the trends were evaluated for each month separately. Under these circumstances, all values in each of 12 series can be considered independent. For every station, we evaluated the number of months with statistically significant trends toward drier/wetter conditions. For stations without statistically significant trends, we examined the slope of the regression line.

3. RESULTS

3.1. Dry spells in the 1961–2014 period

Due to the relatively large number of stations and good spatial coverage (Fig. 1b), we selected the percentage of stations in severe to extreme drought (Table 1) as an indicator of the spatial extent of the droughts. As observed in Fig. 2, the number and spatial extent of short-term drought events (Z-index or 3 mo scSPI and scSPEI) were significantly higher than those of long-term drought spells (12 mo scSPEI and scPDSI). According to the Z-index, >80% of the stations were affected by a severe or extreme drought in 1976, 1983, 2003 and 2007. In particular, the drought of summer 2003 was unique — three-quarters of the stations were hit by extreme drought. Nine short-term drought spells affecting >60% of the stations were detected according to the scZ-index in the summer half-year. When medium-term drought (3 mo) was considered, 5 episodes (1964, 1972–1973, 2000, 2003 and 2012) crossed the severe drought threshold at >60% of the stations. On occasion (such as in 1972 or 2003), a short-term event was a precursor to a long-term drought episode, which led to hydrological impacts (low reservoir levels, limited stream flows, depletion of groundwater).

While the results obtained using the scZ-index were rather similar to those of the 3 mo SPEI, the percentage of stations in a drought according to the scPDSI values correlated well with the 12 mo SPEI. As Fig. 2 shows, there were several major drought spells during 1961–2014; the longest occurred in 1990–1995 and the most intensive in terms of number of stations affected occurred in 2003.

3.2. Delimitation of drought-prone regions

Based on the rSPI, rSPEI, rZ-index and rPDSI, the highest number of drought events occurred in the north-western, south-central and extreme south-eastern parts of the region. The dry episodes in these areas were distinguished by their substantially higher intensity and longer duration, exceeding 4 mo on average. Dry episodes were rarely observed in the mountainous regions along the northern, north-western, eastern and south-western borders of the Czech Republic, north-central part of Slovakia and the highlands located in the center of the Czech Republic and Upper Austria. Nevertheless, the occurrence of short-term drought episodes cannot be excluded even at these locations, which are generally characterized by elevations >800 m with mean annual precipitation totals that exceed 800 mm. When they do occur, these episodes tend to be short, with rSPI values rarely reaching below –2.0. Interestingly, lowland stations in the north-eastern region of the Czech

Table 2. Definition of drought episodes according to individual indices. SPI: Standardized Precipitation Index; SPEI: Standardized Precipitation–Evapotranspiration Index; Z-index: Palmer Z-index; PDSI: Palmer Drought Severity Index

Stages of drought episodes	SPI	SPEI	Z-index	PDSI
Start	Drops below –1.0	Drops below –1.0	Drops below –1.25	Drops below –2.0
Minimum value	At least 1 mo below –1.5	At least 1 mo below –1.5	At least 1 mo below –2.0	At least 1 mo below –3.0
End	Rises above 0.0	Rises above 0.0	Rises above 0.0	Rises above 0.0

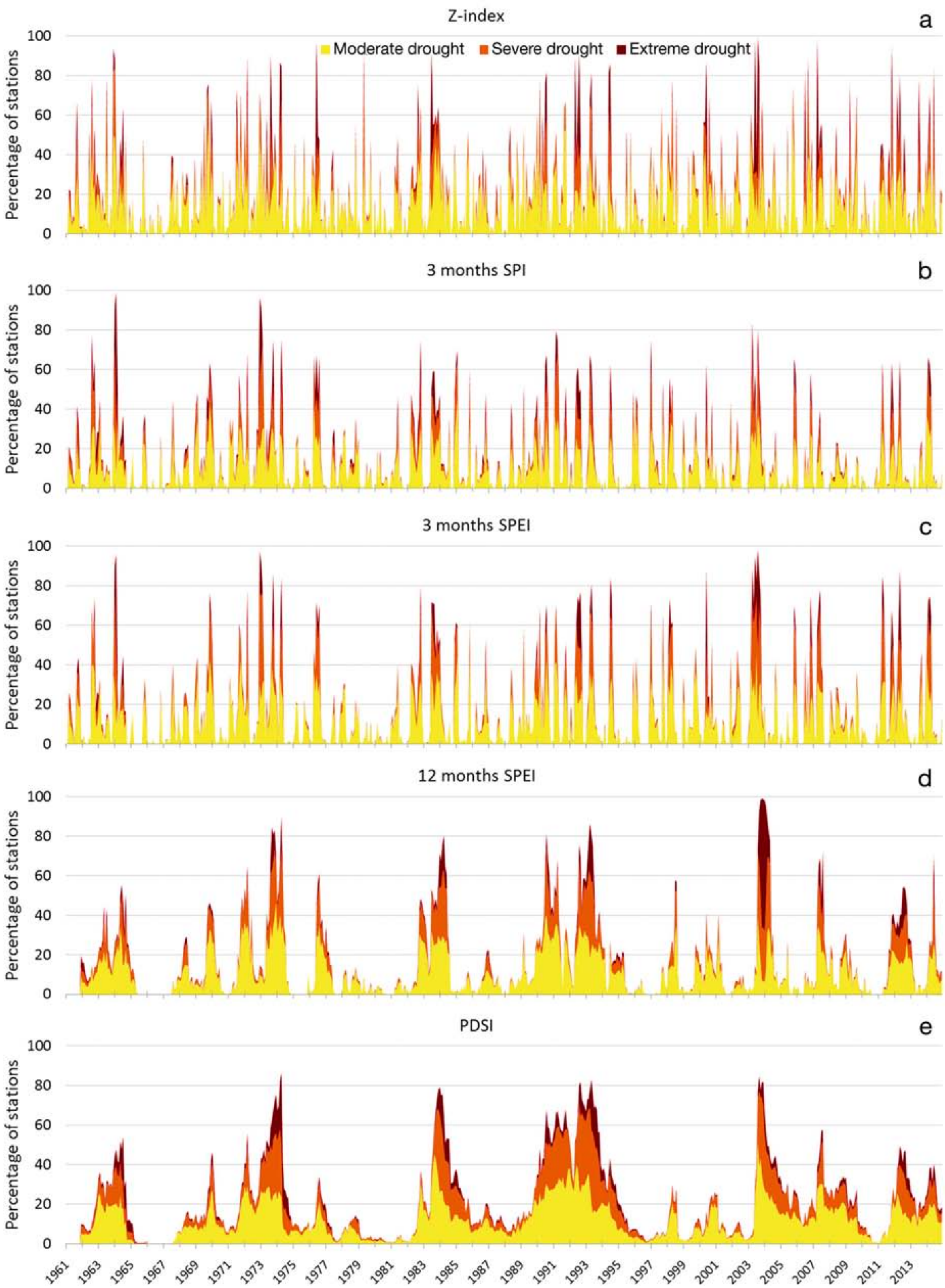

Fig. 2. Percentage of 411 climatological stations with moderate, severe and extreme droughts during the 1961–2014 period according to the (a) self-calibrated Palmer Z-index (scZ-index), (b) 3 mo self-calibrated Standardized Precipitation Index (scSPI), (c) 3 mo self-calibrated Standardized Precipitation–Evapotranspiration Index (scSPEI), (d) 12 mo scSPEI, and (e) self-calibrated Palmer Drought Severity Index (scPDSI)

Republic also have a negligible probability of drought occurrence (Fig. 3). The decisive factor contributing to the lower drought risk in this area is the enhanced precipitation, which is approximately 60% higher on average compared with the corresponding lowland areas located in the south-eastern part of the country (Tolasz et al. 2007). This can be explained by distinctly different precipitation regimes due to a higher frequency of slowly moving Mediterranean cyclones in the northeastern part of the Czech Republic (Hanslian et al. 2000, Kyselý et al. 2007). However, it is precisely in this region in which the 2015 drought was the longest and most intense (www.intersucho.cz).

Further, we also analyzed the 3 and 12 mo rSPI and rSPEI values to evaluate the respective medium- and long-term drought episodes. Although their absolute number decreased with increasing aggregation, these episodes tended to be much longer and showed a much higher level of persistence, as McKee et al. (1993) noted in their original paper. For example, the percentage of months affected by drought according to the 3 mo rSPI reached 70% in the Pannonian area and the Elbe River lowland, while episodes of short-term droughts only accounted for half of the months in the same areas. The differences between the lowland areas and mountains were enhanced by applying the 3 and especially the 12 mo rSPI indices. As several consecutive months with low precipitation are highly unlikely in the mountains, the percentage of time that mountain stations were in a drought according the 12 mo rSPI was negligible (Table 3).

From a climatological point of view, there are several 'epicenters' of drought-prone regions according to the ICDI (Fig. 3). The largest continuous area with a high risk of drought occurrence (>60% of months with dry spells) was observed in the southeastern part of the Czech Republic and across Lower Austria. The second major area extended across south-western Slovakia (including Žitný ostrov Island). Secondary 'epicenters' were located in the north-west (the Elbe River lowland and the lee side of the Krušné hory Mts.) and south-eastern Slovakia. In contrast, the mountain ranges on the Czech border with Germany and Poland, as well as the Bohemian-Moravian Highlands in the center of the Czech Republic, and mountainous regions in the central part of Slovakia and Upper Austria were only rarely affected. Fig. 3 further indicates that the highest drought risk appears on the alluvial soils around the Danube, lower Morava and Tisza rivers, which roughly corresponds to the Pannonian zone (Table 3). The drought susceptibility in these regions is due to the relatively low precipitation and high potential evapotranspiration, which leads to an insufficient accumulation of moisture in the soil profile, particularly during the summer half-year. The local effects of drought depend on the soils. In the case of alluvial

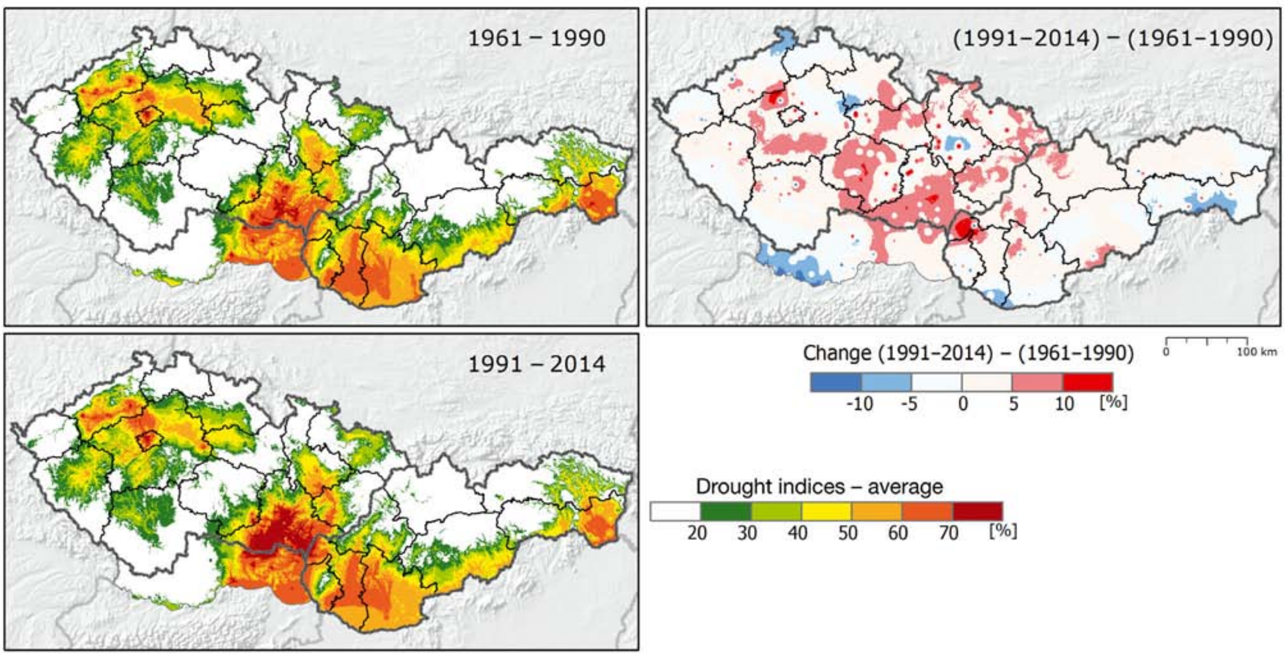

Fig. 3. Percentage of time of drought episodes according to the Integrated Climatological Drought Indicator (ICDI) during the 1961–1990 and 1991–2014 periods as well as the difference between both periods

Table 3. Selected drought characteristics based on the 1 and 3 mo relative Standardized Precipitation–Evapotranspiration Index (rSPEI), relative Palmer Z-index (rZ-index) and relative Palmer Drought Severity Index (rPDSI) for groups of stations divided according to their elevation and environmental zone (according to Metzger et al. 2005). PAN: Pannonian zone; CON: Continental zone; ALS: Alpine South zone

	No. of stations	Mean elevation (m)	Mean annual temperature (°C)	Mean annual precipitation (mm)	Percentage of time in the drought episode during 1961–1990				Change in time (%) in the drought episode in 1991–2014 compared to 1961–1990			
					1 mo rSPEI	3 mo rSPEI	rZ-index	rPDSI	1 mo rSPEI	3 mo rSPEI	rZ-index	rPDSI
Elevation (m a.s.l.)												
90–200	47	148	9.8	563	43.6	55.8	65.1	68.0	+1.3	+3.9	−1	+4.7
200–400	157	296	8.8	640	21.4	28.6	41.3	28.8	+5.1	+4.8	+3.7	+7.3
400–600	124	495	7.7	695	9.5	11.5	23.7	17.9	+4.4	+2.8	+3.1	+2.6
600–1000	65	757	6.3	866	4.5	4.2	9.6	1.8	+1.5	−0.2	+1.6	−0.4
>1000	18	1319	3.1	1160	1.9	0.6	2.0	0.0	+0.1	+0.1	+0.4	0
All stations	411	457	7.9	706	16.8	21.5	32.0	21.5	+3.7	+3.1	+2.5	+4
Environmental zone												
PAN	37	179	10.0	551	51.0	63.2	71.0	77.9	+0.4	+3.8	−1.7	+3.1
CON	312	440	8.0	689	15.2	19.9	31.6	18.6	+4.6	+3.8	+3.4	+5.1
ALS	59	662	6.5	864	4.8	4.9	11.3	2.5	+0.9	−1	+0.5	−1.1
All stations	411	457	7.9	706	16.8	21.5	32.0	21.5	+3.7	+3.1	+2.5	+4

soils, the impacts are frequently mitigated by the high water-holding capacity of these deep soils as well as by capillary water rise at sites with shallow underground water tables (e.g. Žitný ostrov Island in Slovakia).

3.3. Trend analysis

Analysis of the trends in annual precipitation totals recorded at the 411 stations showed statistically significant changes in <20% of the stations (with domination of wetting trends) during the 1961–2014 period. Similarly, the long-term scSPI series for individual stations demonstrated patterns toward a wetter climate for almost one-quarter of the stations. Positive and highly significant trends in mean air temperatures, especially associated with the unusually warm period of 1991–2014, were found for the majority of the 411 stations.

As a direct result of increasing temperature and no change in precipitation, the monthly series of the scZ-index, scPDSI and scSPEI showed decreasing trends, indicating more frequent and/or severe droughts (Table 4). Overall, 36% (34%) of stations showed statistically significant negative trends (increased dryness) in at least 1 month according to the scZ-index (SPEI), compared to 8% (9%), with a positive trend in the summer half-year (Table 4, Fig. 4).

By contrast, wetting trends prevailed in the winter half-year (Fig. 5). The remaining stations did not show any statistically significant trends; however, a large number of stations inclined toward lower scZ-index and SPEI values over time (Figs. 4 & 5). Trends were also pronounced in the scPDSI and 12 mo SPEI, characterizing long-term drought spells compared with shorter spells identified with the scZ-index and 1 mo SPEI (Figs. 4 & 5). Statistically significant trends toward negative scPDSI values in the summer half-year were detected for 35% of the stations, most of which exhibited a significant decrease in PDSI for 3 or more months. Only 7% of the stations showed the opposite tendency. During the winter half-year, 26% of stations showed a negative trend (increased dryness) and 11% a positive trend (increased wetness). Out of the almost 60% of stations with no statistically significant trend, more than two-thirds showed a decrease in scPDSI values rather than an increase or no change. Similar results were found for the 12 mo scSPEI, with 14% of the stations showing a negative trend and 5% a positive trend. However, in the case of the winter half-year trends of 1 and 3 mo scSPEI and scZ-index, the prevalence of stations with a tendency toward wetter conditions is obvious.

As Fig. 4 shows for the summer half-year, the proportions of stations with trends toward higher dryness are much greater than those toward higher wetness. This was also valid for the winter half-year (Fig. 5), particularly for scPDSI and the 12 mo scSPEI. The prevalent trends for long-term drought indicators suggest that the summer half-year drying was not fully compensated by the wetting trends in the winter half-year.

Table 4. Percentage of stations with statistically significant trends toward increased dryness/wetness for at least 1 mo in the summer or winter half-year during the 1961–2014 period. Stations are divided according to their elevation and environmental zones. PAN: Pannonian zone; CON: Continental zone; ALS: Alpine South zone. scSPI: self-calibrated Standardized Precipitation Index; scSPEI: self-calibrated Standardized Precipitation–Evapotranspiration Index; scZ-index: self-calibrated Palmer Z-index; scPDSI: self-calibrated Palmer Drought Severity Index

	No. of stations	Mean elevation (m)	Percentage of stations with significant **drying**/wetting trend							
			1 mo scSPI	1 mo scSPEI	scZ-index	3 mo scSPI	3 mo scSPEI	12 mo scSPI	12 mo scSPEI	scPDSI index
Summer half year										
Elevation (m a.s.l.)										
90–200	47	148	**9** /45	**13**/6	**13**/6	**6**/36	**36**/0	**0**/6	**26**/0	**38**/0
200–400	157	296	**18**/34	**34**/8	**39**/7	**18**/29	**51**/4	**2**/15	**22**/1	**48**/3
400–600	124	495	**26** /40	**44**/6	**44**/5	**14**/44	**51**/6	**2**/31	**10**/3	**31**/6
600–1000	65	757	**25**/34	**37**/15	**38**/11	**22**/34	**42**/8	**2**/35	**8**/11	**17**/15
>1000	18	1319	**0**/44	**11**/28	**17**/28	**6**/67	**11**/61	**0**/56	**0**/44	**6**/44
Environmental zone										
PAN	37	179	**0**/49	**3**/5	**11**/5	**3**/51	**41**/0	**0**/3	**35**/0	**41**/0
CON	312	440	**18**/35	**35**/8	**37**/7	**15**/34	**46**/6	**2**/24	**16**/3	**38**/6
ALS	59	662	**42**/46	**51**/15	**51**/14	**25**/41	**53**/15	**0**/34	**0**/15	**20**/14
All stations	411	457	**20**/37	**34**/9	**36**/8	**16**/37	**46**/7	**1**/24	**15**/5	**35**/7
Winter half year										
Elevation (m a.s.l.)										
90–200	47	148	**6**/32	**19**/19	**13**/6	**2**/11	**2**/4	**0**/11	**23**/0	**26**/0
200–400	157	296	**11**/39	**18**/30	**20**/17	**3**/17	**6**/6	**2**/13	**21**/2	**38**/4
400–600	124	495	**2**/39	**5**/24	**6**/19	**2**/31	**2**/8	**2**/29	**8**/3	**22**/10
600–1000	65	757	**2**/48	**5**/46	**5**/46	**5**/51	**6**/37	**2**/31	**6**/11	**12**/29
>1000	18	1319	**0**/83	**6**/67	**11**/67	**0**/83	**0**/78	**0**/56	**0**/44	**6**/50
Environmental zone										
PAN	37	179	**8**/27	**24**/16	**16**/0	**8**/0	**8**/0	**0**/5	**30**/0	**35**/0
CON	312	440	**6**/43	**12**/30	**14**/21	**2**/28	**4**/11	**2**/22	**15**/3	**29**/9
ALS	59	662	**2**/42	**2**/44	**2**/47	**0**/47	**0**/37	**0**/31	**0**/15	**10**/25
All stations	411	457	**6**/42	**11**/31	**12**/23	**2**/29	**4**/15	**1**/22	**14**/5	**26**/11

3.4. Comparison of droughts in the 1961–1990 and 1991–2014 periods

Drying trends inevitably also affect the duration of droughts, as documented in Table 3. There was a tendency toward an increased time during which the stations were influenced by drought episodes in the 1991–2014 period compared with 1961–1990. While the change was not major, the tendency was fairly robust. An increased occurrence of the most extreme drought categories can be seen as subtle shift in the occurrence of the most extreme categories (Fig. 6). We noted a slight increase across all drought indicators with respect to the frequency of the severe and extreme drought categories, as these events occurred more frequently and had a longer duration in 1991–2014. Interestingly, there was no decrease in number of extremely wet events, especially at the 1 and 3 mo scales. The ICDI values in Fig. 3 correspond to the shifts noted above. The most obvious increase in drought frequency was evident in the south-central part of the study region, with subtle changes in southern Slovakia. In the eastern and north-western areas, there were subtle changes in drought hotspots; in some cases, even very small reductions in drought frequency were recorded.

3.5. Regionalization of droughts

Table 3 shows distinct differences in the frequency of drought indicated by the relative drought indices between individual elevations and environmental zones. The greatest shift toward more frequent drought occurred between elevations of 200 and 600 m and in the CON zone. In addition, the PAN zone shifted toward higher drought occurrence according to the 3 mo SPEI and rPDSI, but to a lesser extent. On the other hand, there was an obvious tendency toward wetter conditions, especially in the winter half-year for stations located at elevations above 1000 m and in the ALS zone.

This can be partly explained by the higher proportion of liquid precipitation and an overall increase in

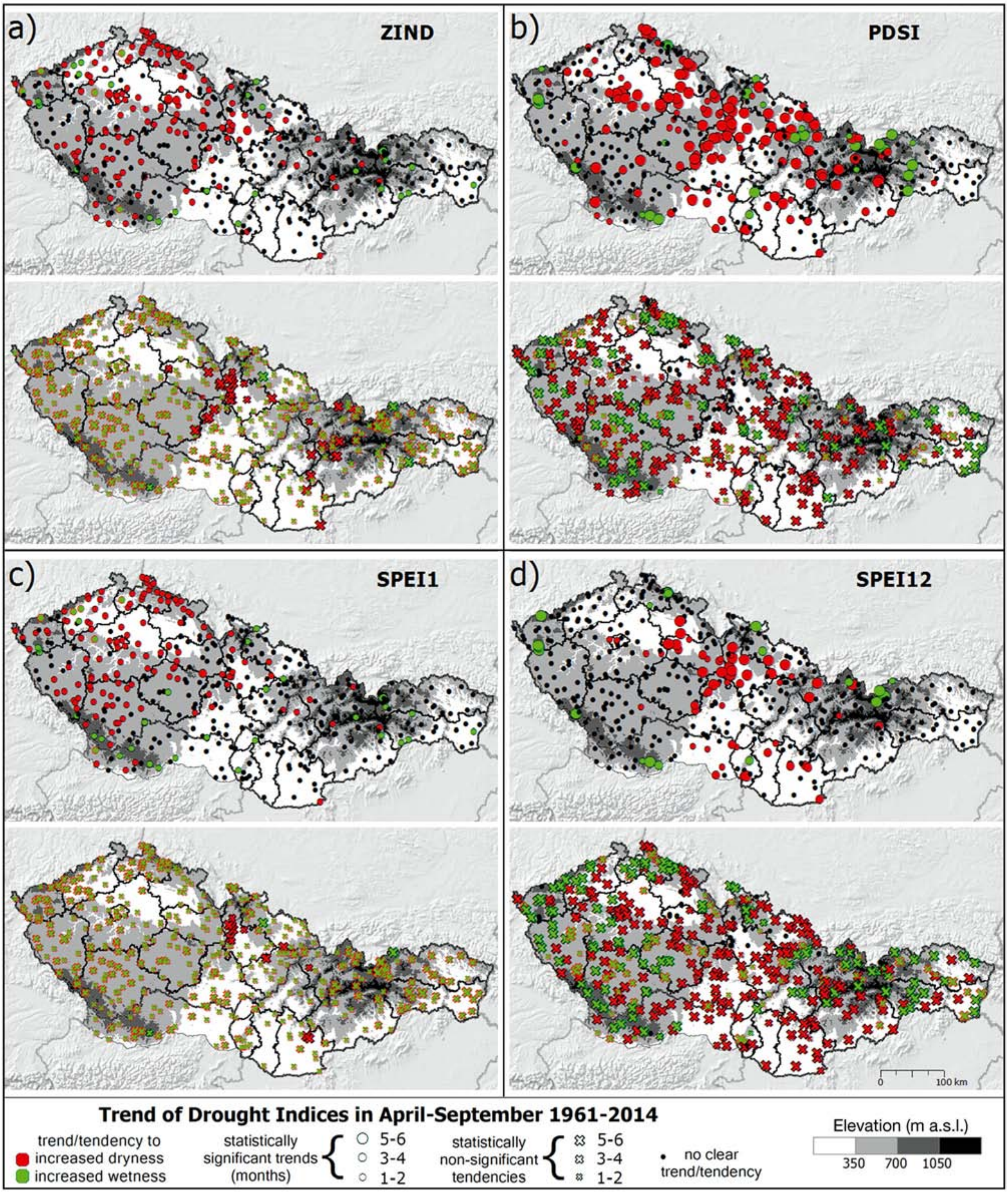

Fig. 4. Number of months within the summer half-year (April–September) with positive and negative significant trends (α = 0.05, upper panels) and non-significant tendencies (lower panels) for the (a) self-calibrated Palmer Z-index (scZ-index), (b) self-calibrated Palmer Drought Severity Index (scPDSI), (c) 1 mo self-calibrated Standardized Precipitation–Evapotranspiration Index (scSPEI), and (d) 12 mo scSPEI. Evaluations of trends/tendencies were carried out individually for each month in the 1961–2014 period. Green symbol with red outline: both types of trends/tendencies occurred. Note: negative trends/tendencies signal increasing drought duration/intensity

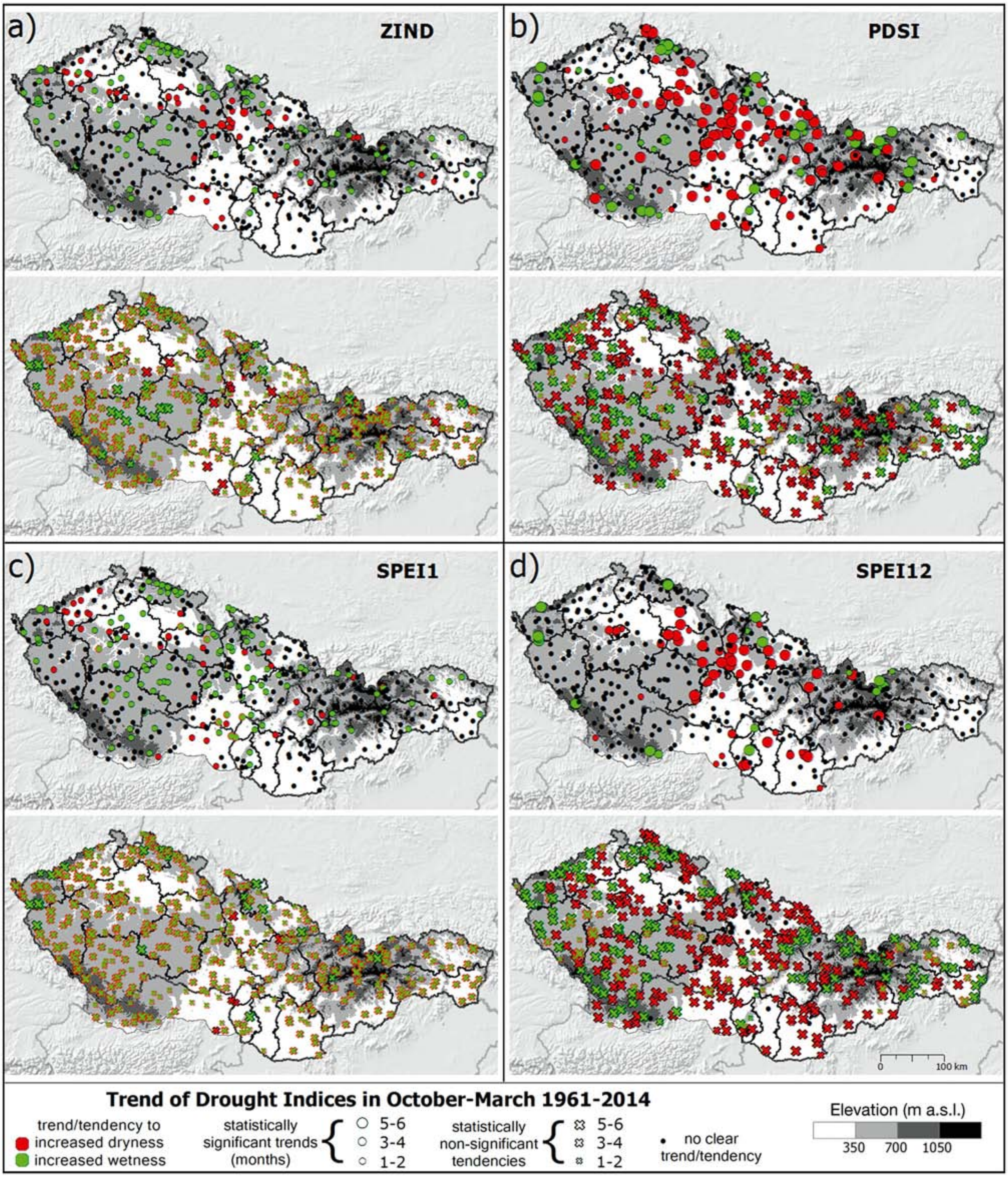

Fig. 5. As in Fig. 4 for the number of months in the winter half-year (October–March) with positive and negative significant trends

precipitation totals that leads to higher availability of water, and results in the more positive (i.e. 'wetter') index values. However, this also means that water that would be released later in the spring during snow-melt reaches streams and soil earlier. This will change the pronounced seasonality in runoff in the Alpine zone (Fürst et al. 2008, Blaschke et al. 2011, APCC 2014). At the same time, almost the opposite

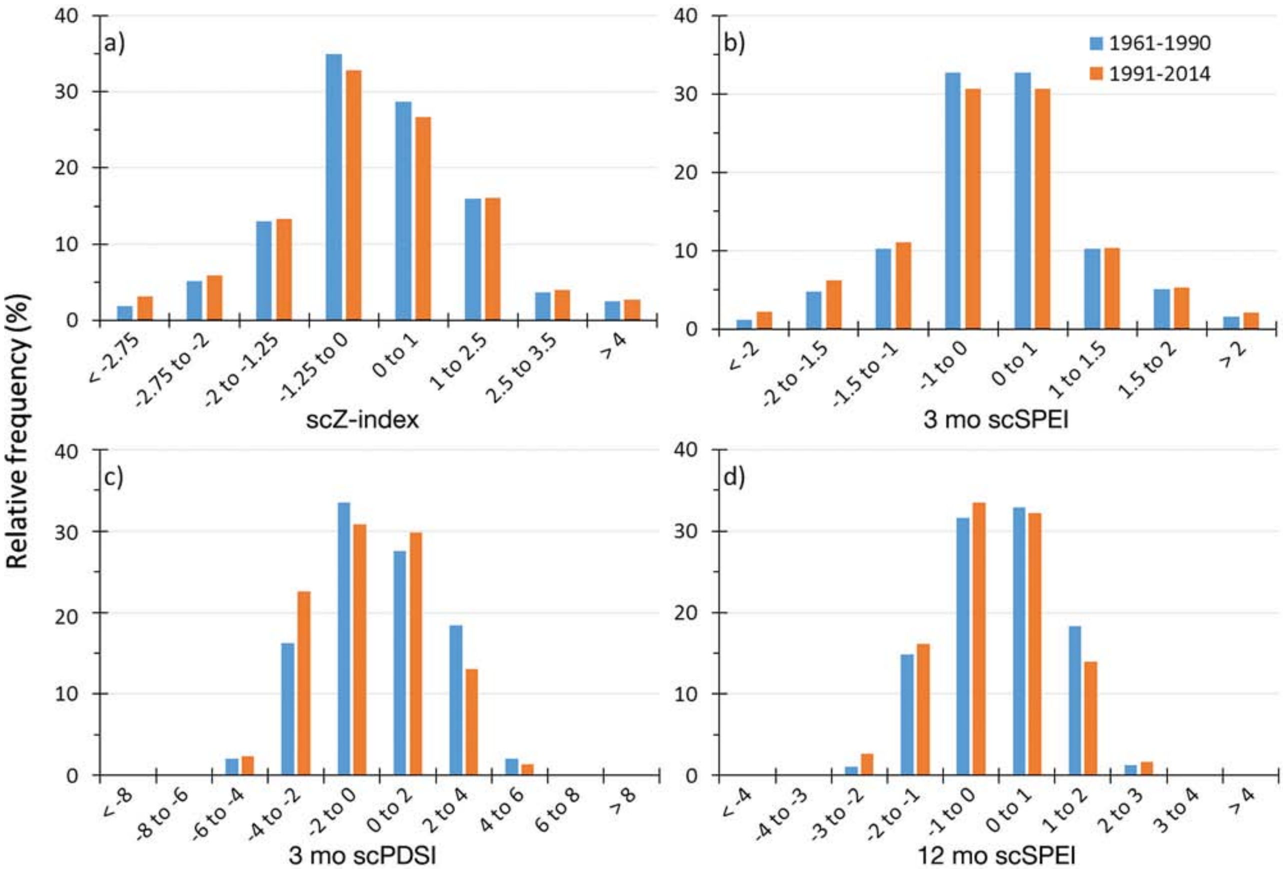

Fig. 6. Comparison of relative frequencies of drought indices for the 1961–1990 and 1991–2014 periods calculated for 411 climatological stations based on the (a) self-calibrated Palmer Z-index (scZ-index), (b) 3 mo self-calibrated Standardized Precipitation–Evapotranspiration Index (scSPEI), (c) self-calibrated Palmer Drought Severity Index (scPDSI), and (d) 12 mo scSPEI. Categories are based on Table 1

situation occurred in the summer half-year in the warmest Pannonian zone and at elevations below 200 m, and to some extent at elevations between 201–600 m or in the CON zone. This means that while dry regions became increasingly drier, the stations at higher elevations showed trends toward increased wetness; however, this occurred at the expense of snow cover and therefore lowered the potential water flow at lower elevations during the season.

4. DISCUSSION

4.1. Potential evapotranspiration and baseline period

Some drought indices such as the SPI are based on precipitation alone and only provide a measure of water supply. They are very useful as a measure of precipitation deficit or meteorological drought (Spinoni et al. 2015), but are limited because they do not address the water demand side of the water balance. The concept of the SPI was extended to SPEI, which is a product that includes both precipitation and PET data. The PDSI takes this one step further by accounting for the balance of precipitation, evapotranspiration and runoff and has the ability to incorporate local soil and possibly vegetation properties, making it a fairly comprehensive and flexible index of relative drought (Trenberth et al. 2014). Both SPEI and PDSI use the Thornthwaite (1948) method to account for evapotranspiration effects. This approach considers only monthly precipitation and temperature, and has the major advantage of being easily calculated because of the availability of these data for most global land areas. The disadvantage is that it cannot account for changes in solar and infrared radiation, humidity and wind speed, which we discuss below. A more realistic and complex approach to estimating PET in the PDSI is the method outlined by Penman in 1948 and modified by Monteith to yield the Penman-Monteith formulation, which incorporates the effects of wind and humidity, plus solar and longwave radiation.

In global or large-scale studies, most of the data needed to estimate PET through the Penman-Monteith approach are not readily available (Trenberth et al. 2014, Spinoni et al. 2015) or generally suffer from temporal and spatial inhomogeneity. However, for Central Europe, the datasets were properly homogenized and can be considered high-quality records. Fig. 7 shows that there are indeed very small differences between the SPEI using the Thornthwaite and Penman-Monteith algorithms, while the difference seems to be higher for different versions of PDSI. The higher sensitivity of the PDSI to different methods of the Penman-Monteith calculation stems from the way in which the drought/wet transition probabilities are calculated; hence, a small difference in the PET estimate might have significant consequences (Palmer 1965).

Another important issue that has emerged in recent research (Sheffield et al. 2012, Trenberth et al. 2014) is the choice of the baseline period to define and calibrate the drought categories. Sheffield et al. (2012) and Spinoni et al. (2015) used a baseline period of 1950–2008 and 1951–2010, respectively, while Dai (2013) used 1950–1979, which was globally relatively wet. Obviously, such selection influences the results (Trenberth et al. 2014). The ideal baseline period should sample natural variability fully, i.e. longer records are preferable. However, there is also a problem in using a more recent baseline period (e.g. 1951–2010) because the effects of recent anthro-

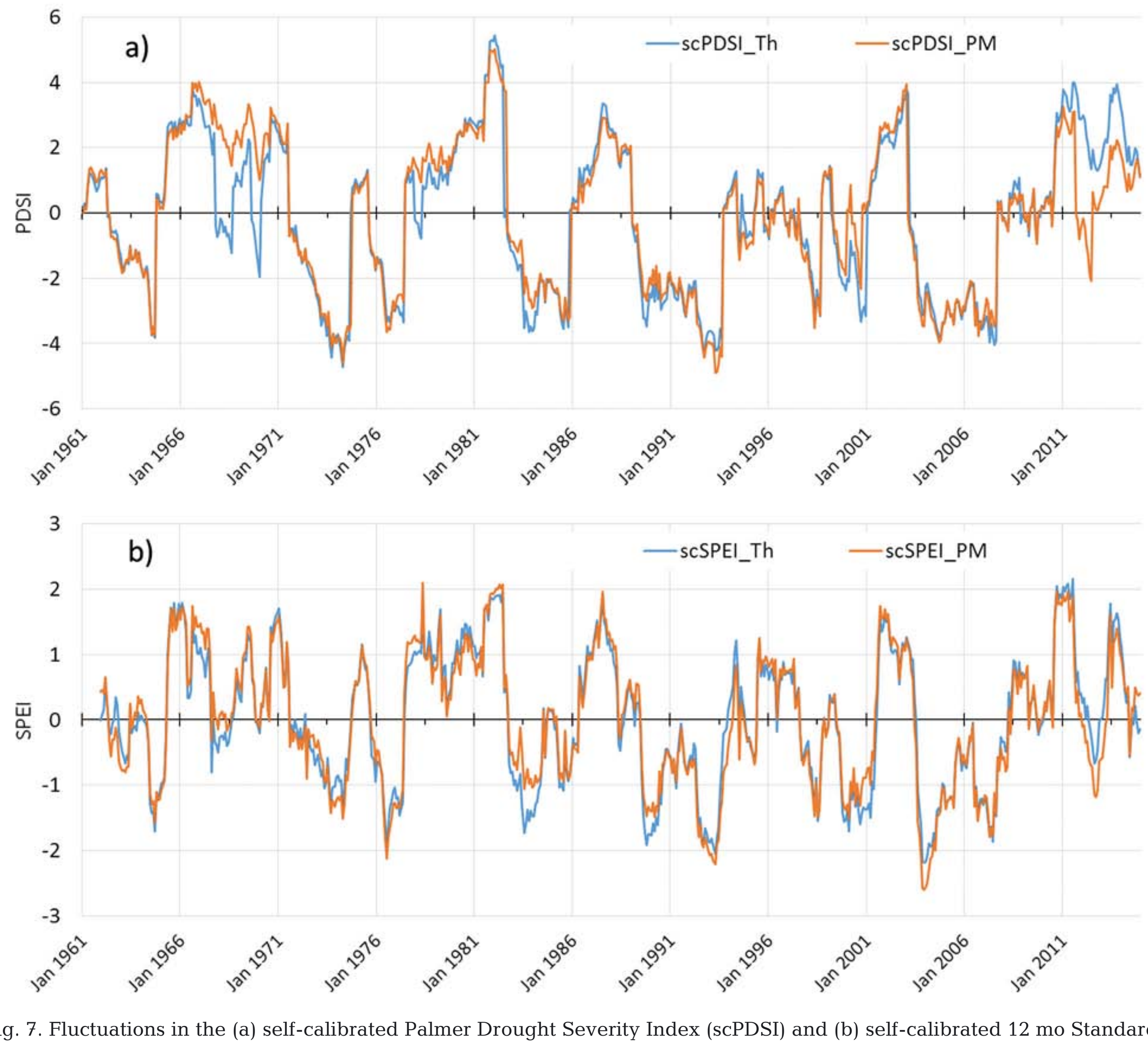

Fig. 7. Fluctuations in the (a) self-calibrated Palmer Drought Severity Index (scPDSI) and (b) self-calibrated 12 mo Standardized Precipitation–Evapotranspiration Index (scSPEI) series calculated for the Doksany station (Czech Republic) for the 1961–2014 period using the Thornthwaite (Th) and Penman-Monteith (PM) methods

pogenic forcings will be included. This alters the range of observed variability against which the long-term variations that characterize changes are scaled. Hence, it greatly reduces any prospects of identifying a climate change signal in the results of the analysis. Therefore, we selected 1961–1990 as the calibration period. Within this period, both extremely dry and wet episodes occurred (cf. Figs. 2 & 7).

4.2. Regional and large-scale context

The results obtained can be compared with continental-scale studies. Dai et al. (2004) and Dai (2013) reported the existence of a notable drying trend since the beginning of the 20th century throughout Europe that was linked to increasing air temperatures. Other studies, using a different dataset with a higher spatial resolution (0.5° grid), reported either strong or very strong drying trends for the area corresponding to our study (i.e. 48–51° N and 13–23° E). This includes the PDSI-based paper by van der Schrier et al. (2006) and more recent global studies by Sheffield et al. (2012) and van der Schrier et al. (2013). Spinoni et al. (2014), using precipitation-based SPI, showed a statistically significant tendency toward a higher number of droughts in the east of the Czech Republic, but this was not confirmed by our SPI station trends.

Brázdil & Kirchner (2007) evaluated scPDSI trends for stations within the Czech Republic for the 1850–2003 period. They reported a statistically significant trend toward lower PDSI with value of –0.1 decade^{-1}. The study by Brázdil et al. (2015a) for the 1805–2012 period showed an increase in spring–summer droughts (based on SPEI, Z-index and PDSI) and revealed the importance of the North Atlantic Oscillation phase and the aggregate effect of anthropogenic forcing (driven largely by increases in CO_2 concentration) on the frequency and severity of droughts. The longest drought reconstruction available for the region so far covers the 1501–2015 period (Brázdil et al. 2016a this Special). While individual drought episodes in recent decades have not reached the magnitudes of the most pronounced droughts, such as those of the 1720s, this drought reconstruction shows that a slow but continuous and robust drying has occurred since the late 19th century. More recent periods evaluated in different parts of the region also showed a consistent prevalence of drying trends over wetting tendencies during the past 50 yr in the Czech Republic (Brázdil et al. 2009a, Trnka et al. 2009, 2015, Potop et al. 2014). This corresponds with the results of the detailed analysis of air temperature series performed by Květoň (2001), Huth & Pokorná (2005), Chládová et al. (2007) and Brázdil et al. (2009b) as well as the results obtained in the adjacent areas of Poland (Degirmendžič et al. 2004) and the Alps (Casty et al. 2005).

Furthermore, results for Slovakia (Labudová et al. 2015a, 2015b) indicate prevailing drying tendencies in the lowlands and surrounding lower parts of the territory. These drying tendencies are not triggered by the precipitation decline but by increasing temperatures enhancing evapotranspiration (Labudová et al. 2015a). This agrees well with previous papers published by Melo et al. (2007) and Pecho et al. (2008), which indicated such drying trends in earlier periods. In Austria, climatological research revealed detailed spatial-temporal trends by establishing long-term homogenized datasets such as HISTALP (Auer et al. 2005, Böhm 2006). No general precipitation trends can be found for the whole of Austria. However, due to the important influence of the Alpine ridge, Austria has to be divided into 3 different precipitation regions (Matulla et al. 2003). The most drought-prone region occurs in the north-eastern part of Austria and is highly correlated with patterns in the neighboring Czech territory, as confirmed in this study. Similar to Austria, analysis of drought in Saxony using the decile method (Hänsel 2014) for the period 1901–2010 showed some drying tendency, but only in warm half-years, which waned in recent decades.

5. CONCLUDING REMARKS

Our analysis of a selected part of Central Europe showed that the most drought-prone region is north of the Danube River, including the junction of the borders of Austria, the Czech Republic and Slovakia. A second prominent region includes the north-western Czech Republic around the Elbe River and the third region is the south-eastern corner of Slovakia. These areas, mostly belonging to the PAN environmental zone, have shown increases in long-term drought occurrence. Trend analysis indicates that shifts in drought severity during the 1961–2014 period are not driven by a decrease in precipitation but rather by increased evaporation demand towards the end of the 20th century and in the early 21st century. The indicators that consider both precipitation and evaporative demand, i.e. SPEI, PDSI, Z-index of the atmosphere (or soil moisture), confirm strong trends toward increased dryness in the monthly and long-term water balance deficits at many stations. This was driven not only by increasing temperatures but also by decreasing relative air humidity and increasing solar radiation in some months (Trnka et al. 2015). Moreover, most negative drying trends were found at lower elevations where the impacts on agriculture and forestry also tended to be the most intense. A significantly smaller number of stations in the area studied indicated that the conditions became wetter.

While the detected trends are not uniform, they strongly indicate tendencies toward increased dryness across the 3 countries. In fact, this agrees well with analyses based on documentary and/or tree ring data (Büntgen et al. 2011a, Dobrovolný et al. 2015, Brázdil et al. 2016a), and shows that the expected drying of the analyzed region — shown by the majority of the global and regional circulation models — is substantiated by observed changes in the recent past.

Acknowledgements. M.T., R.B., P.H., J.B., D.S., P.Z., Z.Ž. and P.Š. acknowledge funding from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant number LO1415. R.B. also acknowledges Grant Agency of the Czech Republic for project no. 13-19831S. The work of J.E. and M.T. was supported by AgroDroughtAustria (ADA, 2013–2016), Project No. KR12AC5K01071 of the Austrian Climate Research Program (ACRP). The work of P.H., J.B. and M.T. was also supported by Grant Agency project no. 13-04291S. P.H. and M.T. were also supported by project IGA AF MENDELU no. TP 7/2015 with the support of the Specific University Research Grant, provided by the Ministry of Education, Youth and Sports of the Czech Republic. The authors thank 2 reviewers for their helpful comments and suggestions.

LITERATURE CITED

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome

Alley WM (1984) The Palmer Drought Severity Index: limitations and assumptions. J Clim Appl Meteorol 23: 1100–1109

APCC (Austrian Panel on Climate Change) (2014) Österreichischer Sachstandsbericht Klimawandel 2014 (AAR14). Verlag der Österreichischen Akademie der Wissenschaften, Vienna

Auer I, Böhm R, Jurkovi A, Orlik A and others (2005) A new instrumental precipitation dataset for the greater Alpine region for the period 1800–2002. Int J Climatol 25: 139–166

Blaschke AP, Merz R, Parajka J, Salinas J, Blöschl G (2011) Auswirkungen des Klimawandels auf das Wasserdargebot von Grund- und Oberflächenwasser. Oesterr Wasser Abfallwirtsch 63:31–41

Bochníček O, Borsányi P, Čepčeková E, Faško P and others (2015) Klimatický atlas Slovenska (Climate Atlas of Slovakia). Slovenský hydrometeorologický ústav, Bratislava

Böhm R (2006) ALP-IMP (EVK-CT-2002-00148) Multi-centennial climate variability in the Alps based on instrumental data, model simulations and proxy data. Short version. (Final report for RTD-project). Central Institute for Meteorology and Geodynamics, Vienna

Brázdil R, Kirchner K (eds) (2007) Vybrané přírodní extrémy a jejich dopady na Moravě a ve Slezsku (Selected natural extremes and their impacts in Moravia and Silesia). Český hydrometeorologický ústav, Prague

Brázdil R, Chromá K, Dobrovolný P, Tolasz R (2009a) Climate fluctuations in the Czech Republic during the period 1961–2005. Int J Climatol 29:223–242

Brázdil R, Trnka M, Dobrovolný P, Chromá K, Hlavinka P, Žalud Z (2009b) Variability of droughts in the Czech Republic, 1881–2006. Theor Appl Climatol 97:297–315

Brázdil R, Zahradníček P, Pišoft P, Štěpánek P, Bělínová M, Dobrovolný P (2012) Temperature and precipitation fluctuations in the Czech lands during the period of instrumental measurements. Theor Appl Climatol 110:17–34

Brázdil R, Dobrovolný P, Trnka M, Kotyza O and others (2013) Droughts in the Czech Lands, 1090–2012 AD. Clim Past 9:1985–2002

Brázdil R, Trnka M, Mikšovský J, Řezníčková L, Dobrovolný P (2015a) Spring-summer droughts in the Czech Land in 1805–2012 and their forcings. Int J Climatol 35: 1405–1421

Brázdil R, Trnka M, Řezníčková L, Balek J and others (2015b) Sucho v českých zemích: minulost, současnost, budoucnost (Drought in the Czech Lands: past, present and future). Centrum výzkumu globální změny Akademie věd české republiky, Brno

Brázdil R, Dobrovolný P, Trnka M, Büntgen U, Řezníčková L, Kotyza O, Valášek H (2016a) Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501. Clim Res 70:103–117

Brázdil R, Raška P, Trnka M, Zahradníček P and others (2016b) The Central European drought of 1947: causes and consequences, with particular reference to the Czech Lands. Clim Res 70:161–178

Büntgen U, Brázdil R, Dobrovolný P, Trnka M, Kyncl T (2011a) Five centuries of southern Moravian drought variations revealed from living and historic tree rings. Theor Appl Climatol 105:167–180

Büntgen U, Tegel W, Nicolussi K, McCormick M and others (2011b) 2500 years of European climate variability and human susceptibility. Science 331:578–582

Calanca P (2007) Climate change and drought occurrence in the Alpine region: How severe are becoming the extremes? Global Planet Change 57:151–160

Casty C, Wanner H, Luterbacher J, Esper J, Böhm R (2005) Temperature and precipitation in the European Alps since 1500. Int J Climatol 25:1855–1880

Chládová Z, Kalvová J, Raidl A (2007) The observed changes of selected climate characteristics in the period 1961–2000. Meteorol Čas 10:13–19

Christensen N, Wood A, Voisin N, Lettenmaier D, Palmer R (2004) Effects of climate change on the hydrology and water resources of the Colorado River basin. Clim Change 62:337–363

Cook ER, Seager R, Kushnir Y, Briffa KR and others (2015) Old World megadroughts and pluvials during the Common Era. Sci Adv 1:e1500561

Dai A (2013) Increasing drought under global warming in

observations and models. Nat Clim Change 3:52–58
Dai A, Trenberth KE, Taotao Q (2004) A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. J Hydrometeorol 5:1117–1130
Degirmendžič J, Kozuchowski K, Zmudzka E (2004) Changes of air temperature and precipitation in Poland in the period 1951–2000 and their relationship to atmospheric circulation. Int J Climatol 24:291–310
Dobrovolný P, Rybníček M, Kolář T, Brázdil R, Trnka M, Büntgen U (2015) A tree-ring perspective on temporal changes in the frequency and intensity of hydroclimatic extremes in the territory of the Czech Republic since 761 AD. Clim Past 11:1453–1466
Dubrovský M, Svoboda MD, Trnka M, Hayes MJ, Wilhite DA, Zalud Z, Hlavinka P (2009) Application of relative drought indices in assessing climate change impacts on drought conditions in Czechia. Theor Appl Climatol 96: 155–171
Feng S, Trnka M, Hayes M, Zhang Y (2016) Why different drought indices show distinct future drought risk outcomes in the US Great Plains? J Clim (in press)
Fürst J, Nachtnebel HP, Kling H, Hörhan T (2008) Trends in Niederschlag und Abfluss. Mittblatt Hydrogr Dienst Oesterr 85:1–43
Hänsel S (2014) Introducing the decile concept for studying the spatiotemporal characteristics and variability of long-lasting dry and wet periods. Theor Appl Climatol 118: 223–235
Hanslian D, Brázdil R, Štekl J, Kakos V (2000) Vliv cyklon středomořského původu na vysoké denní úhrny srážek na Milešovce a Lysé hoře v období 1961–1995 (The effect of cyclones of Mediterranean origin on high daily precipitation totals at Mt. Milešovka and Mt. Lysá hora in the 1961–1995 period). Meteorol Zpr 53:33–41
Heim RR Jr (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165
Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Zalud Z, Mozný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric Meteorol 149: 431–442
Horridge M, Madden J, Wittwer G (2005) The impact of the 2002–2003 drought on Australia. J Policy Model 27: 285–308
Kalis AJ, Merkt J, Wunderlich J (2003) Environmental changes during the Holocene climatic optimum in central Europe — human impact and natural causes. Quat Sci Rev 22:33–79
Kendall MG (1990) Rank correlation methods, 5th edn. Charles Griffin, London
Květoň V (2001) Normály teploty vzduchu na území české republiky v období 1961–1990 a vybrané teplotní charakteristiky období 1961–2000 (Climatological normals of air temperature of the Czech Republic in the 1961–1990 period and selected air temperature characteristics of the 1961–2000 period). Národní klimatický program České republiky, Prague
Kyselý J, Picek J, Huth R (2007) Formation of homogeneous regions for regional frequency analysis of extreme precipitation events in the Czech Republic. Stud Geophys Geod 51:327–344
Labudová L, Faško P, Ivaňáková G (2015a) Changing climate and changes in climate regions. Moravian Geogr Rep 23:71–82
Labudová L, Turňa M, Nejedlík P (2015b) Drought monitoring in Slovakia. In: Šiška B, Nejedlík P, Eliašová M (eds) Towards climatic services: proceedings of an international scientific conference, 15–18 September 2015, Nitra. Slovak University of Agriculture, Nitra
Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22:1571–1592
Matulla C, Penlap EK, Haas P, Formayer H (2003) Comparative analysis of spatial and seasonal variability: Austrian precipitation during the 20th century. Int J Climatol 23: 1577–1588
McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time steps. In: Eighth conference on applied climatology, January 17–22, Anaheim, CA, p 179–184
Melo M, Lapin M, Damborská I (2007) Detection of climatic trends and variability at Hurbanovo. In: Střelcová K, Mátyás C, Kleidon A, Lapin M and others (eds) Bioclimatology and natural hazards. International Scientific Conference, 17 –20 September 2007, Pol'ana nad Detvou. Slovak Bioclimatological Society, Bratislava
Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of Europe. Glob Ecol Biogeogr 14:549–563
Palmer WC (1965) Meteorological drought. Office of Climatology Research Paper 45. US Weather Bureau, Washington, DC
Pecho J, Faško P, Melo M (2008) Precipitation deficit periods in the Danubian lowland in Slovakia. In: Brilly M, Šraj M (eds) 24th Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management, 2–4 June 2008, Bled
Potop V, Boroneant C, Možný M, Štěpánek P, Skalák P (2014) Observed spatiotemporal characteristics of drought on various time scales over the Czech Republic. Theor Appl Climatol 115:563–581
Prescott JA (1940) Evaporation from a water surface in relation to solar radiation. Trans R Soc S Aust 64:114–118
Šercl P, Lett P (2002) Výpočet rastruřsrážek v prostředí GIS (s využitím ArcView Spatial Analyst). Uživatelská příručka verze 2.0.1. (Calculation of precipitation grid in the GIS using ArcView Spatial Analyst. User guide version 2.0.1). čHMÚ, OPV, Prague
Sheffield J, Wood EF, Roderick ML (2012) Little change in global drought over the past 60 years. Nature 491: 435–438
Škvarenina J, Tomlain J, Hrvol J, Škvareninová J, Nejedlík P (2009) Progress in dryness and wetness parameters in altitudinal vegetation stages of West Carpathians: time-series analysis 1951–2007. Időjárás 113:47–54
Sönmez FK, Kömüscü AÜ, Erkan A, Turgu E (2005) An analysis of spatial and temporal variability dimension of drought vulnerability in Turkey using the Standardized Precipitation Index. Nat Hazards 35:243–264
Spinoni J, Naumann G, Carrao H, Barbosa P, Vogt JV (2014) World drought frequency, duration, and severity for 1951–2010. Int J Climatol 34:2792–2804
Spinoni J, Naumann G, Vogt J, Barbosa P (2015) European drought climatologies and trends based on a multi-indicator approach. Global Planet Change 127:50–57
Štěpánek P, Zahradníček P, Skalák P (2009) Data quality control and homogenization of air temperature and precipitation series in the area of the Czech Republic in the period 1961–2007. Adv Sci Res 3:23–26
Štěpánek P, Zahradníček P, Brázdil R, Tolasz R (2011)

Metodologie kontroly a homogenizace časových řad v klimatologii (Methodology of data quality control and homogenization of time series in climatology). Český hydrometeorologický ústav, Prague

Thaler S, Eitzinger J, Trnka M, Dubrovsky M (2012) Impacts of climate change and alternative adaptation options on winter wheat yield and water productivity in a dry climate in Central Europe. J Agric Sci 150:537–555

Thornthwaite CW (1948) An approach towards a rational classification of climate. Geogr Rev 38:55–94

Tolasz R, Míková T, Valeriánová A, Voženílek V (eds) (2007) Atlas podnebí česka (Climate Atlas of Czechia). Český hydrometeorologický ústav, Prague

Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J (2014) Global warming and changes in drought. Nat Clim Change 4:17–22

Trnka M, Žalud Z, Eitzinger J, Dubrovský M (2005) Global solar radiation in Central European lowlands estimated by various empirical formulae. Agric Meteorol 131:54–76

Trnka M, Dubrovský M, Svoboda M, Semerádová D, Hayes M, Žalud Z, Wilhite D (2009) Developing a regional drought climatology for the Czech Republic. Int J Climatol 29:863–883

Trnka M, Kocmánková E, Balek J, Eitzinger J and others (2010) Simple snow cover model for agrometeorological applications. Agric Meteorol 150:1115–1127

Trnka M, Kersebaum KC, Eitzinger J, Hayes M and others (2013) Consequences of climate change for the soil climate in Central Europe and the central plains of the United States. Clim Change 120:405–418

Trnka M, Brázdil R, Možný M, Štěpánek P and others (2015) Soil moisture trends in the Czech Republic between 1961 and 2012. Int J Climatol 35:3733–3747

van der Schrier G, Briffa KR, Jones PD, Osborn TJ (2006) Summer moisture variability across Europe. J Clim 19: 2818–2834

van der Schrier G, Efthymiadis D, Briffa KR, Jones PD (2007) European alpine moisture variability 1800–2003. Int J Climatol 27:415–427

van der Schrier G, Barichivich J, Briffa KR, Jones PD (2013) A scPDSI-based global dataset of dry and wet spells for 1901–2009. J Geophys Res 118:4025–4048

van Loon AF, Ploum SW, Parajka J, Fleig AK, Garnier E, Laaha G, van Lanen HAJ (2015) Hydrological drought types in cold climates: quantitative analysis of causing factors and qualitative survey of impacts. Hydrol Earth Syst Sci 19:1993–2016

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multi-scalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J Clim 23:1696–1718

Viney NR, Bates BC (2004) It never rains on Sunday: the prevalence and implications of untagged multi-day rainfall accumulations in the Australian high quality data set. Int J Climatol 24:1171–1192

Wardlow BD, Anderson MC, Verdin JP (2012) Remote sensing of drought: innovative monitoring approaches. CRC Press, Boca Raton, FL

Wells N, Goddard S, Hayes M (2004) A self-calibrating Palmer Drought Severity Index. J Clim 17:2335–2351

White W, Mickeon G, Syktus J (2003) Australian drought: the interference of multi-spectral global standing modes and travelling waves. Int J Climatol 23:631–662

Wilhite DA (ed) (2000) Drought: a global assessment. Routledge Publishers, London

Wilhite DA (2005) Drought and water crises: science, technology, and management issues. CRC Press, Boca Raton, FL

Zahradníček P, Trnka M, Brázdil R, Možný M and others (2015) The extreme drought episode of August 2011–May 2012 in the Czech Republic. Int J Climatol 35: 3335–3352

Editorial responsibility: Donald Wilhite (Guest Editor), Lincoln, Nebrasca, USA

Submitted: March 29, 2016; Accepted: August 4, 2016
Proofs received from author(s): September 7, 2016

Vol. 70: 161–178, 2016
doi: 10.3354/cr01387

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

The Central European drought of 1947: causes and consequences, with particular reference to the Czech Lands

Rudolf Brázdil[1,2,*], Pavel Raška[3], Miroslav Trnka[2,4], Pavel Zahradníček[2,5], Hubert Valášek[1,6], Petr Dobrovolný[1,2], Ladislava Řezníčková[1,2], Pavel Treml[7], Zdeněk Stachoň[1]

[1]Institute of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
[2]Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic
[3]Department of Geography, J. E. Purkyně University, České mládeže 8, 400 96 Ústí nad Labem, Czech Republic
[4]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[5]Czech Hydrometeorological Institute, Brno Regional Office, Kroftova 43, 616 67 Brno, Czech Republic
[6]Moravian Land Archives, Palackého nám. 1, 625 00 Brno, Czech Republic
[7]T. G. Masaryk Water Research Institute, Podbabská 30, 160 62 Praha 6, Czech Republic

ABSTRACT: A drought of exceptional severity took place in Central Europe in 1947, with marked socio-economic consequences and far-reaching political responses in the Czech Lands. A rich body of meteorological observations from the Czech Lands is drawn upon to construct a comprehensive picture of the various direct and indirect factors that led to this extreme event and to describe its impacts across a range of spatiotemporal scales. In terms of the Czech Lands in their entirety and the full 1804–2014 period of instrumental measurements, the 1947 drought, which lasted from April to October, may be expressed as very low monthly values of Standardised Precipitation Evapotranspiration Index for 1 month (SPEI-1), Standardised Precipitation Index for 1 month (SPI-1), and Palmer's *Z*-index. Independent evidence from mean monthly patterns of sea-level pressure suggests it originated in an anticyclone over Central Europe and ridges of high pressure extending over the area. Duration and deficiency volumes recorded at selected Czech hydrological stations indicate that the 1947 event was one of the 3 most important hydrologic drought episodes since the late 1880s. Severe agricultural drought was reflected in a low to extremely bad harvest of cereals and other agricultural crops. A critical lack of cereals was remedied by 'brotherly help', i.e. relief shipments from the Soviet Union given for reasons that were far more political than altruistic. The whole process received considerable attention in the national media, influencing public opinion for decades. It also led to various administrative responses and decisions at local, regional and even state levels. This study demonstrates that the 1947 drought was a significant climatic anomaly of great spatial extent, and with wide-ranging socio-economic consequences.

KEY WORDS: 1947 drought · Meteorological drought · Hydrological drought · Agricultural drought · Drought impact · Socio-economic responses · Czech Lands

1. INTRODUCTION

Drought, primarily originating out of deficiency in precipitation totals compared with mean patterns over a given area (meteorological drought), differs from other meteorological or hydrological extremes in its slow onset. However, delayed impacts and consequences for water management (hydrological and

*Corresponding author: brazdil@sci.muni.cz

Publisher: Inter-Research · www.int-res.com

underground water droughts), agriculture (agricultural drought) and other fields (e.g. forestry) may have dramatic socio-economic consequences, including famine, epidemics, socio-political unrest and human migration (Heim 2002, Mishra & Singh 2010). The recent drought episodes in Russia in 2010 (Trenberth & Fasullo 2012), USA in 2011–2012 (Hoerling et al. 2014), China in 2013 and Brazil in 2014 were, for each particular year, among the 10 natural disasters worldwide with the highest recorded damage; the losses arising out of them and economic consequences were comparable with those of earthquakes and tropical cyclones (Munich Re 2015).

On a more regional scale, that of Central Europe and particularly of the Czech Lands (now the Czech Republic), drought is comparable with flood. These are the 2 most disastrous natural events that affect this region. This has recently been reflected, in the light of experience of the 2015 drought and other events from previous years, in the Water–Drought Commission report (Czech Government Resolution no. 620/2015) commissioned jointly by the Czech Ministry of Agriculture and the Czech Ministry of the Environment. The potential impact of drought on agriculture, forestry and water resources in the Czech Republic has recently been summarised by Brázdil & Trnka (2015).

Despite the fact that intense droughts have occurred in the Czech Lands relatively frequently at least as far back as ~500 yr, in the instrumental as well as in pre-instrumental periods (Brázdil et al. 2009, 2013, Trnka et al. 2009, Brázdil & Trnka 2015), the 1947 episode remains one of the most remarkable. Various drought indices lead it to be categorised as either the most severe — or at least among the most severe — drought events in Czech history. Hardly surprisingly, responses to it included a large number of contributions to the Czech Meteorological Journal (*Meteorologické zprávy*), in which later droughts, largely from the 1950s, were always compared with that of 1947, and this episode has served as a benchmark for more than 2 generations of Czech climatologists. Moreover, the event stimulated further activities directed at mitigating potential damage from future drought events by means of irrigation, creation of windbreaks, construction of ponds, etc.; particularly in the province of South Moravia which, together with the Polabská nížina Lowlands (for local names and places in the Czech Republic see Fig. 1), constitutes one of the most important agricultural regions in the Czech Republic.

Because the 1947 drought occurred when the country was renewing itself, both logistically and politically, after the rigours of the Second World War, reactions in agriculture, water management, forestry and other sectors were more marked and longer lasting than might have been the case in a more stable economy. In particular, failure of the harvest at a time of very low reserves provoked a number of responses at various levels of the state administration, all de-

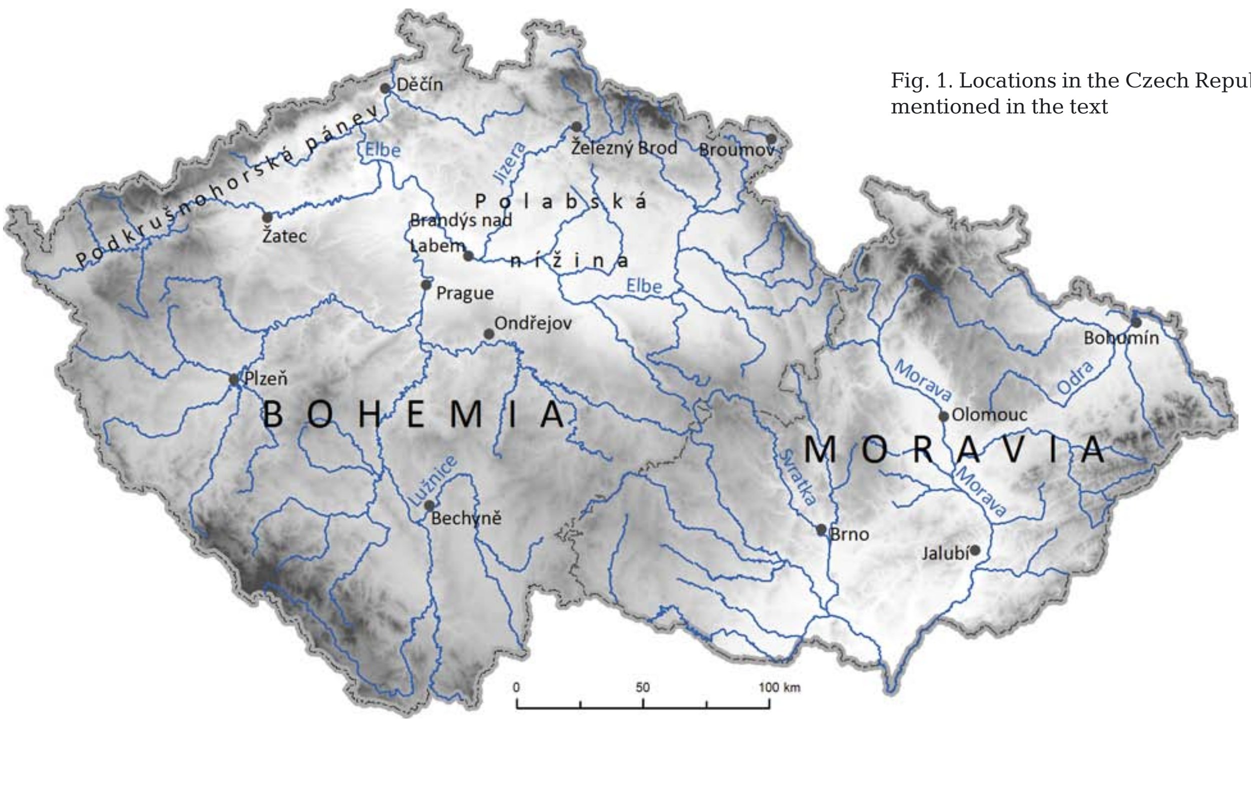

Fig. 1. Locations in the Czech Republic mentioned in the text

signed to mitigate negative impacts. The sheer magnitude of this event means that approaches and responses to the 1947 drought are of great informational value in reducing the future impacts of natural disasters. This holds especially true of the first decade of the 21st century, when several authors analysed social responses to historic disaster events with the aim of utilising society's past experiences to address current disaster risks (Poliwoda 2007, Schenk 2007, Pfister 2009). Learning from past disasters is considered to increase societal resilience to them (Voss &Wagner 2010, Raška & Brázdil 2015). According to Juneja & Mauelshagen (2007), the main issues relevant to historical disaster research include the level of success with which past societies have faced disasters, the ways of interpreting past disasters, and processes of learning from disasters and passing on lessons of the experience to subsequent generations.

The present paper provides a comprehensive analysis of the 1947 drought episode in the Czech Lands, with particular attention to its physical nature, socioeconomic and political impacts and responses to it.

2. DATA AND METHODS

2.1. Meteorological data

Homogenised series of the monthly precipitation totals from the 787 stations of the Czech Hydrometeorological Institute (CHMI) were used to calculate April–October totals for 1961–1990 (Štepánek et al. 2011, 2013), providing a reference period and constructing a territorial distribution over the Czech Lands by means of orographic interpolation with universal linear kriging (Šercl & Lett 2002). The same approach was applied to the 398 stations that recorded April–October 1947 totals. Comparison of the 2 maps (grids) enabled a geographical distribution of percentage portions of the 1947 totals with respect to the 1961–1990 period (see Fig. 4a). Similarly, N-year return periods for the April–October 1947 totals were calculated in the light of Gaussian distribution with respect to the 1961–2014 period (see Fig. 4b). Further, 4 stations were selected to represent the annual course of daily air temperature and precipitation: Žatec and Ondřejov in Bohemia (western part of the Czech Lands), Brno and Olomouc in Moravia (eastern part of the Czech Lands). Variations in mean daily temperatures at these stations in 1947 were expressed as deviations from the mean variations of the 1961–1990 reference period. Daily precipitation totals in 1947 were expressed as a cumulative curve compared with those of the 1961–1990 reference period (see Fig. 3).

This study also employs series of mean monthly Czech temperatures, calculated from 10 stations for 1800–2014, and mean monthly Czech precipitation totals calculated from 14 stations for 1804–2014 (Brázdil et al. 2012, extended for 2011–2014). From these 2 series, SPI-1, the Standardised Precipitation Index for one month (McKee et al. 1993), SPEI-1, the Standardised Precipitation Evapotranspiration Index for one month (Vicente-Serrano et al. 2010) and *Z*-index (Palmer 1965) were calculated for evaluation of droughts in the Czech Lands at a monthly level. The SPI, calculated from monthly precipitation totals, may be interpreted as the number of standard deviations by which an observed anomaly deviates from the long-term mean. The SPEI is similar to SPI, but rather than concentrating on precipitation alone, it is based on monthly differences between precipitation and potential evapotranspiration. It may therefore indicate anomalies in climatological water balance. The *Z*-index serves mainly to express anomalies in soil moisture, given as deviation of precipitation from climatological optimum in a given month. Compared to the more frequently used Palmer Drought Severity Index (PDSI), it represents only the current state of water balance without reference to antecedent soil moisture status.

General meteorological patterns are indicated in terms of annual variation in mean monthly Czech temperature and precipitation (expressed as deviations from the 1961–1990 mean in °C or %), complemented by annual variations in SPI-1, SPEI-1 and *Z*-index (see Fig. 2). Drought indices were then evaluated in the long-term context for the 1805–2014 period.

Synoptic conditions in the driest months of 1947 (May, August, September, October) were analysed on the basis of monthly maps of mean sea level pressure (SLP), employing the HadSLP2r database (Allan & Ansell 2006) and expressed for a section from the Atlantic-European area. However, it should be borne in mind that such SLP fields are the results of monthly averaging of daily synoptic situations that could correspond to quite different features in individual SLP fields. In addition, the frequency of synoptic types in any given month in terms of CHMI classification (Brádka et al. 1961) was compared with mean frequency in the 1961–1990 reference period. For the Czech Lands, Brádka (1972) indicated that precipitation occurs more frequently and in much higher amounts during cyclonic synoptic situations compared with anticyclonic types.

2.2. Hydrological data

Figures from the Děčín station on the River Elbe, which drains most of Bohemia, were used for analysis of hydrological drought. Deficiency volumes, i.e. the cumulative volumes of water absent from threshold discharge Q_{330} (i.e. the discharge achieved as a mean for 330 days of the year) were calculated from daily discharges in the 1888–2010 period. Because deficiency volume depends on the discharge value for a given river, this is standardised by dividing deficiency volume by the threshold discharge Q_{330}. Deficiency volume may also be expressed as a multiple of mean annual missing water with respect to Q_{330} (for more information on this method, see e.g. Hisdal & Tallaksen 2000, Tallaksen & van Lanen 2004). Six further CHMI stations were used for comparison with the Děčín–Elbe station: Brandýs nad Labem–Elbe (1911–2005), Železný Brod–Jizera (1912–2009), Bechyně–Lužnice (1911–2009), Olomouc–Morava (1921–2009), Bohumín–Odra (1920–2010) and Brno–Svratka (1923–2009). These are used to characterise the order of the 1947 drought within series in Table 1 (Brázdil & Trnka 2015).

For spatial analysis of the 1947 hydrological drought, Vlnas et al. (2010) calculated standardised deficiency volumes and duration of hydrological drought with respect to annual discharge Q_{95} (i.e. 95% of mean annual discharge) from series of monthly discharges at 118 hydrological stations in the Czech Lands and expressed them as a map. From this, a simplified map was constructed for the purposes of the present study, demonstrating the main features of the 1947 drought (see Fig. 7).

Table 1. Duration and deficiency volumes of the 1947 drought for 7 hydrological stations in the Czech Lands expressed in long-term context by their order (adapted from Brázdil & Trnka 2015)

Station–river	Duration		Deficiency volume		
	Date	Order	Volume (10^6 m^3)	Standardised (%)	Order
Děčín–Elbe	18 Jul–11 Nov	2	516.5	48	1
Brandýs nad Labem–Elbe	29 Jul–10 Nov	2	112.2	40	2
Železný Brod–Jizera	27 Jul–6 Nov	1	17.1	39	1
Bechyně–Lužnice	29 Jul–9 Sep	19	6.7	35	41
Bohumín–Odra	10 Sep–10 Nov	7	20.3	38	20
Olomouc–Morava	24 Jul–11 Nov	2	31.3	47	3
Brno–Svratka	1 Aug–13 Nov	3	5.6	31	3

2.3. Other data

The variety of documentary data sources that enable reconstruction of the social impacts of natural disasters, and responses to them, is broad, but thorough critical analyses are required with respect to their credibility and reliability (Stanford 1986, Raška et al. 2014). The data sources used in this study are listed in the Appendix. Four major types of data are used:

(1) Official country-scale sources. These take the form of parliamentary records kept in the digital repository of the Czech Parliament (Archival Source 4 [AS4] in the Appendix; www.psp.cz/eknih/index.htm) and include stenographic records of requests for guidance and action from regional representatives as well as proposals for legislation and the reports of committees that responded to them. The stenographic records are particularly important since they provide detailed information of the impacts of drought at local and regional scales. However, these records must be interpreted in the context of the political and ideological positions of the representatives generating them.

(2) Official regional sources. The official regional sources, largely consisting of the records of National Land Committees, are available from land archives and provide detailed reports concerning regional impacts of a given drought episode and subsequent mitigation measures.

(3) The media. *Rudé právo* (AS6), the leading communist daily newspaper, was a major nation-wide source of public information in this period. Although the style and contents of its reporting are often constrained by an agenda dictated by the political aims of the Communist Party (see McCombs & Shaw 1972), this newspaper provides fundamental information about the spatial extent of drought impact by reporting from a large number of localities and regions.

(4) Regional sources. Keeping local and village chronicles has a long tradition in the Czech Lands, and these often serve to complement the picture of the social impacts of an extreme event by adding qualitative narrative data.

The economic and social impacts of the drought, and consequent mitigation efforts, were reconstructed from documentary sources of a number of types. First, agricultural losses are calculated from annual yield series of main agricultural crops at national level (no data for district level exists). Supplementary parliamentary data on regional agricultural losses were extracted and aggregated for district level and represented as percentage decreases in production compared with 1946, and/or as total financial loss. Finally, the reconstructed territorial distribution of drought impacts was completed with data from national newspapers. Parliamentary records provided a chronology for the drought and other related events (mainly hailstorms, pest outbreaks and disease epidemiology) that contributed to total agricultural and financial losses in the regions. The chronology was supplemented with data referring to mitigation efforts, both as financial subsidies and acts of parliament. Such mitigation measures were extracted from documentary data and divided into specific groups according to their territorial scope and function.

3. RESULTS

3.1. Meteorological drought and its synoptic causes

Based on 3 drought indices (SPI-1, SPEI-1 and *Z*-index), the meteorological drought of 1947 in the Czech Lands had already started in winter months, despite a high precipitation total in February (calculations of all 3 indices take snow into account, meaning that high precipitation in drought indicies occurs when the snow melts, in the first month with air temperature >0°C — here March). The next dry period started in April and continued all the way to October, with above-normal temperatures from April to September, the latter being the month with the highest positive deviation (Fig. 2). The reduction in precipitation was at its most pronounced in May and August–October, less so in June, while the July total achieved the 1961–1990 mean. In terms of annual variation, the drought culminated in September.

This picture may be further enhanced by the annual variation of mean daily temperatures and cumulative precipitation totals in comparison with the 1961–1990 means for the 4 stations representing western Bohemia (Žatec), central Bohemia (Ondřejov), southern Moravia (Brno) and central Moravia (Olomouc) (Fig. 3). A very cold period for January–March appears in daily temperatures, while positive deviations started to prevail from April onwards until around the end of 1947. High temperatures were also accompanied by heat waves. For example, 40 d of annual heat wave duration and 46.9°C of annual cumulative daily maximum temperature in excess of

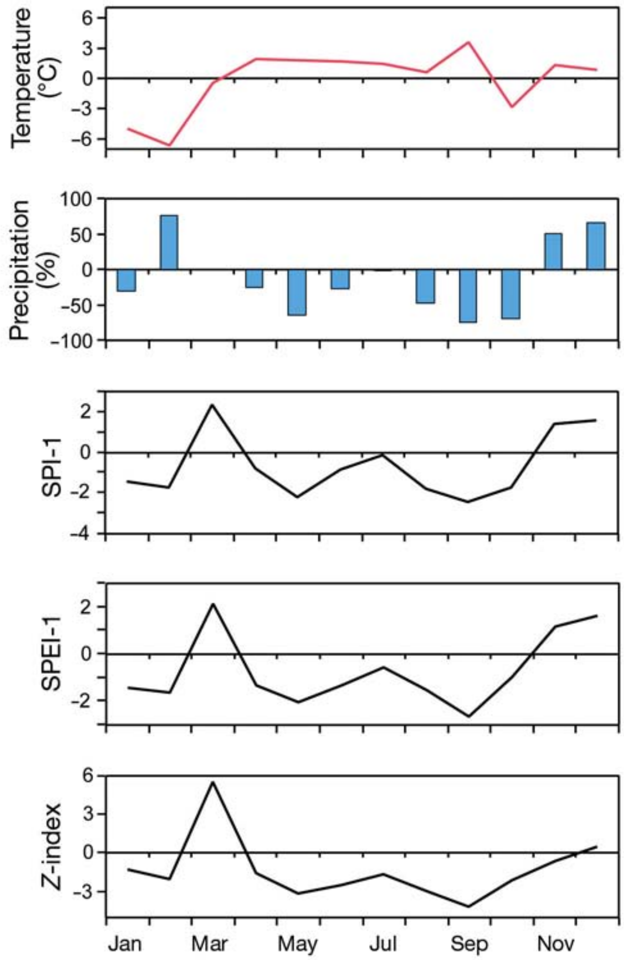

Fig. 2. Annual variation of monthly air temperature, precipitation, Standardised Precipitation Index for one month (SPI-1), Standardised Precipitation Evapotranspiration Index for one month (SPEI-1) and Palmer's *Z*-index in the Czech Lands in 1947. Temperature and precipitation are expressed as deviations with respect to the 1961–1990 reference period

30°C in the heat waves during 1947, ranking second only to the year 1994 at the Prague-Klementinum station in the 1901–1997 period (Kyselý 2002). A nearly standard development of precipitation (i.e. around the mean totals) from the beginning of 1947 was interrupted in April, after which the precipitation deficit grew until October; in the following 2 mo the rate of deficit decreased slightly. The highest precipitation deficits, occurring in summer and autumn, reached around 150 to 200 mm over the Czech Lands as a whole, but were much greater in central Bohemia (Ondřejov).

With respect to the 1961–1990 reference period, the character of the territorial distribution of April–October precipitation totals in 1947 is erratic (Fig. 4a). Central Bohemia was especially dry, with a

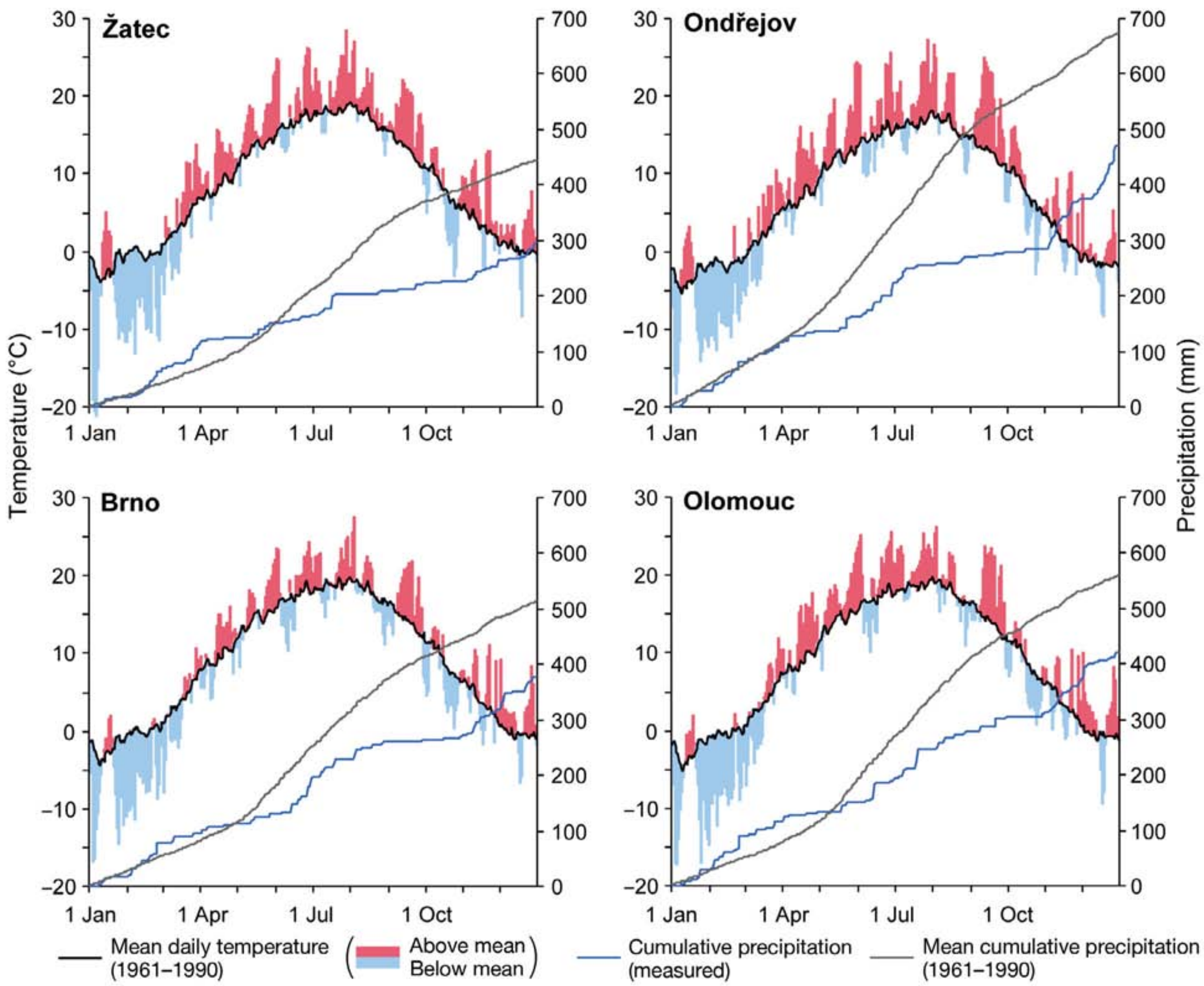

Fig. 3. Variations in mean daily temperatures and precipitation totals for the Žatec, Ondřejov, Brno and Olomouc stations in 1947: mean daily temperatures for 1961–1990 (black line); measured mean daily temperatures (red bars: above mean; blue bars: below mean); mean cumulative precipitation for 1961–1990 (grey line); measured cumulative precipitation (blue line)

belt of low precipitation extending to the Podkrušnohorská pánev Basin and 2 irregular belts extending from southeast to northwest in Moravia. More than two-thirds of the territory of the Czech Lands recorded precipitation totals of between 40 and 60% of the 1961–1990 mean (with values of 40.1 to 50.0% and 50.1 to 60.0% in 30 and 38% of the territory, respectively). Precipitation between 60.1 and 70.0% of the reference mean occurred over 18% of Czech territory, while precipitation over 7% of the Czech territory was between 30.1 and 40.0% of the reference mean. The low April–October precipitation totals correspond to a 100 yr return period, longer over the greatest part of the Czech Lands (Fig. 4b). Lower return periods occurred particularly in southern Bohemia, with an extension to Plzeň, in northern Bohemia, and in north-eastern Moravia.

Synoptic reasons may be found for the very low monthly totals. In May 1947, the Czech Lands were under the influence of high pressure extending from the North Atlantic and Scandinavia over the Baltic Sea from the northwest to the southeast (Fig. 5). Anticyclonic synoptic types, according to CHMI classification (Brádka et al. 1961), occurred on 17 May days (i.e. 8 days more than in the 1961–1990 reference period). Low precipitation in August and September was associated with a ridge of high pressure extending from the Azores High to Central Europe. While in August its axis was directed towards the British Isles, in September it ran towards the northern Black Sea (Fig. 5). In August the Czech Lands were under the dominant influence of a northeasterly airflow for 25 days (cyclonic synoptic types: 15 days; anticyclonic: 10 days). Anticyclonic types made up 18 September

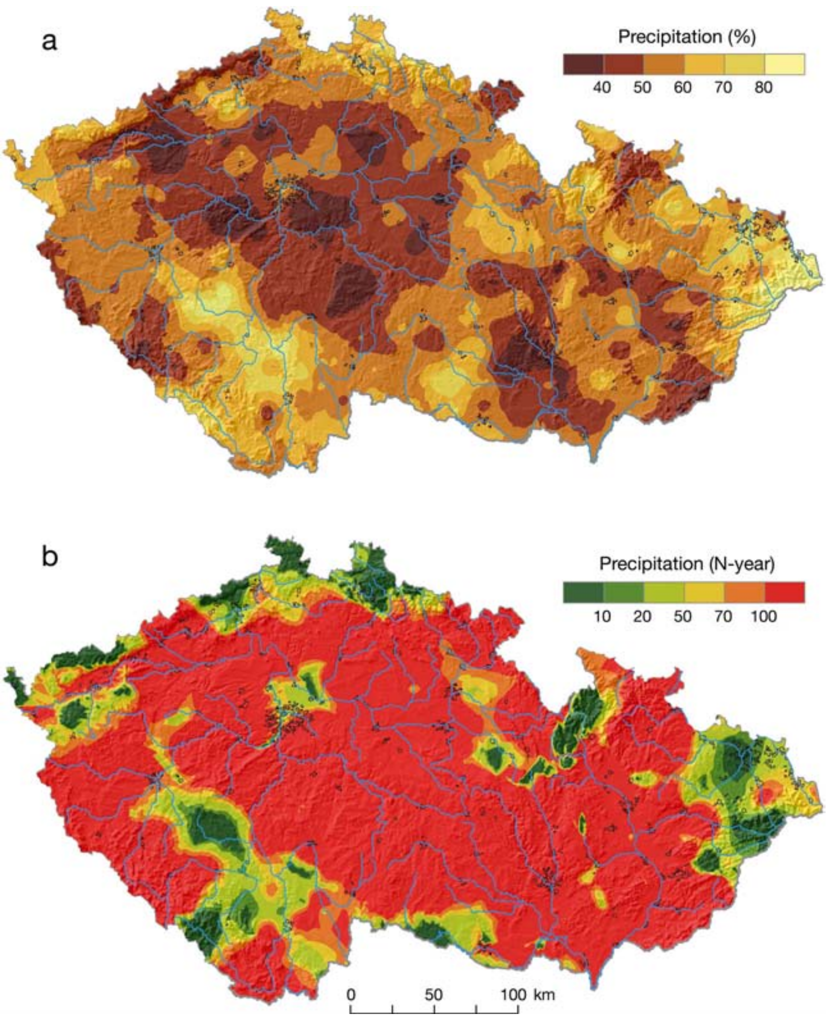

Fig. 4. Territorial distribution of April–October 1947 precipitation totals in the Czech Lands: (a) percentage of mean precipitation for the 1961–1990 reference period; (b) N-year return period of the 1947 drought event. Urban areas represented with black borders

days, i.e. 6 days more than in the 1961–1990 reference period. In October, the greater part of Europe was under the influence of high pressure with an isolated anticyclone extending from Central Europe to the Black Sea (Fig. 5). Anticyclonic synoptic types occurred in the Czech Lands on 25 October days (i.e. 10 days more than in the reference period).

3.2. Hydrological drought

The main period of hydrological drought started around the latter half of July and continued until 11 November (Table 1, Fig. 6). However, unusually low discharges were already occurring from May onwards (the period March–May was marked by large discharges associated with snowmelt), which were related to low precipitation. In the main drought period, the standardised deficit volumes with respect to Q_{330} at 7 hydrological stations was >30 %. For the Rivers Elbe, Jizera, Morava and Svratka, the 1947 hydrological drought was one of the 3 most severe events since the late 1880s. Relatively wetter patterns in southern Bohemia, and water released from extensive fish-farming ponds, meant that water levels on the River Lužnice in 1947 were not among the 10 driest years in the same reference period; moreover, the continuous drought there lasted only to September (Table 1).

On the River Elbe at Děčín, which has the longest series of daily discharges of the 7 stations studied, as much as half of the volume was lacking compared to the long-term mean, representing 516.5 × 10^6 m^3 of water. The main drought period at this station lasted 117 d there, from 18 July to 11 November (the second longest drought period), while 161 days with drought were recorded for the whole year – the third highest (Fig. 6). In terms of annual water balance, 83 times more water than is usual were absent from Děčín, the second highest extreme since 1888.

Fig. 7 shows the distribution of the hydrological drought of 1947 for the territory of the Czech Lands expressed by standard deficiency volumes and drought duration for individual hydrological stations (Vlnas et al. 2010). Over the majority of the area, standardised deficiency volumes with respect to Q_{95} were between 1 and 3, and duration of hydrological drought was >3 mo. Some regional effects are quite pronounced, reflected in smaller deficiency volumes as well as shorter durations of drought. This is particularly so for southern Bohemia in the region extending to Plzeň, where precipitation totals for 1947 were higher than in other areas (see Fig. 4a) and rivers received discharges of water from numerous man-made fish-farming lakes. A further extended area of weaker hydrological drought is apparent in northern and northeastern Moravia, again corresponding to relatively higher precipitation totals in this area in 1947 (see Fig. 4a). Smaller areas of weaker drought

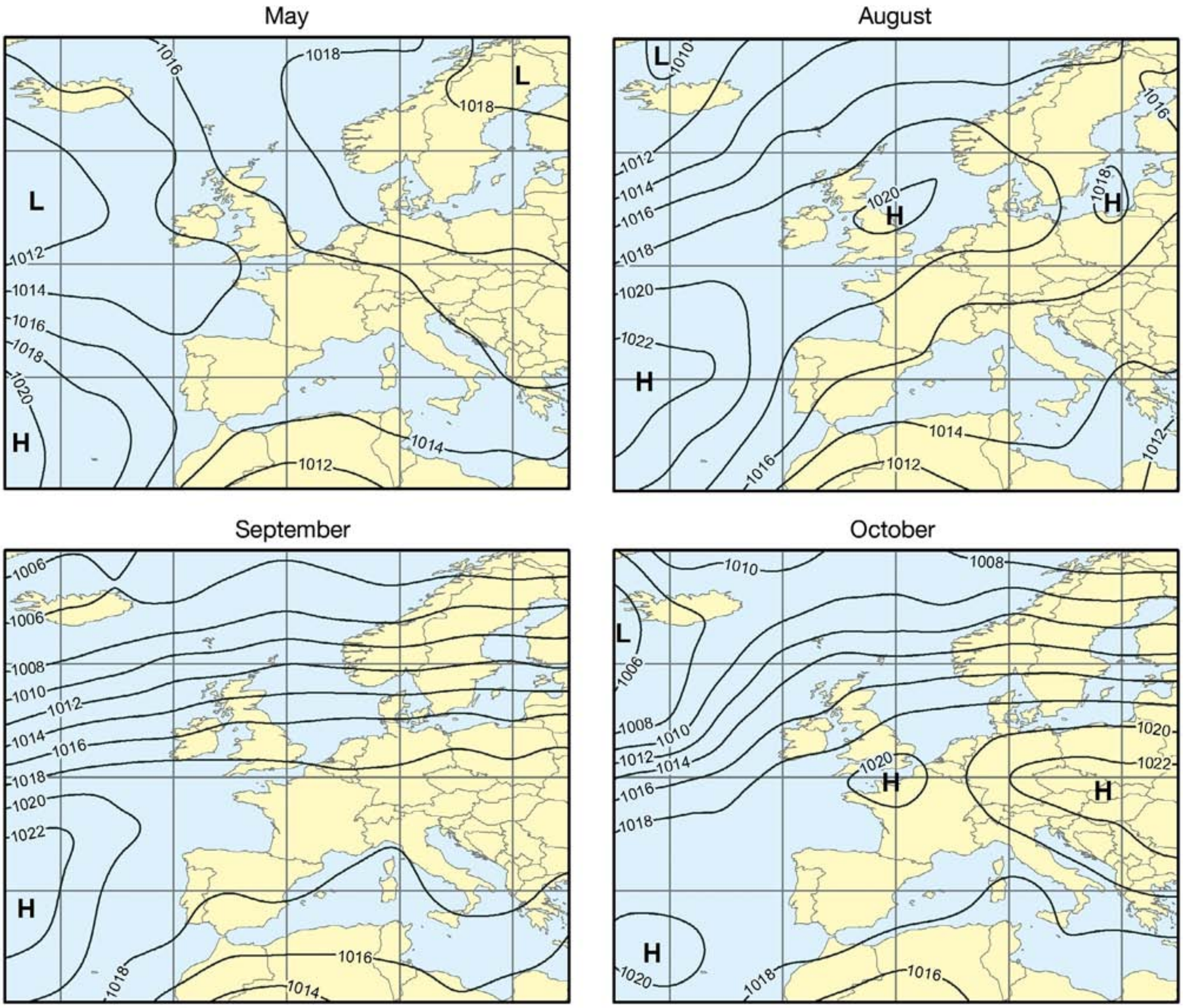

Fig. 5. Mean sea-level pressure (hPa) in the European-Atlantic area for the months of May, August, September and October 1947 when below-mean precipitation totals were recorded in the Czech Lands (adapted from Brázdil & Trnka 2015)

also occurred in south Moravia and in the Broumov promontory, perhaps related to rain from convective storms.

3.3. Agricultural drought

The drought significantly influenced the course of work in the fields as well as yields of agricultural crops. Descriptions in the chronicle of the village of Jalubí, near Uherské Hradišt in Moravia, provide one example of impacts arising out of extreme drought (AS7, fol. 37v–38v):

> Spring started late […] Drought sets in. Late-sown beets did not germinate. Germination came as late as the end of May. […] Still no rain. Catastrophe threatens. Crop remained very sparse, particularly wheat. A profusion of weeds growing. Harvest delayed due to drought. [15 June.] Still deep drought. Not raining at all, just negligible precipitation. Cattle-drawn reaping due to small, short stalks […] Yields of the first fodder crops are very low (30%). No green fodder crops available; they dried out after sowing. Most of the feed is [now] straw. […] Farmers are leaving for northern Moravia to get hay there by mowing and drying. […] Most farmers have not bedded their cattle and [thus] save the straw for feeding. Stubble-tillage of stubble fields not finished due to drought. […] The potatoes were dug out in September, in small amounts and suffering from withered tubers. No sowing because there is [still] catastrophic drought. Beets are dug out. [Mechanical] beet-lifters breaking due to hardened soil. The

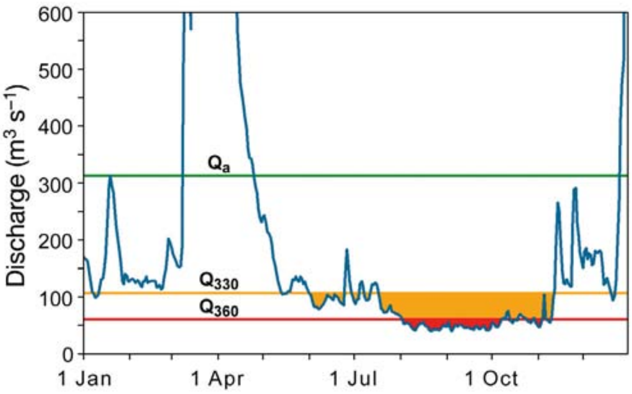

Fig. 6. Annual variation in daily discharges for the River Elbe at Děčín in 1947 showing mean annual discharge Q_a and threshold discharges Q_{330} and Q_{360} (the discharge achieved as a mean for 360 days of the year) Orange and red areas indicate deficiency volumes in terms of Q_{330} and Q_{360} respectively

draught cattle cannot pull them. [The beet] is excavated by pickaxe. Yield of beet is below normal. […] Fear that sowing will be impossible. […] Dry soil is ploughed, clouds of dust during ploughing. […] Grapes in the month of September were drying up in high temperatures and drought, and were picked early. Fruit fell from the trees and rotted heavily. […] There was a lack of seed, particularly wheat […] As a consequence of lack of feed, cattle and horses as well are sold off. […] Leaves are being raked up in the forest because of a complete shortage of straw. […] Dried potato stalks are being used for feed.

Similar reports of failure of the harvest of the majority of agricultural crops, together with problems for plant and animal production, may be found in many other written sources.

Fig. 8 shows relative fluctuations in annual yields of selected agricultural crops for the Czech Lands in 1946–1950, expressed as percentages of yields in 1946. The data come from the Czech Statistical Office in Prague. The drought had no visible effect on barley, which was saved by precipitation in winter and early spring, nor on flax. Among the cereals, the largest drop was for wheat, 26% down on the 1946 yield, with 19% for maize for grain and 10% for rye and oats. Oil plant yields also fell off sharply, for rape by as much as 46%, with this decrease continuing into 1948. Hay was particularly short, with permanent meadow yields down by 26.5% and arable soil hay by 36%. There is no data for district level losses but it is reasonable to assume that the reduction in yields in some localities was much greater than at national level.

Detailed insight into regional agricultural and financial losses may be derived from reports presented to parliament by regional representatives, mainly

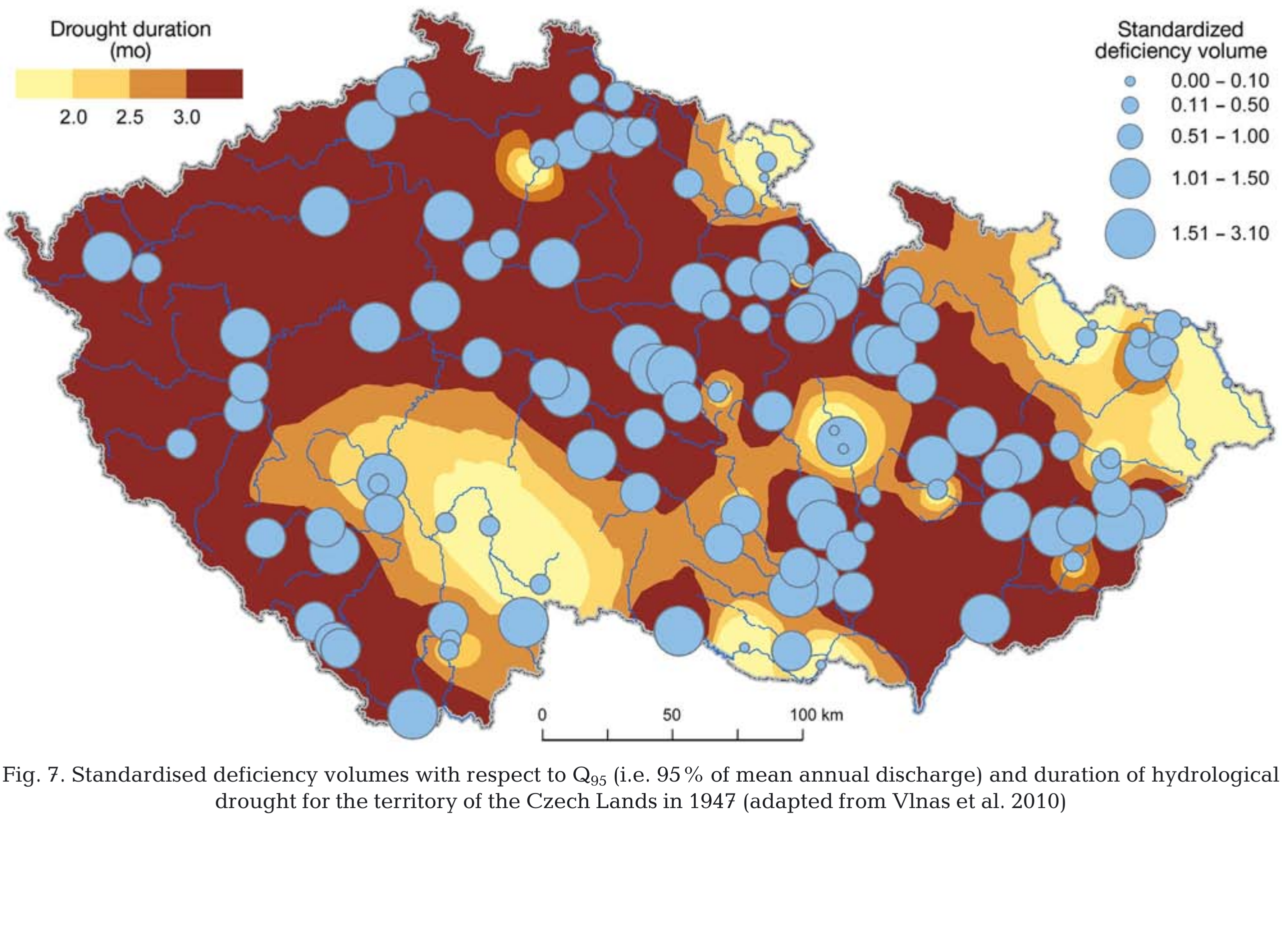

Fig. 7. Standardised deficiency volumes with respect to Q_{95} (i.e. 95% of mean annual discharge) and duration of hydrological drought for the territory of the Czech Lands in 1947 (adapted from Vlnas et al. 2010)

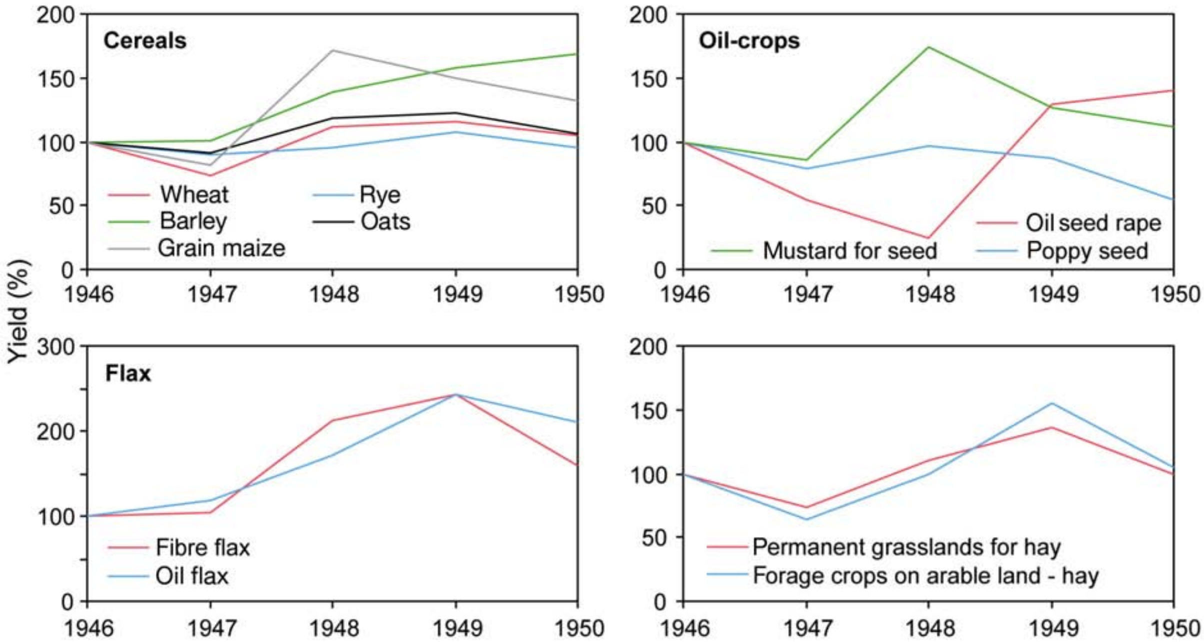

Fig. 8. Relative fluctuations in annual yields of selected agricultural crops in the Czech Lands during 1946–1950. Yields are expressed as percentages of 1946 yields (100 %)

from southern and central Bohemia (Fig. 9). While statements of financial loss for some localities feature estimated values, many other cases mention only the percentage loss in relation to the previous year of 1946, and in some cases specific information is entirely missing. The reported estimated loss for 266 municipalities was 180 million Czechoslovak crowns (hereafter Kčs), giving an average of 676 000 Kčs per municipality (at the time, an average worker earned around 820 crowns per month in Czechoslovakia). Two further districts together lost 234 million Kčs and there are another 88 localities and one district without indicated loss. The reported percentage loss in comparison with the previous year of 1946 was between 18 and 100 %. Financial losses were exacerbated by the combination of drought with other events, mainly summer hailstorms (blue hatching in Fig. 9; see also chronology in Fig. 10), pests (aphids *Aphidoidea*, thrips *Thysanoptera* and cabbage butterfly *Mamestra* larvae, Colorado beetle *Leptinotarsa decemlineata*, and viral or fungal leaf curl) and cattle disease (osteomalacia, a softening of the bones) related to lack of quality fodder. In 55 localities in southern Bohemia, reports also mention that the summer drought worsened an already critical situation caused by spring rainstorms and fungal disease ('snow mould' *Monographella nivalis*). Although parliamentary reports indicate a major agricultural drought in southern and central Bohemia, supplementary data from *Rudé právo* (AS6; locations in violet in Fig. 9) show that the drought significantly affected northern Bohemian districts as well.

3.4. Immediate responses to the drought

All over the country, the supply of agricultural products was in crisis, a situation reflected in the state administration as well as at regional and local levels. The parliamentary responses of regional representatives suggested a number of mitigation measures: (1) financial support, (2) tax write-offs, (3) releasing fixed bank deposits to enable purchase of fodder and seed, and (4) direct supply of fodder and seed. The total financial subsidy proposed by the national government was 500 million Kčs. The extent and severity of impact was thoroughly analysed, case by case, by the national statistical office both *in situ* and in regional administration offices. Subsidy was provided to farmers according to estimation of total losses, which had to be higher than 900 Kčs per hectare. Despite this proposal, regional representatives (mainly from the Communist Party) repeatedly made demands in late 1947 (Fig. 10) that the remaining part of the financial support (ca. 60 million Kčs) should be provided to the most affected farmers in southern Bohemia who had not obtained subsidy. However, the response to this demand, given by the

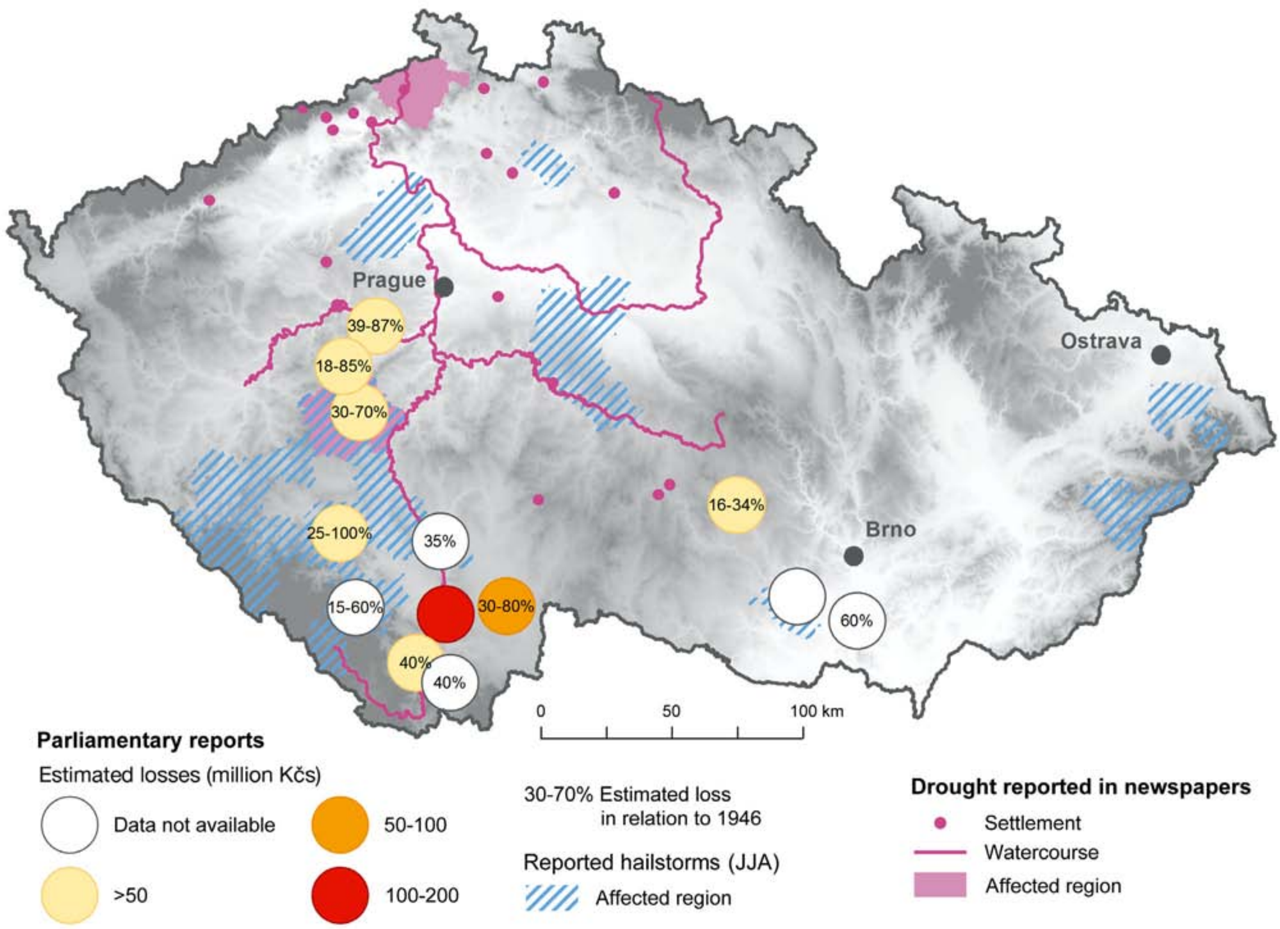

Fig. 9. Regional impacts of drought and related events from parliamentary records and other affected localities reported in *Rudé právo* (AS6)

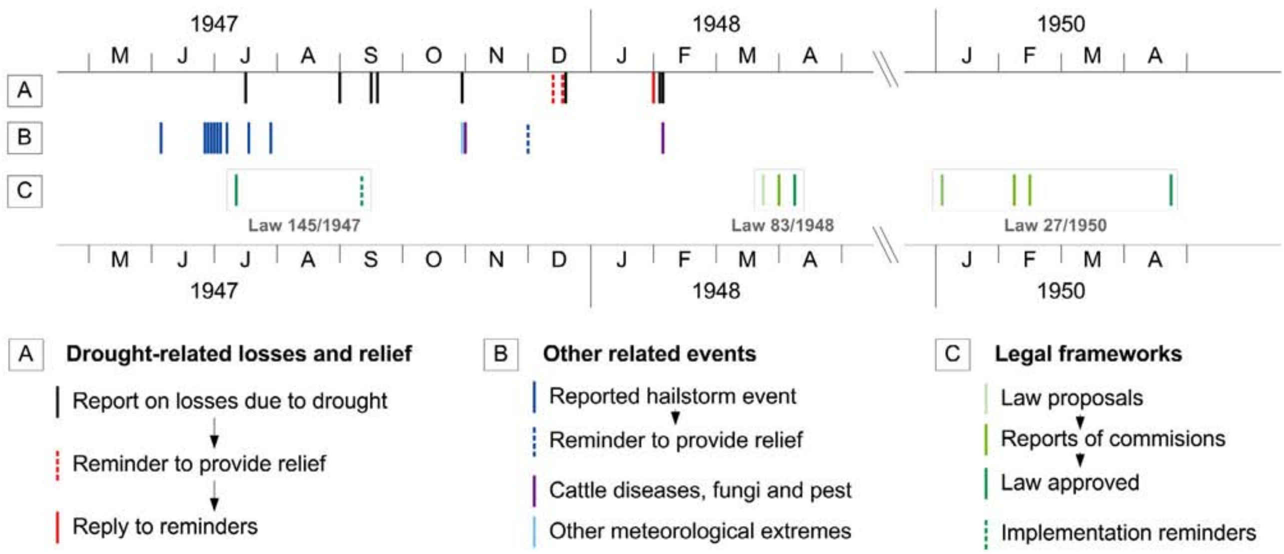

Fig. 10. Chronology of the reports on 1947 drought in the Czech Lands and related events, and of the evolution of relevant legal frameworks

Minister of Agriculture on 30 January 1948 noted that

> the remaining part of the subsidy has already been used to increase the subsidy for 2 districts and to provide a support for another 54 Czech districts

and that

> the farmers who did not obtain financial support did not meet the criterion of a loss of 900 Kčs per hectare

Of 60 million Kčs remaining from the total financial subsidy, newly-provided support to southern Bohemian districts was ca. 10 million Kčs. The constant demands and governmental responses exemplify a long-running political dispute between the Communist Party and governmental parties, framed on this occasion by the disastrous impacts of drought.

Detailed descriptive comments on drought impact mitigation are available from regional sources. Florián Gloziga, Chairman of the Extraordinary Land Commission for Nutrition, a Communist Party representative, reported the situation of supplies for the population, together with some measures taken, at a meeting of the National Moravian-Silesian Land Committee in Brno on 16 December 1947 (AS5, fol. 3r, 4r):

> An extraordinary drought and bad harvest of cereals following on from it, in our country, as in Europe and other continents, places us under an uncompromising obligation to provide the grain needed to secure the nutrition of our nation primarily from our own sources. […] The situation that came about in this way, or rather, its perspectives, have been reflected in an avalanche of efforts [on the part] of the population to buy grain for bread, particularly wheat, by way of the black market immediately after the harvest. […] The amount of mandatory supply was determined under these circumstances, for the Moravian-Silesian Land a total of 18500 railway cars, 6938 of which were wheat and 11562 rye.

However, as of 15 December, only 54% of the wheat, 73% of the rye, and 45% of the feed grain (but 102% of the barley) from the mandated quantities of cereals had been supplied. Thus, despite these measures, it was clear that Czechoslovakia was in need of international help. Leading politicians saw a remedy for the lack of grain in help from the Soviet Union, as further reported by Florián Gloziga (AS5, fol. 5r–6r):

> […] for supply and provision of grain for bread from abroad, apart from smaller amounts from Canada, Yugoslavia and Bulgaria, given the present-day international situation — realistically considered — whatever purchase was and is beyond our means. […] Further, the great merit of our Soviet ally should be appreciated for basic help with our nutrition plan realised in July 1947 by the Czechoslovak delegation headed by Prime Minister Klement Gottwald in Moscow, when the supply of grain for bread and animal feed for our state was negotiated […] The Soviet government and its premier 'Generalissimus' Stalin in person […] guaranteed a supply of 200,000 tons of wheat and 200,000 tons of grain for feed. […] In summer it was not yet possible determine the exact extent of crop failure. The consequences of the drought made it clear that in autumn [matters were] far worse and acute supply problems threatened Czechoslovakia […] In this situation, on 25 November of this year Prime Minister Gottwald turned to USSR premier 'Gen.' Stalin with a personal letter […] and requested whether, among other things, it would be possible to increase the supply of Soviet grain by at least around 150,000 tons. 'Gen.' Stalin's telegraphed reply of 29 November informed [us] that, after consultation with the relevant Soviet officials, Czechoslovakia is offered not 150,000 tons, but 200,000 tons of grain for bread over and above the amount that was agreed in summer. […] Thus the Soviet Union will provide us a total of 600,000 tons of grain from the 1947 harvest, 400,000 tons of it for bread, i.e. wheat and rye, and 200,000 tons of feed grain. Of this, 50,000 tons of grain for bread and 50,000 tons of feed grain will be supplied by the end of this year, the remainder progressively to the end of April 1948.

The catastrophic impacts of the 1947 drought also led to new approaches to legal frameworks for support during and after disasters. Since 1927, when an act came into law as a consequence of disastrous flash floods (Raška & Brázdil 2015), subsidies to agriculture had been provided from a fund set up for this purpose. The funds were progressively subsidised, but the financial amounts were not sufficient to cover the impacts of high-magnitude events, the scheme lacked supportive tools to provide relief and the scope of fund management authority was unclear. The similar situation was clearly described in a statement to parliament on 11 September 1947:

> According to Act No. 145/1947 [AS2] on the organization of Czechoslovak agriculture, the farmers' unions are obliged to support those affected by natural extremes […]

This was done from regional funds, e.g.

> The disaster fund in Brno established in 1939 […], which received by 9.5 million Kčs annually in donations.

However, the extent of the regions affected by drought exceeded the original scope of the fund. Parliamentary representatives therefore called for an increase in governmental subsidies to the fund and suggested supportive measures for provision of financial relief. The government resolution from 2 September on an extraordinary surcharge on purchase prices and on payment of extraordinary support was the first legislative response to the 1947 drought (cf. Fig. 10).

In April 1948, Act 83/1948 (AS3) on a fund for mitigation of impacts arising out of the extreme drought of 1947 was approved. The act resolved some of the former problems associated with disaster funds (see above) and defined the financial sources, in accord with communist policies, as: (1) extraordinary charges for 'excessive property', (2) a luxury tax, and (3) other special arrangements. Moreover, it defined the areas of financial subsidy that should now cover: (1) extraordinary surcharges on purchase prices of agricultural products, (2) expenses for transport of extraordinary subsidies of fodder, (3) expenses for pest control (Colorado beetle *Leptinotarsa decemlineata*), (4) additional expenses arising from the differences between foreign and domestic prices (i.e. reduction of prices of imported products to ensure their availability to local farmers), (5) a financial subsidy to farmers of up to 500 million Kčs (see above), (6) compensation to farmers who had not contributed to prescribed contingency funds (up to 12 million Kčs), (7) obligations related to loans, and (8) losses arising out of cattle deaths (up to 30 million Kčs). The financial subsidy had to be applied for by the end of 1948.

4. DISCUSSION

4.1. Spatial and temporal context of 1947 drought

That the 1947 drought in the Czech Lands was very severe follows from analysis of the entire period of instrumental meteorological observations, i.e. 1804–2014. The drought episode from April to October 1947 was evaluated as the most extreme meteorological drought event according to SPEI-1 and *Z*-index (followed by April–October droughts in 1868 and 1834 for both indices). According to precipitation-based SPI-1, April–October 1947 was the most extreme drought in the period, together with that of 1842 (for a detailed overview of all severe droughts in the Czech Lands, see Brázdil & Trnka 2015).

The hydrological drought of 1947, considered in terms of daily discharge, i.e. duration and deficiency volume of water, was one of the 3 most important drought events since the late 1880s (together with 1904, 1911 and 1921). Where precipitation totals were higher, or certain anthropogenic interventions were in play, the drought was far less extreme. The spatial distribution of the hydrological drought over the territory of the Czech Lands (Fig. 7), based on characteristics calculated from monthly discharges, tallies well with the distribution of April–October precipitation totals (Fig. 4a).

A large number of publications have addressed the drought of 1947 in the territories surrounding the Czech Lands. Lauscher (1948) analysed temperatures and precipitation for 1947 in Austria, drawing particular attention to the long period of above-mean temperatures from April to September (particularly September) and low precipitation totals in the growing season, around only 50 to 60% of the long-term mean. September and October were the driest, while all the months from April to October were below mean. A similar situation was described for Switzerland by Bider (1948), making partial use of the data from long-term series for Basle and further data from around the country. He even compared the warm and dry patterns of 1947 with those of 1540, to which more recently — based on extensive European documentary data — the term 'megadrought' has been applied (Wetter et al. 2014). More detailed analysis of the 1947 drought in Switzerland was contributed later by Schorer (1992) and Widmer (2003). Petrovič (1948) reported on the catastrophic drought of 1947 with particular reference to southern and central Slovakia. Based on data from the Hurbanovo station, he found this to have been the most severe drought since the beginning of observations in 1871 (for example, the dry period from 25 July to 17 October was almost without rain, except for a few showers with totals below 1 mm). He attributed the 1947 drought to high-pressure conditions and the absence of cyclones from the south. There is similarly rich information from Germany (e.g. Geiger 1948, 1951, DWD 1941). In Poland, Mager et al. (2000) considered the country's 171 days with low river flow in 1947 the eighth most severe hydrological drought in the 1901–1995 period; 87% of the area of Poland experienced 'atmospheric' drought, ranking 1947 equal fifth with 1921 for the 1891–1995 period. The last significant locust invasion was recorded in Hungary in 1947 (Kiss 2012). These reports from a number of countries confirm that the 1947 drought was a significant Central European climate anomaly. Moreover, Briffa et al. (1994) classified summer 1947 as the driest in terms of mean PDSI and spatial extent of moderate drought (PDSI <-2) over Europe for the 1892–1991 period. As indicated in Fig. 11a, April–October 1947 in Europe was very warm in a broad belt extending from the Iberian Peninsula over Central Europe to Turkey, while below-mean precipitation totals also prevailed in the greater part of this belt (Fig. 11b). That PDSI values showed dry patterns over the major part of Europe is hardly surprising (Fig. 11c).

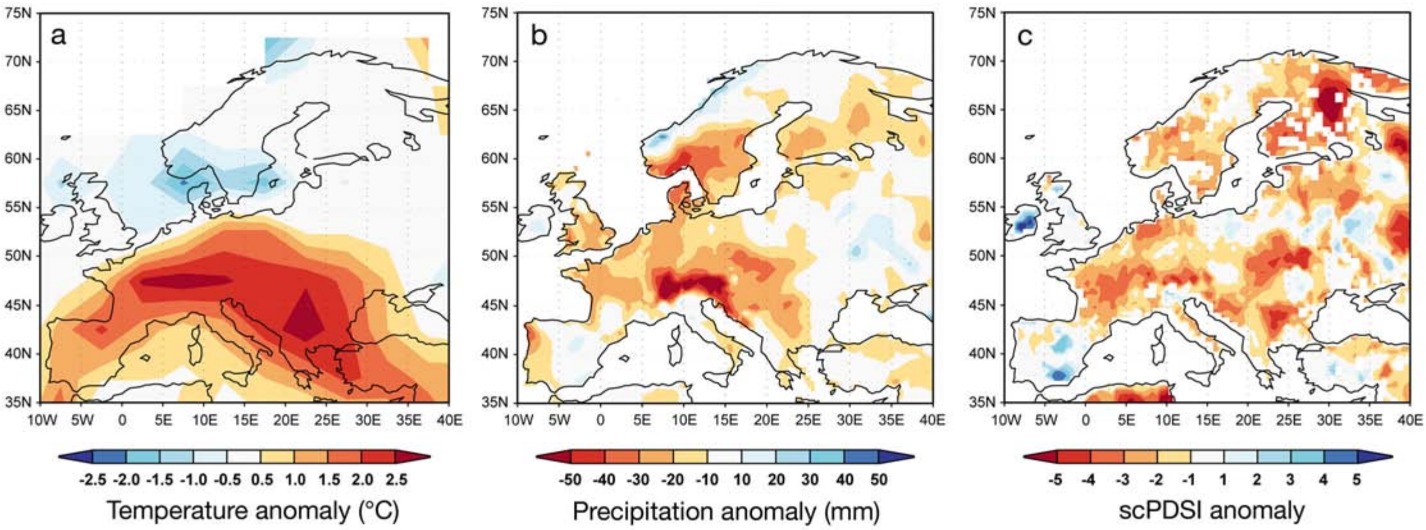

Fig. 11. April–October 1947 anomalies of (a) air temperatures (HadCTRU4 database, Morice et al. 2012), (b) precipitation totals (CRU TS3.23 database, Jones & Harris 2008), (c) self-calibrating Palmer Drought Severity Index (PDSI) (CRU self-calibrating PDSI 3.21, van der Schrier et al. 2006) in Europe, compared to the 1961–1990 reference period

4.2. Impacts of the 1947 drought

Consideration of the agricultural impacts of the 1947 drought must take into account that it was preceded by a particularly cold January and February, in which heavy frosts (Figs. 2 & 3) affected winter crops. Part of the areas originally sown with winter cereals had to be re-ploughed and sown again, or were not harvested. This situation is comparable to the winter of 2002–2003 (Trnka et al. 2010) and its subsequent severe drought (Ciais et al. 2005). This left the agricultural sector particularly exposed to drought in the April–June period, as winter crops are less sensitive to drought in these months (Hlavinka et al. 2009). The decrease of acreage of all crops from 1946 to 1947 is consistent with severe damage, since it made no financial sense to harvest at all. The sheer duration of the 1947 drought, from April to October, is a further unusual characteristic, meaning that later-maturing crops (e.g. potatoes, beet, sugar beet, forage crops) were severely affected. If drought occurs early in the season (April–June), the early-maturing crops (e.g. barley, wheat, oilseed rape) suffer, as was the case in 2000 and 2012. If drought occurs later (July–September), it affects later-maturing crops (e.g. maize, potatoes, beet, sugar beet, hay) as occurred in 2003 and 2015. The later-maturing crops are able, in the course of their crop calendar and with a longer growing season, to compensate to a certain extent for drought early in the season (Hlavinka et al. 2009). As droughts only rarely occur throughout the whole vegetation season, the agricultural sector production as a whole is usually fairly stable.

The exceptional losses in 1947 were partly due to the fact that extreme drought, to a varying extent and in certain regions (Figs. 3 & 4), persisted throughout sensitive periods for all the major crops. Drops in agricultural production appeared in many European areas. As pointed out by Schorer (1992), FAO data shows that the national yields of wheat were lower in 1947 than 1942–1949 yields all over Europe; falls in production reached 36.3% in Belgium, 33.8% in France, 32.5% in Czechoslovakia, 31.0% in Finland, 29.7% in Denmark, 27.6% in Hungary, and 27.1% in Germany, to mention only a few. The deepest drops in potato production were recorded in Czechoslovakia (24.3%), Great Britain (15.0%) and Germany (14.6%). This demonstrates that the territory then known as Czechoslovakia was particularly affected.

Drought impacts in 1947 were not confined to agriculture. For example, Bider (1948) reports lack of water in some towns, navigation restriction on the River Rhine and reduced electricity capacity in Switzerland. Geiger (1951) reported that 1.4 million m^3 of timber was felled in Bavaria as a direct consequence of the 1947 drought. The final damage to forestry was even more severe, because this number could not include trees damaged by the bark beetles that prospered in drought-weakened forests.

4.3. Political factors and additional responses to catastrophic drought

The disastrous drought of 1947 and the associated dramatic failure of the harvest struck in the immediate post-Second World War period, when the political situation was in a state of flux. The UNRRA (United Nations Relief and Rehabilitation Administration) programme ended in summer 1947, and the newly-offered Marshall Plan (European Recovery Program) was rejected by the Czechoslovak government on 10 July 1947 (Michálek 2007). The 'Soviet grain aid' (Section 3.4) to Czechoslovakia came at a time of great famine in the Soviet Union (1946–1948, with 1947 as core year) for which Ellman (2000) reports excess mortality in the range of 1.0 to 1.5 million people (see also Volkov 1992 for details). This was a consequence of bad harvests caused by drought and of reduced food availability. He argues that the surplus stocks held by the state would probably have been sufficient to save all the people who died of starvation, but the priorities of the Soviet government lay elsewhere. The 'brotherly help' for Czechoslovakia may have been one of them, aimed at consolidating the Soviet hold on the Central European region and diminishing US influence there. This aid became an effective propaganda tool for the Communist Party, which finally swept to power in Czechoslovakia in early 1948. After that, such Soviet aid held a special place in the public memory for decades, and was even reflected in the historiography of Czechoslovakia (e.g. Husa 1961).

Legal frameworks, too, altered in response to the drought. Experience with fund-based disaster relief during the 1947 event exposed significant shortcomings in previous approaches and finally led to the proposal of a new system, defined by Act 27/1950 (AS1) on state support during natural disasters. The new act ended the fund-based principle of disaster relief and defined the sources, types of subsidies (finance, goods and other), aims, eligibility of recipients and controlling mechanisms for subsidies. This law remained valid until a new act was passed subsequent to the disastrous flood of 2002 in the Czech Republic (Brázdil et al. 2005).

At a regional and local level, the 1947 drought resulted in reconsideration of the landscape-ecological measures associated with territorial planning. General policies of the time were based on 2 major principles: centralisation in the interests of economic production, and the transformation of nature by means of technological progress, intended to optimise production and profits. Both these principles had emerged from communist ideology and strategies in the Soviet Union, where Stalin's 'Great Plan for the Transformation of Nature' was approved on 20 October 1948 (Brain 2010).

An example of landscape planning responses to the 1947 drought in the Czech Lands may be found in action taken in southern Moravia. The land committee approved a plan to create a system of windbreaks in order to protect fields from wind erosion (Šanovec 1948). More than 300 ha of windbreaks were planted during 1948–1952 and ca. 1100 ha by 1960, when the windbreak strategy for land amelioration gave way to the construction of large water reservoirs (Orsillo 2015).

5. CONCLUSIONS

The 1947 drought episode in the Czech Lands — through its physical nature and severity and particularly in its economic and social-political impacts, responses and consequences — holds an exceptional position among all the severe drought events from the 19th century to the present time. No other episode motivated researchers and administrations to such broad responses, or occupied a place in public memory for such a long time. The exceptional nature of the 1947 drought was accentuated by the fact that it came at the time of post-war renewal in the country, when the economy was still destabilised. Further, it was followed by more relatively dry years from 1948 to 1954. The authors consider this study a necessary, truly objective and independent evaluation of impacts of 1947, which was impossible prior to the profound change of the country's political direction in 1989. Moreover, information about the 1947 drought and its impacts in other European countries shows that it was an important climate anomaly of great territorial extent with significant socio-economic impacts, well worthy of detailed study on a broader European scale.

The disastrous drought of 1947 may be also put into the context of increasing dryness observed in the Czech Republic in the course of recent decades, particularly after the year 2000 (Brázdil & Trnka 2015). Moreover, existing climate change projections with multiple GCMs indicate an increased risk of drought events in the Central European region (e.g. Dai 2013, Dubrovsky et al. 2015) as well as increased likelihood of drought occurrence during critical periods for agricultural crops (e.g. Trnka et al. 2014, 2015). This means that droughts of the '1947 type' may occur even more frequently in the 21st century, with the disastrous impacts on agriculture, water management, forestry and other sectors of the national economy that became all too evident in that year.

Acknowledgements. R.B., P.D., L.Ř., H.V. and P.Z. acknowledge support of the Grant Agency of the Czech Republic for project no. 13-19831S and P.R. for project no. 13-02080P. M.T. acknowledges support from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant no. LO1415 and grant LD13030. Christian Pfister (Bern) is acknowledged for the reference to Swiss papers for 1947 drought. Tony Long (Svinošice) improved the English.

LITERATURE CITED

Allan RJ, Ansell TJ (2006) A new globally complete monthly historical mean sea level pressure data set (HadSLP2): 1850–2004. J Clim 19:5816–5842

Bider M (1948) Meteorologische Betrachtung zum Sommer 1947. Leben und Umwelt 4:111–116

Brádka J (1972) Srážky na území ČSSR při jednotlivých typech povětrnostní situace (Precipitation on the territory of the CSSR in particular types of weather situation). Sborník prací Hydrometeorologického ústavu v Praze 18: 8–62

Brádka J, Dřevikovský A, Gregor Z, Kolesár J (1961) Počasí na území Čech a Moravy v typických povětrnostních situacích (Weather over the territory of Bohemia and Moravia in typical weather situations). Hydrometeorologický ústav, Praha

Brain S (2010) The great Stalin plan for the transformation of nature. Environ Hist 15:670–700

Brázdil R, Trnka M (eds) (2015) Sucho v českých zemích: minulost, současnost, budoucnost (Drought in the Czech Lands: past, present, future). Centrum výzkumu globální změny Akademie věd České republiky, v.v.i., Brno

Brázdil R, Dobrovolný P, Elleder L, Kakos V and others (2005) Historické a současné povodně v České republice (Historical and recent floods in the Czech Republic). Masarykova univerzita, Český hydrometeorologický ústav, Brno, Praha

Brázdil R, Trnka M, Dobrovolný P, Chromá K, Hlavinka P, Žalud Z (2009) Variability of droughts in the Czech Republic, 1881–2006. Theor Appl Climatol 97:297–315

Brázdil R, Zahradníček P, Pišoft P, Štěpánek P, Bělínová M, Dobrovolný P (2012) Temperature and precipitation fluctuations in the Czech Lands during the period of instrumental measurements. Theor Appl Climatol 110:17–34

Brázdil R, Dobrovolný P, Trnka M, Kotyza O and others (2013) Droughts in the Czech Lands, 1090–2012 AD. Clim Past 9:1985–2002

Briffa KR, Jones PD, Hulme M (1994) Summer moisture variability across Europe, 1892–1991: an analysis based on the Palmer Drought Severity Index. Int J Climatol 14: 475–506

Ciais P, Reichstein M, Viovy N, Granier A and others (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437:529–533

Dai A (2013) Increasing drought under global warming in observations and models. Nat Clim Change 3:52–58

Dubrovsky M, Trnka M, Holman IP, Svobodova E, Harrison PA (2015) Developing a reduced-form ensemble of climate change scenarios for Europe and its application to selected impact indicators. Clim Change 128:169–186

DWD (Deutscher Wetterdienst) (1949) Der heiße und trockene Sommer 1947. Berichte des Deutschen Wetterdienstes in der US-Zone 7, Bad Kissingen

Ellman M (2000) The 1947 Soviet famine and the entitlement approach to famines. Camb J Econ 24:603–630

Geiger R (1948) Die Auswirkungen der Dürre (Dürrezahlen und Dürrewirkungzahlen). Meteorol Rundsch 1:513–516

Geiger R (1951) Die Waldgefährdung durch den Dürresommer 1947. Forstwissenschaftliches Centralblatt 70: 349–355

Heim RR (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165

Hisdal H, Tallaksen LM (eds) (2000) Drought event definition. Technical report to the ARIDE Project No. 6. Department of Geophysics, University of Oslo

Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Žalud Z, Možný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric For Meteorol 149: 431–442

Hoerling M, Eischeid J, Kumar A, Leung R and others (2014) Causes and predictability of the 2012 Great Plains drought. Bull Am Meteorol Soc 95:269–282

Husa V (1961) Dějiny Československa: k 40. výročí založení KSČ (History of Czechoslovakia: for the 40th anniversary of the Czechoslovak Communist Party). Orbis, Praha

Jones PD, Harris I (2008) Climatic Research Unit (CRU) time-series datasets of variations in climate with variations in other phenomena. NCAS British Atmospheric Data Centre, http://catalogue.ceda.ac.uk/uuid/3f89448 00cc48e1cbc29a5ee12d8542d (accessed 12 Oct 2015)

Juneja M, Mauelshagen F (2007) Disasters and pre-industrial societies; historiographic trends and comparative perspectives. Mediev Hist J 10:1–31

Kiss A (2012) A sáskajárások néhány területi és tájtörténeti vonatkozása a Kárpát-medencében (Some regional and areal consequences of historical locust invasions in the Carpathian Basin). In: Füleky G (ed) A táj változásai a Kárpát-medencében. Történeti emlékek a tájban. Szent István Egyetem, Gödöllő, p 123–132

Kyselý J (2002) Temporal fluctuations in heat waves at Prague–Klementinum, the Czech Republic, from 1901–97, and their relationships to atmospheric circulation. Int J Climatol 22:33–50

Lauscher F (1948) Das abnormale Witterungsjahr 1947. Wetter und Leben 1:1–6

Mager P, Kuźnicka M, Kępińska-Kasprzak M, Farat R (2000) Change in the intensity and frequency of occurrence of droughts in Poland (1891–1995). Geogr Pol 73:41–47

McCombs M, Shaw D (1972) The agenda-setting function of mass media. Public Opin Q 36:176–184

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time steps. In: Preprints, 8th Conference on Applied Climatology, Anaheim, CA, 17–22 January 1993. American Meteorological Society, Boston, MA, 179–184

Michálek S (2007) Odmítnutí Marshallova plánu. Československá politika mezi Východem a Západem (Rejection of the Marshall Plan. Czechoslovak politics between East and West). Dějiny a současnost 29:33–36

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol (Amst) 391:202–216

Morice CP, Kennedy JJ, Rayner NA, Jones PD (2012) Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 dataset. J Geophys Res 117:D08101

Munich Re (2015) Topics Geo. Natural catastrophes 2014. Analyses, assessments, positions. Münchener Rückversicherungs-Gesellschaft, München

Orsillo N (2015) Zmírnit pohyb vzdušných proudů … (To reduce the movement of air flows …). Dějiny a současnost 2:22–25

Palmer WC (1965) Meteorological drought. Office of Climatology Research Paper 45. US Weather Bureau, Washington, DC

Petrovič Š (1948) Sucho roku 1947 (The drought of 1947). Slovenské pol'nohospodárstvo 3:58–62

Pfister C (2009) Learning from natural-induced disasters: theoretical considerations and case studies from Western Europe. In: Mauch C, Pfister C (eds) Natural disasters, cultural responses. Lexington Books, Plymouth, p 17–40

Poliwoda G (2007) Learning from disasters: Saxony fights the floods of the river Elbe 1784–1845. Hist Soc Res (Koln) 32:169–199

Raška P, Brázdil R (2015) Participatory responses to historical flash floods and their relevance for current risk reduction: a view from a post-communist country. Area 47:166–178

Raška P, Zábranský V, Dubišar J, Kadlec A, Hrbáčová A, Strnad T (2014) Documentary proxies and interdisciplinary research on historic geomorphologic hazards: a discussion of the current state from a central European perspective. Nat Hazards 70:705–732

Šanovec J (1948) Větrolamy, nový způsob meliorace pozemků (Windbreaks, a new method of land amelioration). Brázda, Praha

Schenk GJ (2007) Historical disaster research: state of research, concepts, methods and case studies. Hist Soc Res (Koln) 32:9–31

Schorer M (1992) Extreme Trockensommer in der Schweiz und ihre Folgen für Natur und Wirtschaft. In: Geographica Bernensia, G40. Geographisches Institut der Universität Bern, Bern

Šercl P, Lett P (2002) Výpočet rastru srážek v prostředí GIS (s využitím ArcView Spatial Analyst). Uživatelská příručka verze 2.0.1. (Calculation of precipitation grid in the GIS [using ArcView Spatial Analyst]. User Guide Version 2.0.1). ČHMÚ, OPV, Praha

Stanford M (1986) The nature of historical knowledge. Blackwell, Oxford

Štěpánek P, Zahradníček P, Brázdil R, Tolasz R (2011) Metodologie kontroly a homogenizace časových řad v klimatologii (Methodology of data quality control and homogenisation of time series in climatology). Český hydrometeorologický ústav, Praha

Štěpánek P, Zahradníček P, Farda A (2013) Experiences with data quality control and homogenization of daily records of various meteorological elements in the Czech Republic in the period 1961–2010. Időjárás 117:123–141

Tallaksen LM, van Lanen HAJ (eds) (2004) Hydrological drought: processes and estimation methods for streamflow and groundwater. Developments in water science 48. Elsevier, Amsterdam

Trenberth KE, Fasullo JT (2012) Climate extremes and climate change: The Russian heat wave and other climate extremes of 2010. J Geophys Res 117:D17103

Trnka M, Dubrovský M, Svoboda M, Semerádová D, Hayes M, Žalud Z, Wilhite D (2009) Developing a regional drought climatology for the Czech Republic. Int J Climatol 29:863–883

Trnka M, Kocmánková E, Balek J, Eitzinger J and others (2010) Simple snow cover model for agrometeorological applications. Agric For Meteorol 150:1115–1127

Trnka M, Rötter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Žalud Z, Semenov MA (2014) Adverse weather conditions for European wheat production will become more frequent with climate change. Nat Clim Change 4: 637–643

Trnka M, Hlavinka P, Semenov M (2015) Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change. J R Soc Interface 12:20150721

van der Schrier G, Briffa KR, Jones PD, Osborn TJ (2006) Summer moisture variability across Europe. J Clim 19: 2818–2834

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multi-scalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J Clim 23:1696–1718

Vlnas R, Novický O, Kašpárek L, Hanslík E and others (2010) Časová a plošná variabilita hydrologického sucha v podmínkách klimatické změny na území České republiky (Temporal and spatial variability of hydrological drought in conditions of climate change over the territory of the Czech Republic). Výzkumný ústav vodohospodářský T. G. Masaryka, v.v.i., Praha

Volkov IM (1992) The drought and famine of 1946–47. Russ Stud Hist 31:31–60

Voss M, Wagner K (2010) Learning from (small) disasters. Nat Hazards 55:657–669

Wetter O, Pfister C, Werner JP, Zorita E and others (2014) The year-long unprecedented European heat and drought of 154 — a worst case. Clim Change 125: 349–363

Widmer M (2003) Die Trockenheit von 1947: der extreme Trockensommer von 1947 in seiner Wirkung auf das sozio-ökonomische System der Schweiz. Lizentiatsarbeit, Historisches Institut der Universität Bern

Appendix. Archival sources

(AS1) Act 27/1950. Zákon o státní podpoře při živelních pohromách (Act 27/1947 on state support during natural disasters)

(AS2) Act 145/1947. Zákon o organisaci zemědělců republiky Československé (Act 145/1947 on the organization of Czechoslovak agriculture)

(AS3) Act 83/1948. Zákon o zřízení fondu pro zmírnění škod způsobených mimořádným suchem v roce 1947 v oboru zemědělství a výživy (Act 83/1948 on a fund for mitigation of impacts on agriculture and food provision arising out of the extreme drought of 1947)

(AS4) Digital parliamentary repository of the Czech Republic. Available at www.psp.cz/eknih/index.htm (accessed 30 Sep 2015)

(AS5) Moravský zemský archiv Brno, fond B 280 Zemský národní výbor Brno, Volené orgány a sekretariát, 1945–1948, inv. č. 12 Zápisy z 12. schůze pléna ZNR, orig., 16–19/12, 1947

(AS6) *Rudé právo* newspaper, year 1947. National Library of the Czech Republic, Prague

(AS7) Státní okresní archiv Uherské Hradiště, fond MNV Jalubí, I: Kronika obce Jalubí, 1. svazek 1924–1947

Editorial responsibility: Ulf BŸntgen (Guest Editor), Birmensdorf, Switzerland

Submitted: November 3, 2015; Accepted: March 2, 2016
Proofs received from author(s): June 2, 2016

Vol. 70: 179–193, 2016
doi: 10.3354/cr01424

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

Projection of drought-inducing climate conditions in the Czech Republic according to Euro-CORDEX models

Petr Štěpánek[1,2,*], Pavel Zahradníček[1,2], Aleš Farda[1], Petr Skalák[1,2], Miroslav Trnka[1,3], Jan Meitner[1], Kamil Rajdl[1]

[1]Global Change Research Institute CAS, Belidla 986/4a, Brno 60300, Czech Republic
[2]Czech Hydrometeorological Institute, Na Šabatce 2050/17, Praha 14306, Czech Republic
[3]Institute of Agriculture Systems and Bioclimatology, Mendel University in Brno, Zemedelska 1, 613 00 Brno, Czech Republic

ABSTRACT: The end of the 20th century and the beginning of the 21st century in the Czech Republic were characterized by frequent extreme water cycle fluctuations, i.e. the occurrence of increased incidences of flood and drought events. Drought occurs irregularly in the Czech Republic during periods with low precipitation amounts. The most noteworthy droughts with significant impact, especially to agriculture, occurred in the years 2000, 2003, 2007, 2009, 2012, 2014 and 2015. A significant increase in frequency and length of drought periods was detected in future climate projections based on the latest model outputs, such as from the Euro-CORDEX 0.11° resolutions for the European area. For these model experiments, the following greenhouse gas emissions scenarios were used: Representative Concentration Pathway (RCP) 4.5 (milder scenario) and RCP8.5 (pessimistic scenario). Since the climate models suffer from potentially severe biases, it is necessary to statistically correct their outputs. For this purpose, a suitable reference dataset was prepared, based on quality-controlled, homogenized and gap-filled station time series. The correction method applied was based on variable correction using individual percentiles. From the corrected model outputs, selected extreme indexes with respect to drought analysis were calculated. From the results, it follows that we can expect both an increase in air temperature and in precipitation (with increased amounts per event), as well as an increase in other extremes with the capability of inducing drought (number of tropical days, heat waves, etc.).

KEY WORDS: Euro-CORDEX simulations · Model bias correction · Climate change · Drought indices · Czech Republic

1. INTRODUCTION

As is shown in several studies in this CR Special, drought constitutes a potential threat to people's livelihoods and socioeconomic development, including in the Central European region (e.g. Brázdil et al. 2016, this issue). Compared to hazards such as floods, drought tends to occur less frequently. However, when it does occur, it generally affects a broad region for seasons or years at a time (UNISDR 2009). Drought originates from a deficiency of precipitation over an extended period of time, usually a season or more. This deficiency can result in water shortage for some activities, groups or environmental sectors. Drought is different from other hazards in that it develops slowly, sometimes over years, and its onset can be masked by a number of factors. Drought is an issue concerning all European Union (EU) countries. According to Spinioni et al. (2016) the drought episodes affected, on average, 15 % of the EU territory and 17 % of the EU population from 2006 to 2010. This caused considerable damages and economic losses that were esti-

*Corresponding author: stepanek.p@czechglobe.cz

Publisher: Inter-Research · www.int-res.com

mated at over €100 billion (e.g. Spinioni et al. 2016). Water shortage in Europe is a serious problem in many regions (Vogt & Somma 2013), and estimates for the 21st century show an increasing chance of drought across most of the European continent (Stocker et al. 2013). However, the character of these changes is important for adaptation options. For instance, for a number of catchments in Central Europe, the projected average annual changes in water level are relatively small, despite considerable changes in seasonal distribution, even for high-impact scenarios (e.g. Hanel et al. 2012, 2013). This suggests that the development of accumulation capacities might be an adaptation option. However, if the periods of drought cover multiple years, this adaptation option may no longer be efficient. As another example, the timing of drought onset and the maximum deficit is important for the impacts on agricultural production. In the studied region, more crops and larger areas are vulnerable to drought in the first half of the growing season (especially April–June) than in July–September, with the notable exception of maize, potatoes and sugar beet (Hlavinka et al. 2009). The year-to-year variability of drought can be related to circulation patterns, as shown e.g. by Trnka et al. (2009) and Kingston et al. (2015). There is evidence that the trends in soil moisture anomalies in Central Europe are indeed linked to the occurrence of atmospheric circulation patterns that are conducive to drought. It also appears that long-term trends in the frequency of drought-conducive circulation patterns have contributed to a change in the duration and intensity of drought episodes (Trnka et al. 2009). This phenomenon is particularly pronounced during the early vegetation period (April–June), which is crucial both for the productivity of managed ecosystems (e.g. rain-fed field crops) as well as for the net primary production of central European ecosystems as a whole. Recent studies have introduced evidence of decreasing soil moisture content since 1961 (Trnka et al. 2015), and attributed it to increasing CO_2 levels related to anthropogenic forcing (Brázdil et al. 2015).

High-resolution information about future climate is needed for proper adaptation and mitigation of the impacts of climate change and variability. Driven by a suite of IPCC assessment reports and accompanied by increasing public awareness of ongoing climate change, the past decades have seen rapid development in the corresponding methods for climate scenario generation (Kotlarski et al. 2014). The primary tools used for this task are climate models. Unfortunately, high-resolution climate simulations are still not computationally affordable with global climate models (GCMs). A coarse resolution also precludes global models from providing an accurate description of extreme events, which are of fundamental importance to users of climate information with respect to the regional and local impacts of climate variability and change (Giorgi et al. 2009). To obtain climate change information at the regional to local scale, different downscaling techniques are applied on GCMs' outputs. Dynamical downscaling (Giorgi & Mearns 1991) using a regional climate model (RCM) is an example of such a technique.

RCMs (Giorgi & Mearns 1999, Wang et al. 2004) are widely used tools for providing regional climate information over limited areas. The availability and reliability of RCM simulations for Europe has increased rapidly in recent years, thanks to projects such as PRUDENCE (Christensen & Christensen 2007), STARDEX (Goodess et al. 2012), ENSEMBLES (van der Linden & Mitchell 2009), and recently, NARCCAP (Mearns et al. 2012) and CORDEX (Giorgi et al. 2009). However, RCMs feature considerable systematic errors (see e.g. Frei et al. 2003, Suklitsch et al. 2010), which hampers easy application of RCM results in climate change impact research.

Since model outputs suffer from systematic errors (due to a necessary simplification of complex real-world processes: coarser spatial resolution, parameterizations, etc.), it is necessary to correct them to obtain meaningful results on the simulated properties of the climate system. Generally, when dealing with mean values of meteorological elements (e.g. seasonal and annual values), the changes given by the models can be treated as they are, without any modifications. The problem occurs in the analysis of daily data and extreme values (such as temperature maxima and minima, precipitation values over given thresholds, etc.), where incorrect statistical distribution simulated by a model (in particular withregards to its tail parts) for a given meteorological element may lead to incorrect conclusions. To cope with distorted statistical moments of different order, different model correcting techniques are applied (a list of these is given in e.g. Themessl et al. 2012). In the present work, the model outputs were corrected using our own correction method (distribution adjusting by percentiles, or DAP) that is based on the quantile mapping (QM) approach of Déqué (2007) (see details in Section 2.3).

Our previous analyses of climate change for the Czech Republic (Štěpánek et al. 2012, Brázdil & Trnka 2015) were based only on the Special Report on Emissions Scenarios (SRES) emissions scenario A1B and 2 models, ALADIN-Climate/CZ, either in 25 or 10 km resolution (Farda et al. 2010), or RegCM (Pal et al. 2007). Here we present new results based on an ensemble of 11 simulations of Euro-CORDEX RCMs (described in Section 2.2). Euro-CORDEX simulations are based on Representative Concentration Pathway (RCP) scenarios (Moss et al. 2008). These scenarios take radiative forcing (W m^{-2}) as the characteristic driving variable, instead of the concentration of the equivalent CO_2 (ppm). The RCPs are consistent with a wide range of possible changes in future anthropogenic greenhouse gas emissions. RCP2.6 assumes that global annual greenhouse gas emissions will peak around 2010–2020, with emissions declining thereafter. Emissions in RCP4.5 are expected to peak around 2040, and then decline. In RCP6 (not used in the present study), emissions peak around 2080; in RCP8.5, emissions continue to rise throughout the 21st century (Meinshausen et al. 2011). The differences between the older results (based on SRES scenarios) and these new results are discussed in Section 4.

Since the volume of obtained results is enormous and there is not enough space in this article to show them all, only selected features of a combination of all 11 experiments for the whole Czech Republic (spatial aggregates) will be presented here (in Section 3). Nonetheless, the obtained material will serve for further analysis and be published on the web portal designated for the exchange of information on climate change impacts, vulnerability and adaptation measures on the territory of the Czech Republic (www.klimatickazmena.cz/en/).

2. METHODS

2.1. Station data

For proper validation of the RCM outputs and their later correction, station data of the highest quality has to be used. First, the underlying raw station data should be subject to thorough quality control. Data quality control applicable to large datasets was developed by Štěpánek et al. (2009). Automation of the process (preserving a good ratio of true and false alarms) was achieved through a combination of several methods of temporal and spatial analysis.

Once the erroneous data are removed from the series during quality control, the series are the subject of homogenization, applying several statistical tests for the detection of inhomogeneities, and found discontinuities are corrected in the daily scale (again, several methods are applied to decrease the uncertainty of the correction estimates). Further details on the homogenization can be found in e.g. Štěpánek et al. (2013) or in the documentation of the software (Štěpánek 2010). Quality control and correction of inhomogeneities were performed on a daily (subdaily) basis for all key meteorological variables (air temperature, precipitation, sunshine duration, relative humidity, wind speed) over the territory of the Czech Republic since 1961 (as well as for neighboring countries, such as the Slovak Republic and Austria, within international projects).

After quality control and homogenization, missing values were filled in. Calculation of the 'new' values was based on geostatistical interpolation methods, improved by standardization of neighboring stations' values to the altitude of a given location by means of regional regression analysis (Štěpánek et al. 2011). Parameter settings of the calculation differ for each meteorological element, and the optimal settings were found by means of cross-validation.

Data quality control, homogenization and the filling in of missing values led to the creation of a so-called 'technical' series for mean, maximum and minimum temperatures, precipitation totals, sums of sunshine duration, relative humidity (mean water vapor pressure) and wind speed. These were calculated for 268 climatological and 787 rain-gauge stations of the Czech Hydrometeorological Institute (CHMI) network in the 1961–2009 period, and actual values are continually being added. Despite the fact that a smaller number of stations was available for some of the studied characteristics (e.g. for sunshine duration or water vapor pressure), the 'technical' series were completely calculated (both for arbitrary station location and regular gridded network). In this way, we have a complex set of meteorological variables for each position of a climatological station, which could easily be applied in any climate analysis or impact study in this territory.

2.2. Model simulations

Our analysis of future climate conditions is based on RCM simulations prepared within the European part of the global Coordinated Regional Climate Downscaling Experiment (CORDEX, www.cordex.org). CORDEX is an international effort supported by the World Climate Research Programme (WRCP), aimed at producing a set of climate change projections covering individual world regions with multiple RCMs and several emissions scenarios. Thus, the climate research community gets more reliable information on future climate parameters, including information on related uncertainty. To account for greenhouse gases and aerosol forcing, RCP scenarios are used (van Vuuren et al. 2011). The GCM output from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) has been utilized as the source of driving data for the RCMs. Generally, CORDEX models follow a unified model setup, including control, historic (hindcast) and future climate projection experiments.

The European domain of CORDEX is covered within the frame of the Euro-CORDEX sub-project (www.euro-cordex.net). Model experiments are performed here in 2 spatial resolutions: 0.44° and 0.11°. In total, 10 different RCMs and 13 driving GCMs have been employed. In our paper, we focus only on the 0.11° resolution experiments forced by the RCP2.6 (van Vuuren et al. 2007), RCP4.5 (Clarke et al. 2007) and RCP8.5 (Riahi et al. 2007) scenarios, respectively. The following RCMs were used in our study: ALADIN53, CCLM4-8-17, HIRHAM5, RACMO22E and RCA4. Two of the 5 RCMs were driven by >1 GCM. The selection of the experiments was based on their availability in July 2015, and is summarized in Table 1. Also included in Table 1 is the identification code of the particular simulation (e.g. r1i1p1) taken from the CMIP5 GCM ensemble to drive an RCM.

Table 1. Selected Euro-CORDEX experiments of regional climate models (RCMs) and their driving global climate models (GCM)

RCM	Driving GCM	GCM ensemble member	Scenarios
ALADIN53	CNRM-CM5	r1i1p1	RCP4.5, RCP8.5
CCLM4-8-17	CNRM-CM5	r1i1p1	RCP4.5, RCP8.5
	EC-EARTH	r12i1p1	RCP4.5, RCP8.5
	MPI-ESM-LR	r1i1p1	RCP4.5, RCP8.5
HIRHAM5	EC-EARTH	r3i1p1	RCP4.5, RCP8.5
RACMO22E	EC-EARTH	r1i1p1	RCP4.5, RCP8.5
RCA4	CNRM-CM5	r1i1p1	RCP4.5, RCP8.5
	EC-EARTH	r12i1p1	RCP2.6, RCP4.5, RCP8.5
	HadGEM2-ES	r1i1p1	RCP4.5, RCP8.5
	IPSL-CM5A-MR	r1i1p1	RCP4.5, RCP8.5
	MPI-ESM-LR	r1i1p1	RCP4.5, RCP8.5

2.3. RCM bias correction

The climate simulated by numerical models shows systematic deviations from reality (true observed climate), which limits their applicability for impact models. Therefore, climate model outputs have to be post-processed to match the observed climate (Christensen et al. 2008, Maraun 2013). One common way of dealing with model errors in climate change impact studies is the delta change approach (Räty et al. 2014). Besides the delta approach, more sophisticated RCM post-processing methods have been proposed and evaluated, and their list is given in e.g. Themessl et al. (2012). These approaches belong to the family of model output statistics (MOS), a concept developed in weather forecasting and now commonly used in climate science (Maraun et al. 2010).

In a comprehensive intercomparison study of 7 empirical-statistical downscaling and error correction methods (DECMs) for daily precipitation from a 10 km resolved RCM, Themessl et al. (2011) conclude that QM outperforms all other investigated DECMs. In addition, they also show — at least for daily precipitation linear regression approaches, although optimized by predictor transformation and randomization — that RCM error characteristics are not systematically reduced by these methods. The distribution mapping method was recommended as the best-performing correction method by Teutschbein & Seibert (2013), where various bias correction techniques were compared (delta change correction, linear transformation, local intensity scaling [LOCI], power transformation, variance scaling, distribution mapping), finding that QM was best able to cope with non-stationary conditions.

Based on the those results, QM was chosen for the bias correction purposes in the present work. Our method originates from an approach described in e.g. Déqué (2007). It is applied as parameter-free (using empirical cumulative density distributions, rather than theoretical cumulative distribution functions). An empirical method is recommended over the parametric one, since the latter is not robust enough, given the limited length of the time period (Gutjahr & Heinemann 2013), and also, using theoretical distribution, QM becomes less flexible in its application to different parameters and regions as *a priori* information about the shape of the probability density functions is needed (Themessl et al. 2012).

Based on validation of the QM method within model control runs, we further adopted some settings that best suit the purpose of bias correction of various meteorological elements (including precipitation, which is difficult to handle on both distribution tails). For example, the final corrections (obtained for individual percentiles) were smoothed with a low-pass Gaussian filter (over 20 percentiles) to reduce noise in the individual percentile values. Each month was treated separately and a time window including the previous and following month was applied: thus,

Table 2. Model bias for air temperature (°C) as difference between original (uncorrected) model and reality, areal averages for different altitudes

Altitude (m)	CNRM-CM5_ ALADIN	EC-EARTH_R ACMO	EC-EARTH_ RCA	HadGEM2-ES_ RCA	MPI-ESM-LR_ CCLM
0–300	–2	–2.46	–1.81	–0.3	–0.7
300–600	–1.92	–2.21	–1.76	–0.24	–0.66
600–900	–1.39	–1.92	–1.6	–0.06	–0.43
900–1200	–0.51	–1.42	–1.19	0.34	0.18
Above 1200	0.37	–0.4	–0.32	1.23	1.23
Whole Czech Republic	–1.83	–2.21	–1.74	–0.21	–0.62

we get rid of the steps between the individual months and at the same time comply with different bias sizes in different parts of a year. To preserve reasonable extrapolated values (in the tails of the distribution), changes between individual values of the highest (or lowest) percentiles (likely to be very noisy) were limited to certain values (such as a coefficient of 1.5 for maximal extrapolated value compared to the last percentile, and a ratio of 3.0 as a change between the last percentiles values).

The QM method was applied on a daily basis and for each grid cell/location separately. To be suitable for impact studies where station data are preferred (and because these data are also available for the current climate), the correction/localization was done by finding the nearest grid points for a given location (station) and applying the correction several times, 5 times in the case of precipitation to 10 times in the case of other elements. In practice, the first (nearest) neighbor was applied as the final correction, but the other results were used to evaluate uncertainty coming from the correction process.

We call this correction method DAP (distribution adjusting by percentiles), simply to distinguish it from other QM methods, since it differs by the above-mentioned parameters settings. For the data processing, the software packages AnClim (Štěpánek 2008), LoadData and ProClimDB (Štěpánek 2010) were created. They offer a complex solution, from tools for handling databases, through data quality control, to homogenization of time series, as well as time series analyses, extreme value evaluation and model output verification and correction. The software is available on the webpage www.climahom.eu.

3. RESULTS

3.1. Bias in model data

Over the Czech Republic, we found bias patterns similar to those discussed in Kotlarski et al. (2014) and briefly described in Section 4 (the present study). In this subsection we summarize our main findings for some of the meteorological variables influencing evapotranspiration and drought occurrence.

Biases between projection and reality were analyzed, in detail, mainly for 5 selected experiments. A control run was compared with the real meteorological data. For spatial comparison, individual maps with values interpolated into 500 m resolution were obtained for each data source (stations or model grid points).

Air temperature is underestimated by uncorrected models (Table 2). The greatest differences were observed for the experiment EC-EARTH_RACMO for which the average annual temperature is about 2.2°C lower than reality. In spring, it is underestimated by about 4°C. The lowest biases were achieved by HadGEM2-ES_RCA, where the difference from reality is only –0.2°C. Overall, for all 5 selected experiments, the worst results were found in the spring season (Fig. 1).

A bias analysis was also performed in regard to different altitudes (since model orography differs from actual orography). We chose 5 levels: up to 300 m, 301–600 m, 601–900 m, 901–1200 m and >1200 m. The results are surprising. The highest model biases are observed within the lower altitudes (up to 300 m); in contrast, the model simulations for mountain regions are relatively non-biased. Two of the experiments are different, HadGEM2-ES_RCA and MPI-ESM-LR_CCLM, which have quite accurate results. These 2 experiments did, however, overestimate the temperature in the highest mountains (Fig. 2).

For a selected experiment (EC-EARTH_RACMO22, whose values are, after bias correction, in the middle of a value spread of other models), we tested whether the bias is constant or changes over time. Spatial biases for different decades of the control run are shown in Fig. S1 (in the Supplement at www.int-res.com/articles/suppl/c070p179_supp.pdf). The biggest underestimation is observed in the case of older values (first decades of the control run period). A bias of about

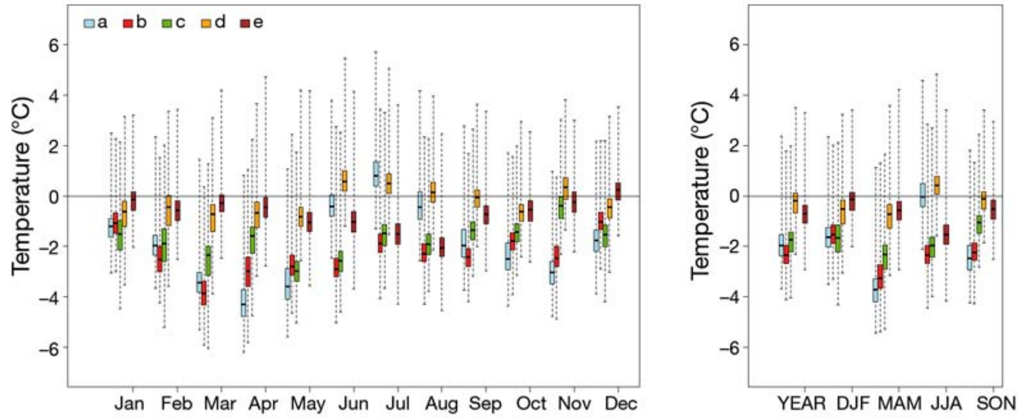

Fig. 1. Temperature bias, difference between original (uncorrected) model and reality, for 5 experiments, by month (left panel) and by season (right panel): (a) CNRM-CM5_ALADIN (1961–2005), (b) EC-EARTH_RACMO (1961–2005), (c) EC-EARTH_RCA (1970–2005), (d) HadGEM2-ES_RCA (1970–2005), (e) MPI-ESM-LR_CCLM (1961–2005). Boxplots — central line: median; box: interquartile range (IQR); whiskers: outlier limits (1.5 × the IQR)

−2.5°C is found for the period 1961–1970 (Table 3), while a bias of only −2°C is found in the last years of the control run (1991–2005). This means that the modeled air temperature increase in the current climate is more rapid than it is in reality.

Precipitation sums are overestimated by the uncorrected model outputs (Fig. 3). From the 5 selected experiments, the wettest conditions are modeled by MPI-ESM-LR_CCLM; its average daily precipitation is higher by about 0.65 mm (Table 4). In contrast, almost bias-free precipitations are simulated by the EC-EARTH_RACMO experiment. The remaining 3 models overestimated the precipitation by about 0.35 mm d^{-1}. Spring is wetter compared to the other seasons.

More precipitation is simulated for the Bohemia (west) region than for Moravia (east) (Fig. 4). Spatial differences of biases by altitude are not as evident as in the case of the air temperature. The precipitation sums in lowlands are overestimated, especially by the CNRM-CM5_ALADIN and MPI-ESM-LR_CCLM experiments (Table 4). Mountain regions are modeled with a higher amount of precipitation in the case of the EC-EARTH_RCA and HadGEM2-ES_RCA experiments. In contrast, the EC-EARTH_RACMO experiment predicts lower precipitation sums than the reality for altitudes above 600 m.

Table 3. Model bias for air temperature (°C) as difference between original (uncorrected) EC-EARTH_RACMO22 and reality, areal averages for the Czech Republic

Period	Average	Minimum	Maximum
1961–1970	−2.46	−4.18	0.38
1971–1980	−2.27	−4.11	0.66
1981–1990	−2.1	−3.89	0.84
1991–2000	−2.09	−3.8	0.97
2001–2005	−1.9	−3.69	1.28

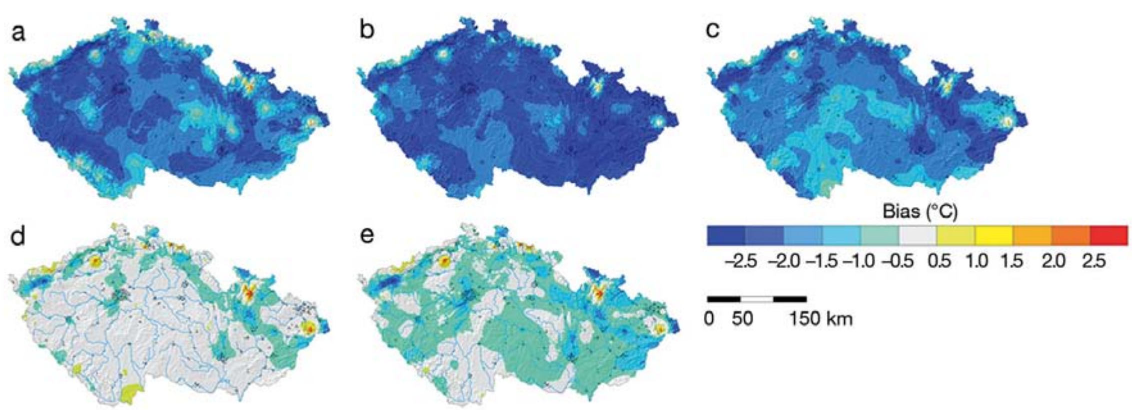

Fig. 2. Temperature spatial bias for 5 experiments across the Czech Republic: (a) CNRM-CM5_ALADIN (1961–2005), (b) EC-EARTH_RACMO (1961–2005), (c) EC-EARTH_RCA (1970–2005), (d) HadGEM2-ES_RCA (1970–2005), (e) MPI-ESM-LR_CCLM (1961–2005)

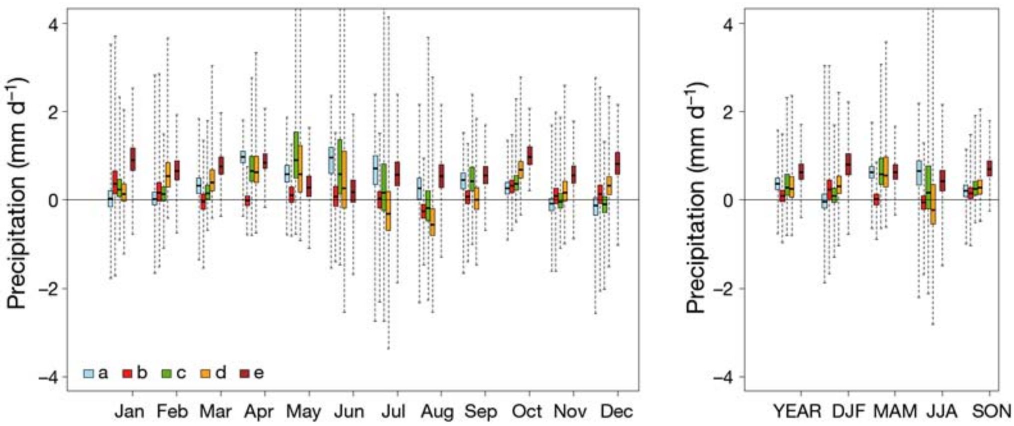

Fig. 3. Precipitation bias, difference of original (uncorrected) model and reality, for 5 experiments, by month (left panel) and by season (right panel): (a) CNRM-CM5_ALADIN (1961–2005), (b) EC-EARTH_RACMO (1961–2005), (c) EC-EARTH_RCA (1970–2005), (d) HadGEM2-ES_RCA (1970–2005), (e) MPI-ESM-LR_CCLM (1961–2005). Boxplots — central line: median; box: interquartile range (IQR); whiskers: outlier limits (1.5 × the IQR)

The number of days with precipitation ≥1 mm are overestimated by RCMs (Fig. 5, left), the same as with precipitation sums. The overestimation ends with number of days with ≥10 mm (with underestimation for JJA and overestimation for MAM). For 20 mm, JJA and DJF are underestimated (resulting in the whole year being underestimated). For 50 mm, all seasons are underestimated (more JJA and DJF). Some examples are given in the Section 3.2.

The initially large differences among the individual experiments (as seen e.g. on Fig. 5) become more consistent after the bias correction. From this, we can conclude that for impact studies in which absolute values play an important role (compared to climatological analysis, which are usually based only on value changes between various periods), bias correction is necessary to obtain meaningful results comparable with the current station (baseline) period.

3.2. Future climate for the Czech Republic

We analyse future climate in this study based on bias-corrected data. To comprehensibly estimate change in climate for the whole area of the Czech Republic, simple means over all possible grid points were calculated (in the Discussion section, we give information about comparison of various ways of areal averaging). For time series analysis, the values of the individual experiments were smoothed with a 10 yr low-pass Gaussian filter to get rid of incomparable individual yearly values. To better assess possible change based on all the available experiments, an ensemble mean was created from the individual corrected model outputs (see Figs. S2 & S3 in the Supplement), and is further used in this study.

Based on all available experiments, air temperature in the Czech Republic will increase by 2.0°C annually by the end of the 21st century using RCP4.5, or by 4.1°C in the case of the RCP8.5 scenario compared to the reference period (1981–2010). As can be seen in Fig. S2 (in the Supplement), the air temperature will increase similarly to the year 2050 irrespective of the emissions scenarios. The temperature will be about 1°C higher in the period 2021–2040 compared to 1981–2010. We see growing differences between emissions scenarios after the year 2050. Temperatures predicted by RCP8.5 rise steeply, and,

Table 4. Model bias for precipitation (mm d^{-1}) as difference between original (uncorrected) model and reality, areal averages for different altitudes

Altitude (m)	CNRM-CM5_ ALADIN	EC-EARTH_ RACMO	EC-EARTH_ RCA	HadGEM2-ES_ RCA	MPI-ESM-LR_ CCLM
0–300	0.41	0.11	0.18	0.12	0.51
300–600	0.36	0.07	0.33	0.29	0.68
600–900	0.22	−0.01	0.68	0.67	0.78
900–1200	0	−0.25	0.97	0.97	0.66
Above 1200	−0.1	−0.48	0.98	0.98	0.27
Whole Czech Republic	0.34	0.06	0.36	0.32	0.65

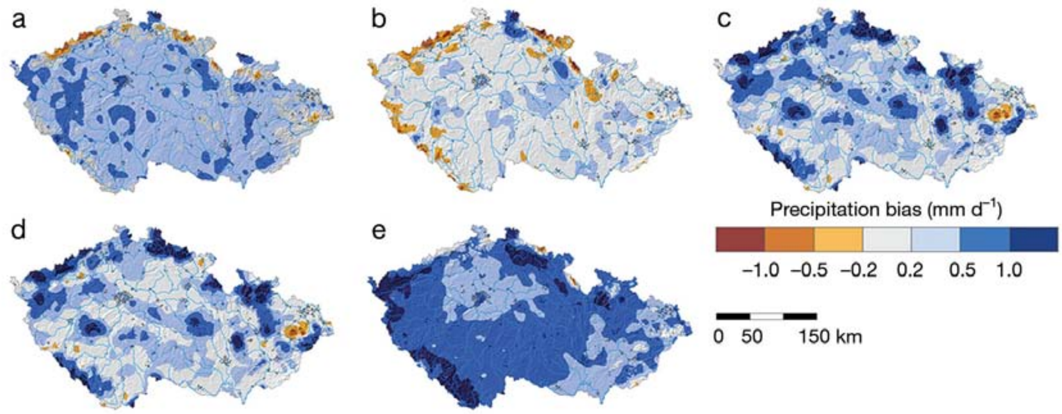

Fig. 4. Precipitation spatial bias for 5 experiments across the Czech Republic: (a) CNRM-CM5_ALADIN (1961–2005), (b) EC-EARTH_RACMO (1961–2005), (c) EC-EARTH_RCA (1970–2005), (d) HadGEM2-ES_RCA (1970–2005), (e) MPI-ESM-LR_CCLM (1961–2005)

for example, the HadGEM2-ES_RCA experiment (having one of the highest trend values) gives, by the end of this century, climate warming of about 5°C compared with the reference period 1981–2010 (Fig. S4 in the Supplement). In contrast, RCP4.5 maintains a practically stable climate from 2061, with a temperature higher by about 2°C compared to the present. According to RCP2.6, the trend will even become negative (and still statistically significant, $p = 0.05$) by the end of the 21st century. Of the individual seasons, the highest increase in air temperature is modeled for winter. By the end of the 21st century, winter temperature should be higher by about 4.9°C (RCP8.5) (Table 5).

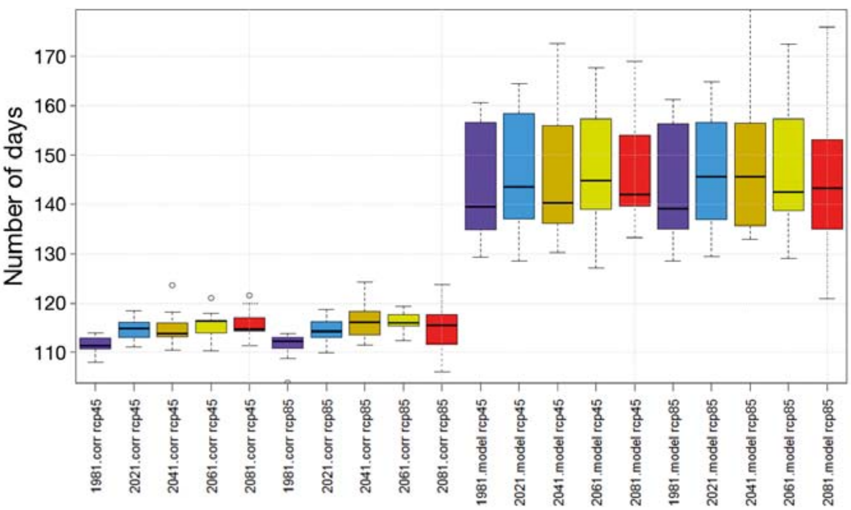

Fig. 5. Boxplots over all 11 experiments for number of days with precipitation ≥1.0 mm (corr: bias-corrected model outputs; model: original model values), for 30 yr (1981–2010) and future 20 yr periods (beginning of periods given on *x*-axis), and 2 scenarios: RCP4.5 and RCP8.5. Boxplots — central line: median; box: interquartile range (IQR); whiskers: outlier limits (1.5 × the IQR); small circles: outlier values (values beyond the outliers limit). Colours show different decades

Maximum temperature is to increase mainly in winter, and the least in spring. Absolute maxima reach values of 2.3°C for the year and 3.4°C for winter (RCP4.5) and 4.6°C for the year and 6.0°C for winter (RCP8.5), respectively. Minima are expected to increase even more, again mainly in winter (4.5°C) and then in spring (3.5°C) for RCP4.5 and by 8.3°C (winter) and 8.3°C (spring) for RCP8.5. The minima increase in annual values is similar to those of winter.

Precipitation sums are distinguished by high spatial and temporal variability. This is determined mainly by atmospheric circulation; the amount of precipitation depends on the type of synoptic situation. The complex orography of the Czech Republic has a significant influence as well. Long-term changes in rainfall are not detected. The annual variability is stronger than the trend.

Projection of the precipitation sums based on all 11 experiments shows a slight increase of about 7–13% for RCP4.5 and 6–16% for RCP8.5. Higher amounts of precipitation are observed by the end of the 21st century (Fig. S3 in the Supplement). A statistically significant trend (8.3 mm per 10 yr, $p = 0.05$) is found for RCP4.5 for the period 2061–2100. The RCP8.5 emissions scenarios give a statistically significant trend of 16 mm per 10 yr in the period 2021–2060 and 13 mm per 10 yr in 2061–2100. RCP2.6 supposes an increase in precipitation only in the first period, 2021–2060 (14.7 mm per 10 yr). The biggest difference is observed for winter precipitation, where the increase could be up by 35% by the end of the 21st century (Table 6). In con-

Table 5. Difference in air temperature (°C) calculated from 11 experiments for individual periods and seasons (DJF: winter, MAM: spring, JJA: summer, SON: autumn) compared with reference period 1981–2010

Emissions scenario	Period	Year	DJF	MAM	JJA	SON
RCP4.5	2021–2040	0.9	1.1	0.8	0.7	0.8
	2041–2060	1.3	1.4	1.3	1.3	1.1
	2061–2080	1.8	2.2	1.8	1.7	1.5
	2081–2100	2.0	2.4	1.9	1.7	1.7
RCP8.5	2021–2040	1.0	1.1	1.1	0.9	0.9
	2041–2060	1.8	2.1	1.8	1.6	1.8
	2061–2080	2.8	3.3	2.8	2.6	2.6
	2081–2100	4.1	4.9	3.8	3.8	3.9

Table 6. Ratio of precipitation sums calculated from 11 experiments for individual periods and seasons (DJF: winter, MAM: spring, JJA: summer, SON: autumn) compared with reference period 1981–2010 (100%)

Emissions scenario	Period	Year	DJF	MAM	JJA	SON
RCP4.5	2021–2040	106.6	109.3	105.9	105.0	107.4
	2041–2060	107.0	110.5	111.5	100.9	108.7
	2061–2080	110.3	115.9	115.1	104.4	109.5
	2081–2100	112.7	114.0	119.3	107.5	112.4
RCP8.5	2021–2040	106.5	110.6	109.3	103.4	106.2
	2041–2060	112.2	120.4	115.4	105.8	112.3
	2061–2080	113.7	126.1	118.7	104.3	113.8
	2081–2100	116.3	135.1	123.5	102.4	115.9

trast, the smallest change can be expected in summer precipitation.

As can be seen in Fig. S5 (in the Supplement), the changes in the precipitation sums are not spatially consistent. Again using the example of the Had GEM2-ES_RCA experiment, it is shown that the smallest increase should occur in South Moravia, which is among the most important agricultural regions. The differences between the periods and the emissions scenarios are large. Quite a large difference can be observed between the periods 2041–2060 (RCP4.5) and 2061–2080 (RCP8.5). In the first case, similar precipitation sums as for the present are predicted, but with the latter case, significantly higher precipitation sums of >20% are modeled.

During the last decade (in the current climate in the Czech Republic), we have observed a change in precipitation patterns but with no similar change in the average. To capture such behavior, other precipitation characteristics also need to be investigated. We analyzed the number of days with precipitation equal or higher than 1, 10, 20 and 50 mm. No statistically significant trends (for $p = 0.05$) are observed for the number of days with 1 mm and higher, but for 10, 20 or 50 mm, positive statistically significant ($p = 0.05$) linear trends were found. The increase of these intense rainfalls is mainly predicted by emissions scenario RCP8.5. For example, the number of days above 10 mm will increase in RCP8.5 by about 0.6 d per 10 yr in the period 2021–2060 and by about 0.5 d per 10 yr in 2061–2100. As can be seen in Table 7, the differences between the individual models are not so large. In the future, there will be about 1 additional day of intense rainfall of ≥20 mm compared to the present.

Table 7. Number of days with precipitation >20 mm for 3 experiments

Period	RCP	EC-EARTH_ RACMO	HadGEM2-ES_ RCA	MPI-ESM-LR_ CCLM	Czech Republic
1981–2010					4.6
2021–2040	RCP4.5	4.7	5.2	5.5	
	RCP8.5	4.5	5.4	5.0	
2081–2100	RCP4.5	5.3	5.8	5.7	
	RCP8.5	6.2	5.9	5.9	

3.3. Drought in the future

Drought is becoming a very important phenomenon in our region, as it has been more and more frequent in recent years (drought occurred in the Czech Republic in 2012, 2013, 2014 and 2015). The reason for the droughts in the Czech Republic is below-normal amounts of precipitation and/or very high temperatures. The new Euro-CORDEX experiments predict slightly higher sums of precipitation, but, in connection with increased air temperature and a change in the precipitation pattern (change in rain frequency), we can expect an increase in evapotranspiration; thus, conditions will likely favour drought more in the future (Zahradníček et al. 2015). The drought in 2015 was one of the worst in the last 20 yr, and can be considered an example of how such periods could look in the future. The drought in 2015 started inconspicuously and then quickly escalated dramatically due to the high temperatures during the summer months (a record number of tropical days). This caused a significant drought across the whole country. It is for this reason we focus mainly on temperature extremes in this section.

Several consecutive days with high temperatures cause heat waves, which have the potential to deepen the drought. As a threshold for defining a heat wave for our analysis, we used 3 d with temperatures above 30°C. The results are presented in the example of the 3 experiment outputs (Table S1 in the Supplement). In the 1981–2010 period, 3.7 d yr^{-1} with heat waves occurred. No significant difference between RCP4.5 and RCP8.5 is predicted for the near future. The EC-EARTH_RACMO experiment gives an even higher number of days in heat waves for RCP4.5. In any case, the number of days nearly doubles. The large increase in the number of such days and also the increase in the difference between both emissions scenarios occur during the last period of 2081–2100. Compared to the other 2 experiments, HadGEM2-ES_RCA models a significantly higher number of days in heat waves. This experiment predicts 1 mo (33 d) in heat waves for emissions scenario RCP8.5, which is 10 times more than in the baseline period.

A tropical day occurs when the maximum air temperature reaches or exceeds the limit of 30°C. The number of tropical days occurs only a few times a year, but, in the last 2 decades, the number has significantly increased. Such days can be described as uncomfortable for both people and nature. It causes an increase in evapotranspiration and quicker drying of the landscape. If we compare the number of tropical days in the 1960s with the beginning of the 21st century, it is occurring almost twice as often. The number of tropical days has increased mainly in the Moravian lowlands and lowlands around the river Elbe, which are places of importance for agricultural activity (Rožnovský & Zahradníček 2014).

In the first future period (2021–2040), we do not observe a significant increase in the number of tropical days. The values correspond with those in the 2000s and 2010s. Greater variance in the projections between the models and even different emissions scenarios is observed for the end of the century. Emissions scenario RCP4.5 predicts twice the number of tropical days than observed in the period 1981–2010. The EC-EARTH_RACMO experiment predicts about 20% fewer tropical days than the other 2 models (Table S2 in the Supplement). Big differences are modeled by RCP8.5 (Fig. 6). Model HadGEM2-ES_RCA calculated about 50% higher number of tropical days than the other studied experiments. Such a significant increase in these hot days may cause major problems, not only in terms of drought, but also in the population's health, the energy sector, etc. Interestingly, in 2015, we measured 35–40 tropical days in the Czech Republic, which was higher than the projections of most models for the end of the 21st century.

4. DISCUSSION AND COMPARISON WITH PREVIOUS RCM RESULTS

As mentioned in the Introduction and Section 2.3, the models suffer from biases. Given our knowledge about physical processes in the atmosphere, computational possibilities, etc., results within the same group of models usually have similar problems. Kotlarski et al. (2014) summarizes some of these biases evaluated from the ERA-Interim-driven (Dee et al. 2011) Euro-CORDEX RCMs. They point to a predominant cold and wet bias in most seasons and over most parts of Europe and a warm and dry summer bias over southern and southeastern Europe. The other well-known issue with RCMs is, for instance, systematic underestimation of the dry-day frequency and, on the other hand, overestimation of light (between 0.1 and 1 mm d^{-1}) and heavy precipitation frequency (Themessl et al. 2012). As has been shown in Section 3, we confirm similar bias patterns in our results for the Czech Republic.

In Section 3.2, we presented results based on bias-corrected results and spatial aggregation over all available grid-points. To answer a possible question about the role of location density in the estimation of such an areal average for the Czech Republic, we analyzed averaging based on several versions of input datasets. The datasets are: the simple average of the values of 523 grid points of Euro-CORDEX simulations, and averages over 268 (air temperature) in respect to 787 (precipitation) station locations. We compared several characteristics for a 30 yr period (1981–2010): air temperature, number of tropical days, precipitation sum and number of days with precipitation ≥1 mm. As a reference dataset, we used an areal average based on a 500 m resolution grid layer obtained through geostatistical interpolation, namely, regression kriging applying the dependence of input station data (268 for temperature, 787 for precipitation) on altitude, longitude, slope, exposition and roughness. When comparing the results from these 4 data sources, they are practically the same, with the differences being a maximum of 0.1°C for air temperature and 4% in the case of precipitation or number of days. To conclude, the density of the Euro-CORDEX grid points does not have much effect on the results; it is comparable with other ver-

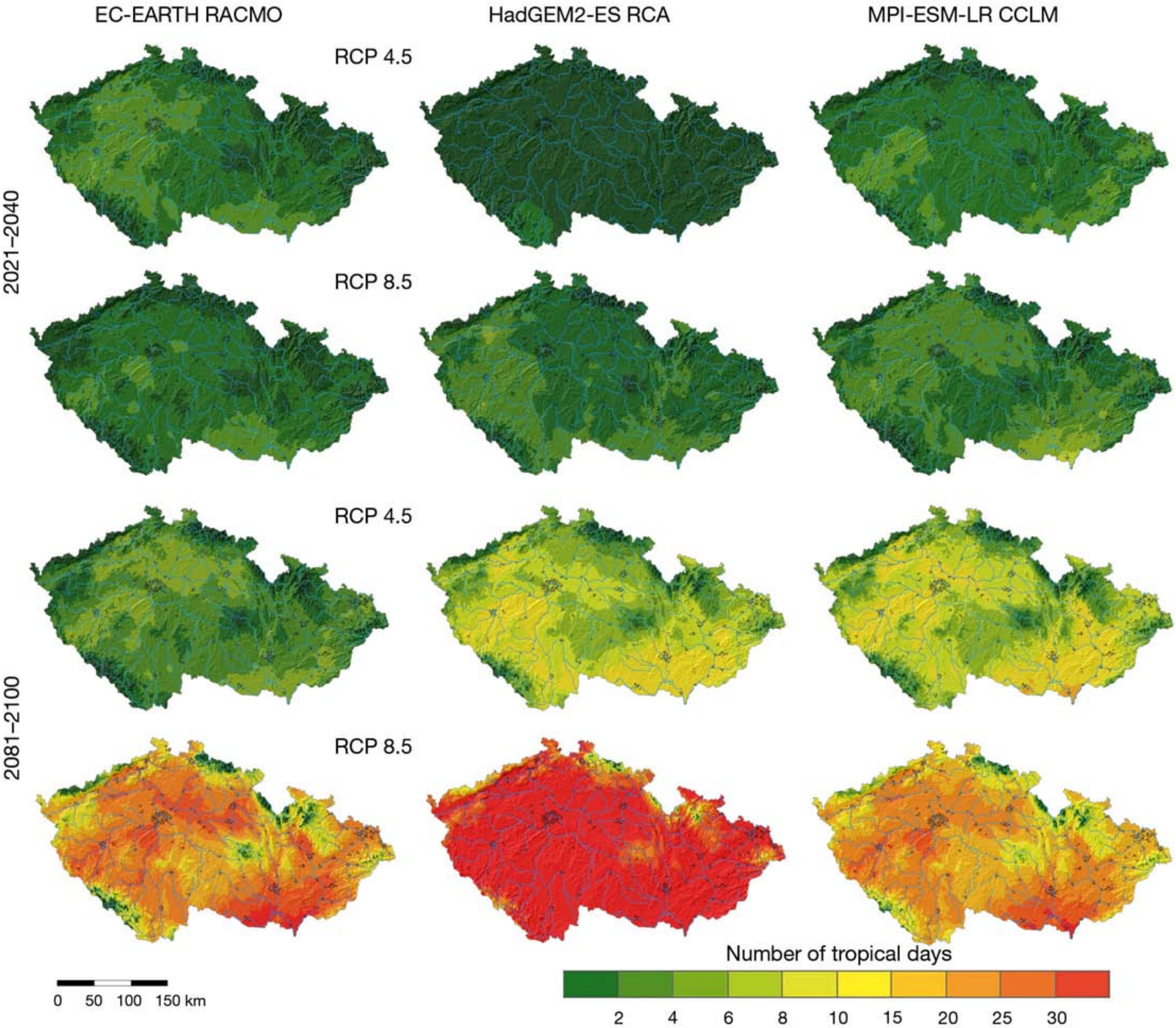

Fig. 6. Spatial differences in number of tropical days between future periods (2021–2040 and 2081–2100) and the present (1981–2010), for 3 experiments (EC-EARTH_RACMO, HadGEM2-ES_RCA, and MPI-ESM-LR_CCLM), and 2 scenarios (RCP4.5 and RCP8.5) across the Czech Republic

sions of national mean average with a different number of points used for the calculation.

The previous studies of future climate in the Czech Republic were mostly based on 3 simulations of 2 RCMs: ALADIN-Climate/CZ in 10 km and 25 km resolutions (ALADIN-10 and ALADIN-25), and RegCM3 in 10 km resolution (RegCM-10). Since these results are still widely used (at least within the Czech Republic), we decided to discuss the differences between the new findings presented in Section 3 of the present paper and the previous studies. Both simulations at 10 km resolution (ALADIN-10 and RegCM-10) were originally prepared within EU FP6 CECILIA (www.cecilia-eu.org/), covered 2 future periods, 2021–2050 and 2071–2100, and followed the path of greenhouse gas emissions according to the IPCC A1B (SRES) emissions scenario. The same emissions scenario was also chosen for the ALADIN-25 km transient simulation, covering the period 1961–2100. The ALADIN-Climate/CZ simulations were directly driven by the stretched version of the ARPEGE GCM. The GCM stretching technique increases the resolution of a GCM over a selected region (to ca. 50 km in the case of ARPEGE) and reduces it on the opposite side of the globe. Thus, GCM stretching reduces the jump in spatial resolution between the driving GCM and the downscaling RCM. In the case of the RegCM-10 experiment, a double nesting from ECHAM GCM via 25 km RegCM3 simulation was used. According to all 3 experiments, air temperature will climb in the future. In the near future, 2021–2050, air temperature in the Czech Republic will rise by about 1.2–1.5°C. This increase is within the range of warming calculated for the RCP4.5 and RCP8.5 emissions scenarios from the Euro-CORDEX models. For the periods 2021–2041 and 2041–2061, the Euro-CORDEX models expect a warming of 0.9–1.3°C for RCP4.5 and 1.0–1.8°C for RCP8.5. For the last 30 yr of the 21st century (2071–2100), older experiments (with the A1B scenario) indicated an air temperature rise of 3.2–3.3°C. This temperature change is close to what simulations based on the RCP8.5 scenario expect (2.8–4.1°C). RCP4.5-based simulations envisage rather milder warming (1.8–2.0°C). The older and newer generations of RCM experiments differ in seasonal temperature change. A slightly higher increase in the temperature is predicted in winter and summer by ALADIN-10 in the period 2021–2050. In contrast, RegCM-10 calculated the change in temperatures during the summer to be significantly smaller than in other seasons. The ALADIN-25 model gives a relatively similar increase for all seasons; the only lower trend is predicted for spring. Both models based on ALADIN-Climate/CZ calculated a higher increase in the temperatures in summer for the distant future (2071–2100). In contrast, RegCM-10 predicts a higher increase in the winter temperature for the period 2071–2100. For both emissions scenarios, the climate models based on Euro-CORDEX calculated a higher growth rate in air temperatures in the winter season for both the near and distant future. The changes in the seasons' air temperatures calculated by Euro-CORDEX are probably closest to the projections of the former RegCM-10 model.

Further, previous experiments calculated a slightly higher annual amount of precipitation on average for the whole Czech Republic for the period 2021–2050. The increase in rainfall was modeled between 4 and 7%. This is relatively consistent with the new results, which predict an increase in annual precipitation of between 7 and 12%. Differences are observed in the projections for seasonal changes. A significant decrease in winter precipitation was indicated by the ALADIN-10 and ALADIN-25 experiments. The decrease in winter precipitation was about 15%. Similar phenomena occurred in the present climate, with the last 5 winters having a lower amount of precipitation and snow. A decrease in winter precipitation is not modeled by RegCM-10, however. The new results of the Euro-CORDEX experiments do not show a decrease in winter precipitation; on the contrary, they indicate an amount higher by about 9–20%. Previous experiments expected an increase of about 20% in autumn precipitation and about 10% for summer. Conversely, the new results show only a slight increase in summer precipitation, which could be very dangerous in connection with the higher temperature (significantly higher evaporation). Autumn precipitation is predicted by the new models to be higher by only about 7–12%, which is lower than the assumption of previous experiments. The differences between the previous and current versions of the climate models are pronounced in the case of precipitation in the distant future (2071–2100). ALADIN-10 and ALADIN-25 predicted slight decreases in annual precipitation (2–3%). Conversely, new models in accordance with older model outputs RegCM-10 gives annual precipitation increasing by about 10–16%. The ALADIN-Climate/CZ model (ALADIN-10, ALADIN-25), unlike during the first period, did not predict such decline in winter precipitation (4%), while there is a visible modeled decline in summer precipitation (10–12%). The RegCM-10 models an increase in winter, autumn and spring rainfall of up to 20%, but does not predict any significant change in summer precipitation. The outputs of the new experiments predict an ongoing increase in winter precipitation in the distant future, as opposed to the older model outputs by ALADIN-Climate/CZ. Winter precipitation is modeled to be higher by an amount of about 26–35%, especially for emissions scenario RCP8.5. A decline in summer precipitation is not observed in the new model outputs.

5. CONCLUSIONS

In the case of the original (uncorrected) model outputs, the differences between the individual models are large. After bias correction, the absolute values for future climate became more stable and suitable for ongoing analysis within impact studies.

All 11 available Euro-CORDEX experiments were bias-corrected. Most experiments underestimated temperature by up to 2.5°C. Conversely, the increase in air temperature is greater than in reality (for the control run). The found biases are not spatially identical; they vary significantly with altitude. The precipitation sums are overestimated by uncorrected experiments by up to 0.65 mm d^{-1}, but the differences between models are large. The spatial differences of the model biases are not the same for all the experiments, and their analysis by altitude level does not show clear results. Uncorrected RCM outputs would be useless for an impact study of a regional character, since uncorrected RCMs do not capture the conditions for the Czech Republic well.

Air temperature will increase similarly up to 2050 irrespective of the emissions scenario. Temperature will be higher by about 1°C in the period 2021–2040 compared to 1981–2010. After the year 2050, we observe growing differences between the emissions scenarios. For the whole Czech Republic, based on all 11 available experiments, air temperature will increase by 2.0°C (RCP4.5) to 4.1°C (RCP8.5) for the whole year and for the end of the 21st century compared to the reference period (1981–2010). In contrast, RCP2.6 predicts the halting of growth in air temperature by 2060, and even indicates a slow decline. Looking at individual seasons, the highest increase in temperature is modeled in winter. The projections for precipitation gives a slight increase of about 7% (2021–2040) to 13% (the end of the 21st century) for RCP4.5, and 6% to 16% for RCP8.5. The changes are mostly statistically significant ($p = 0.05$). A stronger trend can be found in the outputs for emissions scenario RCP8.5. The biggest difference is observed in winter precipitation, which could end up with an increase of 35% by the end of the 21st century, whereas the smallest change can be expected in summer precipitation.

Climate change is also reflected in the climatic indices. The experiments predict an increase in the number of tropical days, which is also manifested in the growing number of heat waves. Alarming results by the end of the 21st century are predicated mainly with emissions scenario RCP8.5. These results are not unrealistic, as a similar number of tropical days as predicted by RCP8.5 for the period of 2081–2100 occurred in the year 2015 in the Czech Republic. Higher temperatures can lead to more intense rains from thunderstorms. Significant trends were found in the number of days with precipitation of 10, 20 and 50 mm and higher.

Considering the simulated changes in air temperature and changes in the precipitation regime for the future, we can expect more frequent and severe drought occurrences. In this article, the conclusions are based solely on the climate variables that induce drought, but special drought indices were calculated as well, and we will follow up with articles devoted to their analysis.

Acknowledgements. This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant no. LO1415. We further acknowledge these projects: P.Š.: project no. LD14043 'Validation and correction of RCMs outputs in the area of the Czech Republic for purposes of impact studies' (Ministry of Education, Youth and Sports, Czech Republic); and project no. 14-12262S (Czech Science Foundation). P.Z. was supported by the project 'Hydrometeorological extremes in Southern Moravia derived from documentary evidence' (Czech Science Foundation, no. 13-19831S), and M.T. was supported by project no. 16-16549S 'Soil moisture and run-off droughts in future climate'.

LITERATURE CITED

Brázdil R, Trnka M (eds) (2015) Sucho v českých zemích: minulost, současnost, budoucnost (Drought in the Czech Lands: past, present, future). Centrum výzkumu globální změny Akademie věd České republiky, v.v.i., Brno

Brázdil R, Trnka M, Mikšovský J, Řezníčková L, Dobrovolný P (2015) Spring-summer droughts in the Czech Land in 1805–2012 and their forcings. Int J Climatol 35: 1405–1421

Brázdil R, Raška P, Trnka M, Zahradníček P and others (2016) The disastrous drought of 1947 in the Czech Lands: its course, trigger-factors, impacts and consequences. Clim Res 70:161–178

Christensen JH, Christensen OB (2007) A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Clim Change 81:7–30

Christensen JH, Boberg F, Christensen OB, Lucas-Picher P (2008) On the need for bias correction of regional climate change projections of temperature and precipitation. Geophys Res Lett 35:L20709

Clarke L, Edmonds J, Jacoby H, Pitcher H, Reilly J, Richels R (2007) Scenarios of greenhouse gas emissions and atmospheric concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the US Climate Change Science Program and the Subcommittee on Global Change Research. Office of Biological and Environmental Research, US Department of Energy, Washington, DC

Dee DP, Uppala SM, Simmons AJ, Berrisford P and others (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. QJR Meteorol Soc 137:553–597

Déqué M (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Global Planet Change 57:16–26

Farda A, Déqué M, Somot S, Horányi A, Spiridonov V, Tóth H (2010) Model ALADIN as regional climate model for Central and Eastern Europe. Stud Geophys Geod 54: 313–332

Frei C, Christensen JH, Déqué M, Jacob D, Jones RG, Vidale PL (2003) Daily precipitation statistics in regional climate models: evaluation and intercomparison for the European Alps. J Geophys Res Atmos 108:4124

Giorgi F, Mearns LO (1991) Approaches to the simulation of regional climate change: a review. Rev Geophys 29: 191–216

Giorgi F, Mearns LO (1999) Introduction to special section: regional climate modelling revisited. J Geophys Res Atmos 104:6335–6352

Giorgi F, Jones C, Asrar G (2009) Addressing climate infor-

mation needs at the regional level: the CORDEX framework. WMO Bull 58:175–183
Goodess CM, Aganostopoulou C, Bárdossy A, Frei C (2012) An intercomparison of statistical downscaling methods for Europe and European regions — assessing their performance with respect to extreme temperature and precipitation events and the implications for climate change applications. Tech Rep Climatic Research Unit, Norwich
Gutjahr O, Heinemann G (2013) Comparing precipitation bias correction methods for high-resolution regional climate simulations using COSMO-CLM: effects on extreme values and climate change signal. Theor Appl Climatol 114:511–529
Hanel M, Vizina A, Maca P, Pavlasek J (2012) A multi-model assessment of climate change impact on hydrological regime in the Czech Republic. J Hydrol Hydromech 60: 152–161
Hanel M, Mrkvičkova M, Maca P, Vizina A, Pech P (2013) Evaluation of simple statistical downscaling methods for monthly regional climate model simulations with respect to the estimated changes in runoff in the Czech Republic. Water Resour Manage 27:5261–5279
Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Žalud Z, Možný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric For Meteorol 149: 431–442
Kingston DG, Stagge JH, Tallaksen LM, Hannah DM (2015) European-scale drought: understanding connections between atmospheric circulation and meteorological drought indices. J Clim 28:505–516
Kotlarski S, Keuler K, Christensen OB, Colette A and others (2014) Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci Model Dev 7:1297–1333
Maraun D (2013) Bias correction, quantile mapping and downscaling: revisiting the inflation issue. J Clim 26: 2137–2143
Maraun D, Wetterhall F, Ireson AM, Chandler RE and others (2010) Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. Rev Geophys 48:RG3003
Mearns L, Arritt R, Biner S, Bukovsky MS and others (2012) The North American Regional Climate Change Assessment Program: overview of Phase I results. Bull Am Meteorol Soc 93:1337–1362
Meinshausen M, Smith SJ, Calvin K, Daniel JS and others (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim Change 109: 213–241
Moss R, Babiker M, Brinkman S, Calvo E and others (2008) Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. IPCC, Geneva
Pal JS, Giorgi F, Bi X, Elguindi N and others (2007) Regional climate modeling for the developing world: the ICTP RegCM3 and Reg-CNET. Bull Am Meteorol Soc 88: 1395–1409
Räty O, Räisänen J, Ylhäisi J (2014) Evaluation of delta change and bias correction methods for future daily precipitation: intermodel cross-validation using ENSEMBLES simulations. Clim Dyn 42:2287–2303
Riahi K, Gruebler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Change 74:887–935
Rožnovský J, Zahradníček P (2014) Air temperatures and conditions for recreation. In: Fialová J, Pernicová D (eds) Public recreation and landscape protection — with man hand in hand. Křtiny, 5–6 May 2014, p 27–31
Spinoni J, Naumann G, Vogt J, Barbosa P (2016). Meteorological droughts in Europe: events and impacts—past trends and future projections. Publications Office of the European Union, Luxembourg, EUR 27748 EN, doi:10.2788/450449
Štěpánek P (2008) AnClim — software for time series analysis. Department of Geography, Faculty of Natural Sciences, Masaryk University, Brno. www.climahom.eu/AnClim.html
Štěpánek P (2010) ProClimDB – software for processing climatological datasets. Czech Hydrometeorological Institute, regional office, Brno. www.climahom.eu/ProcData.html
Štěpánek P, Zahradníček P, Skalák P (2009) Data quality control and homogenization of air temperature and precipitation series in the area of the Czech Republic in the period 1961–2007. Adv Sci Res 3:23–26
Štěpánek P, Zahradníček P, Huth R (2011) Interpolation techniques used for data quality control and calculation of technical series: an example of Central European daily time series. Id járás 115:87–98
Štěpánek P, Skalák P, Farda A, Zahradníček P (2012) Climate change in the area of the Czech Republic according to various model simulations. In: Kožnarová V, Sulovská S, Hájková L (eds) Proc BIOCLIMATE 2012 — Bioclimatology of Ecosystems, 29–31 August 2012, Ústi nad Labem, Prague
Štěpánek P, Zahradníček P, Farda A (2013) Experiences with data quality control and homogenization of daily records of various meteorological elements in the Czech Republic in the period 1961–2010. Id járás 117:123–141
Stocker TF, Qin D, Plattner GK, Tignor M and others (eds) (2013) Climate change 2013: the physical science basis. Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
Suklitsch M, Gobiet A, Truhetz H, Awan NK, Göttel H, Jacob D (2010) Error characteristics of high resolution regional climate models over the Alpine area. Clim Dyn 37:377–390
Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498
Teutschbein C, Seibert J (2013) Is bias correction of regional climate model (RCM) simulations possible for non-stationary conditions? Hydrol Earth Syst Sci 17:5061–5077
Themessl MJ, Gobiet A, Leuprecht A (2011) Empirical-statistical downscaling and error correction of daily precipitation from regional climate models. Int J Climatol 31: 1531–1544
Themessl MJ, Gobiet A, Heinrich G (2012) Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. Clim Change 112:449–468
Trnka M, Kysely J, Možny M, Dubrovsky M (2009) Changes in Central-European soil-moisture availability and circulation patterns in 1881–2005. Int J Climatol 29:655–672
Trnka M, Brázdil R, Možný M, Štěpánek P and others (2015) Soil moisture trends in the Czech Republic between 1961 and 2012. Int J Climatol 35:3733–3747
UNISDR (United Nations Secretariat of the International Strategy for Disaster Reduction) (2009) Drought risk

reduction framework and practices. Contributing to the implementation of the Hyogo Framework for Action. UNISDR, Geneva

van der Linden P, Mitchell JFB (2009) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. Tech Rep. Met Office Hadley Centre, Exeter

van Vuuren DP, den Elzen MGJ, Lucas PL, Eickhout B and others (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim Change 81:119–159

van Vuuren DP, Edmonds J, Kainuma M, Riahi K and others (2011) The representative concentration pathways: an overview. Clim Change 109:5–31

Wang Y, Leung LR, McGregor JL, Lee DK, Wang WC, Ding Y, Kimura F (2004) Regional climate modeling: progress, challenges, and prospects. J Meteorol Soc Jpn 82: 1599–1628

Zahradníček P, Trnka M, Brázdil R, Možný M and others (2015) The extreme drought episode of August 2011/ May 2012 in the Czech Republic. Int J Climatol 35: 3335–3352

Editorial responsibility: Michael Hayes (Guest Editor), Lincoln, Nebraska, USA

Submitted: April 4, 2016; Accepted: August 16, 2016
Proofs received from author(s): October 19, 2016

Vol. 70: 195–214, 2016
doi: 10.3354/cr01426

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

Changing regional weather–crop yield relationships across Europe between 1901 and 2012

M. Trnka[1,2,*], J. E. Olesen[3], K. C. Kersebaum[4], R. P. Rötter[5,6], R. Brázdil[1,7], J. Eitzinger[8], S. Jansen[9], A. O. Skjelvåg[10], P. Peltonen-Sainio[5], P. Hlavinka[1], J. Balek[1], H. Eckersten[11], A. Gobin[12], V. Vučeti [13], A. Dalla Marta[14], S. Orlandini[14], V. Alexandrov[15], D. Semerádová[1,2], P. Štěpánek[1], E. Svobodová[1], K. Rajdl[1]

[1]Global Change Research Institute, Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic
[2]Institute of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[3]Department of Agroecology and Environment, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark
[4]Institute for Landscape Systems Analysis, Leibniz-Center of Agricultural Landscape Research, Eberswalder Str. 84, 15374 Müncheberg, Germany
[5]Natural Resources Institute Finland, Viikinkari 4, 00790 Helsinki, Finland
[6]Department of Crop Science, Georg-August-University, 37077 Göttingen, Germany
[7]Institute of Geography, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
[8]Institute of Meteorology, University of Natural Resources and Life Sciences (BOKU), Peter-Jordan Str. 82, 1190 Vienna, Austria
[9]Alterra Wageningen UR, Alterra-Earth observation and environmental informatics group, PO Box 47, 6700AA Wageningen, The Netherlands
[10]Department of Plant and Environmental Sciences, Norwegian University of Life Sciences, PO Box 5003, 1432 Ås, Norway
[11]Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Box 7043, 750 07 Uppsala, Sweden
[12]Flemish Institute for Technological Research, Boeretang 200, 2400 Mol, Belgium
[13]Agrometeorological Department, Meteorological and Hydrological Service, Grič 3, 10000 Zagreb, Croatia
[14]Department of Agrifood Production and Environmental Sciences, University of Florence, Piazzale delle Cascine 18, 50144 Firenze, Italy
[15]National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences, Tzarigradsko shose 66, 1784 Sofia, Bulgaria

ABSTRACT: Europe is, after Asia, the second largest producer of wheat in the world, and provides the largest share of barley. Wheat (and to a similar extent, barley) production in Europe increased by more than 6-fold during the 20th century. During the first half of the 20th century, this was driven by expanding the harvested area. This was followed, from the mid-20th century, by a massive increase in productivity that in many regions has stalled since 2000. However, it remains unclear what role climatic factors have played in these changes. Understanding the net impact of climatic trends over the past century would also aid in our understanding of the potential impact of future climate changes and in assessments of the potential for adaptation across Europe. In this study, we compiled information from several sources on winter wheat and spring barley yields and climatological data from 12 countries/regions covering the period from 1901–2012. The studied area includes the majority of climatic regions in which wheat and barley are grown (from central Italy to Finland). We hypothesized that changes in climatic conditions have led to measurable shifts in climate–yield relationships over the past 112 yr, and that presently grown wheat and barley show a more pronounced response to adverse weather conditions compared to crops from the early 20th century. The results confirm that climate–yield relationships have changed significantly over the period studied, and that in some regions, different predictors have had a greater effect on yields in recent times (between 1991 and 2012) than in previous decades. It is likely that changes in the climate–yield relationship at the local level might be more pronounced than those across the relatively large regions used in this study, as the latter represents aggregations of yields from various agroclimatic and pedoclimatic conditions that may show opposing trends.

KEY WORDS: Climatic trend · Weather–crop yield relationship · Wheat · Barley · Yield trend · Drought · Europe

*Corresponding author: mirek_trnka@yahoo.com

Publisher: Inter-Research · www.int-res.com

1. INTRODUCTION

Land management for food production is a fundamental human activity, supporting the lives of nearly everyone on this planet and providing livelihoods for a large part of the population. At present, more than 1.5 billion ha — approximately 12% of the world's land area — is used for crop production (FAO 2013). Wheat *Triticum aestivum* L., rice *Oryza sativa* L., maize *Zea mays* L., soybeans *Glycine max* (L.) Merr., barley *Hordeum vulgare* L. and sorghum *Sorghum bicolor* (L.) Moench. are the 6 most widely grown crops in the world. The production of these crops accounts for approximately 40% of global cropland area, 55% of non-meat calories and over 70% of animal feed (FAO 2006, 2013). Europe is a close second to Asia in global wheat production and provides the largest share of barley output. During the 20th century, wheat (and to a similar extent barley) production increased in some European regions by more than 6-fold (e.g. Slafer & Rawson 1994). This increase was initially due to an expansion in harvested area that occurred during the first half of the century, which was followed from the 1950s onwards by an increase of ca. 150% in global mean yield per unit land area (Slafer & Rawson 1996). For example, according to Slafer & Peltonen-Sainio (2001), the relative increase in countries such as Canada, Denmark and Finland between the 1950s and the 1990s was up to 83% for barley and 131% for wheat. In northern Europe, significant increases in the share of wheat grown over the cultivated area have been reported; for example, Denmark showed an 8-fold increase between 1971 and 1997 (Olesen et al. 2000). In recent years there has been a stagnation in cereal yields in most parts of Europe, which has been attributed (at least in part) to changes in agricultural policies, input intensities and changes in climatic patterns (Brisson et al. 2010, Finger 2010, Ray et al. 2012)

Limitations due to climatic conditions play an important role in the geographical distribution of crop species in Europe (Ewert et al. 2005, Elsgaard et al. 2012). In Mediterranean countries, cereal yields are limited by water availability, heat stress and the short duration of the grain filling period, while under the continental climate of eastern Europe (eastwards from central Poland), drier conditions and greater fluctuations in annual temperature limit the range of crops that can be grown. The most productive regions in Europe in terms of climate and soils are located in the 'North European lowland plains', which were shaped by the most recent ice age, have a largely Atlantic temperate climate and stretch from southeast England through France, Benelux and Germany and into Poland. There are additional lowland regions (e.g. the Hungarian Plain) that also have quite favorable conditions for crops. From a global perspective, food supply security in Europe is likely to be less influenced by climate change than it may be in other regions because of technologically sophisticated agricultural practices (Brown & Funk 2008), but climate-induced uncertainty (i.e. substantial fluctuations) in food production may result from elevated temperatures and associated changes in the frequency of adverse events in the future (e.g. Trnka et al. 2015). This agrees with the views of Lobell & Burke (2008), and more recently with those of Porter et al. (2014), who proposed that research should focus on crop responses to elevated temperatures to assist in designing cropping systems that are resilient to the effects of global warming. While production for all crops has increased substantially since 1961, temperature and precipitation, spatially weighted for each crop, have also exhibited significant trends (Lobell & Field 2007). For wheat, maize and barley, there is a clearly negative response of global yields to increased temperatures (Porter et al. 2014). Based on their sensitivity and the observed climatic trends, it has been estimated that warming since 1981 has resulted in an annual combined loss of these 3 crops representing approximately 40 Mt (megatons), which represents \$5 billion yr^{-1} as of 2002 prices (Lobell & Field 2007).

Many studies have considered the effects of past climate variability on agriculture (e.g. Calderini & Slafer 1998, Lobell & Field 2007, Finger 2010, Peltonen-Sainio et al. 2010, Lobell et al. 2011, Olesen et al. 2011). However, they have mainly focused on the most recent decades, for which yield and climatological data are relatively easy to obtain. They also relied only on national statistics due to the better availability of long-term datasets (e.g. Calderini & Slafer 1998). Therefore, such studies generally do not consider crop–climate relationships prior to the recent warming that has occurred during the last 3 decades of the 20th century. It is likely that warming (a global increase of 0.74°C between 1906–2005, according to Solomon et al. 2007; or 0.85°C between 1880–2012, according to Stocker et al. 2013) has improved the agroclimatic conditions in many regions of Europe, and hence increased the yields of many crops, but it has also led to less favorable conditions and yield reductions in other regions (e.g. Trnka et al. 2011). It is also possible that such differences would more likely be found within relatively small regions than at a national level, which usually represent the aggregation of yields from various agroclimatic and pedoclimatic conditions, as Trnka et al. (2012) showed in comparing the late 19th century and contemporary district/county level yields in central Europe.

An understanding of the net global impact of climatic trends over the past century would aid in our understanding and quantitative assessment of the potential impact of future climate changes, and in determining future agricultural adaptive potentials. The major challenge in setting up 'historical' studies in Europe stems from the extensive changes that have occurred with respect to borders (both national and regional), state systems and inventory methodologies, which in some regions seriously affect the availability of yield data and to some extent that of climatological data. In addition, socio-economic crises, often caused or followed by wars, have had severe impacts on agricultural production and the productivity of crops. This study compiled several sources of data for 12 European countries/regions (see Fig. 1), aiming to collect the most complete datasets for the 1901–2012 period.

2. DATA AND METHODS

The regions studied are located along a north–south transect of Europe and represent the area between 41° 14′–71° 11′ N and 2° 33′–31° 35′ E (see Fig. 1). The regions cover 1 620 847 km^2 of land (representing 37% of the present area of the EU), 205 866 km^2 of which is arable, corresponding to 19% of the arable land in the EU (see Table 1). Regions were selected according to the following criteria: (1) comparable acreage of arable land (8400–37 200 km^2); (2) targeted crops (barley and wheat) are significant crops in terms of acreage, and are the most common cereal crops in the area; (3) little or no change in the administrative borders of the region during the 1901–2012 period; (4) availability of yield data.

The final selection included 10 countries and 2 regions at the sub-national level (Lower Saxony and Tuscany) (see Fig. 1, Table 1) that represent a broad range of climatic patterns, changing from warm and dry Mediterranean conditions (Tuscany, Croatia) or those of the Black Sea area (Bulgaria) through central Europe (Austria, Czech Republic) to the northern margins of agriculture in Europe (Norway, Finland). Some of the regions belong to traditional farming areas with high yields of both crops (The Netherlands, Belgium, Lower Saxony, Denmark), but other regions are in areas that are close to the northern (Norway, Finland) or southern (Tuscany, Bulgaria, Croatia) extents of the growing areas for both crops in Europe. The final selection also included 3 'eastern' European countries, where production and productivity were enhanced through different mechanisms (former communist countries) than those used in their western counterparts between ~1945 and 1990. The Czech Republic, Croatia and Bulgaria then experienced a period of transition to a free-market economy, which was achieved on joining the EU in 2000.

The monthly minimum, mean and maximum values for air temperature, precipitation, number of precipitation days and drought severity, expressed in terms of the Palmer Z-index and Palmer Drought Severity Index (Palmer 1965), were used as predictors of inter-annual yield variability (for a more detailed description of the Palmer Z-index, see Trnka et al. 2009). The monthly climatological data for each region were based on the CRU TS 3.21 dataset (released on 16 July 2013 at http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts [note that the site requires that one resgisters before accessing the data]; for more details see Mitchell & Jones 2005, Harris et al. 2014). Gridded data with a resolution of 0.5 × 0.5 degrees were based on mean monthly temperatures provided by >4000 weather stations around the world. Using this gridded data, a series of each climate variable was calculated for each region, using the proportion of arable land within the given grid and region as a weighting factor. For individual periods, the proportion of arable land within each grid was derived as the mean value for the given period using Global Cropland Data (1700–2007), which provides revised data described by Ramankutty & Foley (1999) and is available at www.earthstat.org/data-download/. The final series of climate variables are provided in Supplement 1 at www.int-res.com/articles/suppl/c070p195_supp/.

Originally, 6 crops were considered for analysis: wheat, barley, rye *Secale cereale* L., oat *Avena sativa*, potato *Solanum tuberosum* L. and sugar beet *Beta vulgaris* var. *altissima*. However, only wheat (particularly winter wheat) and barley (particularly spring barley) had sufficiently large acreage and yield data available in all regions during the periods analyzed. Therefore, they were selected for analysis in this study (see Supplement 2 at www.int-res.com/articles/suppl/c070p195_supp/). The bulk of the data were provided by individual co-authors of the study from regionally available data, and these were confirmed — when possible — with supranational databases (particularly http://faostat3.fao.org/home/E and http://ec.europa.eu/eurostat/data/database). The final dataset used in the analysis is given in Supplement 2. An extensive search of the relevant archives did not provide any further data for other periods beyond those analyzed in this paper. Although some of the European regions in this study went through significant changes in their borders and even their statehoods (e.g. Czech Republic, Austria or Croatia) during the period examined, the impact of these changes on the methodology of data collection were relatively small. In preparing the analysis, we aimed to select areas where yield data were thought to be available and where changes in regional borders were relatively minor during the 20th century. However, in some cases data could not be obtained. For example, despite prolonged efforts, no yield data in the 1901–1920 period could be found for Tuscany or the Czech Republic. In addition, the war years from 1941–1945 were characterized by a higher number of missing data. Based on the analysis of break-points in the yield series, we defined 3 periods for which relationships between climatic variables and the yields of spring barley and winter wheat were studied: 1901–1950, 1951–1990 and 1991–2012.

Instead of using the annual means for each climatic variable, we defined a key period of the growing season during which barley and wheat are most sensitive to climatic variables. For both crops and the majority of the regions, we found that climatic patterns during April–June played a key role in determining yield, which is in agreement with results of Hlavinka et al. (2009) and Gobin (2012), as well as with the local knowledge of the authors of this study. As there was concern that conditions during July could significantly influence crop yields in cooler European regions (Kristensen et al. 2011), the initial analyses were made for all potential combinations; i.e. all months, all seasons and several month combinations (in total, 24 different time windows). The overall April–June period showed the most stable results with April–July or May–July being notably worse in the central and southern part of the evaluated region. The added value of using the April–July or May–July or June–July period for regions in the north of the regions compared to April–June was very limited and led to the same results. Therefore, the April–June period was selected to decrease the number of assumptions. However, for a consequent analysis (which is planned for those countries where the Nomenclature of Territorial Units for Statistics [NUTS 4] data will be available, at least in past decades) the effort will likely utilize a varying time window as one approach. To evaluate links between the yield series and climate, we always analyzed the relationships between deviations in the climate variables and the crop yields. We used 3 methods, which were based on (1) first order differences, (2) deviations from local means and (3) deviations from the trend curve.

(1) Approaches based on a first order difference series for yield and climatic variables (i.e. the difference from one year to the next) have been applied in a number of studies (e.g. Lobell & Field 2007, Trnka et al. 2012). We transformed the first order differences of climatic variables and yields (yield estimates) into a z-score series using the mean and standard deviation of the period analyzed. We then performed multiple linear regressions, with the first order differences in yield (Yield) as the response variable and the first order differences in mean temperature (Tavg), maximum temperature (Tmax), minimum temperature (Tmin), precipitation totals (PREC), number of frost days (FRS), number of precipitation days (WetD), water vapor pressure deficit (VAP), potential evapotranspiration (PET), Palmer Z-index (ZIND) and Palmer Drought Severity Index (PDSI) as predictors.

(2) We also calculated deviations from the local mean yield (calculated as the difference from the 6 closest values in the database for the given region) which were transferred into z-scores, and z-scores of the particular climatic variable.

(3) When applying the approach based on the deviation from the trend curve, we used the difference from the trend line, or the 2nd, 3rd or 4th order polynomial that fit to the line that best described the yield development. The difference was again transformed into z-scores and correlated with climatic variables.

As the results of all 3 approaches were not significantly different, we used the first order differences method as this is the simplest and requires a lower number of assumptions than the other two. In the preparation phase, other variables were also considered e.g. standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI) or amount of snow cover. However, in case of SPI and SPEI the results were similar to PREC and ZIND/PDSI respectively, while monthly data based snow cover estimates did not correspond with observed daily data. Therefore we focused on the 10 straightforward climate predictors defined above.

The detrending method was used, as it is designed to minimize the influence of slowly changing factors, such as crop management techniques and farm technology, and allows for the examination of the season-to-season (or season to long-term yield level) responses of yields to changes in the selected climatic variables. It was assumed that year-to-year management changes were not correlated with the climatic variables for the given year, but rather resulted from the experience gained in the previous years as a continuous process of learning from past mistakes throughout the time period analyzed in the paper. In addition, the division of the analysis period around 2 break-points, when yearly rate of yield changed markedly, allowed comparability over the whole analyzed period.

We also assumed that errors in a yield database were independent of climatic parameters. There were very significant shifts in the type of cereals being grown; rye was replaced by wheat, and oats by barley (e.g. Olesen et al. 2000). However, wheat and barley were among the 10 most commonly grown crops in most of the European regions throughout the study period. Therefore, they were assumed to always be present at sufficient acreage across the region of interest.

3. RESULTS

3.1. Changing production levels

The selected regions represent a climate gradient for the production of spring barley and winter wheat (Table 1, Fig. 1). They include regions with rather low annual and April–June temperatures that have either relatively dry (Finland or Sweden) or wet (Norway) spring and early summer conditions. Furthermore, the study included the highly productive areas of Lower Saxony, Denmark, Belgium and The Netherlands, as well as some regions with significant water limitations, such as in the Czech Republic, Austria and those more to the south in Tuscany and Bulgaria. As shown in Fig. 1d,e, climatic conditions between the periods of 1921–1940 and 1991–2010 changed considerably. All regions showed a significant increase in annual mean temperatures, which in some regions was even more pronounced from April–June. Annual precipitation totals either increased or remained the same, with the exception of Tuscany, which had a decrease in precipitation. The April–June precipitation levels markedly decreased in Bulgaria, Tuscany and Croatia and were notably increased in Norway, Sweden and Belgium. Fig. 1 shows that the 12 regions include not only the main crop producing areas but also regions with relatively low proportions of wheat and barley. The selected areas also represent a range of the environmental zones defined by Metzger et al. (2005) (Fig. 1a). In these regions, wheat and barley were

Table 1. Land-use, soil conditions and crop productivity in the 12 European countries/regions included in this study. Environmental zones follow those in Fig. 1a

	Finland (FI)	Norway (NO)	Sweden (SE)	Denmark (DE)	Lower Saxony (LS)	The Netherlands (NL)	Belgium (BE)	Czech Republic (CZ)	Austria (AT)	Tuscany (IT)	Croatia (CR)	Bulgaria (BG)
Total area (10^3 km^2)	333.7	322.4	449.1	43.3	47.7	37.4	31.0	78.9	83.9	57.9	56.5	110.9
Total area of arable land (10^3 km^2)	30.0	16.1	31.4	27.7	18.6	10.1	8.4	32.3	15.1	12.2	9.6	28.8
Proportion of arable land (%)	9	5	7	64	39	27	27	41	18	21	17	26
Mean altitude of arable land (m a.s.l.)	73	155	71	32	61	3	95	372	316	136	102	228
Mean annual temperature (°C) (arable land)												
1901–1950/	3.2	3.3	5.2	7.6	8.6	8.7	9.3	7.5	7.1	11.8	10.6	10.8
1951–1990/	3.2	3.3	5.2	7.7	8.5	8.6	9.3	7.8	7.4	11.9	10.6	10.9
1991–2012	4.1	4.0	5.9	8.5	9.4	9.5	10.2	8.6	8.4	12.5	11.6	11.4
Mean annual precipitation (mm) (arable land)												
1901–1950/	522	1039	548	675	667	672	763	672	985	730	909	572
1951–1990/	535	1083	566	707	686	705	794	648	948	744	871	588
1991–2012	563	1153	622	723	709	746	825	655	966	711	875	601
Soil water-holding capacity (mm m^{-1})	80–130	100–140	140–190	100–140	100–140	140–190	>190	140–190	140–190	140–190	140–190	140–190
Environmental zones	BOR, NEM	BOR, NEM	NEM, CON	ATN, CON	ATN, CON	ATC, ATN	ATC, CON	CON, PAN	PAN, CON	MDN, MDM	PAN, MDM	PAN, MDN

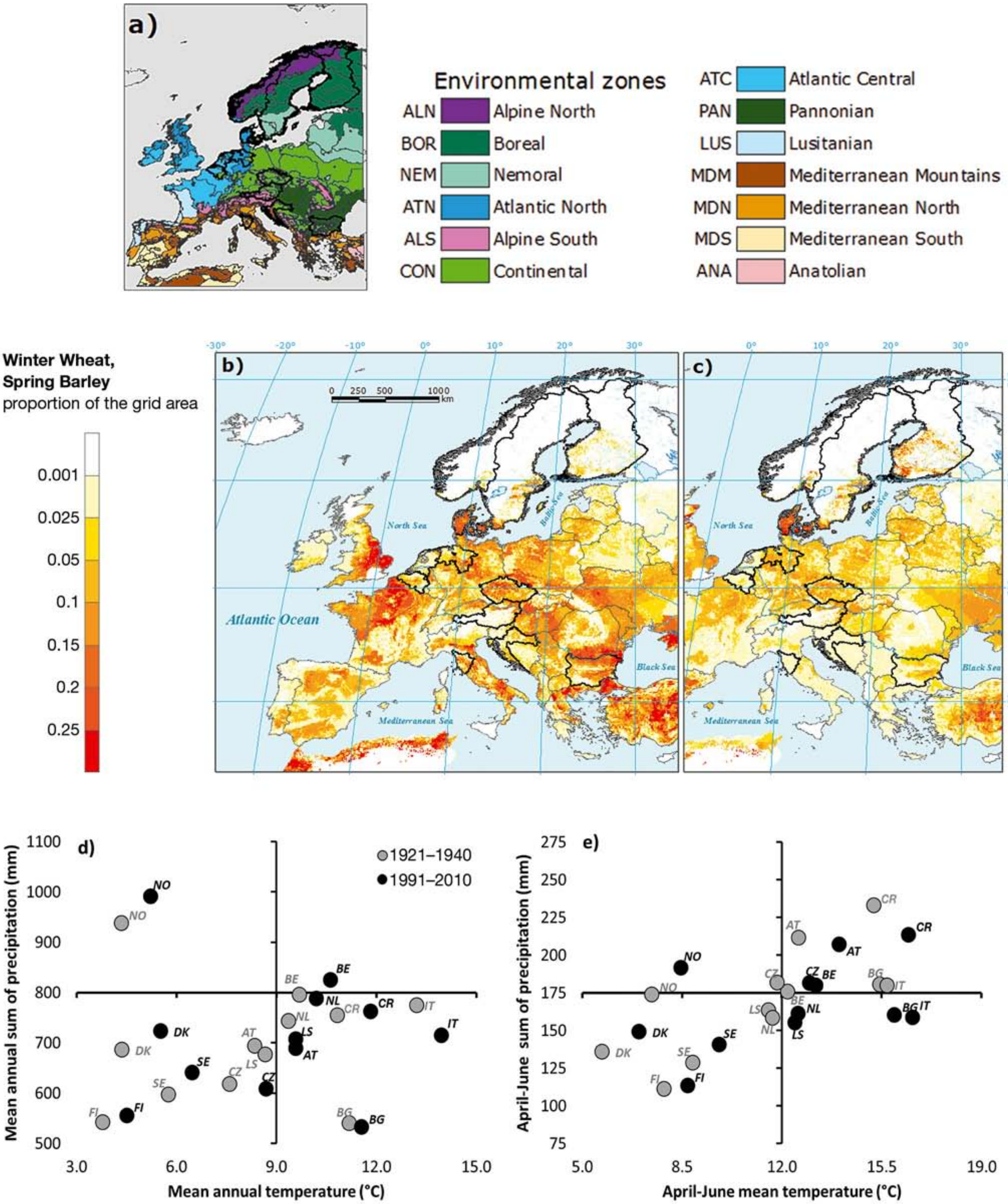

Fig. 1. (a) Main environmental zones in Europe, based on Metzger et al. (2005); (b) wheat and (c) barley growing areas in Europe, based on Monfreda et al. (2008), and the locations of the 12 countries/regions assessed in the study (thick borders). Mean (d) annual and (e) April–June temperature and precipitation for the 12 countries/regions (for abbreviations see Table 1) over the periods 1921–1940 and 1991–2010. Climatological data were weighted according to the proportion of arable land in each grid of the region

mostly grown in the Atlantic North, Atlantic Central, Continental, Pannonian and Mediterranean (northern and mountainous regions) zones, but Nemoral and Boreal zones are also represented.

Table 1 and Supplement 2 show that the 1951–1990 and 1991–2012 periods are fairly well covered by yield data (with some exceptions for the 1950s in Sweden, Norway, Bulgaria and Austria). The 1901–1950 period has the worst coverage (see also Supplement 2), but with exception of Tuscany, each region is represented by at least 25 yr of yield data. In the 1915–1919 and 1939–1948 periods, yields were affected by World Wars I and II and their aftermath. Especially in these years, data were missing for some countries (e.g. Austria, Czech Republic or Croatia) as yields were considered secret information. However, we included all available data even from these periods, because farmers would have strived to maximize production even during periods of war. Potentially disruptive events and major changes in the socio-economic structure of the society that could affect yield levels and overall agricultural practices are listed in Table 2 for each country. Rain was the source of water for virtually all of the cereal production during all periods analyzed.

Crop compositions and land allocation were comparable and did not differ by more than 1/3 across all regions (Fig. 2e,f). Fig. 2 (based on Ramankutty & Foley 1999) shows considerable changes in the proportion of arable land across Europe in the 20th century. However, one of methodological aims of this study was to analyze primarily those regions where

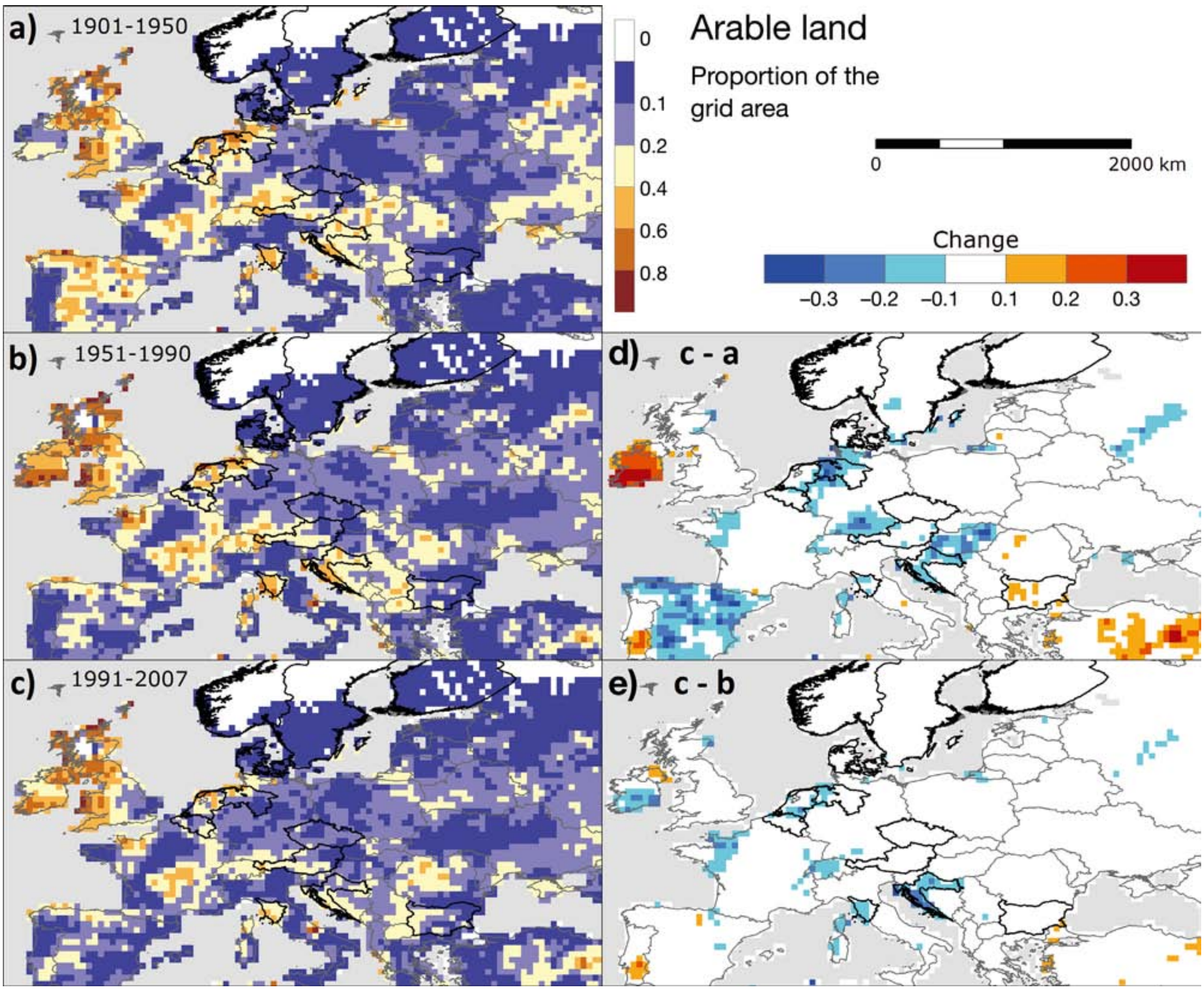

Fig. 2. Proportion of arable land based on the updated Ramankutty & Foley (1999) study for the periods (a) 1901–1950, (b) 1951–1990 and (c) 1991–2007, and the differences between the periods (d) 1991–2007 and 1901–1950 and (e) 1991–2007 and 1951–1990. The 12 countries/regions considered in the study are indicated by thick borders

Table 2. Key factors influencing productivity in the 12 European countries/regions studied (ordered from north to south). See Table 1 for country/region abbreviations

Country/ region	1901–1950	1951–1990	1991–2012
All	Introduction of mineral fertilizers and a period of technological development prior to WWI	Large-scale use of fertilizers, pesticides, and later, growth regulators, machinery and new types of cultivars	Efforts to reduce the environmental impacts of agricultural production. Farmers, due to subsidy systems, were less motivated to maximize yields
FI	Traditional crop rotations prevailed with little mineral fertilizer input and mechanization limited	In the 1950s and early 1960s, Finland still suffered from a lack of capital for investments due to reparation payments to Russia in the aftermath of the 'winter war' and WWII	Finland joins the European Union in 1995 and adheres to more stringent environmental regulations. Drastic cereal price decreases and decreases in N and especially P fertilizer rates due to Agro-Environmental Programme subsidies led to extensification and an increase in cereal crop area (to mainly less-favorable land)
NO	A regionalization of agricultural production was initiated and completed. Cereal production was located mainly in southeast and central Norway. Milk and meat production was mainly located in areas less climatically favorable for cereal production. Mechanization was boosted and the application of fertilizers and pesticides increased continuously until environmental issues required more attention	A regionalization of agricultural production was initiated and completed. Cereal production was located mainly in southeast and central Norway. Milk and meat production was mainly located in areas less climatically favorable for cereal production. Mechanization was boosted and the application of fertilizers and pesticides increased continuously until environmental issues required more attention	Norway did not join the European Union and agriculture is not a part of the (EEA) agreement with the EU on economic affairs. However, according to the agreement, several EU regulations were also applied in Norway
SE	Wheat started to replacing rye. Fertilization rates slowly increased	Mechanization of agriculture reduced the number of horses and cows. Leys were increasingly replaced by barley for pig production. Cereal monocultures became more common. Increased fertilization rates	Agriculture became market oriented and economy regulated cropping. Subsidies were based on area. Larger farms developed. Fertilization rates were reduced and yields stagnated
DK	Increasing exports of cereals. Dairy and meat organized through cooperatives stimulated productivity	Mechanization combined with the increased use of fertilizers and pesticides increased productivity, and this was linked to the increased specialization of production systems	Increased environmental regulations to reduce pollution from nitrogen (in particular nitrate leaching) and pesticide use impacted crop management and limited increases in productivity
LS	Earlier harvests before the introduction of combine harvesters. Nitrogen limitation, because mineral N was not yet used extensively. Therefore, wheat was mainly cultivated on good loess soils in the south	Strong increase in wheat (4-fold) and barley (6-fold) area, partly as extensions on former grasslands, which was drastically reduced	Reduction of nitrogen surplus, further reduction of grassland to 1/5 of the 1^{st} period, reduction of barley area by 50 % (mainly replaced by silage maize), and a further increase in wheat area by another 40 % relative to 1990
NL	A somewhat delayed but then rapidly recovering and expanding agriculture along with land reclamation (polders)	Heavy investments in agricultural research and technology on all levels resulting in large increases in agricultural production. An awareness of excess nutrients developed towards the end of the period	Emphasis on resource use optimization
BE	More than 1/3 of the population worked in agriculture and related sectors, and more than 2/3 of the territory was farmland	Growing industrialization encouraged the specialization and mechanization of agriculture and agro-industries. From the 1970s, a clear trend existed towards fewer and larger farms	Increasing agricultural productivity while reducing environmental impacts was key. Increased exploitation of agricultural and horticultural expertise in the retail market and in the international niche markets

Table 2 (continued)

Country/ region	1901–1950	1951–1990	1991–2012
CZ	Following land-reforms in 1920, large scale farms were redistributed, and institutional support of breeding and crop improvement occured. Post-WWII recovery was relatively slow and was affected by 1947 drought	Complete land re-distribution and establishment of ever-larger cooperatives. From the mid-1970s, industry-like agriculture farms with ever increasing size	Shift in priority from the highest yield to the highest profit and a general reduction in the application rate of fertilizers and pesticides. The effects of EU agricultural policies from the mid-1990s are apparent
AT	Increasing use of mineral fertilizers and farm technologies (machinery), which was slowed down significantly by 2 world wars and the negative socio-economic impacts, and the fact that practices were based on very small farm units in most regions. Crop breeding improvements and the introduction of new crops, such as maize, occured	Strong improvements in applied farm technologies, significantly replacing man-powered machinery in all farming sectors. Strong improvements in crop breeding success and crop management methods, such as soil cultivation techniques, pest and disease control. Better demand-driven crop fertilizing, improved extension services and education resources and options for farmers. Significant structural changes in farms to larger farm units and farm-based specialization to one production type (i.e. giving up cattle and milk production in arable regions, focusing on different crop production only or in combination with meat production)	Further ongoing strong structural changes in farms leading to larger farm units. Strong dependence of farm productivity and economic survival, especially in disadvantaged regions (i.e. Alpine region), on second income options and subsidies. Further improvements in the implementation of sophisticated, new and more resource-efficient farming technologies and methods in all farming sectors. Significant loss of agricultural land due to the demand for area for urbanization, infrastructure and reforestation (Alpine region). Increasing share of farms and agricultural land under ecological production as an option for keeping smaller, family-farm based production
CR	Traditional agricultural production on small family farms where conventional tillage and soil fertilization using manure dominated	After a failed collectivization, state agricultural enterprises were established on 10% of the agricultural land, and the rest of the agricultural land remained privately owned. Agriculture within the state-owned agricultural enterprises was intensified and focused on high yields at the expense of ecological and economic efficiency	Family farms and agricultural enterprises were the main drivers of agricultural production. Transition to a market economy. Subsidies were introduced. Orientation towards organic and integrated agriculture production
IT	Crop rotation was widely adopted, no mineral fertilization was adopted, and a varietal selection of wheat grown had a very strong impact	Introduction of mechanization and the adoption of intensive agricultural practices. Crop rotations were abandoned in favor of increased mineral fertilization	More attention to grain quality in addition to high yields, sowing density increased for controlling tillering ('one seed, one ear'), and crop rotations were re-introduced in agricultural practices.
BG	Agricultural development through extensive growth. Productivity gains only played a marginal role to output increases. No significant growth of yields before 1940	Among the countries of Eastern Europe, Bulgaria was the first to complete collectivization, had the most collectivized agriculture, and experienced the most rapid rate of growth of agricultural production since the end of World War II. Emphasis on high-value products and significant improvement of the relatively low level of agricultural production by increasing the supply of fertilizer, machinery, other investments, and improved plant varieties. Extensive development of irrigation	In 1990, the total irrigated land was 25% of the arable land. During transition, the amount of water used for irrigation sharply declined post-1990. Wheat and barley replaced more water-intensive crops, including vegetables, rice and maize. Irrigation systems and other infrastructure elements were built to serve large production units during socialism and did not meet the needs of the huge number of small-scale landowners that emerged following the land restitution process

the changes in the proportion of arable land have been less pronounced. Fig. 2e,f shows that in most regions, the area of arable land has not changed considerably, with exception of Belgium, Croatia and Tuscany. Comparing 1991–2012 with 1901–1950, the decreases in arable land were between 10 and 20% in some areas within these 3 regions. These areas have been mainly converted to permanent grassland or, to a lesser extent, to forest. From 1991–2012, the proportion of arable land did not change dramatically in any of the evaluated regions when compared to the proportion in 1951–1990 (Fig. 2f). Fig. 2 allows for the analysis of changes in the weights assigned to the individual grids that were used to calculate the agroclimatic conditions within individual countries. These changes were rather small and were thus kept constant over the whole study period, with the distribution of the year 2000 being used. However, some changes were not covered by Ramankutty & Foley (1999), as Table 2 shows for Lower Saxony.

3.2. Yield trends

Fig. 3 shows that the series of barley and wheat yields exhibited slow rates of increase until approximately the late 1940s, at which point the annual yield increased much faster and reached a plateau that has lasted since the 1990s.

The yield variability (when normalized by the mean yield level) did not differ significantly between periods. When data from all regions were pooled together there was a good agreement on the 'break-points' in the wheat and barley series. The period of slower annual yield growth ended in 1952 for barley and 2 yr later for wheat. The following period of rapid annual yield growth ended in 1989 and 1990 for wheat and barley, respectively. There are obvious and significant differences between individual regions with some having only one distinctive 'break-point' around early 1950s. However, a break-point analysis was used to select the following 3 distinctive periods for the subsequent analysis: 1901–1950, characterized by slower changes in annual yield; 1951–1990, showing rapid increase in annual yield; and 1991–2012, with a recent slow-down in changes in annual yield.

The large differences between the 3 selected periods are well depicted in Fig. 3a,b. In the most recent period (1991–2012), we can distinguish 3 groups of regions. (1) The 3 Nordic countries (Finland, Norway, Sweden) had generally lower yields than other regions and smaller yield increments relative to those from the 1951–1990 period, and even relative to those from 1901–1950 period. (2) Comparable results were found for the central and southern European regions (Czech Republic, Austria, Croatia, Tuscany, Bulgaria), where yields of barley were similar to those of the Nordic countries, but wheat yields were markedly higher. This partly follows from differences in soil conditions, i.e. the often sandy (relatively poor in nitrogen and phosphorous) or relatively shallow or water-logged soil profiles in some Nordic countries compared to the generally deeper and more fertile soils in central (Austria and Czech Republic) and southern (Tuscany, Bulgaria) Europe. Wheat is primarily grown on better soils due to its generally higher yields. (3) The third group is represented by Denmark, Lower Saxony, The Netherlands and Belgium, where wheat yields in particular were much higher than in the other regions and the yield differences between the 1991–2012 and 1951–1990 periods were the greatest, primarily due to favorable climatic conditions. In addition, apart from climatic factors, high yields could be to some extent attributed to (i) surplus manure stemming from high livestock densities, (ii) relative land scarcity due to high population pressures encouraging higher and more cost-efficient investments in farm infrastructure (particularly in Belgium and The Netherlands), (iii) past investment into agricultural research and development and (iv) more homogeneous terrain in the northwestern/central countries than in the Nordic ones or those in the central/southern regions.

3.3. Climatic effects on wheat yields

3.3.1. Individual climatic parameters

Only negative associations were established between first order differences of annual wheat yields and selected climatic parameters (Table 3). In the case of minimum temperatures and water vapor pressure deficits there was a significant (yet weak) relationship across all 3 periods. Yields across all regions and over the whole period responded significantly to all parameters, with the exception of potential evapotranspiration — which is not surprising as actual evapotranspiration would be a better indicator of water availability. Overall, inter-annual climatic variations explained only a small fraction of the wheat yield variations when they were considered separately. At the level of the individual regions, individual climatic parameters tended to explain a greater proportion of the year-to-year yield variations. Total precipitation explained up to 60% of the year-to-year yield vari-

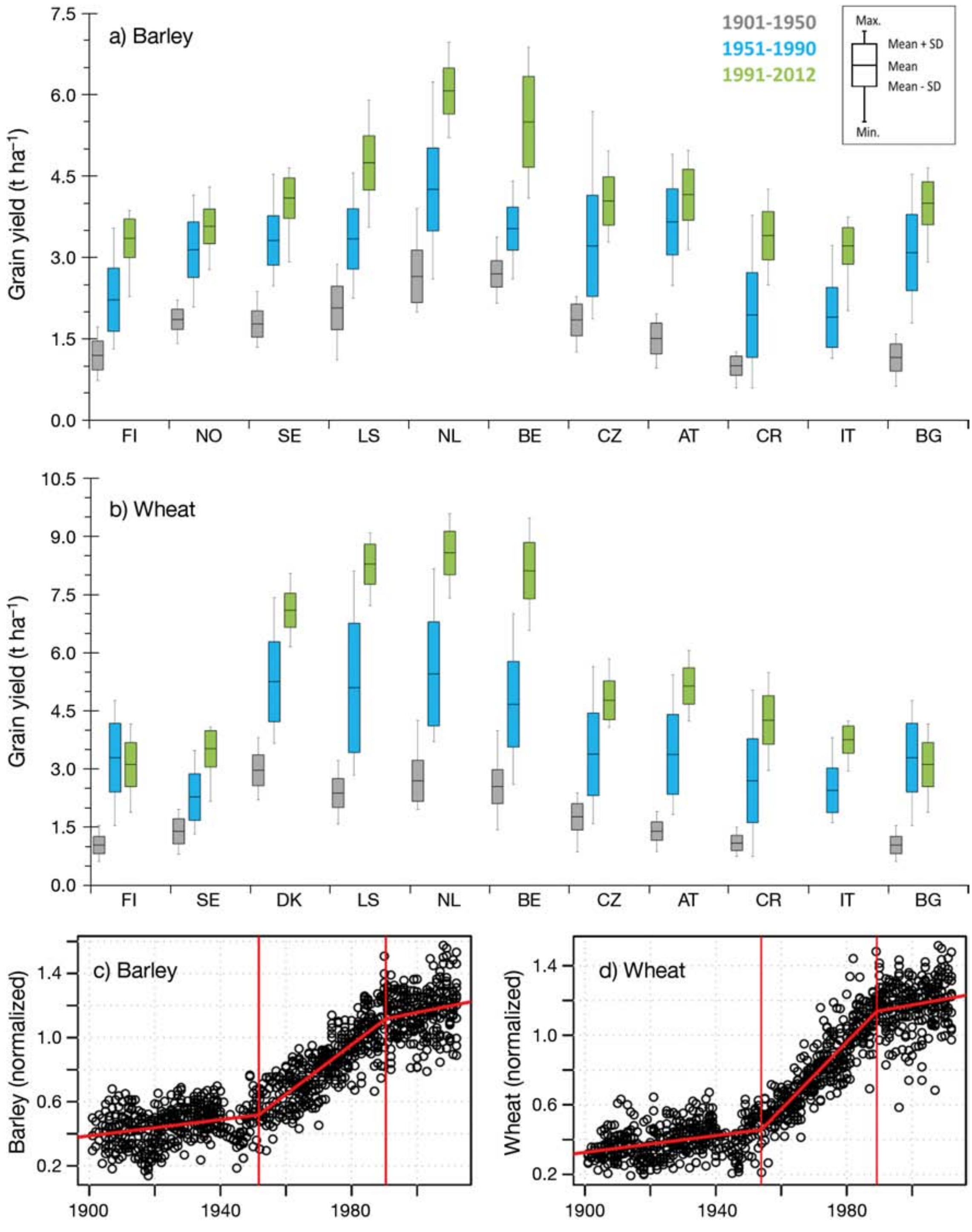

Fig. 3. Distribution of (a) barley and (b) wheat yields expressed as box-plots for the countries/regions included in the study for the 1901–1950, 1951–1990 and 1991–2012 periods. (c,d) Inter-annual variability of normalized yields for (c) barley and (d) wheat in all countries/regions with 'break' lines

ability in Belgium, The Netherlands and Lower Saxony, and a similar response was found across all 3 periods studied. On the other hand, temperature-related characteristics had a better predictive value for both the Nordic countries and those below 50° N latitude. However, temperature variations were unable to explain >1/3 (and usually much less) of the inter-annual variability. The number of statistically

Table 3. Explained variability (adjusted R^2) of the inter-annual differences in wheat and barley yields (first order differences) as explained by individual climatic parameters for April–June. Tmin: mean monthly minimum temperature; Tavg: mean monthly temperature; Tmax: mean monthly maximum temperature; DTR: mean daily temperature range; VAP: water vapor pressure deficit; PREC: precipitation total; WetD: number of precipitation days; PET: potential evapotranspiration; ZIND: Palmer Z-index; PDSI: Palmer Drought Severity Index. Only values of relationships significant at the 0.05 significance level are listed

Country/region	Period	Tmin	Tavg	Tmax	DTR	VAP	PREC	WetD	PET	ZIND	PDSI
Wheat											
Finland (FI)	1901–1950			0.10						0.11	0.11
	1951–1990	0.11	0.10	0.08						0.25	
	1991–2012										
Sweden (SE)	1901–1950									0.13	
	1951–1990		0.16	0.19	0.15		0.13	0.13	0.18	0.38	0.12
	1991–2012										
Denmark (DK)	1901–1950				0.10		0.18			0.25	0.24
	1951–1990				0.11						
	1991–2012										
Lower Saxony	1901–1950										0.14
(LS)	1951–1990				0.32		0.45	0.42	0.09	0.36	0.08
	1991–2012						0.64	0.19		0.39	
The Netherlands	1901–1950							0.12			0.25
(NL)	1951–1990				0.27		0.42	0.41	0.17	0.34	0.13
	1991–2012						0.20				
Belgium (BE)	1901–1950	0.29	0.19					0.19			
	1951–1990				0.17		0.27	0.21		0.21	0.16
	1991–2012						0.19				
Czech Republic	1901–1950	0.20	0.26	0.29	0.21	0.21			0.30		
(CZ)	1951–1990	0.10	0.09			0.14					
	1991–2012								0.18		
Austria (AT)	1901–1950	0.14	0.10			0.12					0.14
	1951–1990	0.12	0.09			0.28					
	1991–2012		0.14	0.15					0.19		
Croatia (CR)	1901–1950	0.21	0.27	0.28	0.14				0.30		
	1951–1990					0.08		0.11			
	1991–2012										
Tuscany (IT)	1901–1950	0.27	0.26						0.35		
	1951–1990										
	1991–2012				0.14						
Bulgaria (BG)	1901–1950					0.11	0.20	0.14		0.19	
	1951–1990	0.11	0.12	0.10		0.18					0.13
	1991–2012			0.19				0.42	0.27		
All countries/	1901–1950	0.05	0.05	0.03		0.04		0.02	0.06		0.07
regions	1951–1990	0.01			0.07	0.04	0.11	0.11	0.03	0.10	0.06
	1991–2012	0.04	0.04	0.03		0.02			0.03		

Country/region	Period	Tmin	Tavg	Tmax	DTR	VAP	PREC	WetD	PET	ZIND	PDSI
Barley											
Norway (NO)	1901–1950							0.12		0.05	
	1951–1990		0.30	0.38	0.34		0.12	0.17	0.40	0.29	
	1991–2012										
Finland (FI)	1901–1950						0.10				
	1951–1990		0.08	0.10			0.12		0.18	0.24	0.09
	1991–2012										
Sweden (SE)	1901–1950										
	1951–1990				0.19		0.11	0.15		0.23	0.15
	1991–2012										
Lower Saxony	1901–1950			0.09	0.17				0.21		
(LS)	1951–1990										
	1991–2012	0.27	0.16			0.17					
The Netherlands	1901–1950									0.08	0.12
(NL)	1951–1990	0.13			0.12	0.09	0.14	0.12			
	1991–2012										0.22
Belgium (BE)	1901–1950										
	1951–1990										0.10
	1991–2012										
Czech Republic	1901–1950	0.31	0.34	0.33	0.13	0.29			0.33		
(CZ)	1951–1990	0.09				0.09					
	1991–2012										
Austria (AT)	1901–1950		0.10	0.10		0.12		0.12	0.17	0.11	
	1951–1990										
	1991–2012	0.18	0.19	0.17				0.22	0.17		
Croatia (CR)	1901–1950	0.30	0.34	0.34	0.13	0.16	0.12		0.38	0.14	
	1951–1990										
	1991–2012										
Tuscany (IT)	1901–1950	0.30	0.25						0.29	0.27	
	1951–1990	0.13				0.13					0.12
	1991–2012				0.22			0.15			
Bulgaria (BG)	1901–1950		0.13	0.16	0.12	0.16	0.39	0.35	0.17	0.40	
	1951–1990	0.21	0.19	0.15		0.33					
	1991–2012					0.22		0.20			
All countries/	1901–1950	0.03	0.03	0.03		0.03	0.01		0.05	0.01	
regions	1951–1990	0.02			0.04	0.05	0.04	0.04		0.04	0.06
	1991–2012	0.06	0.04	0.03		0.05			0.03		0.03

significant relationships between climatic variables and annual yield changed over the individual periods. The number was broadly similar for the first 2 periods, but the ability of inter-annual climatic variations in single parameters to explain yield variability sharply decreased for the 1991–2012 period.

3.3.2. Combined climatic factors

Table 4 indicates that even combining the selected pool of climatic variables for April–June did not explain a large portion of the year-to-year variability in wheat yield between 1901 and 2012, but this also differs strongly by region. Even in the regions where a larger portion of the annual yield variability was explained by climatic factors (e.g. Sweden and Belgium), the mean absolute error (MAE) and root mean square error (RMSE) values indicated that even these relationships were not useful for yield prediction. However, precipitation, number of frost days and other parameters related to temperature seemed to be essential for explaining yield variability, while this was not the case for drought indicators. In general, precipitation totals played a negative role determining yield variations; i.e. year-to-year increases in precipitation totals suggested a decline in yield, which was also generally the case for Tmax.

For wheat, we recorded only a small number of cases when the relationship with climatic variables changed markedly with the time period (Table 5). It is, however, worth noting that such changes were recorded in Finland and Bulgaria (i.e. in the northern and southeastern end of the area studied). However, climatic variables that were able to explain a reasonable amount of yield variability from 1991–2012 in these 2 countries failed (or showed a much lower capacity) to do so from 1901–1950. This tendency

Table 4. Explained variability (adjusted R^2), relative mean absolute error (MAE) and root mean square error (RMSE) of the inter-annual differences in wheat and barley yield (first order differences) as explained by a combination of climatic parameters for April–June in the period 1901–2012 in the individual European countries/regions. Tavg: mean monthly temperature; Tmin: mean monthly minimum temperature; Tmax: mean monthly maximum temperature; DTR: mean daily temperature range; FRS: number of frost days; PREC: precipitation total; WetD: number of precipitation days; VAP: water vapor pressure deficit; PET: potential evapotranspiration; ZIND: Palmer Z-index; PDSI: Palmer Drought Severity Index. X (Y) identifies significant contributors at the 0.1 significance level, x (y): non-significant contributors. X (x): yield increases with an increasing value of the climatic parameter, Y (y): the opposite relationship. The significance of the single variables should be interpreted with caution as the predictors are mutually correlated, e.g. when Tavg is significant and Tmax is not, the significance of Tmax is probably only 'hidden' by the multicollinearity

	R^2_{adj}	MAE (%)	RMSE (%)	Tavg	Tmin	Tmax	DTR	FRS	PREC	WetD	VAP	PET	ZIND	PDSI
Wheat														
Finland (FI)	0.05	96	134		y	y	y	y			Y	Y		
Sweden (SE)	0.41	77	97		Y				Y				Y	
Denmark (DK)	0.20	86	112			Y	Y	Y		y		y		
Lower Saxony (LS)	0.34	85	105	y				y	Y					
The Netherlands (NL)	0.21	89	111	y	Y		y	y						
Belgium (BE)	0.40	74	93	Y	Y	Y		Y	Y				Y	y
Czech Republic (CZ)	0.20	89	115						Y			Y		
Austria (AT)	0.16	90	127			Y	Y	Y	Y		y			y
Croatia (CR)	0.06	93	122	Y	Y		Y	y			y	y		
Tuscany (IT)	0.25	87	108					Y	Y	Y			Y	Y
Bulgaria (BG)	0.31	90	117						Y	Y	y		Y	y
All countries/regions	0.13	94	125			Y	Y	Y	Y					
Barley														
Finland (FI)														
Norway (NO)	0.05	96	127	y		x	y							
Sweden (SE)	0.28	82	108		y	x	y	Y	X		x		Y	
Lower Saxony (LS)	0.09	94	121	x	y					x		y	y	
The Netherlands (NL)	0.24	83	107	X		Y	X		y				x	Y
Belgium (BE)	0.15	88	121						Y				X	Y
Czech Republic (CZ)	0.20	88	115		Y			Y						
Austria (AT)	0.19	95	126	X		Y	X		y			Y	x	
Croatia (CR)	0.17	91	114					y	Y				X	Y
Tuscany (IT)	0.07	98	139		x	y	x	Y						
Bulgaria (BG)	0.27	89	111		X	Y	X		Y				X	Y
All countries/regions	0.10	95	128			Y	X	Y	Y					

Table 5. As Table 4 for 3 different periods (1901–1950, 1951–1990, 1991–2012). Only those parameters significant at the 0.05 significance level during the 1991–2012 period are listed

Country/region	Period	R^2_{adj}	MAE (%)	RMSE (%)	Tavg	Tmin	Tmax	DTR	FRS	PREC	WetD	VAP	PET	ZIND	PDSI
Wheat															
Finland (FI)	1901–1950	0.01	99	130		y	x	y	y			y	y		
	1951–1990	0.20	88	110		X	Y	X	x			Y	y		
	1991–2012	0.24	81	98		X	Y	X	Y			X	X		
Sweden (SE)	1901–1950	0.51	71	92		Y				X				Y	
	1951–1990	0.51	62	78		y				X				Y	
	1991–2012	0.18	90	101		Y				X				Y	
Denmark (DK)	1901–1950	0.35	82	96			Y	X	Y		x		X		
	1951–1990	0.06	78	108			y	x	y		x		x		
	1991–2012	0.25	71	99			Y	X	Y		X		X		
Lower Saxony (LS)	1901–1950	0.13	91	109	Y				y	Y					
	1951–1990	0.50	64	81	x				X	Y					
	1991–2012	0.71	51	65	Y				Y	Y					
The Netherlands (NL)	1901–1950	0.32	80	101	y	x		x	y						
	1951–1990	0.24	81	104	x	y		y	x						
	1991–2012	0.29	75	94	X	Y		Y	Y						
Belgium (BE)	1901–1950	0.43	66	85	X	Y	Y		Y	x				y	Y
	1951–1990	0.52	58	76	x	y	y		y	Y				X	Y
	1991–2012	0.59	57	66	X	Y	Y		Y	Y				X	Y
Czech Republic (CZ)	1901–1950	0.33	80	96						y			Y		
	1951–1990	0.04	98	118						y			Y		
	1991–2012	0.34	70	95						Y			Y		
Austria (AT)	1901–1950	0.27	72	92			y	X	y	y		x			Y
	1951–1990	0.40	73	89			y	x	y	y		Y			Y
	1991–2012	0.49	69	79			Y	X	Y	Y		X			X
Croatia (CR)	1901–1950	0.32	55	70	y	x		x	x			y	y		
	1951–1990	0.01	86	109	x	y		y	y			y	y		
	1991–2012	0.62	61	74	Y	X		X	Y			Y	Y		
Tuscany (IT)	1901–1950	0.36	65	87					x	y	y			X	Y
	1951–1990	0.31	75	94					Y	Y	Y			X	Y
	1991–2012	0.47	69	79					Y	Y	Y			X	Y
Bulgaria (BG)	1901–1950	0.15	75	101						x	x	y		y	X
	1951–1990	0.44	72	92						Y	X	y		x	X
	1991–2012	0.61	58	75						Y	X	X		X	Y
All countries/ regions	1901–1950	0.16	91	120			Y	X	Y	Y					
	1951–1990	0.16	90	117			Y	X	Y	Y					
	1991–2012	0.17	95	118			Y	X	Y	Y					

(Table continued on next page)

was also found for Lower Saxony. However, in the rest of the countries, the explained variability did not change to any great extent. While one would expect the most variability to be explained by the regression analysis of the data from 1991–2012 (as climatic variables were selected using these data), this was not the case, and 4 of the 11 regions showed that a higher or much higher proportion of the variability was explained in the earlier periods. Fig. 4a shows that the adjusted R^2 (i.e. the explained variability) was higher and the relative RMSE was lower for the period from 1991–2012 than for 1901–1950 and 1951–1990. This indicates that factors affecting yield variability indeed changed over time, although this change must have been relatively subtle.

3.4. Climatic effects on barley yields

3.4.1. Individual climatic parameters

The first order differences of the selected climatic parameters for barley (Table 3) were, in general, poor predictors of yield change. Only minimum temperatures and water vapor pressure deficits showed significant (yet weak) relationships across all 3 periods. Yields across all regions and the whole period studied responded significantly to all parameters, with the exception of potential evapotranspiration — but as observed for wheat, only an insignificant fraction of yield variation was explained by the variation of individual climatic indicators. While a larger portion of yield variation was explained for individual re-

Table 5 (continued)

Country/region	Period	R^2_{adj}	MAE (%)	RMSE (%)	Tavg	Tmin	Tmax	DTR	FRS	PREC	WetD	VAP	PET	ZIND	PDSI
Barley															
Finland (FI)	1901–1950														
	1951–1990														
	1991–2012														
Norway (NO)	1901–1950	0.00	94	113	x		y	x							
	1951–1990	0.48	64	80	X		Y	X							
	1991–2012	0.05	88	123	Y		X	Y							
Sweden (SE)	1901–1950	0.09	79	101		y	x	x	y	x		y		y	
	1951–1990	0.40	69	83		x	y	x	y	X		y		Y	
	1991–2012	0.58	51	69		Y	X	Y	Y	X		X		Y	
Lower Saxony (LS)	1901–1950	0.24	77	96	y	x					x		Y	y	
	1951–1990	0.00	94	120	y	y					x		x	y	
	1991–2012	0.60	52	63	X	Y					X		Y	Y	
The Netherlands (NL)	1901–1950	0.13	95	124	x		y	x		x				y	X
	1951–1990	0.39	71	84	x		y	x		Y				X	Y
	1991–2012	0.60	54	63	X		Y	X		Y				X	Y
Belgium (BE)	1901–1950	0.00	93	147						y				x	Y
	1951–1990	0.17	83	111						Y				X	Y
	1991–2012	0.32	79	94						Y				X	Y
Czech Republic (CZ)	1901–1950	0.28	85	101		Y			y						
	1951–1990	0.11	88	110		Y			y						
	1991–2012	0.24	84	103		Y			Y						
Austria (AT)	1901–1950	0.13	91	132	x		y	x		x			y	y	
	1951–1990	0.00	85	105	x		y	x		x			y	y	
	1991–2012	0.67	49	64	X		Y	X		Y			Y	X	
Croatia (CR)	1901–1950	0.36	76	96					y	y				X	Y
	1951–1990	0.09	93	108					y	Y				X	Y
	1991–2012	0.32	72	88					Y	Y				X	Y
Tuscany (IT)	1901–1950	0.09	71	91		x	y	x	x						
	1951–1990	0.36	81	103		Y	X	Y	Y						
	1991–2012	0.40	74	95		X	Y	X	Y						
Bulgaria (BG)	1901–1950	0.42	69	88		X	Y	X		y				x	y
	1951–1990	0.22	81	100		y	x	Y		y				x	Y
	1991–2012	0.57	57	71		X	Y	X		Y				X	Y
All regions	1901–1950	0.07	94	131	y	x	x	Y					Y		Y
	1951–1990	0.12	91	119	y	x	x	X					x		Y
	1991–2012	0.15	92	117	X	X	Y	X					Y		Y

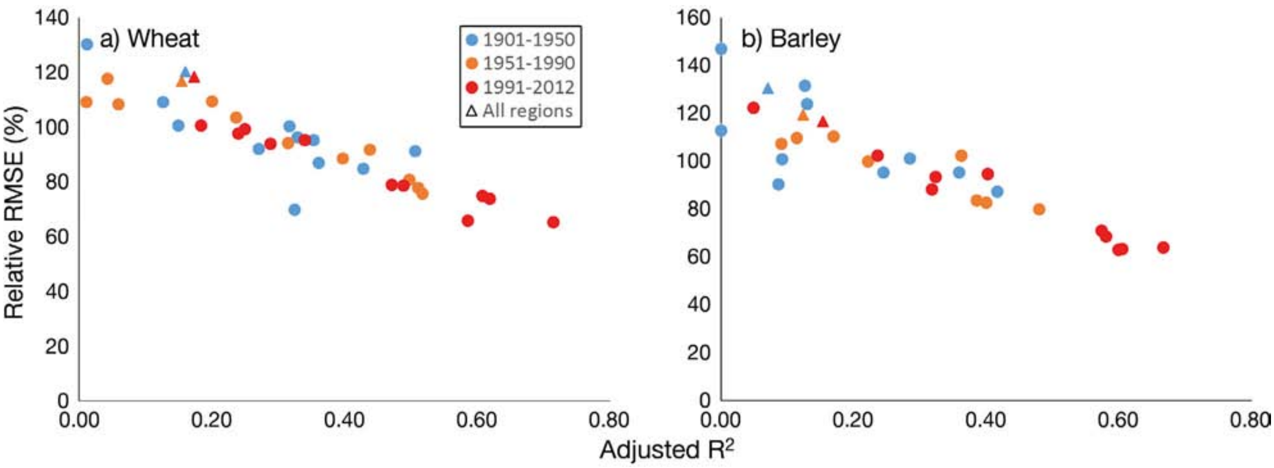

Fig. 4. Relationship between adjusted R^2 and mean absolute error of the best-fit stepwise regression function between first order differences of climatic variables (see Table 4) and inter-annual yield variations for (a) wheat and (b) barley. Individual dots represent regions listed in Table 4, with triangles showing the results for all regions

gions, it was not consistent across the periods. Compared to those for wheat, the adjusted R^2 values were generally smaller. The sharp decline in the ability of single factors to explain yield variations in the period from 1991–2012 was even stronger for barley than it was for wheat.

3.4.2. Combined climatic factors

Combined climatic factors from April–June using the data from 1901–2012 explained a relatively small share of the year-to-year variability in barley yield when all regions were pooled, and their predictive ability was lower than they were for wheat yield (Table 4). Interestingly, no significant relationship was found for Finland, which is likely due to a later harvest occurring in this country (mid- to late August) compared to other regions. For Norway, Lower Saxony and Tuscany, the explained variability in yield was <10%. Only in the case of Sweden (southern Sweden, where most agriculture is concentrated), the Czech Republic and The Netherlands could >1/5 of the year-to-year variability be explained by the suite of selected climatic factors over the entire 1901–2012 period. The MAE and RMSE values were similar to those observed for wheat, while the overall influence of climatic patterns appeared to be smaller. For barley, year-to-year yield variations, precipitation totals, number of frost days, daily temperature range and maximum temperatures (all for April–June) seemed to be the most influential of the climatic drivers tested. Similar to the results for wheat, year-to-year increases in precipitation, frost occurrence and maximum temperature from April–June were associated with a decline in barley yield. Short-term droughts seemed to lead to lower yields in Belgium, Croatia and Bulgaria, while long-term droughts in general lowered the overall production level.

Clear evidence of a changing relationship between climatic factors and changes in the yield of barley exist (Table 5). Similar to the observations for wheat, these changes were recorded in northern and south-eastern Europe (Norway, Sweden and Lower Saxony compared to Tuscany and Bulgaria). In addition, climatic variables that were able to explain a fairly large portion of the inter-annual yield variability from 1991–2012 showed a much lower predictive ability for the 1901–1950 and 1951–1990 periods. Fig. 4b shows a visible difference in the adjusted R^2 and RMSE values between the results of the 1991–2012 period and those of the 1901–1950 and 1951–1990 periods, suggesting that the influences of climate on annual crop yields have been changing over the periods considered. It seems that the influence of climatic variables on crop yields has increased in the period from 1991–2012.

4. DISCUSSION

While climate plays an important role in limiting the geographical distribution of particular crops (Elsgaard et al. 2012), it also influences overall production levels (see Fig. 3). The low yields generally reported for the 3 most southern regions are from areas where cereal yields are considered to be limited by water availability, heat stress and the short duration of the grain filling period (Ewert et al. 2005). Cereals in these regions are complemented by perennial crops, such as olive, grapes and fruit trees, as they have deeper root systems and can therefore better withstand long dry periods. Crops in this area also tend to be affected by extreme weather events (such as hail and storms) more often, which can reduce or completely destroy the crop in a given year (Olesen et al. 2011). Irrigation is important for crop production in many Mediterranean countries due to high levels of evapotranspiration and limited rainfall. On the other hand, the most productive regions in Europe in terms of climate and soils are located in the Great European Plain, stretching from southeast England through France and Benelux to Germany. In addition to a milder and more favorable Atlantic climate in these regions (see Fig. 1), the more favorable topography should also be considered, which makes the use of highly mechanized agricultural techniques more efficient. These regions also have better supported rural areas, where rural sectors have a history of receiving comparatively higher levels — and/or perhaps better-managed — research and infrastructure investments. Central Europe (represented by the Czech Republic and Austria) has comparatively drier conditions and a greater range of variation in annual temperatures, limiting the range of crops that can be grown and the yields of those that are grown.

Our analyses showed that overall crop production levels can be at least partly attributed to the prevailing climatic conditions (see Fig. 3). This means that the extent of the progress made in increasing yield in the 20th century has been shaped both by the climatic patterns (determining suitability) and by technological and socio-economic changes. For example, wheat and barley yield levels, as well as the rates of their increase, in the Czech Republic and Austria (or Croatia and Italy) were found to be approximately equal (comparing results in Fig. 3) despite the fact that these countries, which are similar climatically (as shown in Fig. 1), followed very different paths in their development (see Table 1). In contrast, yield levels in Denmark, Belgium, The Netherlands and Lower Saxony were markedly higher across all time periods analyzed than those of the rest of the group. This is to a great extent attributable to more favorable climatic conditions, because all 4 countries are in the same environmental zone (Atlantic North; Fig. 1a), characterized by mild winters, sufficient and well distributed precipitation and cool summers, among other factors (Metzger et al. 2005). In addition, the overall structure of the farming sector, a relatively fast adoption of modern technologies driven by advanced agricultural research, and past and present investment levels have also supported the attainment of higher yields in these countries than in other countries.

As wheat and barley yields are limited in northern Europe by cool temperatures (Holmer 2008) and in southern Europe by high temperatures and low rainfall (Reidsma & Ewert 2008) it was hypothesized that the response to warming within these regions is likely to differ. Indeed, in Finland and Norway we found an increasing influence of temperature, and in Bulgaria and Tuscany of drought, after 1951 (Table 5). Somewhat surprisingly, variations in maximum temperature were shown to explain a portion of yield variability only in some northern and northwestern regions (Table 5), which might be explained by the use of cultivars adapted to the high temperatures of the southern regions. However, this adaptation in the choice of varieties planted and in management is likely also to contribute to generally lower yields. A study by Olesen et al. (2011) seems to support this argument, showing that in Finland, a small yield increase has occurred during the last 10–20 yr that is partly linked to increasing temperatures, which has allowed earlier sowing and a prolonged growing season (Rötter et al. 2013, Peltonen-Sainio & Jauhiainen 2014, Palosuo et al. 2015). On the other hand, the wheat yields in Greece have been declining, which is likely also linked to the increase in temperatures.

The significance of the single variables as presented in Table 4 is likely influenced by the multicollinearity of the individual predictors, and must be interpreted carefully (Farrar & Glauber 1967). For example, when Tavg is significant and Tmax is not, the significance of Tmax is probably only 'hidden' by the multicollinearity. However, the adjusted R^2 values are presented for the whole model and thus the predictability skill of the model is not overestimated. On the other hand, adjusted R^2 might even underestimate predictability, as R^2 is 'adjusted' by the number of variables, but some variables bring only little new predictive power (because of the multicollinearity). Nevertheless, because of the relatively large number of variables used, the 'adjusted' version of R^2 is more realistic that the non-adjusted R^2.

Overall, wheat yields in several European countries have been shown to increase in variability, which can be linked to climatic variability (Olesen et al. 2011). The stagnating wheat (and barley) yields across European regions (as depicted in Fig. 3) have been found to be co-determined by the warming climate (Brisson et al. 2010) and/or by changes in management, especially in the changes to fertilization application due to environmental regulations (Finger 2010, Palosuo et al. 2015, Peltonen-Sainio et al. 2015). Gömann et al. (2015) reported that wheat crops have been extended to less favorable sites during the last decades in Germany. Regardless of the cause, post-1990 yield variability is, in absolute terms, significantly higher in most of the evaluated regions, while in terms of relative variability (accounting for the increase in mean yield), it remains approximately stable. The higher variability in yields with higher yield levels is coupled to the greater impact of yield-reducing factors, such as elevated temperatures that shorten crop growth durations, or greater water consumption by high-yielding crops that enhance the yield reductions caused by drought (Liu et al. 2013).

In the period from 1991–2012, only the combination of climatic factors, and not any single factor, could explain yield variability to some extent (compare results in Tables 3 & 5). This indicates that with the changes brought by technological progress, the influence of climate on yields may have become more complex than in the past. This might also signal that the climatic trends are becoming at least as important as the technological trends (e.g. new machinery, better seeds, new cultivars, fertilizers and pesticides) that have dominated European agriculture, especially in the 1951–1990 period (Fig. 3c,d). In addition, other factors, such as soil compaction and reduced soil organic matter content and fertility are important, and may increase the vulnerability of crops to climatic constraints, at least locally (e.g. Peltonen-Sainio et al. 2015). The increasing availability of fertilizers fostered a shift to growing crops in formerly less productive sites (e.g. those with sandy soils), which might have increased the harmful impact of climatic factors. On the other hand, pests and nutrient deficiencies limited crop growth in the earlier periods analyzed here, but have become less important in many regions in recent decades. There is at least local evidence that in some regions, agri-environmental policies and economic challenges faced by farms (e.g. uncertainty over rented lands) have encouraged reduced use of pesticides and nutrients and less balanced crop rotations in recent years, possibly impacting yields and yield variation (Peltonen-Sainio et al. 2015). Overall yield growth rates across the regions in 1991–2012 were similar to those based on the data from 1901–1950. From a long-term perspective, this constitutes a question of a major importance that should be addressed across Europe.

Although food security in Europe is thought to be less dependent on the climate due to technologically sophisticated agricultural practices (Brown & Funk 2008), our results indicate that climatic variability still has a significant influence on European wheat and barley productivity. However, the key drivers for changes in productivity differ even within similar environmental regions, and they seem to change with time. Efforts to increase the preparedness of the farmers to adapt to climatic variations are needed, and should result in concrete measures enabling sustainable and more stable food production. This is even more urgent when considering the fact that the present study did not account (due to data constraints) for many types of adverse events that can negatively influence yields. This has been reported for several types of extreme events over recent decades in Germany (Gömann et al. 2015), and a potential increase in the frequency of adverse events was noted by Trnka et al. (2011, 2014, 2015), showing the risk of a several-fold increase in the frequency of events known to lead to decreases in crop yield.

5. CONCLUSIONS

This study shows that there is strong (and sometimes counterintuitive) geographical specificity by which factors determine yield variations. For example, while precipitation is amongst the most important factors explaining year-to-year yield changes in Belgium, The Netherlands and Lower Saxony, the indicators of drought variations were found to have only limited explanatory power, even in countries where wheat and barley production is known to be limited by water availability.

It is clear that the influence of climatic variables on yields of wheat and barley has increased in the period from 1991–2012 in most countries. It is important to note that the different set of predictors explained yield variability in this period better than in the periods 1901–1950 and 1951–1990. This leads us to conclude that climate change is altering the sensitivity to particular climatic factors.

Variations in climatic factors (combined together) explained between 18 and 71% of wheat yield variability and between 5 and 60% of barley yield variability in the 1991–2012 period. The ability to explain yields based on climatic factors increases (albeit not markedly) when we take into account country-specific time windows, and shows that the April–June period is critical for yield formation of barley and wheat in most of the studied region.

We also conclude that changes in the climate–yield relationships would likely be more easily established over smaller and more homogenous regions than over those for which we were able to collect corresponding data. However, such data are not available — at least not for the countries we analyzed — and thus we conclude that the study of climate–yield relationships in Europe is significantly hampered by limited accessibility of agricultural statistics, especially prior to 1961. Despite great effort in collecting data on the 12 European regions studied here, it was difficult to produce a sufficiently complete database on crop yields that covered the period between 1901–2012, even for the 2 most widely grown crops. As we primarily selected regions that were not significantly affected by changes in borders, the situation in other regions of Europe is likely to be even worse. The lack of an accessible and reliable NUTS4-level yield database for European Union or Europe in general (similar e.g. to the county yield statistics in the USA) hampers not only this type of research activity in Europe, but limits any studies linking the yield of key agricultural products to environmental factors.

Acknowledgements. We thank Heidelinde Trimmel (University of Applied Life Sciences in Vienna) for her support through the historical FAO yearbook search complementing nation based efforts. The paper is the result of a collaboration within the JPI-FACCE MACSUR project and COST ES1106 with its local Czech project no. LD 13030. M.T., P.H., J.B., P.Š. and K.R. acknowledge support from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I LO1415). M.T. and P.H. were supported by the National Agency for Agricultural Research (project no. QJ1310123) and R.B. by the Czech Grant Agency (project no. 13-19831S).

LITERATURE CITED

Brisson N, Gate P, Gouache D, Charmet G, Oury FX, Huard F (2010) Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Res 119:201–212

Brown ME, Funk CC (2008) Food security under climate change. Science 319:580–581

Calderini DF, Slafer GA (1998) Changes in yield and yield stability in wheat during the 20th century. Field Crops Res 57:335–347
Elsgaard L, Børgesen CD, Olesen JE, Siebert S and others (2012) Shifts in comparative advantages for maize, oat, and wheat cropping under climate change in Europe. Food Addit Contam Part A Chem Anal Control Expo Risk Assess 29:1514–1526
Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I. Estimating changes in crop productivity. Agric Ecosyst Environ 107:101–116
FAO (2006) The state of food insecurity in the world 2006. Food and Agriculture Organization of the United Nations, Rome
FAO (2013) FAO statistical yearbook 2013: world food and agriculture. Food and Agriculture Organization of the United Nations, Rome
Farrar DE, Glauber RR (1967) Multicollinearity in regression analysis: the problem revisited. Rev Econ Stat 49:92–107
Finger R (2010) Evidence of slowing yield growth — the example of Swiss cereal yields. Food Policy 35:175–182
Gobin A (2012) Impact of heat and drought stress on arable crop production in Belgium. Nat Hazards Earth Syst Sci 12:1911–1922
Gömann H, Bender A, Bolte A, Dirksmeyer W and others (2015) Agrarrelevante extremwetterlagen und möglichkeiten von risikomanagementsystemen. Thünen Report 30, Johann Heinrich von Thünen-Institut, Braunschweig
Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations — the CRU TS3.10 dataset. Int J Climatol 34:623–642
Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Žalud Z, Možný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric Meteorol 149:431–442
Holmer B (2008) Fluctuations of winter wheat yields in relation to length of winter in Sweden 1866 to 2006. Clim Res 36:241–252
Kristensen K, Schelde K, Olesen JE (2011) Winter wheat yield response to climate variability in Denmark. J Agric Sci 149:33–47
Liu L, Hu C, Olesen JE, Ju Z, Yang P, Zhang Y (2013) Warming and nitrogen fertilization effects on winter wheat yields in northern China varied between four years. Field Crops Res 151:56–64
Lobell DB, Burke MB (2008) Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environ Res Lett 3:034007
Lobell DB, Field CB (2007) Global scale climate-crop yield relationships and the impacts of recent warming. Environ Res Lett 2:014002
Lobell DB, Schlenker WS, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science 333:616–620
Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of Europe. Glob Ecol Biogeogr 14:549–563
Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712
Monfreda C, Ramankutty N, Foley JA (2008) Farming the planet. 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem Cycles 22:GB1022
Olesen JE, Jensen T, Petersen J (2000) Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Clim Res 15:221–238
Olesen JE, Trnka M, Kersebaum KC, SkjelvÍg O and others (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96–112
Palmer WC (1965) Meteorological drought. Office of Climatology Research Paper 45, US Weather Bureau, Washington, DC
Palosuo T, Rötter RP, Salo T, Peltonen-Sainio P, Tao F, Lehtonen H (2015) Effects of climate and historical adaptation measures on barley yield trends in Finland. Clim Res 65:221–236
Peltonen-Sainio P, Jauhiainen L (2014) Lessons from the past in weather: sowing to ripening dynamics and yield penalties for northern agriculture from 1970 to 2012. Reg Environ Change 14:1505–1516
Peltonen-Sainio P, Jauhiainen L, Trnka M, Olesen JE and others (2010) Coincidence of variation in yield and climate in Europe. Agric Ecosyst Environ 139:483–489
Peltonen-Sainio P, Salo T, Jauhiainen L, Sieviläinen E (2015) Static yields and quality issues: Is the agri-environment program the primary driver? Ambio 44:544–556
Porter JR, Xie L, Challinor AJ, Cochrane K and others (2014) Food security and food production systems. Climate change 2014: impacts, adaptation, and vulnerability. Part A. Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 485–533
Ramankutty N, Foley JA (1999) Estimating historical changes in global land cover: croplands from 1700 to 1992. Global Biogeochem Cycles 13:997–1027
Ray DK, Ramankutty N, Mueller ND, West PC, Foley JA (2012) Recent patterns of crop yield growth and stagnation. Nat Commun 3:1293
Reidsma P, Ewert F (2008) Regional farm diversity can reduce vulnerability of food production to climate change. Ecol Soc 13:art38
Rötter RP, Höhn J, Trnka M, Fronzek S, Carter TR, Kahiluoto H (2013) Modelling shifts in agroclimate and crop cultivar response under climate change. Ecol Evol 3:4197–4214
Slafer GA, Peltonen-Sainio P (2001) Yield trends of temperate cereals in high latitude countries from 1940 to 1998. Agric Food Sci Finland 10:121–131
Slafer GA, Rawson HM (1994) Sensitivity of wheat phasic development to major environmental factors: a re-examination of some assumptions made by physiologists and modellers. Aust J Plant Physiol 21:393–426
Slafer GA, Rawson HM (1996) Responses to photoperiod change with phenophase and temperature during wheat development. Field Crops Res 46:1–13
Solomon S, Qin D, Manning M, Marquis M and others (eds) (2007) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
Stocker TF, Qin D, Plattner GK, Tignor M and others (eds) (2013) Climate change 2013: the physical science basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Trnka M, Dubrovsky M, Svoboda M, Semeradova D, Hayes M, Zalud Z, Wilhite D (2009) Developing a regional drought climatology for the Czech Republic. Int J Climatol 29:863–883

Trnka M, Olesen JE, Kersebaum KC, Skjelvag AO and others (2011) Agroclimatic conditions in Europe under climate change. Glob Change Biol 17:2298–2318

Trnka M, Brázdil R, Olesen JE, Zahradníček P and others (2012) Could the changes in regional crop yields be a pointer of climatic change? Agric For Meteorol 166-167: 62–71

Trnka M, Rötter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Žalud Z, Semenov MA (2014) Adverse weather conditions for European wheat production will become more frequent with climate change. Nat Clim Change 4: 637–643

Trnka M, Hlavinka P, Semenov MA (2015) Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change. J R Soc Interface 12:20150721

Editorial responsibility: Donald Wilhite (Guest Editor), Lincoln, Nebraska, USA

Submitted: April 4, 2016; Accepted: August 19, 2016
Proofs received from author(s): October 24, 2016

Vol. 70: 215–230, 2016
doi: 10.3354/cr01411

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe – from drought response to preparedness'

Relationships between the evaporative stress index and winter wheat and spring barley yield anomalies in the Czech Republic

Martha C. Anderson[1,*], Christopher R. Hain[2], Frantisek Jurecka[3], Miroslav Trnka[3], Petr Hlavinka[3], Wayne Dulaney[1], Jason A. Otkin[4], David Johnson[5], Feng Gao[1]

[1]Hydrology and Remote Sensing Laboratory, USDA-ARS, Beltsville, MD 20705, USA
[2]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20742, USA
[3]Department of Agrosystems and Bioclimatology, Mendel University, 613 00 Brno, Czech Republic
[4]University of Wisconsin-Madison, Madison, WI 53706, USA
[5]USDA National Agricultural Statistics Service, Fairfax, VA 22030, USA

ABSTRACT: There is a growing demand for timely, spatially distributed information regarding crop condition and water use to inform agricultural decision making and yield forecasting efforts. Thermal infrared remote sensing of land-surface temperature has proven valuable for mapping evapotranspiration (ET) and crop stress from field to global scales using energy balance models. This is because canopy temperature is strongly regulated by the transpiration flux, which is reduced under stress conditions. This study investigates the utility of an evaporative stress index (ESI), computed using the thermal-based Atmosphere–Land Exchange Inverse (ALEXI) surface energy balance model, for explaining yield variability over the Czech Republic for the period 2002–2014. ESI timeseries, representing standardized anomalies in the actual-to-reference ET ratio and an indicator of vegetation health, are compared with yield data collected for winter wheat and spring barley crops in 32 agricultural districts, comprising a range of climatic conditions within the Czech Republic. Correlations between ESI and yield anomalies vary with climatic region, with strongest correlations identified in the more drought-prone South Moravian districts and weaker relationships in the wetter highlands regions. In most regions, correlations with spring barley yield anomalies exceeded performance for winter wheat. For both crops, correlations peaked during the 1 to 2 mo period prior to the nominal harvest date. These results provide guidance for effective integration of remotely sensed moisture stress indicators within operational yield forecasting systems.

KEY WORDS: Evapotranspiration · Drought · Agriculture · Remote sensing · Crop yields · Czech Republic

1. INTRODUCTION

Remote sensing indicators are now widely used in agriculture for monitoring crop condition and forecasting yield (Wardlow et al. 2012, Basso et al. 2013, Rembold et al. 2013). Prominent indicators include empirical vegetation indices, such as the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI), which track crop progress and evolution in green biomass amount (Kogan et al. 2003, Mkhabela et al. 2005, 2011, Becker-Reshef et al. 2010, Esquerdo et al. 2011, Fernandes et al. 2011, Gusso et al. 2013, Kouadio et al. 2014). Other more physically based vegetation

*Corresponding author: martha.anderson@ars.usda.gov

Publisher: Inter-Research · www.int-res.com

indices describe light-harvesting capacity or photosynthetic rates, including the leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (fAPAR), or fluorescence spectral features (Lobell et al. 2002, Doraiswamy et al. 2005, Zhang et al. 2005, Rizzi & Rudorff 2007, López-Lozano et al. 2015, Guan et al. 2016). Other remote sensing indicators reflect various aspects of the surface moisture status, i.e. water supply measured as rainfall, water storage in the soil profile and groundwater retrieved using microwave radiometers or gravimetry, and plant water use assessed via satellite-based estimates of evapotranspiration (ET) (Anderson et al. 2007, Bolten et al. 2010, AghaKouchak & Nakhjiri 2012, Houborg et al. 2012).

Many studies have investigated correlations between satellite indices and crop yields, with the goal of identifying robust advance indicators of yield anomalies at harvest (e.g. Unganai & Kogan 1998, Bastiaanssen & Ali 2003, Johnson 2014, Anderson et al. 2016). These combined studies have demonstrated that no single indicator prevails always and everywhere, with relative performance depending on climate, soils, management, crop type, and growing season, as well as specific sensor limitations. For this reason, multi-indicator approaches have emerged to support operational drought and yield monitoring efforts (e.g. Bastiaanssen & Ali 2003, Doraiswamy et al. 2007, Anderson et al. 2012b, Johnson 2014). To support these new approaches, we need to better understand the major drivers of yield correlation variability for different indices in order to be able to optimally combine available satellite assets.

This study focuses on the behavior of the evaporative stress index (ESI), an indicator of agricultural drought expressed as standardized anomalies in the ratio of actual-to-potential ET as retrieved using a land surface temperature (LST) based energy balance algorithm (Anderson et al. 2011, 2013, 2015). ET estimates based on LST have the advantage of being more sensitive to variations in both soil surface and root-zone moisture content in comparison with simpler crop coefficient techniques (Anderson et al. 2012a). LST contains thermal signals of both plant stress and soil moisture deficiency, with elevated canopy and soil temperatures resulting from decreased transpiration and soil evaporation fluxes (Moran 2003). Thermal infrared (TIR) retrievals of LST can provide moisture information at smaller spatial scales than are currently accessible through microwave remote sensing, enabling mapping down to sub-field scales (Anderson et al. 2012a). In addition, studies have demonstrated that LST-based ET estimates often provide earlier warning of declining vegetation health than do standard reflectance-based vegetation indices, particularly during rapid drought onset events (Otkin et al. 2013, 2014, 2015, 2016).

Anderson et al. (2016) evaluated the performance of ESI as an indicator of agricultural drought in Brazil, using yield data collected at both the state and municipal levels as a metric of drought impact. ESI showed advantages over LAI and precipitation anomalies, particularly in response to rapidly changing moisture conditions in northeast and southern Brazil. The variability in ESI correlations with yield anomalies over the country was found to be strongly related to local volatility in yield, with lower performance in states showing low year-to-year variability in yield due to more stable growing conditions and rainfall. In some cases, excess moisture can lead to yield reductions, e.g. due to waterlogging or moisture-favoring pests and diseases. Changes in crop management and technology over the period of analysis can further confound correlation analyses.

In this study, factors influencing ESI-yield correlations are investigated using yield data collected at the district scale from 2002 to 2014 in several agricultural regions within the Czech Republic (CR), which span a range in growing conditions related to local climate and elevation. The study compares ESI performance for 2 important cereal crops in Czech agricultural production: winter wheat and spring barley. These crops together comprise the highest planted acreage in field crops in the CR, and encapture different growing seasons (winter vs. spring), which expose the crops to different seasonal impacts in terms of timing and strength of moisture sensitivities (Hlavinka et al. 2009, Trnka et al. 2012).

2. MATERIALS AND METHODS

2.1. Study area

The study area in the CR is outlined in Fig. 1, along with maps of relevant physical characteristics of the region including elevation and cropping intensity. The districts analyzed in the study (listed in Table 1 and delineated in Fig. 1a) were selected because they had a full record of annual yields for both winter wheat and spring barley over the study period. These districts lie within the regions of Central, South and Northeast Bohemia (STC, JHC, and HKK, respectively), South Moravia (JHM), Northwest and Central

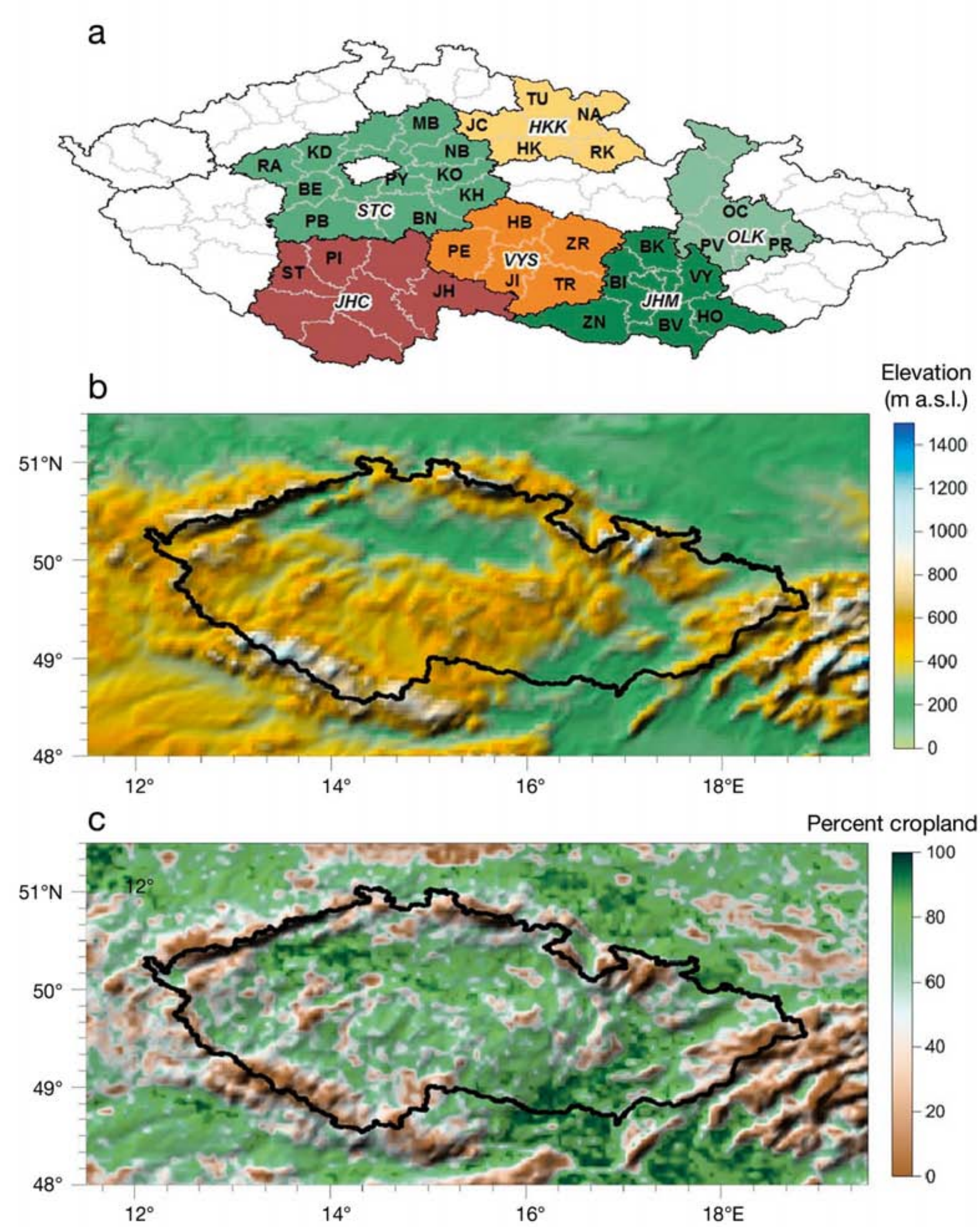

Fig. 1. Study area for investigation of relationships between the evaporative stress index (ESI) and crop yields in the Czech Republic (CR): (a) districts and regions included in the analysis (see Table 1 for abbreviations); (b) average elevation (m a.s.l.); (c) percent cropland in each 0.05° grid cell

Moravia (OLK), and a region straddling the Bohemian-Moravian highlands (VYS).

In the CR, the intensity of cropped area is highest at the lower elevations (JHM, STC and OLK) due to more favorable climate and water availability (Fig. 1b,c). While most crops in the CR are rainfed, irrigation is used to a limited extent as a supplemental water source, mostly for high value crops at the lowest elevations, e.g. in the river valleys in JHM and STC. In the highland regions, rainfall is more plentiful due to terrain-enhanced precipitation. JHC includes forested mountainous terrain bordering Germany, and has the lowest average cropping intensity of the regions studied.

2.2. Yield data and crop characteristics

This study focuses on 2 major cereal crops grown in the Czech Republic: winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare*). Together, they represented in 2015 >42 % of arable land (31 %

Table 1. Abbreviations and summary data for districts and regions in the Czech Republic considered for study of relationships between the evaporative stress index (ESI) and wheat and barley yields. Average (Avg) percentages of cropland are based on Moderate Resolution Imaging Spectroradiometer (MODIS) data; crop yields show values for winter wheat and barley for the period 2002–2014

Abbreviation	District	Region	Elevation (m a.s.l.)	Avg cropland (%)	Avg barley yield (t ha^{-1})	Avg wheat yield (t ha^{-1})
BN	Benešov	Středočeský kraj (STČ),	430	66	3.9	5.4
BE	Beroun	Central Bohemia	378	59	3.2	4.1
KD	Kladno		315	78	4.4	5.3
KO	Kolín		255	80	4.9	5.6
KH	Kutná Hora		361	71	4.8	5.9
MB	Mladá Boleslav		256	66	5.2	5.8
NB	Nymburk		195	75	5.0	5.7
PY	Praha-východ		302	70	5.1	5.9
PB	Příbram		483	50	3.9	4.9
RA	Rakovník		409	60	4.0	5.0
JH	Jindřichův Hradec	Jihočeský kraj (JHČ),	509	47	4.1	4.9
PI	Písek	South Bohemia	447	57	3.9	4.9
ST	Strakonice		477	66	3.8	5.0
HK	Hradec Králové	Královéhradecký	243	74	5.5	6.5
JC	Jičín	kraj (HKK),	308	68	5.2	6.2
NA	Náchod	Northeast Bohemia	422	62	4.4	5.7
RK	Rychnov nad Kněžnou		465	53	4.4	5.2
TU	Trutnov		582	42	3.9	5.1
BK	Blansko	Jihomoravský kraj	485	52	4.3	5.1
BI	Brno-venkov	(JHM), South Moravia	325	68	4.5	5.2
BV	Břeclav		195	80	3.9	4.6
HO	Hodonín		252	68	4.2	4.9
VY	Vyškov		342	67	5.2	5.8
ZN	Znojmo		301	81	4.2	5.0
OC	Olomouc	Olomoucký kraj (OLK),	406	62	5.5	6.5
PV	Prostějov	Northwest/Central	374	77	5.5	6.5
PR	Přerov	Moravia	307	77	4.8	5.7
HB	Havlíčkův Brod	Kraj Vysočina (VYS),	494	67	4.5	5.3
JI	Jihlava	Bohemian-Moravian	579	63	4.8	5.8
PE	Pelhřimov	Highlands	570	65	4.4	5.3
TR	Třebíč		473	75	4.1	5.3
ZR	Ždár nad Sázavou		577	61	4.7	5.5

for winter wheat and 11% for spring barley) according the Czech Statistical Office (https://vdb.czso.cz/vdbvo2/faces/en/index.jsf). The percentage of total acreage comprised of spring barley was even higher in the early part of the analyzed period due to the higher demand for feed grain. Winter wheat is typically sown in late September and spring barley in late March. They are usually harvested from early July to mid August, depending on the season.

These crops were chosen in part to investigate differences in ESI sensitivity for winter versus spring crops. Winter crops are typically less sensitive to spring and summer droughts because they already have well-established rooting systems as the warm growing season commences (Hlavinka et al. 2009). However, they are more sensitive to fall drought and lack of snow cover (Zahradníček et al. 2015). Establishing a parity between spring and winter cereal crops distributes climatic risk and may be an effective means for climatic adapation.

Yield data for the period 2002–2014 were obtained primarily from the Ministry of Agriculture of the Czech Republic (http://eagri.cz/public/web/en/mze/). In districts and years where it was difficult to find any existing data, yield estimates from the Czech Agrarian Chamber were used (www.agrocr.cz/?lang=2). The Czech Agrarian Chamber is an organization of entities doing business in agriculture, forestry and the food industry, and supporting business activities in these areas.

These yield estimates were developed from statistical surveys of farmers operating in each agricultural district, and may have some level of bias due to sampling structure. Differences in the composition and size of the farm sample might also be an issue in several districts. The yield estimates therefore have some level of uncertainty and tend to be lower than observations obtained from small experimental fields. Furthermore, yield estimates are based on area harvested rather than area planted. On years with very poor growing conditions, these estimates may underestimate true yield losses as abandoned crops are not accounted for. Still, they reasonably represent existing variability in the yield levels that can be explained by climatic factors and have been effectively used for spatial analyses of agricultural production in the CR (e.g. Hlavinka et al. 2009, Trnka et al. 2012).

2.3. Evaporative stress index

The ESI represents standardized anomalies in the ratio of actual-to-reference ET (f_{RET}), highlighting areas where landscape evaporative fluxes, including the crop transpiration rate in cropped areas, are higher or lower than normal for a given seasonal interval. Normalization by reference ET reduces the impact of climate and radiation drivers on the ET flux, making the ESI more specifically responsive to soil moisture drivers. A standard FAO-56 Penman-Monteith reference ET for grass (Allen et al. 1998) is used for normalization, based on sensitivity tests by Anderson et al. (2013).

This study uses ESI data for 2002–2014 extracted from a global product created at 0.05° resolution (roughly 5 km) and weekly timesteps. The actual ET data are generated with the time-differential Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance model using day-night temperature differences from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua satellite (Anderson et al. 2015). The global ESI products are routinely created for 4, 8 and 12 wk (roughly 1, 2 and 3 mo) composite timeframes to represent different temporal scales of drought and pluvial conditions. These products are referred to as ESI-1, ESI-2 and ESI-3, respectively. Composited f_{RET} values over these time frames are differenced with climatological mean values and normalized by the variability in f_{RET} over the period of record. For more details, see Anderson et al. (2015).

2.4. Regional variables

2.4.1. Elevation

Elevation data (Fig. 1b) were obtained from the Global 30-Arc-Second Elevation dataset (GTOPO30; Gesch et al. 1999) and averaged onto the 0.05° ESI grid. Elevation is one factor used to understand variations in the ESI–yield relationships.

2.4.2 Percent cropland

Percent cropland in Fig. 1c was extracted from a global 1 km consensus land-cover product which is based on a harmonization of several individual products (Tuanmu & Jetz 2014), including GlobCover (Bicheron et al. 2011), the MODIS land-cover product (MCD12Q1; Friedl et al. 2010), GLC2000 (Bartholomé & Belward 2005) and DISCover-IGBP (Loveland & Belward 1997). The product was aggregated to the 0.05° ESI grid.

2.4.3. Climatological variables

District level measures of average air temperature and precipitation for April to September were obtained from Hlavinka et al. (2009). These variables were determined from station data collected over the period 1961–2000. Although these data do not overlap the period of record studied here, we make the assumption that the relative inter-district variability in climatological variables has not changed significantly, although the absolute values are not likely to be stationary.

2.5. Yield correlations

To better constrain the analysis to agricultural zones within each district, ESI data were averaged over each district area using only pixels with percent cropland >50% as defined by the MODIS product described in Section 2.4.2. This threshold was selected to minimize contributions from pixels with predominantly forest, urban or natural vegetation cover while still retaining a reasonable sample size for district averaging. Anderson et al. (2015) demonstrated that the ESI behavior of forested areas in Brazil in the face of drought significantly differed from that of agriculture and short vegetation. This may be due to a combination of physiological effects or deeper rooting depths characteristic of forests, which add resilience to moisture deficit events. Masking contributions from forest and other non-agricultural landcovers improved ESI-yield correlations in the current study.

Yield anomalies were computed at the district level as departures from a linear regression in time over the 2002–2014 period to remove trends in increasing annual yield that may result from technological advances, land management changes or genetic improvements in cultivars, as follows:

$$yield(u,y)' = yield(u,y) - yield_{lin}(u,y) \quad (1)$$

where u is the political unit in question (CR district), y is the year, and $yield_{lin}$ is given by a linear temporal fit to all yield data for that unit over the period of record.

ESI-yield correlations were quantified using the Pearson correlation coefficient (r) computed from $ny \times ns$ samples, where $ny = 13$ is the number of years of yield data included in the analysis (2002–2014), and ns is the number of districts included in a regional evaluation, which varies from region to region.

For district-level yield analyses, correlations were computed at 7 d intervals between ESI-3 and yield anomalies (Eq. 1). In order to identify optimal compositing windows during the growing season when an index is most predictive of at-harvest yield, a 2-dimensional correlation space was computed for each index, crop and region. In these analytical plots, the x-axis represents the end-date of the index averaging window, and the y-axis represents the length of the window.

3. RESULTS AND DISCUSSION

3.1. Regional timeseries

Annual maps of ESI-3 (3 mo composites) and detrended yield anomalies for winter wheat and spring barley crops in the targeted districts for 2002–2014 are shown in Fig. 2. ESI maps for Week 26 (3 mo period ending 2 July) and Week 30 (ending 29 July) are included to represent the periods of peak correlation with winter wheat and spring barley yield anomalies, respectively (see Section 3.2). In general, there is reasonable spatial and temporal correspondence between the 2 datasets. Drought years (2003, 2006, 2007 and 2012) with large yield reductions were captured by negative anomalies in the ESI. In addition, the high-yield years of 2004 and 2014 are associated with positive ESI values (green in Fig. 2). JHM shows particularly strong interannual volatility in yields (e.g. contrast 2011, 2012 and 2013), related to highly variable rainfall amounts. The 2012 drought in some south Moravian districts was classified as the worst in 130 years, with subtantial yield reductions (particularly in winter crops) and even wildfire outbreaks, which are fairly rare in the region (Zahradníček et al. 2015). In 2009 and 2010, differences in ESI-3 maps between Weeks 26 and 30 indicate rapidly changing moisture conditions during the summer season, in both cases associated with average or below-average yields.

In Fig. 3, time series of district-averaged ESI and yield data for representative districts in each region provide an example of inputs to the temporal correlation analyses discussed in the following sections.

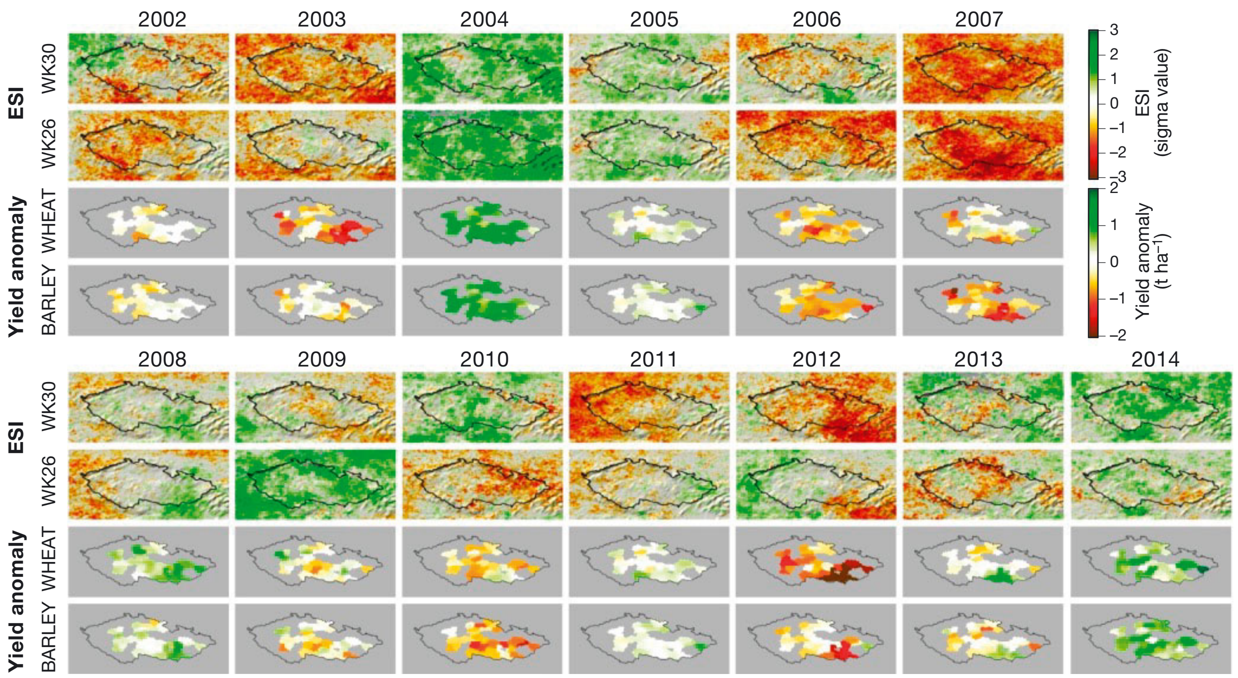

Fig. 2. Time series of maps for 2002–2014 of the 3 mo composite evaporative stress index (ESI-3; in units of sigma values) for Weeks 26 and 30 compared to yield anomalies (t ha^{-1}) for winter wheat and spring barley crops in target agricultural districts in the Czech Republic

These plots clearly demonstrate widespread yield reductions in both 2003 and 2012, particularly in Moravia (JHM and OLK), corresponding to mid-year negative spikes in ESI. However, as in the case of 2007 or most recently 2015, even quite pronounced spring or summer drought may not necessarily lead to severe yield reduction. In these years, the impacts were mitigated, particularly for winter crops, by an earlier start of season which caused the crops to overwinter better and in general establish deeper and more resilient root systems (Trnka et al. 2015). In contrast, droughts that occur in late fall the prior year will be more detrimental to winter crop yields (e.g. in 2012).

3.2. Correlation strength and timing

Results of the regional correlation analyses are summarized in Fig. 4, using detrended yield anomaly and ESI-3 timeseries with a 1 wk averaging window to suppress noise. Data from all target districts within each region were combined to increase sample size. Correlations are significant ($p < 0.01$) for $r > 0.4$ for JHC and OLK (3 districts), $r > 0.3$ for HKK, VYS and JHM (4 to 5 districts), and $r > 0.2$ for STC (10 districts). The week on the *x*-axis indicates the end of the 3 mo ESI composite used in the correlation computation.

The range in peak correlation strength is similar between crops (0.4 to 0.8), but regionally more

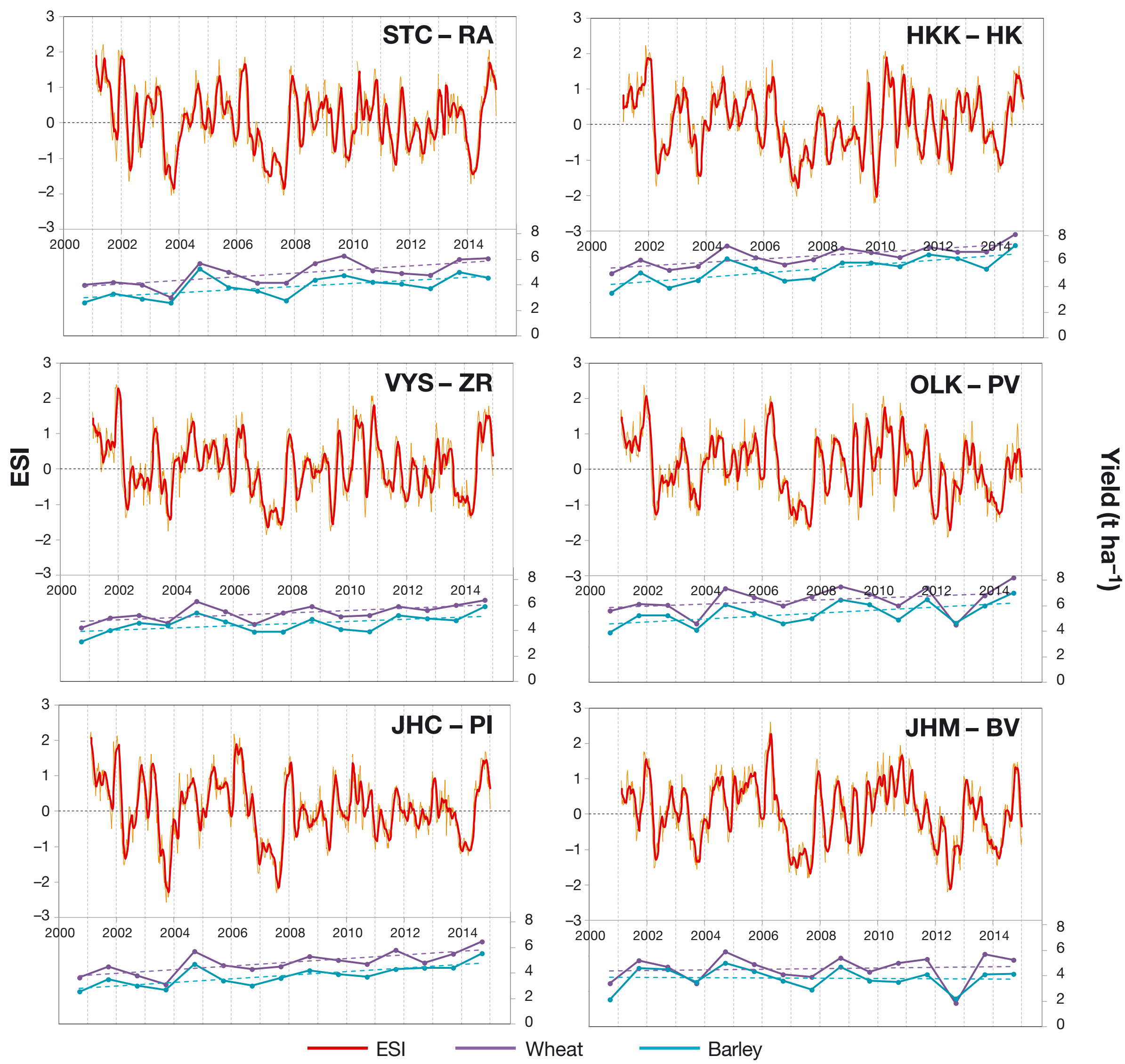

Fig. 3. ESI-3 timeseries averaged over representative districts for each region (see Table 1 for abbrviations) included in the analysis (thin orange line), compared with annual winter wheat (purple line) and spring barley (blue line) yields and linear yield trends (dashed lines). A 6 wk moving average of ESI-3 (thick red line) is included to highlight longer timescale signals

diverse for winter wheat than for spring barley, which is typically above 0.6 (excluding JHC). Due to the longer growing season, winter wheat crops are susceptible to a wider range of climatic events than is spring barley, including fall and summer droughts as well as winter snow cover duration and frosts (Kolář et al. 2014). In some districts, this will reduce index–yield correlations or diffuse them over a broader range in time. Correlations tend to peak earlier for winter wheat, during the 3 mo period ending around Weeks 26 to 28 (early to mid July), with earlier and higher peaks in Moravia than in the Bohemian regions. Spring barley peak correlations occur between Weeks 28 to 30 (mid to late July). Using ESI-1, the peaks correlations occur about 2 wk earlier, although the results have higher noise levels (not shown; the utility of shorter compositing intervals for crop modeling is discussed further in Section 3.4). In general, these findings are consistent with the nominal April–June periods of peak moisture sensitivity identified for these crops by Hlavinka et al. (2009) using a modified Palmer drought severity index, encompassing the critical yield-determining phenophases of grain development for both crops.

For both crops, JHC is an outlier, with statistically insignificant ESI–yield anomaly correlations (<0.4) throughout the growing season suggesting that moisture limitations on crop growth are not strong. This may be due in part to the higher preciptation rates and relatively shallow groundwater tables characteristic of this region. Also the proportion of agricultural land used for growing wheat and barley in JHC is small compared to the other regions studies, with large areas of the region's cropped land used for grazing or fodder production. In contrast, JHM shows the highest peak correlations, between 0.7 and 0.8. Large year-to-year variations in yield experienced in this region (noted in Section 3.1) contribute to the higher magnitudes of correlation here. The regional curves in Fig. 4 for CR crops demonstrate a significantly higher degree of inter-coherence in comparison with results obtained for state-level yields over Brazil (Anderson et al. 2016), likely due to the much smaller geographic extent of the study area in the current analysis.

Correlation window maps in Fig. 5 (described in Section 2.5) expand on the information in Fig. 4, showing correlations obtained over a broad range of index averaging windows. The maps represent correlations obtained for all districts combined, and segregated by region. These plots demonstrate the consistency in peak correlation timing between regions (i.e. the location of green maxima along the *x*-axis), as well as the relative strength of correlation between ESI and crop yields. OLK shows a tendency toward anticorrelation with ESI conditions (r ~ −0.4) around Week 10 for both crops. While this is likely an artifact of the specific set of moisture patterns that occured during the period of record, it does highlight the rapid high-amplitude within-season variability in ESI characteristic of this region (see Fig. 3). JHC, on

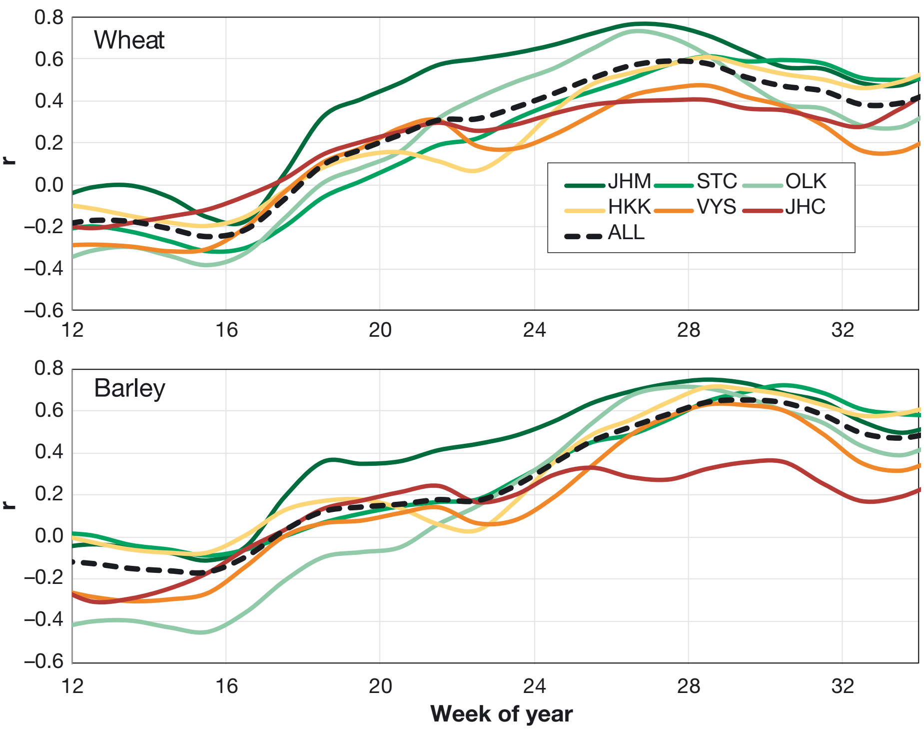

Fig. 4. Correlations between ESI-3 and (a) wheat and (b) barley yield anomalies for 2002–2014 in the Czech Republic as a function of end date (week of year) of the 3 mo composite index value, shown for each region and for all districts combined (ALL). See Table 1 for abbreviations of regions

the other hand, shows signals of even stronger anti-correlation with moisture conditions in the year prior to the current growing season. This too appears to be an artifact, driven largely by strong yield anomalies of opposite magnitude in 2003 and 2004 (Fig. 3). Such artificial features should diminish as more years of yield and remote sensing data become available.

Based on Fig. 5, the ranking in peak correlation strength by region is similar between crops, with JHM and OLK (Moravia) having the highest correlations, followed by HKK and STC (Bohemia), with JHC and VYS (southern highlands) consistently having the lowest correlations. Fig. 6 details correlation window maps for districts within JHM, demonstrating a consistency in correlation structures typical within most of the regions analyzed. Yield departures in the BV district for both crops are strongly related to ESI variations, with peak correlations of 0.85 for winter wheat and 0.81 for spring barley occurring around Weeks 26 to 27. BV is located in a valley at the confluence of the Dyje and Morava rivers, and is the climatologically warmest and driest of all the districts studied, accounting for the high susceptibility of crops to the moisture limiting conditions expressed in the ESI. Potential drivers of regional and inter-district variations in correlation strength are further considered in the following section.

3.3. Regional maps of correlation properties

Fig. 7 contains maps of various quantities describing the spatial variation in correlation between ESI and yield anomalies (timing and magnitude of peak

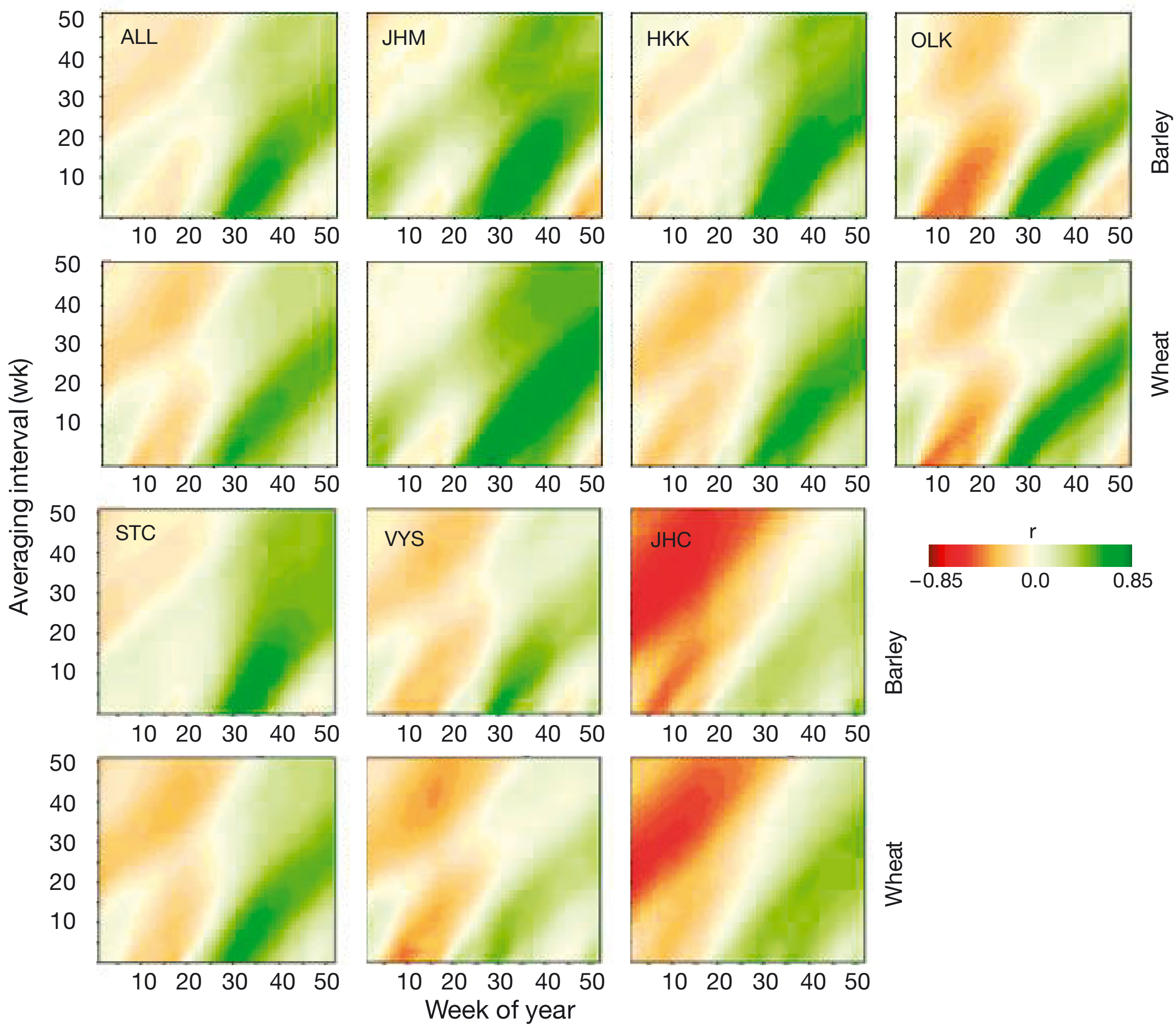

Fig. 5. Correlation of wheat and barley yield anomalies with ESI, plotted as a function of index averaging interval and end date for all 32 districts combined (ALL), and for each individual region. See Table 1 for abbreviations of regions

correlation, and regression yield errors) and potential drivers thereof (yield variability, cropping intensity, elevation, climate). Here 'yield error' is defined as the root mean square difference of the observed yield departures around the ESI-yield regression developed for the week with peak correlation. While it is not a true expected error in predicted yield since it has not been established using an independent data sample, it does provide some estimate of the expected spatial variability in predicted yield accuracy based on the quality of the regression. As more years of yield data become available, independent testing will become more feasible. Relative yield error is computed as yield error divided by the average yield observed over the 13 yr period of record.

In particular, we examine the role of elevation, climate, and yield stability, as described by the coefficient of variation (CV) in observed yield over time, as potential factors that might influence the correlation between ESI and yield anomalies in the CR. At higher elevations, the likelihood is increased that energy limitations (i.e. temperature and insolation) dominate over moisture constraints represented in the ESI. In areas with low yield variability, due to reliable growing conditions or irrigation or other factors that may stabilize yield from year to year, lower correlation coefficients may be expected with any crop indicator due to limitations in the range of variation (López-Lozano et al. 2015, Anderson et al. 2016).

As seen in Fig. 7 and in the scatter plots in Fig. 8, each of these factors appears to be spatially related to ESI correlation strength. The lowest ESI correlations are uniformly obtained at the highest elevations. This relationship reflects the effects of elevation-dependent

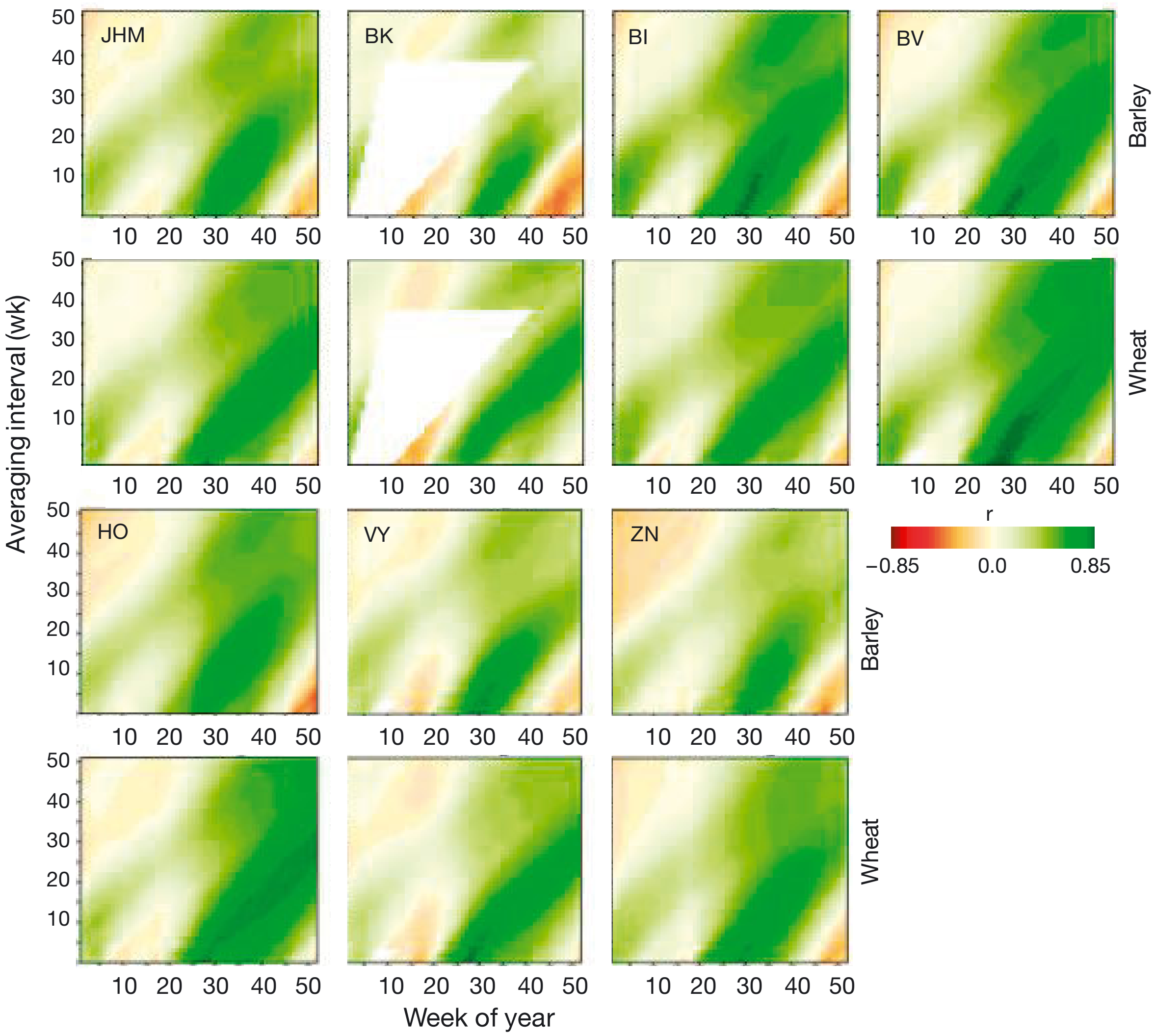

Fig. 6. Correlation of wheat and barley yield anomalies with ESI, plotted as a function of index averaging interval and end date for districts within the JHM (south Moravia) region. See Table 1 for abbreviations of districts

precipitation and temperature regimes, with higher correlations under the drier and warmer climates typically found at lower elevations in the CR, characterizing moisture-limiting growth conditions as in JHM (Fig. 7). These low elevation areas also tend to have higher interannual yield variability. Similar relationships were evident in agricultural regions in Brazil, where highest ESI performance was observed in the semiarid northeast regions, as well as the more humid south which experienced several episodes of flash drought during the study period (Anderson et al. 2016). In the higher elevation districts where rain-

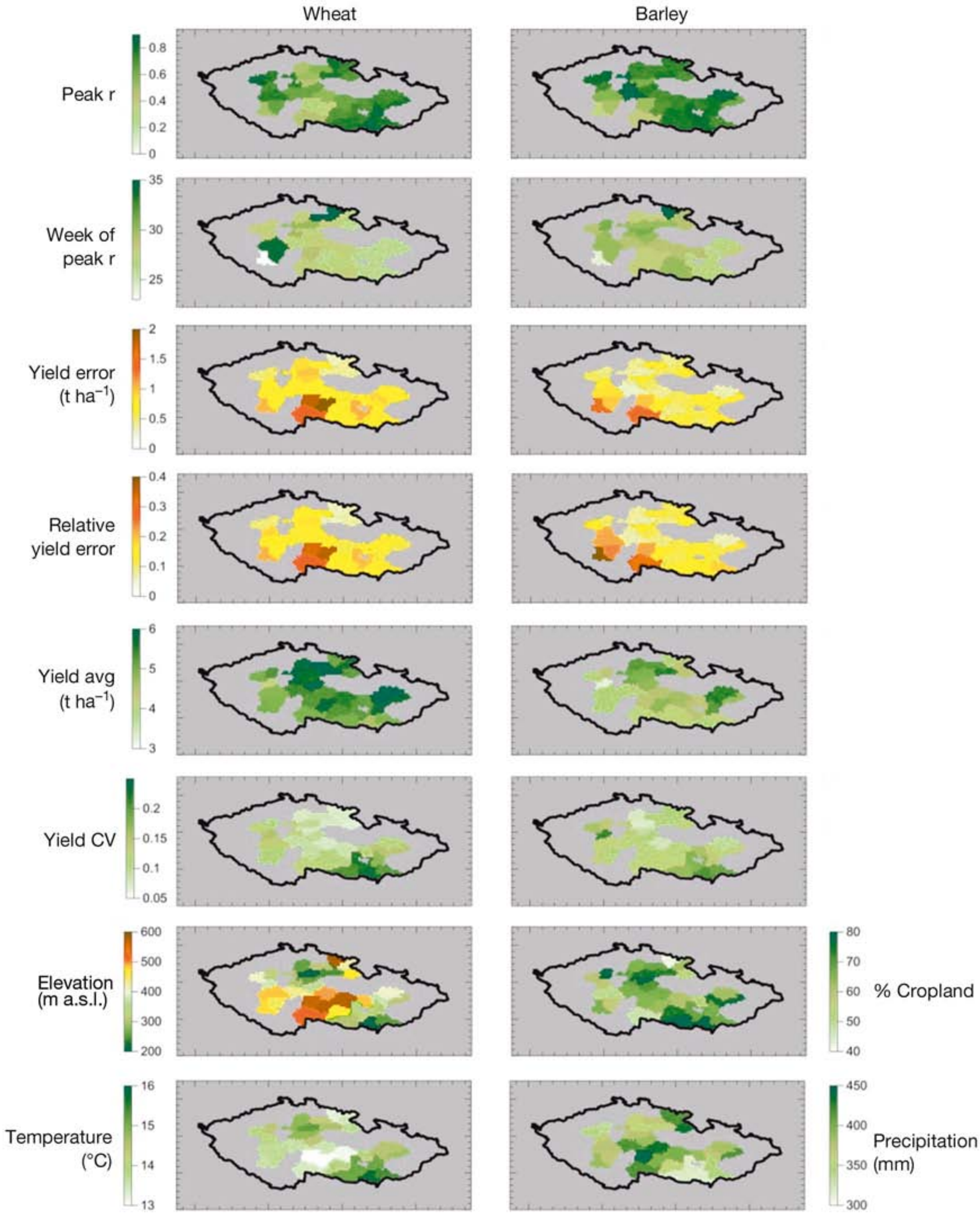

Fig. 7. Maps of properties describing ESI–yield anomaly correlation strength (r-values) for wheat and barley and potential factors that may influence correlations, including yield coefficient of variation (CV), elevation, percentage of cropland, and climatological temperature and precipitation rates

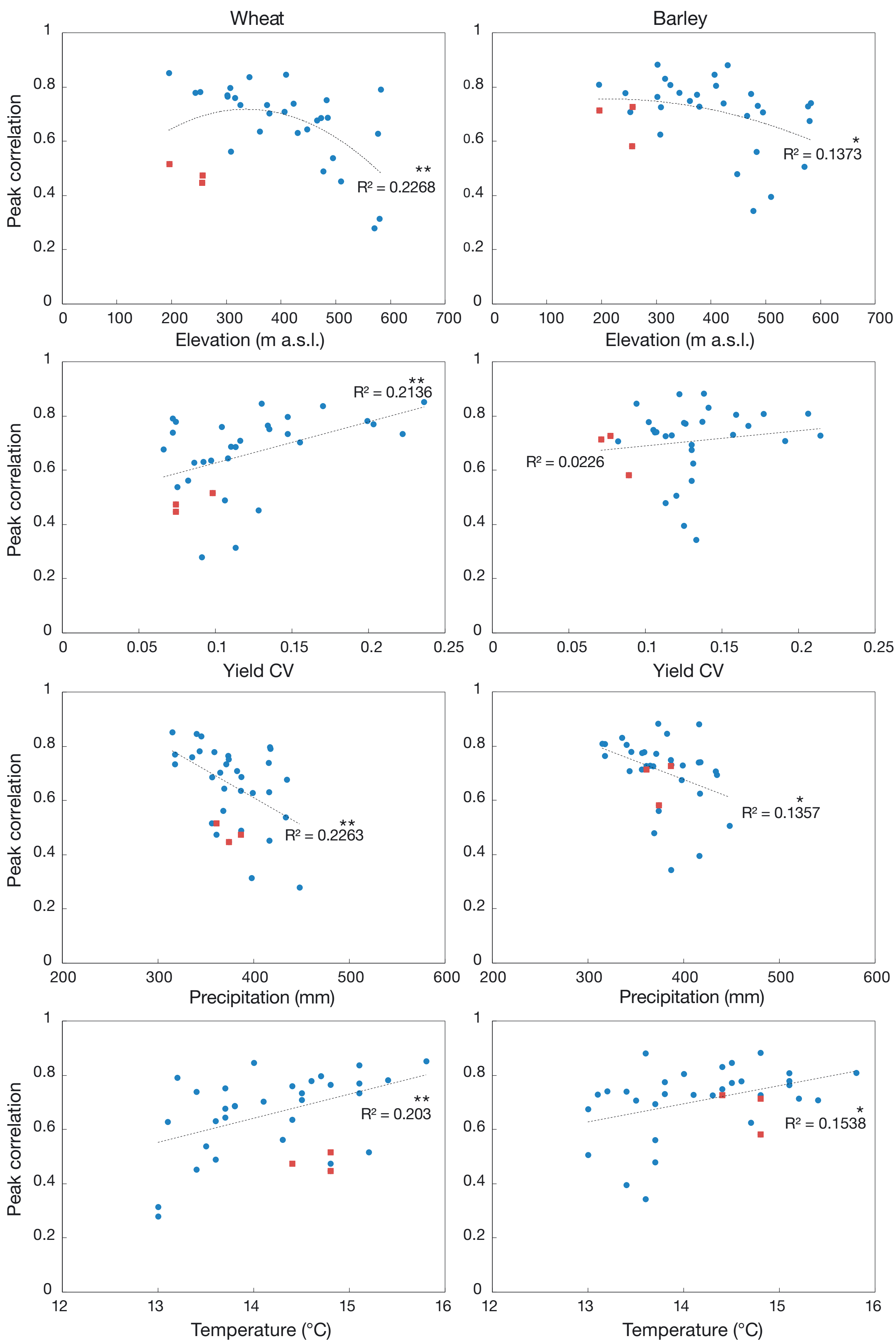

Fig. 8. Comparison of peak ESI-yield anomaly correlation with elevation, yield CV, precipitation and temperature for each target district. Red markers indicate districts KO, MB and NV near the Labe River in STC (see Table 1 for abbreviations of regions and districts). Asterisks indicate correlation with linear or second order polynomial fit is signicant at *$p < 0.05$ and **$p < 0.01$

fall is typically adequate and growing degree days may be a more relevant constraint, it may be that anomalies in LST itself might outperform ESI in terms of yield correlation.

Anomalous districts (KO, MB and NV; shown by red markers in Fig. 8) with relatively low ESI-yield correlations at low elevations, particularly for wheat, are located close to the Labe River (in Germany, known as the Elbe River) in the STC region. These districts also have unusually low yield CV amongst the low-elevation districts (along with HK, also near the Labe River). The lower ESI performance in STC compared to JHM may be related to somewhat higher regional rainfall rates. Furthermore, the 0.05° ESI signal in this area may be capturing additional moisture signals from shallow groundwater and riparian vegetation along the Labe, or from irrigated fields, which while not extensive, are most concentrated in this region. Hain et al. (2015) discuss impacts of ancillary land-surface moisture sources on ET estimates retrieved with ALEXI. This may point to the benefit of using higher resolution ESI products for the CR, to better mask non-agricultural sub-pixel contributions to the perceived crop stress signal.

Relative yield error in the optimal regression function for both winter wheat and spring barley is relatively uniform across regions with the exception of districts in JHC and VYS, where JH, ST, JI and PE have average errors >20% (Fig. 7). Errors in yield departures around the ESI regression function for the week of peak correlation are ~13% for both crops in districts at elevations <450 m, with the highest errors in districts >500 m (Fig. 9). Future investigations will quantify actual prediction errors for each yield-reporting district within the CR.

3.4. Spatiotemporal considerations for an operational yield forecasting system

In this study, a 3 mo ESI composite was used to suppress temporal noise in the correlation curves and to better highlight regional variability in the relationship between ET and yield anomalies. This window, however, is too broad to capture in detail stress events occuring during specific critical phenological stages, such as flowering, when crop yield development is most sensitive to soil moisture deficits. Similarly, the 5 km resolution of the ESI product used here does not allow for the discernment of differences in phenological development between individual crop types. Delayed emergence of a subset of crops within a 5 km pixel, due for example to unusually wet or cold conditions around the planting date, can result in a negative ET anomaly during green-up, which may be falsely interpreted as a drought signal (Anderson et al. 2013).

Yield correlation analyses, such as those presented here, can be considered a first step in elucidating the relative value of remotely sensed indices as predictors of yield anomalies, as well as general spatial and temporal patterns of index performance. With this understanding, the indicators can be more effectively combined within the context of a physiologically based crop modeling framework that takes into consideration stress timing relative to phenological stage in predicting yield impacts. For yield forecasting applications, the moisture stress datastreams will be most usefully developed at spatial resolutions where a significant number of pure crop pixels can be extracted over the region of interest, and at the highest temporal resolution afforded by the remote sensing methods employed.

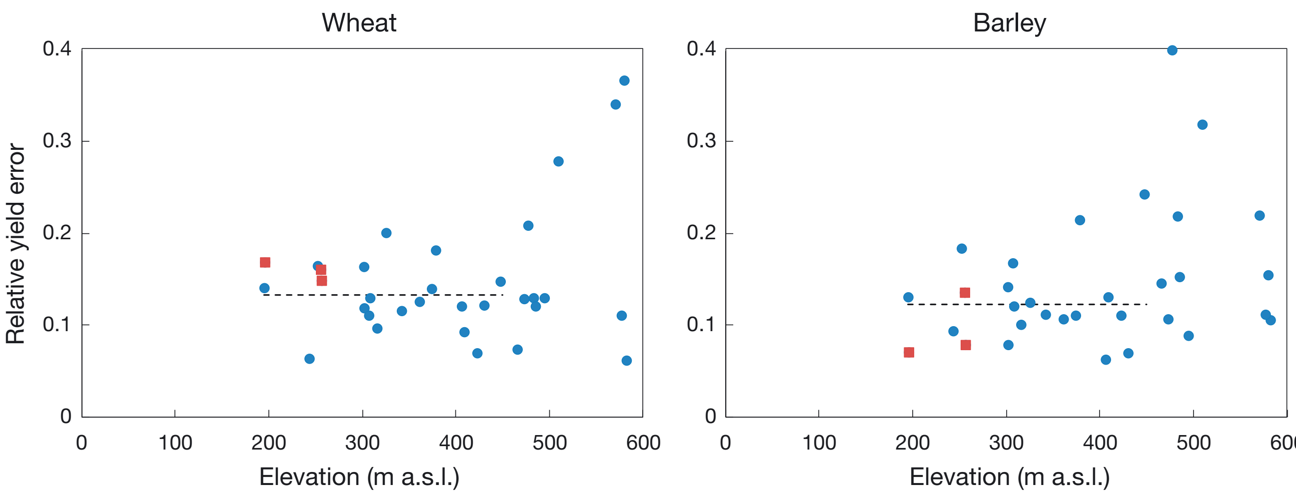

Fig. 9. Relative yield error versus average district elevation for winter wheat and spring barley crops. Dotted line indicates average error for districts below 450 m. Red markers indicate districts KO, MB and NV (see Table 1 for abbreviations)

The average field size in the CR is relatively large in comparison with neighboring countries in the European Union due to the period of collectivization that occurred after World War II, making this region conducive for agricultural remote sensing studies. The 2010 Agricultural Census for the CR (www.czso.cz/csu/czso/2127-12-eng_n_2012-2) gives an estimated mean field block size (i.e. the part of the field with the same crop in a given season) as being over 20 ha (~450 × 450 m^2),which is 2 orders of magnitude larger than in 1948. A new prototype ALEXI ET product at 375 m resolution, generated using day-night LST differences from the Visible Infrared Imaging Radiometer Suite (VIIRS) (the MODIS follow-on instrument) may provide sufficient pure crop pixels for this region. Alternatively, a data fusion system combining ET retrievals from MODIS (~daily, 1 km resolution) and Landsat (bi-weekly, 30 m resolution) could be employed to generate ET datasets at daily timesteps and 30 m resolution (Cammalleri et al. 2013, 2014, Semmens et al. 2016). In practice, a dynamic crop mask would be applied to time-series maps of actual-to-reference ET ratio (f_{RET}) at 30 or 375 m to extract samples of pure pixels for a given crop type. These samples would then reaggregated to the yield monitoring unit (e.g. district level) to produce a localized crop-specific moisture stress function, e.g. of the form as described Doorenbos & Kassam (1979). A 2 wk to 1 mo f_{RET} compositing window would better isolate stress events occurring during moisture-sensitive periods of crop development while still affording some noise reduction capacity. Ongoing research is exploring a combination of high spatiotemporal resolution moisture stress functionals, developed using the data fusion techniques described above, with remotely sensed crop phenology metrics mapped at a similar spatial scale to constrain spatially distributed crop modeling systems of varying complexity (F. Gao et al. unpubl.).

4. CONCLUSIONS

This paper investigates drivers of spatial variability in correlations between ESI products, developed at 0.5° spatial resolution using MODIS retrievals of day–night LST difference, and detrended yield anomalies for spring barley and winter wheat crops grown in several agricultural districts in the CR. For ESI-3 timeseries (3 mo compositing window), correlations for both crops peaked for composite end dates in early-to-mid July, indicating maximum index sensitivity during the April to June period coinciding with the spring and summer drought period. Peak correlation coefficients for winter wheat were more variable among districts than for spring barley, resulting from the longer growing season exposure to different yield-limiting climatic events.

The results suggest that ESI will be most beneficial for yield estimation in agricultural districts where crop growth is primarily moisture-limited; in the Czech Republic, these are at lower elevations which are climatologically warmer and drier. Higher resolution ESI products may be of benefit in some of the districts analyzed, to better mask out sub-pixel contributions from ancillary moisture sources in riparian and irrigated areas, and from non-agricultural land-cover classes. A prototype ESI product at 375 m resolution, generated using VIIRS day-night LST differences, will be evaluated for improved performance in these heterogeneous agricultural landscapes.

Future work will compare ESI performance with that of other indices used for routine drought monitoring in the CR (e.g. www.intersucho.cz/en/) based on modeled soil moisture (Hlavinka et al. 2011) and remotely sensed vegetation condition as reflected in NDVI anomalies, and with anomalies in LST which may better capture energy-limiting crop growth conditions at higher elevations. The ultimate goal is to integrate remote sensing indicators conveying moisture and energy constraints within a spatially distributed crop modeling framework that can appropriately apply these constraints during phenologically sensitive stages of crop growth to forecast yield impacts.

Acknowledgements. This work was supported in part by a grant (award no. NNX12AK90G) from the NASA Applied Sciences Program. Authors M.T., P.H., and F.J. acknowledge support from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I LO1415) and CzechAdapt project (no. EHP-CZ02-OV-1-014-2014). M.T. and P.H. were supported by the National Agency for Agricultural Research (project no. QJ1310123) and F.J. by IGA AF MENDELU project no. IP 14/2016. The USDA is an equal opportunity provider and employer.

LITERATURE CITED

AghaKouchak A, Nakhjiri N (2012). A near real-time satellite-based global drought climate data record. Environ Res Lett 7:044037

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and drainage paper 56, FAO, Rome

Anderson MC, Allen RG, Morse A, Kustas WP (2012a). Use of Landsat thermal imagery in monitoring evapotranspi-

ration and managing water resources. Remote Sens Environ 122:50–65
Anderson MC, Norman JM, Mecikalski JR, Otkin JA, Kustas WP (2007). A climatological study of evapotranspiration and moisture stress across the continental U.S. based on thermal remote sensing. II. Surface moisture climatology. J Geophys Res 112:D11112
Anderson MC, Hain CR, Wardlow B, Mecikalski JR, Kustas WP (2011) Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the continental US. J Clim 24:2025–2044
Anderson WB, Zaitchik BF, Hain CR, Anderson MC, Yilmaz MT, Mecikalski JR, Schultz L (2012b) Towards an integrated soil moisture drought monitor for East Africa. Hydrol Earth Syst Sci 16:2893–2913
Anderson MC, Hain CR, Otkin JA, Zhan X and others (2013) An intercomparison of drought indicators based on thermal remote sensing and NLDAS-2 simulations with US drought monitor classifications. J Hydrometeorol 14: 1035–1056
Anderson MC, Zolin C, Hain CR, Semmens KA, Yilmaz MT, Gao F (2015) Comparison of satellite-derived LAI and precipitation anomalies over Brazil with a thermal infrared-based Evaporative Stress Index for 2003–2013. J Hydrol (Amst) 526:287–302
Anderson MC, Zolin C, Sentelhas PC, Hain CR and others (2016) The Evaporative Stress Index as an indicator of agricultural drought in Brazil: an assessment based on crop yield impacts. Remote Sens Environ 174:82–99
Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. Int J Remote Sens 26:1959–1977
Basso B, Cammarano D, Carfagna E (2013). Review of crop yield forecasting methods and early warning systems. Proceedings of the First Meeting of the Scientific Advisory Committee of the Global Strategy to Improve Agricultural and Rural Statistics. FAO, Rome
Bastiaanssen WGM, Ali S (2003) A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. Agric Ecosyst Environ 94:321–340
Becker-Reshef I, Vermote E, Lindeman M, Justice CO (2010) A generalized regression-based model for forecasting winter wheat yields in Kansas and Ukraine using MODIS data. Remote Sens Environ 114:1312–1323
Bicheron P, Amberg V, Bourg L, Petit D and others (2011) Geolocation assessment of MERIS GlobCover Orthorectified Products. IEEE T Geosci Remote 49:2972–2982
Bolten JD, Crow WT, Zhan X, Jackson TJ, Reynolds CA (2010) Evaluating the utility of remotely sensed soil moisture retrievals for operational agricultural drought monitoring. IEEE J Sel Top Appl Earth Obs Remote Sens 3: 57–66
Cammalleri C, Anderson MC, Gao F, Hain CR, Kustas WP (2013) A data fusion approach for mapping daily evapotranspiration at field scale. Water Resour Res 49: 4672–4686
Cammalleri, C., Anderson, MC, Gao FH, Hain CR, Kustas WP (2014) Mapping daily evapotranspiration at field scales over rainfed and irrigated agricultural areas using remote sensing data fusion. Agric For Meteorol 186:1–11
Doorenbos J, Kassam AH (1979). Yield response to water. Irrigation and drainage paper 33, FAO, Rome
Doraiswamy PC, Sinclair TR, Hollinger S, Akhmedov B, Stern A, Prueger J (2005) Application of MODIS derived parameters for regional crop yield assessment. Remote Sens Environ 97:192–202
Doraiswamy PC, Akhmedov B, Beard L, Stern A, Mueller R (2007) Operational prediction of crop yields using MODIS data and products. In: Baruth B, Royer A, Genovese G (eds) Proc Int Soc Photogrammetry and Remote Sensing (ISPRS) WG VIII/10 workshop 2006: Remote sensing support to crop yield forecast and area estimates, Nov 30–Dec 1, 2006, Stresa, Italy, p 45–50
Esquerdo JCDM, Júnior JZ, Antunes JFG (2011) Use of NDVI/AVHRR time-series profiles for soybean crop monitoring in Brazil. Int J Remote Sens 32:3711–3727
Fernandes JL, Rocha JV, Lamparelli R (2011) Sugarcane yield estimates using time series analysis of spot vegetation images. Sci Agric 68:139–146
Friedl M, Sulla-Manashe D, Tan B, Schneider A, Ramankutty N, Sibley AM, Huang X (2010) MODIS Collection 5 global land cover: algorithm refinements and characterization of new datasets. Remote Sens Environ 114: 168–182
Gesch DB, Verdin KL, Greenlee SK (1999) New land surface digital elevation model covers the Earth. Eos Trans AGU 80:69–70
Guan K, Berry J, Zhang Y, Guanter L, Badgley G, Lobell DB (2016) Improving the monitoring of crop productivity using spaceborne solar-induced fluorescence. Glob Change Biol 22:716–26
Gusso A, Ducati JR, Veronez MR, Arvor D, da Silveira LG Jr (2013) Spectral model for soybean yield estimate using MODIS/EVI Data. Int. J Geosciences 4:1233–1241
Hain CR, Crow WT, Anderson MC, Yilmaz MT (2015) Diagnosing neglected moisture source/sink processes with a thermal infrared-based two-source energy balance model. J Hydrometeorol 16:1070–1086
Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Žalud Z, Možný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric For Meteorol 149: 431–442
Hlavinka P, Trnka M, Balek J, Semerádová D and others (2011) Development and evaluation of the SoilClim model for water balance and soil climate estimates. Agric Water Manage 98:1249–1261
Houborg R, Rodell M, Li B, Reichle RH, Zaitchik BF (2012) Drought indicators based on model-assimilated gravity Recovery and Climate Experiment (GRACE) terrestrial water storage observation. Water Resour Res 48:W07525
Johnson DM (2014) An assessment of pre- and within-season remotely sensed variables for forecasting corn and soybean yields in the United States. Remote Sens Environ 141:116–128
Kogan FN, Gitelson A, Zakarin E, Spivak L, Lebed L (2003) AVHRR-based spectral vegetation index for quantitative assessment of vegetation state and productivity: calibration and validation. Photogramm Eng Remote Sensing 69:899–906
Kolář P, Trnka M, Brázdil R, Hlavinka P (2014) Influence of climatic factors on the low yields of spring barley and winter wheat in Southern Moravia (Czech Republic) during the 1961–2007 period. Theor Appl Climatol 117: 707–721
Kouadio L, Newlands NK, Davidson A, Zhang Y, Chipanshi A (2014) Assessing the performance of MODIS NDVI and EVI for seasonal crop yield forecasting at the ecodistrict scale. Remote Sens 6:10193–10214
Lobell DB, Ortiz-Monasterio JI, Addams CL, Asner GP

(2002) Soil, climate, and management impacts on regional wheat productivity in Mexico from remote sensing. Agric For Meteorol 114:31–43

López-Lozano R, Duveiller G, Seguini L, Meroni M and others (2015) Towards regional grain yield forecasting with 1 km-resolution EO biophysical products: strengths and limitations at pan-European level. Agric For Meteorol 206:12–32

Loveland TR, Belward AS (1997) The IGBP-DIS global 1-km land cover data set, DIScover: first results. Int J Remote Sens 18:3289–3295

Mkhabela MS, Mkhabela MS, Mahinini NN (2005) Early maize yield forecasting in the four agro-ecological regions of Swaziland using NDVI data derived from NOAA's-AVHRR. Agric For Meteorol 129:1–9

Mkhabela MS, Bullock P, Raj S, Wang S, Yang Y (2011) Crop yield forecasting on the Canadian Prairies using MODIS NDVI data. Agric For Meteorol 151:385–393

Moran MS (2003). Thermal infrared measurement as an indicator of plant ecosystem health. In: Quattrochi DA, Luvall J (eds) Thermal remote sensing in land surface processes. Taylor and Francis, Abingdon, p 257–282

Otkin JA, Anderson MC, Hain CR, Mladenova IE, Basara JB, Svoboda M (2013) Examining rapid onset drought development using the thermal infrared based evaporative stress index. J Hydrometeorol 14:1057–1074

Otkin JA, Anderson MC, Hain CR, Svoboda M (2014) Examining the relationship between drought development and rapid changes in the evaporative stress index. J Hydrometeorol 15:938–956

Otkin JA, Anderson MC, Hain CR, Svoboda M (2015) Using temporal changes in drought indices to generate probabilistic drought intensification forecasts. J Hydrometeorol 16:88–105

Otkin JA, Anderson MC, Hain C, Svoboda M and others (2016) Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought. Agric For Meteorol 218-219:230–242

Rembold F, Atzberger C, Savin I, Rojas O (2013) Using low resolution satellite imagery for yield prediction and yield anomaly detection. Remote Sens 5:1704–1733

Rizzi R, Rudorff BFT (2007) MODIS sensor images associated with an agronomic model to estimate soybean grain yield. Pesquisa Agropecu Bras 42:73–80

Semmens KA, Anderson MC, Kustas WP, Gao F and others (2016) Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach. Remote Sens Environ 185:155–170

Trnka M, Brázdil R, Olesen JE, Eitzinger J and others (2012) Could the changes in regional crop yields be a pointer of climatic change? Agric For Meteorol 166-167:62–71

Trnka M, Brázdil R, Možný M, Štěpánek P and others (2015) Soil moisture trends in the Czech Republic between 1961 and 2012. Int J Climatol 35:3733–3747

Tuanmu MN, Jetz W (2014) A global 1-km consensus land-cover product for biodiversity and ecosystem modelling. Glob Ecol Biogeogr 23:1031–1045

Unganai LS, Kogan FN (1998) Southern Africa's recent droughts from space. Adv Space Res 21: 507–511

Wardlow BD, Anderson MC, Verdin JP (eds) (2012) Remote sensing for drought: innovative monitoring approaches. CRC Press/Taylor and Francis, Boca Raton, FL

Zahradníček P, Trnka M, Brázdil R, Možný M and others (2015) The extreme drought episode of August 2011–May 2012 in the Czech Republic. Int J Climatol 35: 3335–3352

Zhang P, Anderson B, Tan B, Huang D, Myneni RB (2005) Potential monitoring of crop production using a satellite-based Climate-Variability Impact Index. Agric For Meteorol 132:344–358

Editorial responsibility: Donald Wilhite, Lincoln, Nebraska, USA (Guest Editor)

Submitted: January 28, 2016; Accepted: June 28, 2016
Proofs received from author(s): August 18, 2016

Vol. 70: 231–249, 2016
doi: 10.3354/cr01421

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe—from drought response to preparedness'

Assessing the combined hazards of drought, soil erosion and local flooding on agricultural land: a Czech case study

Miroslav Trnka[1,2,*], Daniela Semerádová[1,2], Ivan Novotný[3], Miroslav Dumbrovský[4], Karel Drbal[5], František Pavlík[6], Jan Vopravil[3], Pavla Štěpánková[5], Adam Vizina[5], Jan Balek[1,2], Petr Hlavinka[1,2], Lenka Bartošová[1], Zdeněk Žalud[1,2]

[1]Global Change Research Centre, Czech Academy of Sciences, Belidla 986/4a, Brno 60300, Czech Republic
[2]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemedelska 1, Brno 61300, Czech Republic
[3]Research Institute for Soil and Water Conservation, Žabovřeská 250, 156 27 Praha 5 – Zbraslav, Czech Republic
[4]Faculty of Civil Engineering, Department of Landscape Water Management, Brno University of Technology, 60200 Brno, Czech Republic
[5]T. G. Masaryk Water Research Institute, Mojmirovo nam. 16, Brno 61200, Czech Republic
[6]State Land Office, Husinecká 1024/11a, 130 00 Praha 3, Czech Republic

ABSTRACT: Present-day agriculture faces multiple challenges, including ongoing climate change that is at many locations combined with soil degradation. The deterioration of soil properties through unsustainable agricultural practices and changing climate could lead to a fall in productivity beyond the point of no return with devastating effects on ecosystem services in large areas. Identifying areas with the highest hazard levels should therefore be a top priority. The key hazards for agricultural land in the Czech Republic considered in this study include the occurrence of water stress in the topsoil layer during both the first and second half of the growing season, the proportion of fast-drying soils, the risk of sheet and ephemeral gully erosion and the risk of local floods originating primarily from agricultural land. The results clearly marked regions where primary attention should be given to reduce the level of the hazards and/or to increase cropping capacity. These regions were found to be concentrated in the southeastern and northwestern lowland areas. Typical areas with the highest hazard levels were identified: regions with low precipitation and a high proportion of soils with a degraded or naturally occurring low water-holding capacity, and those with steeper than average slopes and terrain configurations in relatively large catchment areas that have urbanized countryside landscapes located at their lower elevations. Despite some limitations, the methods presented in this paper can be applied generally as the first step in developing strategies for efficient reduction of hazard levels.

KEY WORDS: Soil moisture · Sheet erosion · Ephemeral gully erosion · Critical point · Fast-drying soil · Vulnerability · Climate change

1. INTRODUCTION

Food security and its relationship with ongoing climate change featured prominently in the 5th Assessment Report of IPCC Working Group II. The chapter on food security (Porter et al. 2014) has been discussed in great detail, and its conclusions provide a set of key messages for world political leaders (IPCC 2014). The urgency of prioritizing agronomy research that allows humankind to produce sufficient amounts of high-quality food in a sustainable way is driven by multiple pressures. First, there is the sheer

*Corresponding author: mirek_trnka@yahoo.com

Publisher: Inter-Research · www.int-res.com

challenge of increasing food production by 60–70% by 2050 to feed a global population estimated to increase to over 9 billion. Second, that challenge must be achieved using less water and energy than is used today, as agriculture is under pressure to decrease its water, carbon and energy footprints to become sustainable in the long term. Third, the challenge of ongoing climate change showing warming trends across the globe is already leading to changes in the distribution of climate variability and extremes (Rahmstorf & Coumo 2011, Gourdji et al. 2013, Liu & Allan 2013), while a high uncertainty remains in the relationship between global warming and climate variability (Huntingford et al. 2013). There is also concern about deteriorating food quality, which was highlighted by Myers et al. (2014), that projects a lower protein content in key C3 crops than exists at present, or risks posed by the future occurrences of pests and diseases in some key agricultural production regions (e.g. Svobodová et al. 2014). At the same time, there is ever-growing concern with regard to soil fertility. According to the EEA (1998), damage to Europe's soils from modern human activities is increasing and leading to irreversible soil loss due to erosion, local and diffuse contamination and the sealing of soil surfaces. In western and northern Europe, the sealing of soil surfaces due to increased urbanization and new infrastructure is the main cause of soil degradation. Land area in the Czech Republic is about 10.6% urban, with a yearly increase of about 0.4%. In the Mediterranean, soil erosion is the main cause of soil loss. The areas with the most severe soil loss from both wind and water erosion include the Balkan Peninsula, the Black Sea region, and also some central European countries such as the Czech Republic and Slovakia (EEA 1999). The European Union (EU) Mediterranean countries also have severe soil erosion problems, which in some cases are at a critical stage and could lead to desertification. Alarming is the possibility of areas currently not at risk (e.g. parts of the Mediterranean or the Alps) reaching advanced degradation status that cannot be reversed within 2 or 3 generations, with some areas having reached this status over 2 decades ago (e.g. Van Lynden 1994). Central Europe is also showing signs of serious problems in this regard.

Previous studies assessing the agricultural impacts of climate change have demonstrated that the effects depend on the crops being grown, cropping season and region (e.g. Olesen et al. 2007), and very few have considered cropping system responses to changes in the frequency and severity of climatic extremes (e.g. Ruiz-Ramos et al. 2011). However, it is well known that the impacts of such extreme events can be substantial (e.g. Reyer et al. 2013). Studies by Trnka et al. (2014, 2015a) showed that, despite the large uncertainty in climate projections within the CMIP5 ensemble, the overall frequency of adverse events is much more likely to increase than to decrease across the European domain, including Central Europe. It is also obvious that soil degradation is intertwined with the increased drought risk as degraded soils tend to have smaller infiltration rates and much smaller water-holding capacity.

Existing research confirms that climate conditions in April–June have the most profound impact on the yield of field crops (e.g. Hlavinka et al. 2009, Kolář et al. 2014). The interannual yield variance explained by the interannual changes in a single climatic variable could reach 50% on a regional scale (Brázdil et al. 2009, Trnka et al. 2016, this issue). A recent analysis indicated that climatic variability influences yield variability in Central Europe more now than it did in the late 19th and early 20th centuries (e.g. Trnka et al. 2012). Most of the explanatory power of the model was derived from a negative sensitivity to temperature and drought. Interestingly, the biggest changes in drought sensitivity from the late 19th to the late 20th century were found in the regions where processes (wind and water-driven) of soil erosion and of overall soil degradation are considered severe. An awareness of this problem has led to increased attention being paid to the issues of drought vulnerability and soil degradation in recent years (e.g. Trnka et al. 2015b, Zahradníček et al. 2015, etc.). Many farmers partially mitigate drought impacts through crop selection, irrigation, and modified tillage practices, but in many cases, they struggle economically, as the economic returns, especially in dry years, are extremely poor (Vopravil et al. 2012). Until recently, at the state level, the emphasis of disaster management has been largely on the response to and recovery from droughts, with little or no attention paid to drought mitigation, preparedness, prediction and monitoring. The situation is better in relation to soil erosion and local flood risks due to existing EU rules (Panagos et al. 2015), but these measures are usually not intertwined with measures aimed at decreasing the impact of droughts. Increased losses from droughts (as observed in 2000, 2003, 2012 and 2015) suggest a growing societal vulnerability to this hazard. At the same time, erosion risks and the rate of soil degradation are still unsustainable in some areas despite a number of existing measures being taken (Vopravil et al. 2012). It has also been felt by both the Agrarian Chamber (representing the great majority of farmers in the Czech Republic) and some governmental organization (e.g. the State Land Office) that major revisions are needed of existing policies related to the management of soil degradation frequently associated with intensive rains and increased drought risks due to climate change. Therefore, a multidisciplinary task force was formed and supported, called the Master Plan of Landscape Water Management of the Czech Republic (F. Pavlik pers. obs.). It has been recognized that there must be an inevitable shift in policies to change drought management from a reactive, crisis-management approach to a proactive, risk-management approach. At the same time, these measures must complement and support existing policies aimed at suppressing processes of soil degradation. While the former requires detailed monitoring, early warning and planning between events (e.g. Wilhite 2000), the latter can be achieved only through a comprehensive and regionally tailored and coordinated set of long-term policies. The final goal is to lower the risks in real terms arising from the impacts of drought and soil degradation for the whole of the Czech Republic through the implementation of an efficient strategy. Among other factors, this strategy includes selecting areas and 'actors' (i.e. farmers) facing the highest risk and providing them with the proper support as early as possible to prevent a situation from deteriorating beyond the 'point of no return'.

The development and implementation of the methodological framework into an operational procedure considers the overall risk for the Czech Republic's rural landscape as being a function of hazard, exposure and vulnerability (Giupponi et al. 2015). The ultimate goal of the whole procedure is the quantification of these risks, putting into place policies and measures leading to risk reduction, and ensuring their adoption in practice through the use of demonstration areas, as well as through technical and financial assistance. This may be achieved only when hazards, vulnerability and exposure are known, allowing for the calculation of the expected damages related to the risks associated with different hazardous scenarios. Clearly, the first step required is a proper analysis of the hazards themselves.

While according to Kappes (2012), multi-hazard assessment may be understood as an assessment of 'the totality of relevant hazards in a defined area', the present study uses the concept of 'more than one hazard'. The research presented here focuses on drought and soil degradation hazard assessments for the agricultural landscape of the Czech Republic. While the potential indicators for describing the hazards to agricultural land are numerous, their applicability depends both on their policy relevance and the availability of data. We attempt to provide concept hazard and vulnerability to key decision-makers (agricultural producers, natural resource managers, and others), as well as provide them with spatially explicit information. The goal of this study was to develop a method for assessing hazards posed by drought, erosion and floods using geographic processing techniques. The objectives were: (1) identify key indicators that define agricultural drought, soil erosion and local flood hazards for agricultural land across the Czech Republic; (2) evaluate the weight of the indicators that contribute to the combined hazard; and (3) classify and map the combined hazard.

2. MATERIALS AND METHODS

2.1. Setting

The first step towards the implementation of the proposed framework is the identification of the context in which it will be applied. This involves identifying regions with the highest hazards so that the next steps of risk assessment (vulnerability and exposure assessments) and policy application can be targeted to these regions (Fig. 1). Fig. 1a–c shows the Czech Republic's main orographic features and soil characteristics that, together with climate conditions, help to illustrate why land degradation and drought need to be assessed together. The country's mean altitude is 430 m (CSO 2005), and it lacks large mountain chains. However, the combination of the country's morphology, which is dominated by uplands and highlands, the occurrence of areas with considerable slopes even at low altitudes, and the comparatively large field blocks explain why over half of agricultural and especially arable land is exposed to strong water and wind erosion (Janeček et al. 2012). The fact that the most intensively farmed regions are also dotted with high numbers of settlements increases the number of areas in which floodwater from relatively small catchments over the agricultural land poses a frequent hazard for these settlements. The hazard is also higher than in comparable regions of Austria, due to much larger field blocks that contain a single crop. Most Czech agriculture is rain-fed, with irrigation being available for <4% of the area (Batysta et al. 2015) and only ~1.5% being actively used (Batysta et al. 2015). While the Czech Republic's mean annual precipitation of

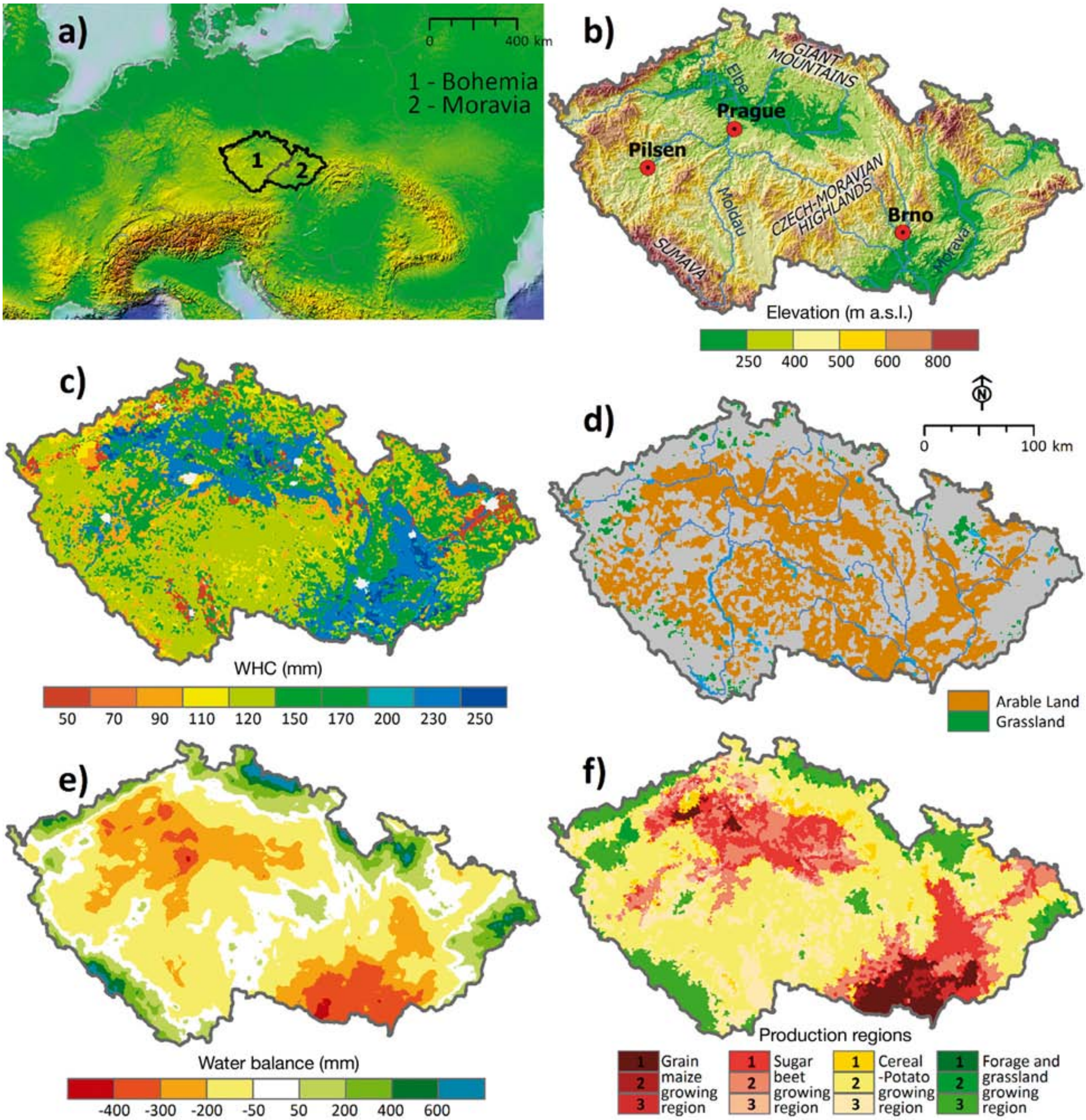

Fig. 1. (a) Overall location of the Czech Republic case study region in Central Europe. (b) Main orographic features of the country. (c) Water-holding capacity (WHC) of the soil in the first 100 cm of the soil profile. (d) Main areas of arable land and grassland for which the assessment was primarily carried out, with other land-uses colored grey. (e) Difference between sum of annual precipitation and annual potential evapotranspiration. (f) Agrometeorological zoning of the country into 4 main production zones. In each production zone 3 sub-classes are distinguished: (1) prime agricultural soil; (2) could be used for agricultural production with limitations; (3): not suitable as agricultural land

700 mm would generally be sufficient, some key producing regions in the northwest and southeast show much lower precipitation totals (450 and 500 mm, respectively). Given the high interannual variability and shifts in the distribution of precipitation, in many seasons production is severely limited by the availability of water. In fact, rain-fed agriculture is only sustainable thanks to a generally favorable distribution of precipitation and to soil that holds enough water to allow crop survival through episodes of drought that are sometimes prolonged (Hlavinka et al. 2009). According to Trnka et al. (2009), the June–August sum of precipitation for the Czech Republic is on average higher than 1/3 of the annual

rainfall total (ranging from 27 to 43%). The driest season that accounts for less than 1/5 of the annual precipitation is winter (December–February). Winter precipitation (if in the form of snow) allows for a recharging of the soil profile just before the growing season, reducing the effects of severe droughts in the early part of growing season, which is critical for crop yield formation (e.g. Hlavinka et al. 2009). As Fig. 1e shows, the majority of the lowlands show higher potential evapotranspiration than precipitation, in particular in the areas where precipitation is the lowest. This deficit is the highest in the southeast, which in addition to low levels of precipitation, also has the highest temperatures and the most hours of sunshine compared to the rest of the country. Climate and soil conditions together with the terrain predetermines the agricultural use of each area. The Czech Republic is traditionally divided into 4 production regions, with those growing sugar beets being the most productive (Fig. 1f), followed by maize-producing regions.

2.2. Indicators of hazards

The potential indicators that could be used for the assessment of hazards are numerous. Because the focus of this study was on assessing combined hazards for agricultural land, we focused on the indicators that in our view can best be used to quantify these hazards. An analysis of the literature, suggestions from specialists, and data availability formed the fundamental assumptions underlying the methodology we used.

In the first step towards the assessment of the combined hazard (Fig. 2) for the agricultural lands analyzed, we identified the following hazards as being the most critical ones:

(a) Drought occurring during the growing season;
(b) Pre-existing poor soil conditions decreasing the ability of the soil to hold water (fast-drying soils);
(c) Increased susceptibility to water erosion, including the occurrence of concentrated runoff pathways;
(d) Pre-existing infrastructure and/or settlements in the path of the concentrated runoff pathways.

It was also clear that the occurrence of one hazard at a greater intensity might contribute to the effects of other hazards becoming more severe. For example, prolonged droughts lead to the disintegration of the soil structure and to a decrease in the vitality of the crop cover, which makes the area more vulnerable to soil erosion (Fig. 2).

2.2.1. Agricultural drought during the growing season

We selected the number of days during which soil moisture was <30% of the relative soil water content (i.e. the percentage to which water fills the soil pores between the so-called wilting point and field capacity) in the topsoil, which was defined as the layer between 0.0 and 0.4 m. The calculation procedure has been explained in detail by Hlavinka et al. (2011) and was further tested by Trnka et al. (2015a,b) and carried out for agricultural land (Fig. 1d). It relies on the SoilClim model (Hlavinka et al. 2011) based on the model of Allen et al. (1998), and accounts for the following factors and processes:

- Water accumulation in snow cover and subsequent melting
- Water-holding capacity of the soil
- Influence of the slope and aspect on the energy balance
- Influence of the type of the vegetation on daily evapotranspiration, interception and runoff
- Dynamically changing properties of the plant cover based on the phenology phase estimated through thermal time (including sowing, harvest, leaf area index, rooting depth, and crop height)
- Influence of underground water and shallow water tables

As the indicator of drought hazard, we selected the median number of days per season (based on 1991–2014 data) with a saturation of the surface soil layer below 30%, which is a good proxy for drought damage to agricultural crops according to our observations (e.g. Zahradníček et al. 2015). In general, this value could be considered as the level below which the physiological processes of the plant begin to be significantly limited by a lack of water (e.g. Larcher 2003). While decreases in the relative saturation of the soil below 50% slows a plant's intake of water, at values below 30% it is no longer able to produce sufficient turgor, and growth stagnates. The calculations were performed in 500 m grids covering the whole of the Czech Republic (Trnka et al. 2015b). Based on the drought-yield relationship, we divided the growing season into 2 parts, April–June and July–September. In the former, mostly spring- and winter-sown cereals (usually harvested in July) are known to be affected the most (e.g. Hlavinka et al. 2009), while the latter season represents the time period in which latter-maturing crops (e.g. maize, potatoes or sugar beets) can be negatively affected.

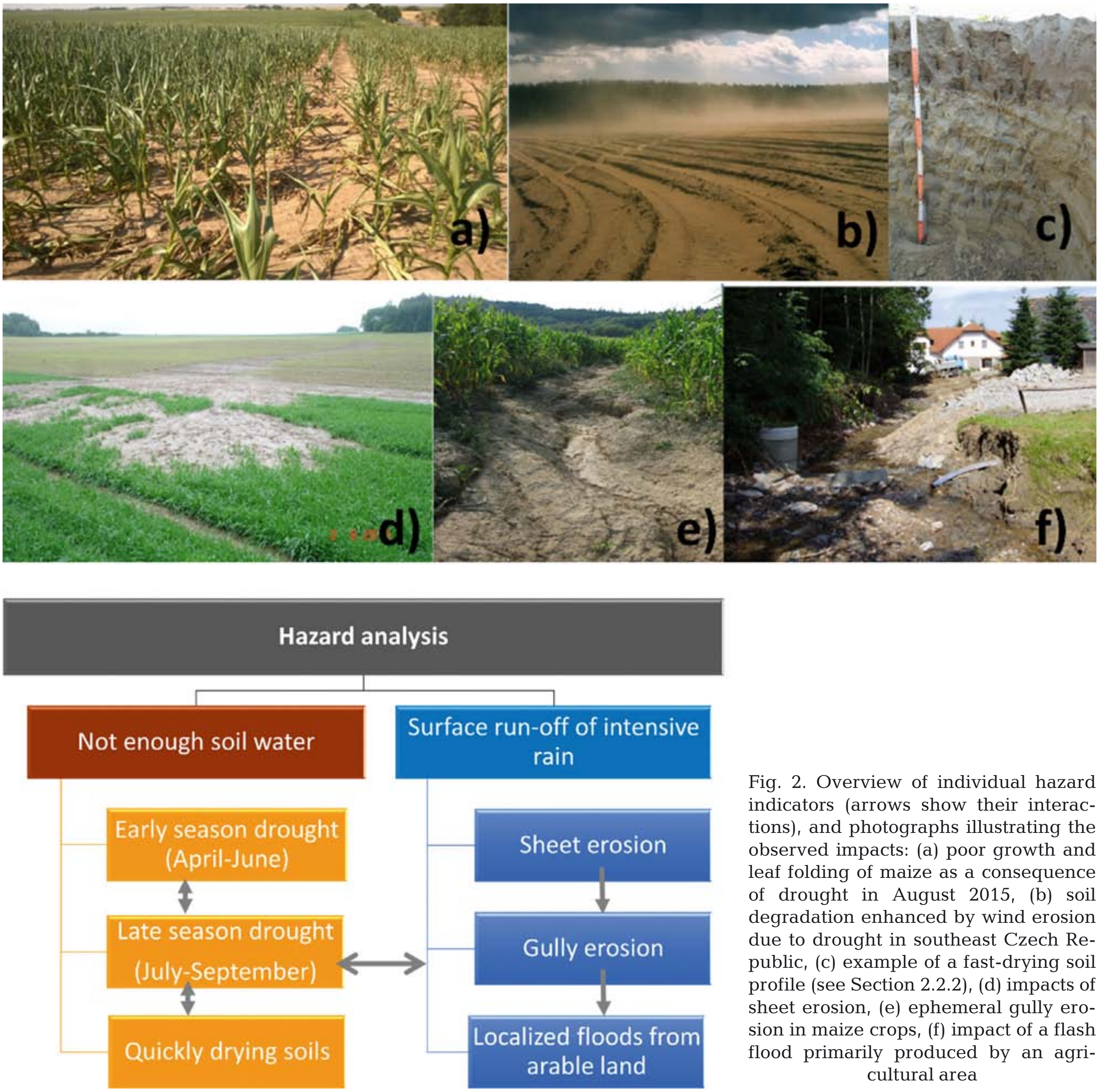

Fig. 2. Overview of individual hazard indicators (arrows show their interactions), and photographs illustrating the observed impacts: (a) poor growth and leaf folding of maize as a consequence of drought in August 2015, (b) soil degradation enhanced by wind erosion due to drought in southeast Czech Republic, (c) example of a fast-drying soil profile (see Section 2.2.2), (d) impacts of sheet erosion, (e) ephemeral gully erosion in maize crops, (f) impact of a flash flood primarily produced by an agricultural area

2.2.2. Fast-drying soils

While the occurrence of drought is primarily driven by climate, and the definitions used account for the influence of terrain, vegetation cover and soil water-holding capacity, it was felt that specific local soil conditions needed to be taken into account. Therefore, the proportion of fast-drying soils that tend to be particularly negatively affected by drought was considered. Fast-drying soils are the result of soil processes that are driven by a long-term lack of water in the soil and the intensive mineralization of organic matter, which leads to a decrease in soil fertility and its water-holding capacity. In the Czech Republic, this issue is of concern in the northwestern and southeastern parts of the country. Including fast-drying soils as a hazard indicator is justified by the fact that the extent of this area has been expanding over the past decades, and the occurrence of fast-drying soils in a region indicates a heightened hazard. The expansion of fast-drying soils is driven by erosion, and many areas with very fertile soils <100 yr ago (e.g. chernozems) are presently fast-drying soils consisting of an underlying loess (giving at least a hope of restoring soil fertility) or sand from the original bottom of the sea that was once present in these areas. The process is accelerated by ongoing climate change connected with the increasingly frequent occurrence of long periods of drought and also by unsuitable tillage practices with a low resupply rate of organic matter to the soil. Determining the occurrence of fast-drying soils was performed through an evaluation of a high-resolution (5 × 5 m) map of the soil conditions, based on information obtained from the soil database that is maintained and permanently updated by the Research Institute for Soil and Water Conservation (RISWC), which includes extensive data on soil and associated components of the environment. Only agricultural land (Fig. 1d) was considered.

2.2.3. Sheet, interrill and rill soil erosion

The first indicator of an erosion hazard for agricultural land (Fig. 1d) focuses predominantly on so-called sheet erosion (i.e. the transport of loosened soil particles by overland flow). We used an approach based on the universal soil loss equation (USLE) (Wischmeier & Smith 1978), which accounts for rainfall erosivity factor (R), soil erodibility factor (K), topographic factors (slope and length) and cropping management factors (C and P). The topography factors were estimated according to the modified equation of Desmet & Govers (1996) using a 5 × 5 digital elevation model. The efficiency factor of erosive rainfall was set at R = 40 MJ ha^{-1} cm h^{-1} (Janeček et al. 2012), and the C factor was based on the actual crop proportions at the same resolution as the slope and length estimates. After estimating annual soil loss, those 5 × 5 m grids showing an annual potential loss higher than 4 t ha^{-1} (i.e. the nationally enforced limit) were marked as those with a significantly higher than permissible erosion rate.

2.2.4. Rill and ephemeral gully erosion

In addition to the classic erosion furrows on the surface slopes of arable land, there are also so-called rills and ephemeral gullies present, which differ from the classic erosion furrows because of their cross-sectional area (>1 square foot or >0.09 m^2) (Morgan 2005). These features tend to appear in places where the basin shape leads to a concentration of the outflowing surface water. They can either follow the flow path of excess water, or they can follow linear landscape elements such as land boundaries, furrows created by agricultural practices or unpaved country roads. The term ephemeral expresses the temporariness of these elements, which are rehabilitated by tillage of the growing season, but they tend to reappear in the same place in the next growing season under the 'right' farming and weather conditions.

For the analysis of ephemeral gully erosion hazards, the method of plotting potential paths of runoff concentration at a resolution of 5 m was used. This method is based on the modeling of flow accumulation from drainage areas, the interpretation of the nature of the terrain and the visual interpretation of aerial photos of the affected land blocks. Contributing areas were used to automatically generate the direction and accumulation of runoff over a digital terrain model with manual correction using raster topographic maps and aerial orthophotos (Dumbrovský 2011).

2.2.5. Localized floods originating from agricultural land

Catastrophic floods with tragic consequences in the Odra river basin in 2009 and similar well-documented events in the following years vividly demonstrate that settlements can be significantly affected in places where there is no (and has not been) any known permanent stream (Drbal 2009). Drbal & Dumbrovský (2009) reported that even a contributing area of 5 ha is sufficient to generate a flow that can cause severe damage to property. The causal factors critical for the formation of a concentrated runoff were determined based on the number of recent flood events from torrential rainfall, and parameters were set to estimate so-called 'critical points'. A critical point (CP) was defined as the point where the trajectory of the concentrated runoff penetrates into the municipality. CPs were thus determined based on the intersection of a municipality (urban) boundary with concentric lines of a track drainage area contributing to a region ≥0.3 km^2. As the area affected by torrential rainfall tends to be limited, the contributing area was also limited to 10 km^2. Torrential rainfalls, while very localized, occur fairly frequently between April and September and in particular over the summer months. However, the spatiotemporal localization of torrential rainfalls or even the mapping of return probabilities is not possible with the present dataset. Therefore, in this analysis we assumed that torrential rain could occur at any location in the Czech Republic.

Table 1. Indicators for the individual hazards

Hazard	Indicator as used at the cadaster unit level	Grid resolution (m)	Unit	Reference period
Early season drought	Median number of days with soil moisture below 30% of maximum available soil water-holding capacity at the surface layer (0–0.4 m) in April–June	500	Days per season	1991–2014
Late season drought	Median number of days with soil moisture below 30% of maximum available soil water-holding capacity at the surface layer (0–0.4 m) in July–September	500	Days per season	1991–2014
Fast-drying soils	Proportion of fast-drying soils per unit of arable land in the cadaster	5	%	Continuously updated
Sheet erosion	Proportion of the arable land in the cadaster unit with significantly higher than permissible erosion rate (>4 t ha^{-1} yr^{-1})	5	%	Continuously updated
Ephemeral gully erosion	Contributing area to ephemeral gully erosion pathways from arable land in the cadaster unit	5	Hectare	Continuously updated
Localized flood from arable land	Proportion of the cadaster unit area belonging to the contributing area for critical points	5	%	Continuously updated

2.3. Multiple hazard analysis

After selecting the key hazards, the indicators that best represented them were formulated. Table 1 lists the indicators for the individual hazards, while Fig. 2 illustrates the impacts that the indicators represent. The original quantification of the indicators was based on different resolutions, with data on drought occurrence being available as a 500 × 500 m grid and the remaining indicators being calculated at a resolution of 5 m due to the importance of the local terrain conditions. As the study aimed at identifying the areas with the highest hazard level for policy-making purposes, the indicators were aggregated at the level of the cadaster unit, which is the smallest administrative unit in the Czech system. Territory in the Czech Republic is composed of 13 091 cadaster units with a mean area of 6 km^2. For each cadaster unit, the value of each indicator was calculated. All indicators were normalized using a *z*-score approach. It is one of the most commonly used normalization procedures in which all indicators are converted into a common scale with an average of zero and a standard deviation of one. The scale described in Table 2 was applied to communicate the results to the stakeholders. As 6 indicators were used, weighting was considered to express the relative importance of individual indicators to calculate a composite hazard index. Weights are essentially value judgments, and thus, they are essentially subjective and can make the objectives underlying the construction of a composite index explicit (e.g. Giupponi et al. 2015). In this case, we applied equal weights to all indicators. In the final determination of the regions with the highest hazards, we combined an averaging of the *z*-scores due to their transparency with an identification of regions affected by at least 2 of the 6 indicators with a *z*-score below −2. The latter was performed to limit the shortcomings of the averaging approach, as a bad score in one criterion can be offset by a good score in another one, even if there is no interaction among the criteria. Apart from the cadaster units, the so-called 4th-order catchments were considered as an alternative spatial unit for aggregating the hazard analysis results. There are almost 9000 of these 4th-order catchments in the Czech Republic, which have a fairly variable area, and a mean area of 9.6 km^2.

2.4. Mapping

The final result of the combination of factors was a numeric value, which was calculated through the 'union' mathematical function in ERDAS Imagine GIS by a simple averaging of the *z*-scores of all 6 indicators. As a second approach, the frequency with

Table 2. *z*-score table used to interpret the standardized values of the indicators, as used in Figs. 4, 5 & 7

Indicator interpretation	*z*-score range
Above average	0–0.5
Markedly above average	>0.5 and <1.0
Highly above average	1.0–1.5
Very highly above average	>1.5 and <2.0
Extremely above average	2.0 and higher

which a given cadaster unit had a z-score <−2.0 for a particular indicator was also mapped. For the analysis, heavily urbanized cadasters were excluded, as were the cadaster units with a large proportion of surface mines (especially in the northwestern part of the country) and water bodies. In general, a low value for a z-score is an indicator that in the given cadaster unit, the hazard value is proportionally higher than in the rest of the country. Therefore, a very low combined z-score signals the occurrence of multiple hazards. The occurrence of a z-score below −2.0 means that for a given indicator, the cadaster unit belongs to several dozen cadaster units with extremely high levels for that particular hazard. These two approaches were then combined in the final map. Finally, we compared the newly developed classification of the cadaster units according the level of multiple hazards with the extent of the less-favored areas (LFA) as defined in accordance with European Commission (EC) regulation 1305/2013, which is used to support areas with existing natural constraints.

2.5. Climate change scenarios

To evaluate the impact of climate change on the values of the selected indicators, we tested the change in the number of days with drought stress in the topsoil layer during the period April–June. For each 500 m grid, the weather data were modified based on the expected climate change conditions for the region. To be able to assess the development of conditions during 2021–2040, we modified 1981–2010 daily weather data using a delta approach and 5 climate models. These models were selected as representations of mean values (IPSL: model of the Institute Pierre Simon Laplace, France) and to best capture the variability of expected changes in precipitation and temperature (BNU: Beijing Normal University, China; MRI: Meteorological Research Institute, Japan; CNRM: National Centre for Meteorological Research, France; and HadGEM: Hadley Centre Global Environment Model, UK). These models were picked from 40 climate models available in the CMIP5 database (Taylor et al. 2012). These projections used the Representative Concentration Pathway (RCP) 4.5 greenhouse gas concentration trajectory and a climatic sensitivity of 3.0 K. Before using all meteorological data as input for subsequent steps, the SnowMAUS model (Trnka et al. 2010) was applied to estimate the appearance of snow cover. In this way, daily precipitation totals were modified to better match the real timing and amount of water infiltration into the soil considering probable snow accumulation, melting and sublimation.

3. RESULTS AND DISCUSSION

3.1. Agricultural drought and the proportion of fast-drying soils

As shown in Fig. 3a,b, the median number of days under drought conditions in the most affected areas is >30 if we consider the whole growing season. For most of the arable land, the value is >10 d yr^{-1}, with the maxima being achieved not only in the southeast of the Czech Republic but also in parts of the northeast, in the northwest area of so-called central Bohemian region and in the southwest. The areas with a high incidence of dry days also include the southern edge of the Czech and Moravian Highlands in the center of the country (Fig. 1a). If we consider the z-score results (Fig. 4a,b), it is clear that the highest drought hazard is indicated over a fairly large and continuous area in the lowlands of the southeast of the Czech Republic and through a number of smaller regions in the northwest, north-central and, to a lesser degree, in the southwest and northeast. The drought hazard depends on which part of the growing season it is. In the first half of the growing season, the west of the Czech Republic tends to be affected more (Fig. 4a), while the southeast follows an opposite pattern, with drought hazards in the east of the Czech Republic increasing significantly from July to September (Fig. 4b).

Hazards posed by a high proportion of fast-drying soils are limited to 2 principal areas at the west and southeast of the country. While partly overlapping with areas that have an increased agricultural drought risk, these areas are not identical. Fast-drying soils are not present at a number of areas potentially influenced by agricultural drought, notably those in the agricultural lowlands of the southwest, north-central and northeast of the country. Obviously, combining a high proportion of fast-drying soils with a high probability of a greater number of drought days increases the hazard level in the respective cadaster units. This criterion also reflects a gradual decline in the fertility area due to a prolonged lack of water, unsustainable rates of erosion and organic matter depletion caused by human activity, and it reflects decreases in soil fertility that are not fully captured by the indicators of agricultural drought, as these calculations did not consider the processes of land degradation leading to the estab-

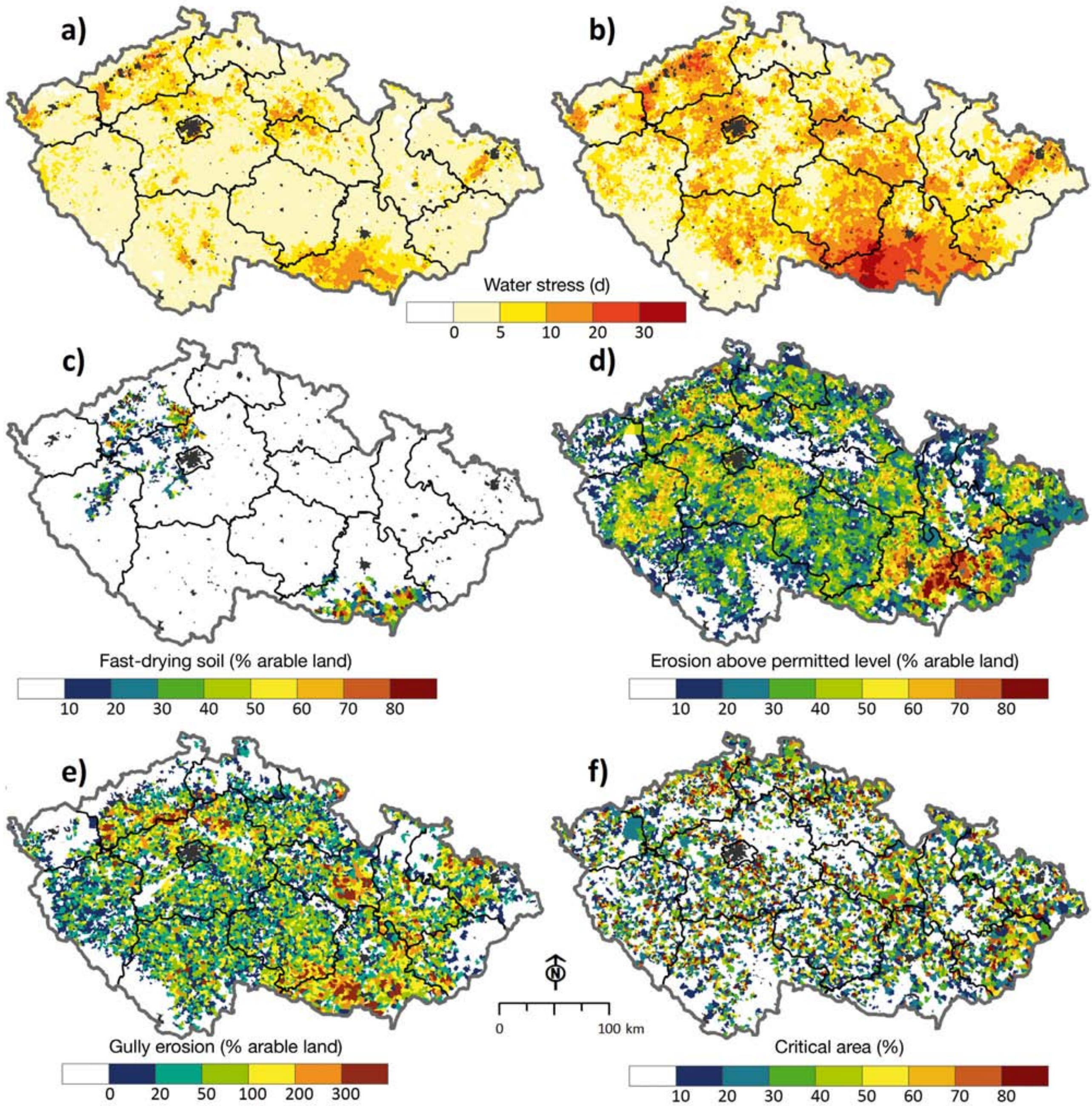

Fig. 3. Map of indicators used for hazard assessment (see Table 1) at the cadaster unit level: (a,b) number of days with water stress in the topsoil (0–40 cm) in (a) April–June and (b) July–September, (c) proportion of arable land in the fast-drying soils category, (d) percentage of arable land within the cadaster unit with erosion rate above permissible levels, (e) proportion of area contributing to ephemeral gully erosion pathways from arable land, (f) proportion of cadaster unit area belonging to contributing area for critical flood points

lishment of fast-drying soils over the last 3 decades. Figs. 3c & 4c clearly show that in terms of fast-drying soils, the most affected areas are concentrated in the southeastern Czech Republic and in an even larger area to the west of Prague and around Pilsen. These areas are likely still expanding, and their growth is proportional to the intensity of the erosion processes.

3.2. Sheet and ephemeral gully erosion

The hazard posed by sheet erosion affects the majority of the key agricultural areas, with the exception of flat areas around large rivers (Elbe and Morava). It is clear that a high percentage of the arable land is at risk of a higher than permissible rate of soil loss (>4 t ha^{-1} yr^{-1}), which is a major cause for

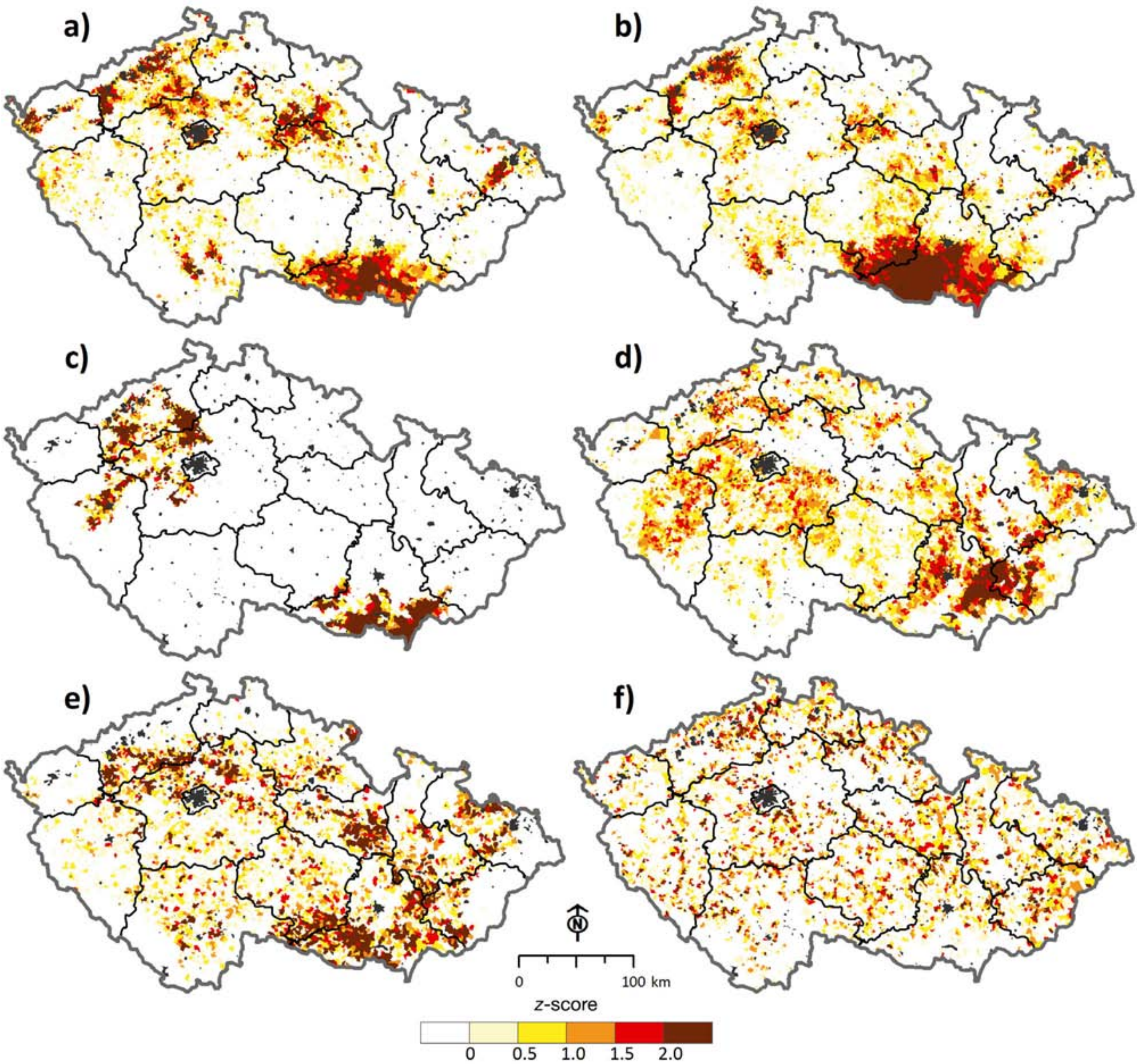

Fig. 4. Hazard indicators expressed as *z*-score at the cadaster unit level: (a) days with water stress in the topsoil (0–40 cm) in (a) April–June and (b) July–September, (c) arable land in the fast-drying soils category, (d) proportion of arable land within each cadaster unit with erosion rate above permissible levels, (e) proportion of drainage area within each cadaster unit contributing to ephemeral gully erosion pathways from arable land, (f) proportion of cadaster unit area belonging to the contributing area for critical points

concern (Fig. 3d). The problem is particularly pronounced in the southeast of the country (albeit in different regions than those affected by drought and fast-drying soils), as Fig. 4d indicates. In each region, one can find 'hot-spots' that are at a markedly greater risk of sheet erosion than the surrounding areas but without a notable 'center', as in the case of the southeast region. On the other hand, the lowest hazard level (apart from areas already listed) is found in the southwest (Fig. 4d).

Compared to the hazard of sheet erosion, the hazard posed by ephemeral gully erosion is more evenly spread across the country. The identification and plotting of potential paths of concentration runoff were based on the modeling of flow accumulation from their collection (contributing) areas, interpretation of the nature of the terrain and a visual interpretation of aerial photos for the affected fields of arable land. We identified >29 000 paths of potential ephemeral gully erosion (pathways for concentrated flow) with a total length of nearly 11 963 km, and for each ephemeral gully erosion path, the contributing area of the arable land was calculated. It is obvious that in some cadasters, the contributing areas are very high (over 200 or 300 ha), indicating potentially large water flows in cases of extreme precipitation (Fig. 3e). Compared to the areas affected by sheet erosion, the areas where ephemeral gully erosion hazards are the greatest tend to be more concentrated, creating an 'arc' in the east of the country and then a 'belt' in the northwest. Using the USLE, land users often underestimate erosion on agricultural fields because it does not account for the loss of soil from ephemeral gullies. It is estimated that ephemeral gully erosion is responsible for up to 20–40 % of the total volume of the sediment from erosion. This is approximately the same magnitude as that of sheet erosion, and has thus far not been accounted for in any hazard analysis. Bennett et al. (2000) presented estimates for the percentage of total soil loss from agricultural watersheds due to ephemeral gullies ranging from 20 to 100 %.

While there is currently no method in the Czech Republic for identifying and predicting the occurrence of sediment delivery from this type of erosion, it needs to be seriously considered, due to its share of the total erosion rate. It is obvious that high erosion rates caused both by sheet and ephemeral gully erosion are, in combination with frequent droughts and unsuitable agronomy practices, the leading causes behind the gradual spreading of the presence of fast-drying soils.

3.3. Localized floods originating from agricultural land

Analysis of the hazard posed by local floods originating from arable land included 6248 municipalities across the Czech Republic, with >35 437 intersections of potential water flow paths with built-up area boundaries, and 9261 were identified as critical points and thus potentially dangerous (Drbal 2009). In total, the contributing areas of these critical points constitute >23 % of the total area of the Czech Republic. For the analysis, the proportion of agricultural land in each cadaster unit that belongs to the contributing area of a so-called 'critical point' (hazard profiles of flash flood risks on boundaries of built-up areas) was considered as the indicator. Unlike for sheet or ephemeral gully erosion, other agricultural land use apart from just arable land was considered in this analysis. Out of all the indicators, the results from this analysis show that the hazards due to flooding are the most evenly spread across the country (Fig. 3f), and it is not possible to pinpoint any particularly vulnerable regions (Fig. 4f). It is critically important that this hazard be included, as it leads to direct threats to property (Fig. 2) and human lives, and could be at least partly addressed by proper agronomic practices.

3.4. Combining the individual hazard indicators

The percentage of territory where the hazard level is highly above average or worse is 8 % (Fig. 5a). Within the multi-criteria analysis, we simultaneously examined how a large part of the territory of the Czech Republic meets at least one of the criteria for an extreme degree of risk (Fig. 5b). This combined approach provides, in our view, a good overview of the areas where the hazard level is significantly higher than the rest of the territory. The last step of this analysis was to define the territory that may be considered to be at a particularly high risk. As such, we considered a territory where the average value of the z-scores was >1.5 and/or where at least 2 criteria had z-scores >2.0 to be at a high risk. These criteria are met by 4.5 % of the territory in the Czech Republic. The percentage is slightly higher when 4th-order river basins are used instead of cadaster units due to a higher mean basin area within the regions with the highest risks. As Fig. 5c shows, 2 areas can be pinpointed as the most at risk. These most vulnerable regions constitute areas where attention and resources should be given the highest priority. This analysis should be taken as an attempt to provide an objective approximation of the most vulnerable regions, and it should be stressed that similar results were found when only 4 indicators were applied (omitting ephemeral gully erosion and combing the 2 drought-day indicators into a single indicator) or when basins were used instead of cadaster units. While there was a great deal of general agreement between the individual approaches, the local differences between the versions suggest that local knowledge should also be applied and that the delimitation of the endangered areas should be inclusive rather than rigid.

The multi-criteria analysis presented here tries to define particularly endangered areas in the Czech Republic in terms of drought hazard and exposure to the risks of erosion (Fig. 6). This analysis indicates relatively 'typical' hazard areas, which include the regions of northwest Bohemia and south Moravia. Northwest Bohemia in particular is at risk from hydrological drought, and these areas have the smallest

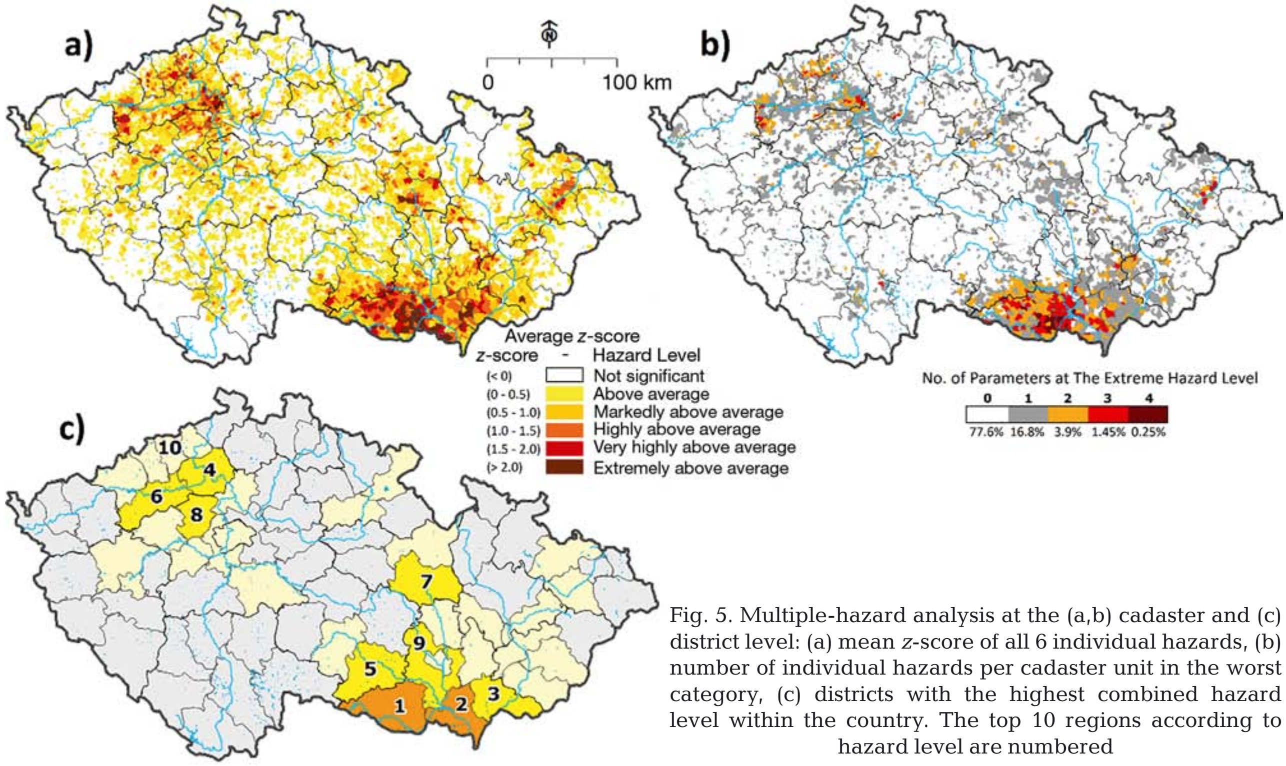

Fig. 5. Multiple-hazard analysis at the (a,b) cadaster and (c) district level: (a) mean z-score of all 6 individual hazards, (b) number of individual hazards per cadaster unit in the worst category, (c) districts with the highest combined hazard level within the country. The top 10 regions according to hazard level are numbered

availability of water resources. These territories also have agroclimatic conditions typical of the corn and sugar beet-growing regions (Fig. 6b) that include the most fertile regions of the country. At the same time, the cadaster units identified as the most vulnerable using the multiple hazard approach show only a 10% overlap with the presently defined LFAs, as Fig. 6a indicates. LFA is a term used within the EU (and defined according a set of EU-based criteria) to describe an area with natural handicaps (lack of water, climate, short crop season and tendencies of depopulation), or that is mountainous or hilly, as defined by its altitude and slope. As the LFAs are defined through the use of more or less common European criteria, it leads to a paradox whereby the regions with the highest combined hazards from drought and soil degradation receive significantly less support than the LFA areas. As LFA regions have seen significant improvement in their agroclimatic conditions and overall productivity thanks to climate change over past 2 decades, it has led to an imbalance that the LFA introduction has attempted to rectify.

3.5. Change in climate conditions

The estimated risks posed by the hazards discussed here are not likely to remain stable in the near future. We demonstrate this in the case of the number of drought days in April–June for the period 2021–2040, assuming an RCP 4.5 emission scenario that predicts a fairly modest increase in CO_2 concentrations. All 5 global circulation models show a marked increase in z-score levels compared to baseline (Fig. 7). The rate of occurrence of the most extreme level (z-score >2.0) is, under the baseline climate, 5.7%, and the average for 2021–2040 is estimated at 14.2% (with the range of the 5 GCMs considered being 10.9–20.1%), which is an almost 3-fold increase in the frequency of this most extreme category. Such changes would mean profound increases in the overall drought hazard. In the southeast, the expansion of the highest hazard area occurs in a northward direction, while in the west, the expansion covers the Elbe River lowland. Both areas are presently considered to be the most fertile regions in the country. An additional factor of concern is the occurrence of drought 'spots' across the entire country, with the only exception being the northeast region. The increased incidence of drought in these sites is driven primarily by a lower soil water-holding capacity. These results indicate that hazard levels are not static and are likely to change in the future. In addition, this dynamic (i.e. hazard levels in relation to climate change) must be considered when areas most at risk are defined. What was surprising, how-

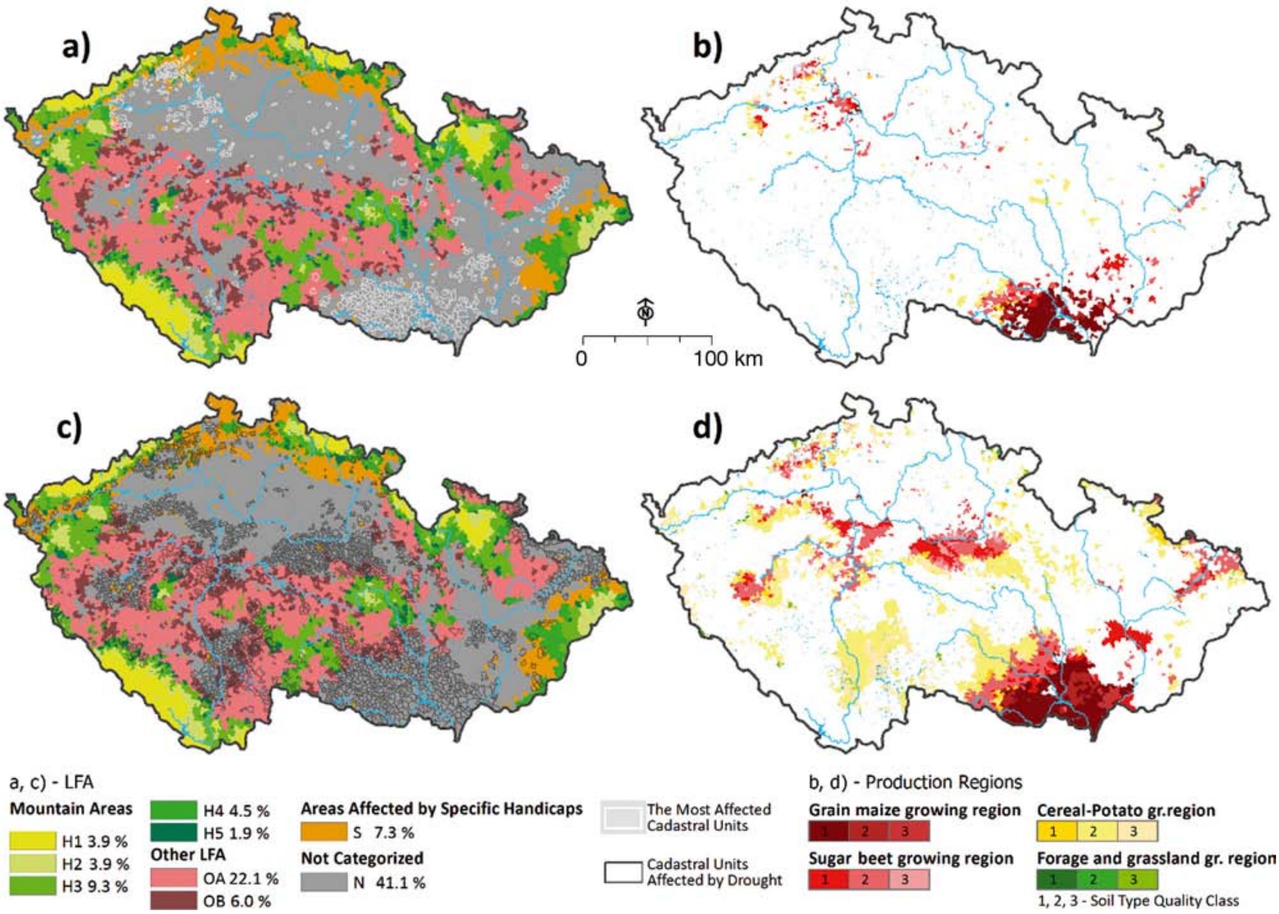

Fig. 6. (a,b) Drought risk and (c,d) multiple hazards. Comparison of cadaster units most at risk from (a) drought and (c) multiple hazards with less-favored areas (LFAs). Agroclimatological production regions belonging to cadaster units with (b) high drought and (d) multiple hazards. Areas marked H1-5 are limited by the altitude and slopes; areas OA and OB by slopes and soil conditions; areas marked S are primarily limited by need to protect water resources

ever, was the magnitude of the predicted changes that could occur over such a short time-frame in the near future. The probability of extreme drought increases considerably under predicted future climate conditions, and these changes may occur much more quickly than is generally anticipated. This leaves relatively little time for a response.

3.6. Uncertainty in hazard classifications

Apart from the presented approach using the 6 hazard indicators and cadaster units, 2 other approaches were tested. One relied on only 4 indicators (drought stress was considered for the entire April–September period, and gully erosion was omitted), and we also considered using 4th-order catchments instead of cadaster units. The use of 4 indicators would increase the weight of each one, while making the approach simpler. The overall area affected by the highest risk levels was slightly smaller but was consistent with the finding presented above (this paragraph). However, it was felt that drought effects in particular were underestimated when using only 4 indicators. As Fig. 4a,b shows, there are considerable differences between the drought hazards in the periods April–June and July–September. When these 2 indicators were considered as a single April–September indicator, some of the areas with known and persistent drought hazards in the northwest of the Czech Republic were left out of the evaluation. Similarly, not including ephemeral gully erosion as a factor led to the omission of some areas where major damage has occurred, as documented in Fig. 2.

The analysis presented here shows the urgent need for explicitly accounting for climate change. This is fairly easy in the case of drought-day-based indicators, as the methodology is flexible and de-

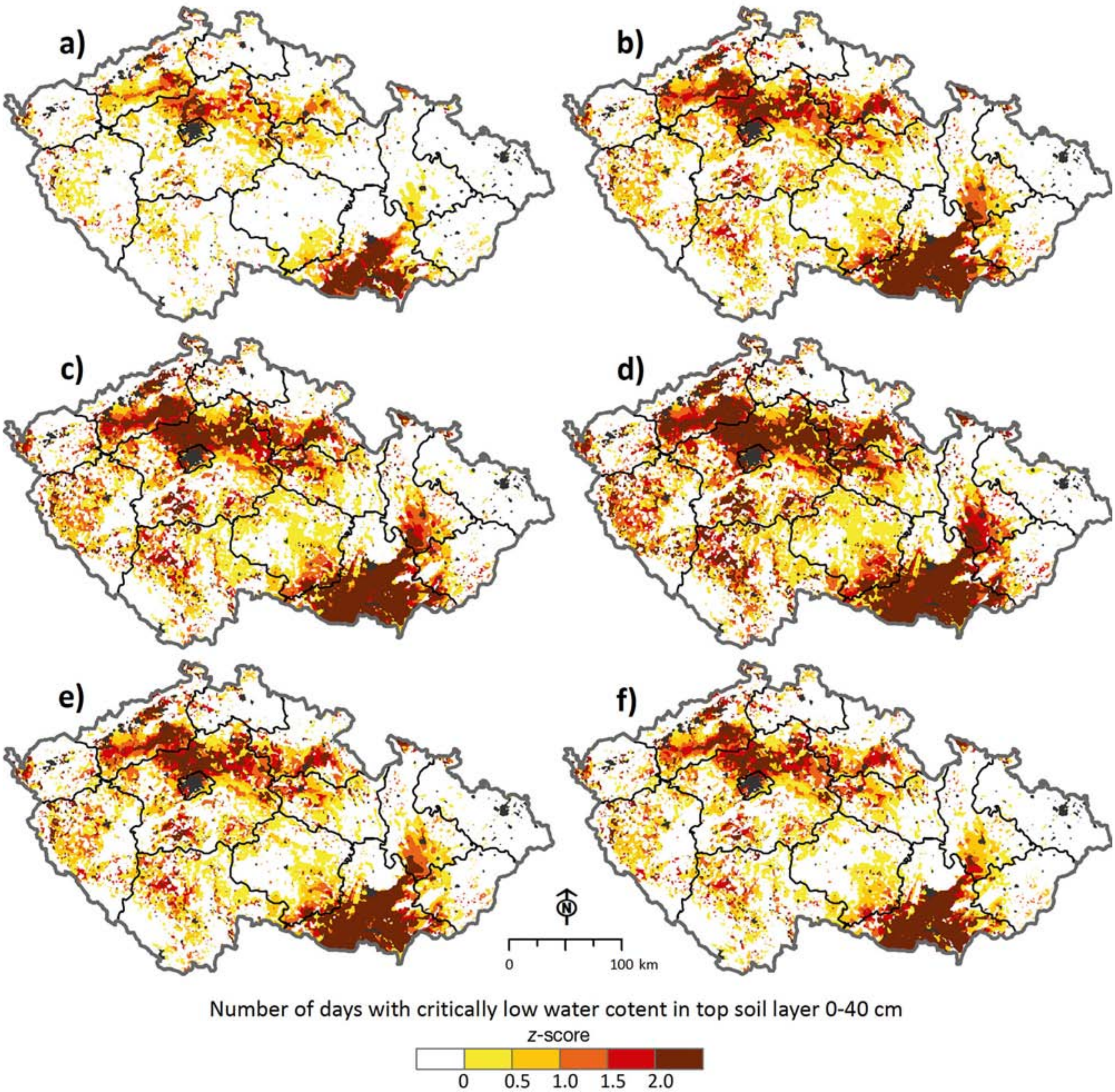

Fig. 7. Hazard of water stress in April–June in the topsoil (0–40 cm) expressed as *z*-scores at the cadaster unit level. (a) The period 1991–2014 was used as the baseline, and *z*-scores for (b–f) the period 2021–2040 were estimated from this baseline. The following models are represented: (b) IPSL, (c) HadGEM, (d) MRI, (e) CNRM, (f) BNU (see Section 2.5 for abbreviations)

signed to handle the effects of climate change (e.g. Trnka et al. 2015a). However, it will be more of a challenge for the remaining 4 indicators. In the case of fast-drying soils, the dynamics of persistently drying soil profiles speeding up soil degradation should be accounted for. Similarly, in the case of sheet and ephemeral gully erosion, changes in the probability of major precipitation events need to be considered, as do changes in the phenological calendar. While there is a general view that the occurrence of higher-intensity events is more likely under future climate conditions (increasing the potential erosion from each event), there is also clear data from previous studies showing the protective effect of vegetation cover. All of these factors need to be analyzed and researched prior to conducting multi-hazard assessments for determining the effects of future climate conditions.

3.7. Analyzing water resources in areas with the highest hazard

The Czech Republic is situated in a region with annual precipitation that ranges from 450 mm in dry regions to 1300 mm in mountainous regions; however, as the country is located on the continental divide, its water resources are driven primarily by rainfall. Previous research (e.g. Hlavinka et al. 2009, Trnka et al. 2012) has shown that areas with considerable lack of water in the top layer of the soil might hamper agriculture, as yields are closely related to the water balance (e.g. Hlavinka et al. 2009, Trnka et al. 2012). Occasional water shortages do not usually result from the overall unavailability of water resources, but rather from the spatiotemporal variability of water supply/demand and the high degree of water resource exploitation.

However, as Hanel et al. (2012) and Trnka et al. (2015b) have indicated, water availability is likely to change due to the projected changes in temperature and precipitation (i.e. an increase in temperature over the whole year and no change in annual precipitation, but with a decrease in precipitation in the summer and an increase in winter). Fig. 8 shows interactions between shifts in rainfall amounts and evapotranspiration. Higher precipitation totals are more than matched by the increase in actual evapotranspiration, as estimated with the BILAN model (Vizina et al. 2015). In summer, although precipitation decreases, the increase in actual evapotranspiration is not as large as would be expected from the increase in temperature (and hence potential evapotranspiration), because it is limited by available water. The observed changes in the difference between precipitation and potential evapotranspiration are shown in Fig. 8 and are becoming more negative in spring and summer.

Trnka et al. (2015b) and Hanel et al. (2012) used different approaches, but agreed on changes in the amount of water fixed in snow. This influences both runoff and the speed of the snow melt, and underground water recharge. An important factor for the changes in runoff is a shift in the snow melt from early spring to winter.

The combination of reduced precipitation and increased temperature leads to measures that attempt to protect water resources. Practical experience indicates that the most robust and effective measures are those that increase the water supply (in our case specifically, the reconstruction of old — or the design of new — reservoirs or water transfer systems) in high-hazard areas.

3.7. Using multi-hazard analysis results in land consolidation process

The approach developed in this paper can be used in the process of land consolidation. It is a multifunctional tool for sustainable development of the land. Land consolidation spatially and functionally arranges the land in the public's interest and consolidates or splits parcels while ensuring its accessibility. Land consolidation provides the conditions for improving the environment, land resource protection, and water management and for improving the ecological stability of the landscape. Land consolida-

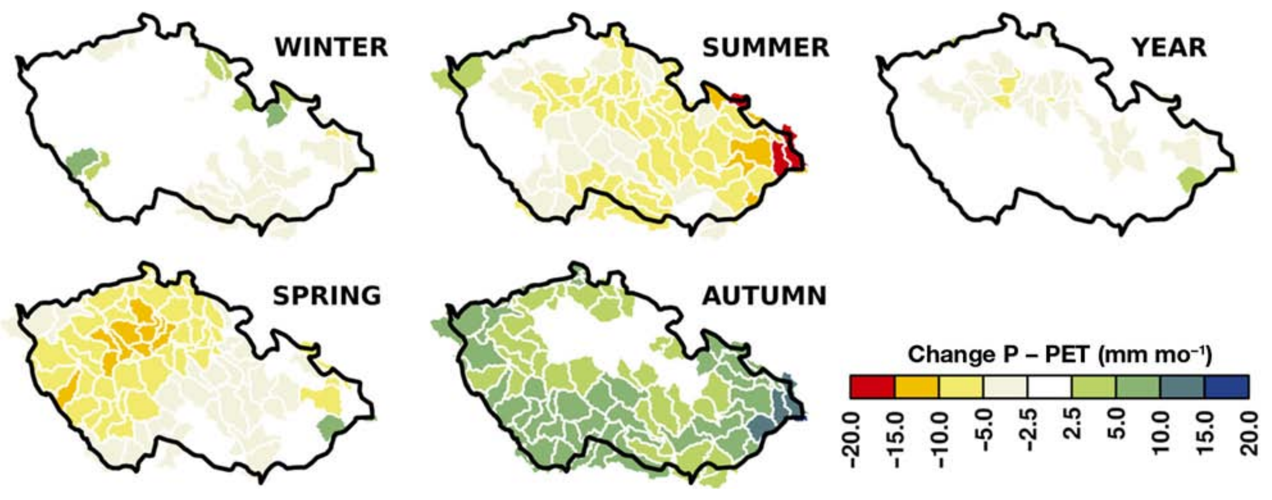

Fig. 8. Changes in observed difference in precipitation (P) and potential evapotranspiration (PET) between the periods 1961–1980 and 1981–2005 for 3rd-order river basins

tion is performed pursuant to Act No. 139/2002 Coll.

This consolidation is the only process in the Czech Republic to solve complex issues in rural areas, including the realization of measures that are in the public's interest. It also addresses considerable issues relating to the property of citizens and legal entities. Therefore, it is obvious that this complex set of issues cannot be managed without objective sources of information. The identification of the most vulnerable areas in the Czech Republic through a multi-hazard analysis is an important source of information in guiding the prioritization of the land consolidation process and its spatial targeting for the State Land Office. In this way, the State Land Office will receive unique material that can be used to improve their ability to mitigate the impacts of climate change. In addition, it will be able to effectively participate in the establishment of a legislative and economic framework that could possibly realize adaptation measures acceptable to agricultural entities.

4. CONCLUSIONS

The mapping of multiple hazards for agricultural land is intended as a first but crucial step in the assessment of the vulnerability of the agricultural sector to the occurrence of drought and extreme precipitation events under the present conditions and under the predicted future climate conditions in the Czech Republic. The map presented here synthesizes a variety of data and serves as an indicator of areas deserving more detailed attention. The key hazards for agricultural land in the Czech Republic include the occurrence of water stress in the topsoil layer during both the first and second half of the growing season, the proportion of fast-drying soils, the risk of sheet and ephemeral gully erosion and the risk of local floods originating primarily from agricultural land. The generation of *z*-scores was used as a standardization method, and a combination of an equal-weighting scheme and *z*-scores below −2.0 signaling the most extreme values were used in drafting the final output map. The final output map also shows results aggregated at the district level to clearly mark regions where primary attention should be given to reduce the level of the hazards and/or to increase cropping capacity. These regions are concentrated in the southeastern and northwestern lowland areas. As for typical areas with the highest hazard levels, we can identify regions with below-average precipitation and a high proportion of soils with a degraded or naturally occurring low water-holding capacity, and those with steeper than average slopes and terrain configurations in relatively large catchment areas that have urbanized landscapes located at their lower elevations. This study also allows for the definition of cases in which data quality limits the usefulness of such hazard mapping. While state of the art digital elevation models were used, the information on the actual soil status had to rely on data from complex soil surveys carried out in the 1970s. While these data have been constantly updated, the last comprehensive campaign completely assessing soil status was carried out approximately 40 yr ago. As the next step in this research, farms in the areas with the highest hazard levels were selected as sites to conduct detailed and thorough assessments of the hazards present and to perform a complete vulnerability analysis. Based on this pilot study of farms and ground-level validation of the concept, a national vulnerability map will be prepared that will also include social aspects of vulnerability.

Despite some limitations, the methods presented in this paper serve as a step forward in developing techniques for reducing hazard levels at the individual cadaster unit, especially in the process of land adjustment, which aims at improving the organization, productivity and sustainability of agricultural production and the optimization of ecosystem services. Our results also point to the fact that the present definition of the LFA does not match the areas threatened by increased drought and erosion hazards, and that other mechanisms should be introduced to support sustainable and viable farming in these regions. This is especially important given that many of the areas at considerable risk are in the regions that are nominally the most productive land in the country and that have the highest taxes levied per hectare of land and the lowest level of support. As we have also shown, ongoing climate change will considerably change the hazard levels compared to those present today. Drought and soil loss are likely to become even more dominant factors affecting production in the future, and therefore, the adaptation of the agrarian sector to these coming conditions is critical. In addition, understanding the present hazard levels can and should lead to adjustments in agricultural practices and to the selection of more appropriate cropping patterns to obtain maximum financial yields during years with normal precipitation, and to reduce declines in crop yields and income loss during drought years, while at the same time conserving the soil. The multiple-hazards map presented here can help decision-makers visualize hazards and communicate them to farmers, natural resource managers and others. The education of the Czech Republic's decision-makers about these multiple hazards has already begun, and includes both grassroots as well as responsible decision-makers, both in the executive and legislative branches of the government.

Acknowledgements. The support of the State Land Office is greatly appreciated by all authors. M.T., P.H., J.B., D.S. and Z.Ž. acknowledge funding from the CzechAdapt Norwegian funds project funded through the Czech Ministry of Finances (no. EHP-CZ02-OV- 30 1-014-2014) and funding from the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Program I (NPU I), grant no. LO1415. We thank the National Agency for Agricultural Research of the Czech Republic, project no. QJ1610072 'System for monitoring and forecast of impacts of agricultural drought', for supporting the purchase of some datasets. We thank Mrs. Svatava Maradová, MBA (head of the State Land Office) and Mr. Václav Hlaváček (vice-president of the Czech Agrarian Chamber) for their comments and improvement of the study.

LITERATURE CITED

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome

Batysta M, Hruška M, Jirásková I, Leibl M and others (2015) Situační a výhledová zpráva Půda. Ministry of Agriculture of the Czech Republic, Prague (in Czech)

Bennett SJ, Casali J, Robinson KM, Kadavy KC (2000) Characteristics of actively eroding ephemeral gullies in an experimental channel. Trans ASAE 43:641–649

Brázdil R, Trnka M, Dobrovolný P, Chromá K, Hlavinka P, Žalud Z (2009) Variability of droughts in the Czech Republic, 1881–2006. Theor Appl Climatol 97:297–315

CSO (Czech Statistical Office) (2005) Statistical yearbook of the Czech Republic. Scientia, Prague

Desmet PJJ, Govers G (1996) A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. J Soil Water Conserv 51: 427–433

Drbal K (ed) (2009) Vyhodnocení povodní v červnu a červenci 2009 na území České republiky (Methodology for flood risk evaluation). Water Research Institute of TGM, Ministry of Environment of the Czech Republic, Prague. www.vuv.cz/files/pdf/problematika_povodni/povoden-2009_cinnost_povodnove_sluzby_a_slozek_izs.pdf

Drbal K, Dumbrovský M (2009) Metodický návod pro identifikaci KB. Ministry of Environment of the Czech Republic, Brno, Prague. www.povis.cz/html/download_smernice.htm

Dumbrovský M (2011) Vymezení přispívajících ploch nad závěrovými profily erozně ohrožených drah odtoku na orné půdě pro potřeby Rámcové směrnice pro vodní politiku 2000/60/ES

EEA (European Environment Agency) (1998) Europe's environment: the second assessment. EEA, Aarhus

EEA (European Environment Agency) (1999) Environment in the European Union at the turn of the century. EEA, Copenhagen. www.eea.europa.eu/publications/92-9157-202-0/SOER_1_1999.pdf/view

Giupponi C, Mojtahed V, Gain AK, Biscaro C, Balbi S (2015) Integrated risk assessment of water related disasters. In: Paron P, Di Baldassare G (eds) Hydro-meteorological hazards and disasters. Elsevier, Amsterdam, p 163–200

Gourdji SM, Sibley AM, Lobell DB (2013) Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. Environ Res Lett 8:024041

Hanel M, Vizina A, Máca P, Pavlásek J (2012) A multi-model assessment of climate change impact on hydrological regime in the Czech Republic. J Hydrol Hydromech 60: 152–161

Hlavinka P, Trnka M, Semerádová D, Dubrovský M, Zalud Z, Mozný M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric For Meteorol 149: 431–442

Hlavinka P, Trnka M, Balek J, Semerádová D and others (2011) Development and evaluation of the SoilClim model for water balance and soil climate estimates. Agric Water Manage 98:1249–1261

Huntingford C, Jones PD, Livina VN, Lenton TM, Cox PM (2013) No increase in global temperature variability despite changing regional patterns. Nature 500:327–330

IPCC (2014) Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ and others (eds) Climate change 2014: impacts, adaptation, and vulnerability. A. Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 1–32

Janeček M, Dostál T, Kozlovsky-Dufková J, Dumbrovský M and others (2012) Erosion control in the Czech Republic-handbook. Czech University of Life Sciences, Prague (in Czech)

Kappes MS, Keiler M, von Elverfeldt K, Glade T (2012) Challenges of analyzing multi-hazard risk: a review. Nat Hazards 64:1925–1958

Kolář P, Trnka M, Brázdil R, Hlavinka P (2014) Influence of climatic factors on the low yields of spring barley and winter wheat in Southern Moravia (Czech Republic) during the 1961–2007 period. Theor Appl Climatol 117:707–721

Larcher W (2003) Physiological plant ecology, 4th edn. Springer-Verlag, Berlin

Liu C, Allan RP (2013) Observed and simulated precipitation responses in wet and dry regions 1850–2100. Environ Res Lett 8:034002

Morgan RPC (2005) Soil erosion and conservation, 3rd edn. Blackwell Publishing, Oxford

Myers SS, Zanobetti A, Kloog I, Huybers P and others (2014) Increasing CO_2 threatens human nutrition. Nature 510: 139–142

Olesen JE, Carter TR, Díaz-Ambrona CH, Fronzek S and others (2007) Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Clim Change 81:123–143

Panagos P, Borrelli P, Poesen J, Ballabio C and others (2015) The new assessment of soil loss by water erosion in Europe. Environ Sci Policy 54:438–447

Porter JR, Xie L, Challinor AJ, Cochrane K and others (2014) Food security and food production systems. In: Field CB, Barros VR, Dokken DJ, Mach KJ and others (eds) Climate change 2014: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate

Change. Cambridge University Press, Cambridge, p 485–533
Rahmstorf S, Coumo A (2011) Increase of extreme events in a warming world. Proc Natl Acad Sci USA 108:17905–17909
Reyer CPO, Leuzinger S, Rammig A, Wolf A and others (2013) A plant's perspective of extremes: terrestrial plant responses to changing climatic variability. Glob Change Biol 19:75–89
Ruiz-Ramos M, Sánchez E, Gallardo C, Mínguez MI (2011) Impacts of projected maximum temperature extremes for C21 by an ensemble of regional climate models on cereal cropping systems in the Iberian Peninsula. Nat Hazards Earth Syst Sci 11:3275–3291
Svobodová E, Trnka M, Dubrovsky M, Semeradova D, Eitzinger J, Stepanek P, Zalud Z (2014) Determination of areas with the most significant shift in persistence of pests in Europe under climate change. Pest Manag Sci 70:708–715
Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498
Trnka M, Dubrovský M, Svoboda M, Semerádová D, Hayes M, Žalud Z, Wilhite D (2009) Developing a regional drought climatology for the Czech Republic. Int J Climatol 29:863–883
Trnka M, Kocmánková E, Balek J, Eitzinger J and others (2010) Simple snow cover model for agrometeorological applications. Agric For Meteorol 150:1115–1127
Trnka M, Brázdil R, Olesen JE, Zahradníček P and others (2012) Could the changes in regional crop yields be a pointer of climatic change? Agric For Meteorol 166–167: 62–71
Trnka M, Rötter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Žalud Z, Semenov MA (2014) Adverse weather conditions for European wheat production will become more frequent with climate change. Nat Clim Change 4:637–643
Trnka M, Hlavinka P, Semenov MA (2015a) Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change. J R Soc Interface 12:20150721
Trnka M, Brázdil R, Možný M, Štěpánek P and others (2015b) Soil moisture trends in the Czech Republic between 1961 and 2012. Int J Climatol 35:3733–3747
Trnka M, Olesen JE, Kersebaum KC, Rötter RP and others (2016) Changing regional weather—crop yield relationships across Europe between 1901 and 2012. Clim Res 70:195–214
Van Lynden GWJ (1994) The European soil resource: current status of soil degradation causes, impacts and need for action. Council of Europe, Strasbourg
Vizina A, Horáček S, Kašpárek L, Hanel M (2015) Nové možnosti modelu BILAN. VTEI 57:4–5
Vopravil J, Rožnovský J, Hladík J, Khel T and others (2012) Možnosti řešení degradace půdy a její ovlivnění změnou klimatu na příkladu aridních oblastí. Ministry of Agriculture of the Czech Republic, Prague
Wilhite DA (2000) Drought as a natural hazard: concepts and definitions, Chapter 1. In: Wilhite DA (ed) Drought: a global assessment. Natural Hazards and Disasters Series. Routledge Publishers, London, p 3–18
Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: guide to conservation planning. US Department of Agriculture, Agriculture Handbook 537. US Government Printing Office, Washington, DC
Zahradníček P, Trnka M, Brázdil R, Možný M and others (2015) The extreme drought episode of August 2011–May 2012 in the Czech Republic. Int J Climatol 35: 3335–3352

Editorial responsibility: Donald Wilhite (Guest Editor), Lincoln, Nebraska, USA

Submitted: April 4, 2016; Accepted: August 9, 2016
Proofs received from author(s): October 24, 2016

Vol. 70: 251–263, 2016
doi: 10.3354/cr01406

CLIMATE RESEARCH
Clim Res

Published October 27

Contribution to CR Special 33 'Drought in Central Europe – from drought response to preparedness'

Using climate information for drought planning

Taryn Finnessey[1,*], Michael Hayes[2], Jeff Lukas[3], Mark Svoboda[2]

[1]Colorado Water Conservation Board, Department of Natural Resources, 1313 Sherman St., Rm 721, Denver, CO 80203, USA
[2]National Drought Mitigation Center, University of Nebraska-Lincoln, 3310 Holdrege Street, Lincoln, NE 68583-0988, USA
[3]Cooperative Institute for Research in Environmental Sciences, Western Water Assessment, University of Colorado, Boulder, CO 80304, USA

ABSTRACT: Historically, drought has been responded to rather than prepared for, yet studies have illustrated that proactive investment in drought risk management reduces impacts and overall response costs. One key element of preparedness is the use of sufficient climate information for monitoring, forecasting, and tracking long-term trends. In the face of a changing climate and increasing variability, these types of data are even more critical for planning and overall resiliency. The systematic use of these data to inform the drought planning component of drought risk management is a relatively recent development. Actionable science has direct applicability for planning and decision-making, and allows for an iterative process between scientists and end users that can build long-term drought resiliency. The article will describe how planners in Colorado are increasingly relying on climate data, ranging from paleoclimatological records to experimental seasonal forecasts, to guide their long-term drought preparedness and climate change adaptation efforts. This information can then be used to inform broader policy and planning efforts, unifying the scientific basis across multiple processes. In addition, the Integrated Drought Management Programme (IDMP), with the World Meteorological Organization (WMO) and the Global Water Partnership (GWP) as co-leads, promotes national policies encouraging proactive risk management, and provides a platform for sharing the lessons learned by the planners, policy makers, and scientists around the world. Data-driven decision-making using climate information can help depoliticize actions and increase overall resiliency and response in times of drought, which will be increasingly important as the world warms.

KEY WORDS: Drought planning · Preparedness · Risk management · Resiliency

1. OVERVIEW OF DROUGHT RISK MANAGEMENT

Recent drought events around the world have demonstrated that droughts are normal, yet costly, natural disasters in most climates. Examples include the California drought in the United States of America, which cost a roughly estimated US$5 billion in agricultural impacts over consecutive years in 2014 to 2015, and illustrates the potentially huge economic impacts resulting from droughts in the developed world (Howitt et al. 2014, 2015). In Brazil, a recent multiple-year drought threatened water supplies for the residents of Sao Paulo, the ninth-largest metropolitan area in the world and the largest in South America. The 2011 drought across the Greater Horn of Africa region confirmed that droughts can cause famines and human mortality. Meanwhile, the 2006 to 2011 drought in the Middle East is indirectly linked to the recent disruptions and chaos across northern Africa and the Middle East, contributing to the current unrest in Syria and the migration crisis facing the European continent (Gleick 2014).

These droughts are occurring within the context of a world facing multiple global risks, including those involving water and food crises, climate change, and

*Corresponding author: taryn.finnessey@state.co.us

Publisher: Inter-Research · www.int-res.com

changing frequencies of extreme weather and climate events. The World Economic Forum (2014) has recently placed each of these topics into a list of the top 10 risks facing the globe, in addition to a world facing 'profound political and social instability'. Therefore, it is essential for drought managers everywhere to adopt a proactive approach that identifies who or what are at risk from drought impacts, and why they have this risk. This approach has been called drought risk management, and its objective is to reduce future drought impacts by improving drought monitoring, planning, and mitigation strategies (Wilhite et al. 2005). The cycle of disaster management illustrated in Fig. 1 demonstrates how officials use crisis management to respond after events take place.

The risk management portion of the cycle, which includes monitoring and early warning, planning, and mitigation, highlights actions and activities that must occur before an event. Using drought as the event, the cycle illustrates that if officials either do nothing or only focus on crisis management, future drought risks will not be addressed and impacts will not be reduced. This key concept demonstrates why proactive drought risk management is a critical paradigm for drought officials, and will continue to be a concern under a changing climate.

This article articulates how climate information can be incorporated into the drought planning component of drought risk management. When drought managers engage in planning, the objective is to develop a plan to reduce the impacts of drought by using an effective and systematic means of assessing

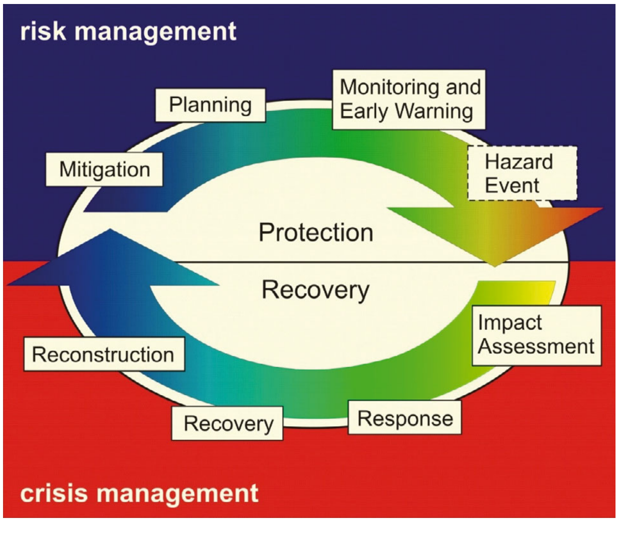

Fig. 1. The cycle of disaster management. Source: National Drought Mitigation Center

drought conditions, identifying who and what is at risk from drought events, developing mitigation strategies that reduce the risk in advance of drought, and devising response options that minimize economic stress, environmental losses, and social hardships during drought. This emphasis on drought planning is applicable at any decision-making level. Drought planning helps decision-makers prepare for multiple hazards, including climate change, and will promote sustainability and natural resource management, leading toward greater economic and societal security at all levels (Geological Society of America [GSA] 2007). Climate information is central to drought planning because the connection between the assessment of current drought conditions and the activities and programs laid out within a plan is critical for the plan to be successful.

Although entities around the world have been slow to adopt a drought risk management approach (Wilhite et al. 2005), several key international initiatives are promoting the importance of drought risk management, as well as the importance of utilizing climate information and related climate services within drought risk management. In 2009, the Global Framework for Climate Services (GFCS) was established, which is a mechanism led by the United Nations to coordinate climate services worldwide. Three GFCS emphases specifically include drought: agriculture and food security, disaster risk reduction, and water. In 2013, the World Meteorological Organization (WMO) hosted the High-Level Meeting on National Drought Policy (HMNDP) in Geneva, Switzerland. Representatives from 92 nations unanimously supported a declaration encouraging countries to develop and implement national drought policies focused on drought risk management. The Integrated Drought Management Programme (IDMP), co-led by the WMO and the Global Water Partnership, was then launched to assist nations in developing a proactive national drought policy. Climate information is integral within these initiatives, and the spatial and temporal characteristics of drought spreading over multiple scales and overlapping numerous political and river basin jurisdictions mean that climate indicators and other physical indicator information are important within the drought monitoring and early warning systems (Wilhite et al. 2014). The state of Colorado in the USA provides an excellent example of how climate information can be applied within its drought-planning activities, and the state's efforts are highlighted in this article.

2. OVERVIEW OF PLANNING

Planning is a task of basic problem-solving, and has been incorporated into many disciplines, including environmental issues related to land management, natural resources, water, and, more recently, drought (Bergman 2014). Water planners are used to dealing with uncertainty. The actual trajectory of population change often departs from the forecasts, the economy may grow faster or slower than anticipated, and weather extremes may develop at the least opportune moments. Water managers and users rely on data to help guide and inform their planning process. Yet, drought, a naturally occurring phenomenon, has largely been overlooked by planners as something that can be planned for, rather than simply responded to. This may be due to its relatively slow onset, or the fact that the beginning and end of a drought event can be difficult to discern, unlike other natural disasters that have very distinct beginnings and ends. This reactive approach has resulted in serious impacts and damages over the last century, some of which could have been reduced if proactive steps had been taken. While developing drought plans involves the commitment of time and money, studies show that proactive investment in natural disaster mitigation can result in significant cost savings as well as reduce overall impacts during an event (Multihazard Mitigation Council 2005).

Comprehensive drought planning provides a systematic and coordinated risk management strategy for planners to reduce overall impacts for people, animals, property, and the environment, over both the short and long term. Proactive planning also enables a more coordinated and rapid response when an event does occur — as with other natural disasters for which comprehensive planning is more common.

Comprehensive drought risk management includes the development of monitoring, mitigation, and response mechanisms that enable decision-makers to detect a drought early, respond in a timely manner, and implement measures to reduce impacts while not in active response mode. The use of climate data has historically been mainly limited to monitoring, but has broader applicability to long-term planning, especially in the face of anthropogenic climate change (Woodhouse & Overpeck 1998). These data can provide robust metrics on which to base decisions, assess vulnerabilities, establish triggers for action, and develop mitigation strategies, all of which are critical components of overall drought risk management.

3. OVERVIEW OF CLIMATE INFORMATION FOR DROUGHT RISK MANAGEMENT

3.1. Instrumental weather and climate observations

Effective drought risk management, including comprehensive drought planning, depends on the coordinated use of multiple types of weather and climate information (Wilhite & Buchanan-Smith 2005, Svoboda et al. 2015). Some of these data types, such as real-time drought-monitoring indicators, have seen decades of operational use in the drought-risk context, while others have been more recently or sporadically applied to drought risk management. Table 1 provides a summary of the key attributes of the different types of climate information with respect to drought planning.

The foundation of effective drought risk management is understanding the history of drought events in a locale or region (Svoboda et al. 2015). This evaluation of the physical (climatic and hydrologic) dimensions of drought has been described by Hayes et al. (2004) as the 'hazard analysis' portion of a broader drought risk analysis. The hazard analysis for drought centers on describing the frequency, intensity, duration, and spatial extent of drought occurrences (Hayes et al. 2004). This is the first step of a risk assessment. A full risk assessment would also include an analysis of vulnerability which examines the people and things that are susceptible to damage or loss as a result of a hazard.

The effective use of observed or instrumental weather and climate data is fundamental to drought risk management (Wilhite & Buchanan-Smith 2005). Two key processes depend on instrumental data: retrospective analysis of past drought events and real-time monitoring of drought conditions. Ideally, these processes will be linked so that they use consistent data and can inform each other. Both processes are predicated on drought indicators: variables that can be used to characterize the severity, duration, and spatial extent of drought (Steinemann & Cavalcanti 2006). Commonly used drought indicators in the USA include percent of normal precipitation, the Palmer Drought Severity Index (PDSI), the Standardized Precipitation Index (SPI), and more recently, the US Drought Monitor (Svoboda et al. 2002). The selection of the most appropriate drought indicator(s) is context-specific: it depends partly on the characteristics of a region's climate, but even more so on the particular societal and ecological vulnerabilities identified in the drought planning process, and the impacts that are desired to be reduced. Ideally, multiple drought

Table 1. The key characteristics of the 5 types of climate information useful drought risk management

Instrumental weather and climate observations: Observed climate records	Instrumental weather and climate observations: Real-time monitoring	Paleoclimate records	Seasonal climate forecasts	Climate model projections
Key information regarding drought risk				
Temporal and spatial patterns and trends in past drought events	Current drought status and direction of change (improving or worsening)	Expanded perspective on past drought events; may show risk to be greater	Anticipate onset, intensification, and amelioration of drought	Future anthropogenic change in drought risk
Time span of information				
30–300 yr ago up to present	Present	300–2000 yr ago up to present	1–12 mo ahead from present	20–80 yr ahead from present
Principal uses in drought risk management and planning				
Establish baseline drought risk for a region; derive drought-of-record; determine appropriate trigger levels for drought response	When triggers for indicators are reached, implement responses	Assess adequacy of observed record in describing baseline drought risk; derive more stressful droughts-of-record	Use in combination with triggers to prepare and respond to emerging drought	Anticipate future changes in drought risk and prepare with long-term policy and investment
Limitations				
Do not capture the full range of natural climate variability; may underestimate future drought risk	Indicators may not consistently capture impacts	Uncertainty in the proxy information; limited to annual resolution; not available for many locations	Difficult to translate the probabilistic forecasts into threshold-based responses	Large uncertainties in future changes, which require consideration of multiple projections; complex datasets that are difficult to obtain, analyze and interpret

indicators will be used in the hazard analysis (e.g. SPI and PDSI), since the unique indicators will represent different dimensions of the same drought event.

The most basic hazard analysis will involve plotting time-series of these indicators, over their full available records, for 1 or more points within the region of interest. From there, the hazard analysis can include these additional components:

- Estimating return periods of droughts of different intensity, duration, and spatial extent
- Looking for consistent patterns in the temporal and spatial features of drought (seasonality of emergence, characteristic spatial footprint)
- Evaluating long-term trends in drought occurrence
- Identifying modes of climate variability (e.g. ENSO phase) associated with greater or lesser drought risk
- Identifying a 'drought of record' that represents a worst-case scenario during the period of instrumental record

This analysis can then be used to determine the baseline drought risk to inform overall drought planning.

The climate data used in a hazard analysis do not necessarily speak for themselves. To inform overall drought risk analysis, the climatic indicators need to be related to the actual drought impacts experienced during the period of instrumental record (National Drought Mitigation Center [NDMC] 2011). When particular historic drought impacts were experienced, such as reservoir depletion, crop losses, or wildfire outbreaks, what were the values of the different indicators? Those values at which the likelihood of certain impacts becomes much greater can then be used as drought triggers in drought plans; i.e. determinants of when a drought response begins or ends (Steinemann 2003).

Through this process of calibration between the data (indicators) and the impacts, the hazard analysis also serves as a testing ground for effective real-time drought monitoring.

Drought indicators can be a single data information source, like the SPI, reservoir storage levels, or soil moisture, or they can be multiple information sources that are compiled into a composite, like the US Drought Monitor (NDMC 2015a). The indicators that, retrospectively, have been effective in capturing key drought impacts are likely to serve well in the future. Real-time monitoring is best founded on indicators for which there is a long history (50 yr or longer), so that the current conditions can be placed into the context of not only the history of that indicator, but the history of drought impacts. Even the US Drought Monitor, which has been produced as a US nationwide product only since 1999, is based on underlying indicators, some of which have approximately 100 yr records in the USA.

Continual monitoring of select indicators, even during non-drought periods, provides baseline data and can help detect emerging drought conditions long before impacts are felt (Wilhite & Buchanan-Smith 2005). Using indicators to determine thresholds or triggers at which actions should be taken provides guidance to decision-makers during the onset of an event (Steinemann et al. 2005). These should be viewed as guidelines rather than rules as droughts seldom look the same from one event to the next: some are prolonged and persistent but not initially intense, while others are short-lived and extremely severe. A response that made sense during one event may not be applicable during the next. The next 3 types of climate information — paleoclimate records, seasonal climate forecasts, and climate projections — have truly emerged as usable data only in the past 10 to 20 yr, and none have been widely incorporated into drought risk management and drought planning. Each addresses a different shortcoming of the instrumental record, and used in conjunction with the other types, each can add significant value to the planning process, reducing vulnerability to unanticipated drought conditions.

3.2. Paleoclimate records

Instrumental climate records are extraordinarily rich in terms of the spatial density and the number of variables measured, but very limited in temporal extent. Only in a handful of locations worldwide do robust instrumental records extend back >200 yr, and most regions have data extending back <100 yr (Bradley 1991, NRC 1998). We know that this window onto the past is too short to capture the full range of natural climate variability experienced during the late Holocene — variability that could plausibly recur in the future (NRC 1998, Hoerling et al. 2013).

Paleoclimate records use environmental proxies, such as stable isotopes from ice-cores and corals, pollen from lake sediment cores, and the width and density of tree rings, to reconstruct past climate prior to the instrumental period. Hydroclimatic reconstructions that capture paleodrought occurrence constitute the largest category of paleoclimate reconstructions available from the World Data Center for Paleoclimatology hosted by the US National Oceanic and Atmospheric Administration National Centers for Environmental Information (NOAA 2016). Reconstructions of precipitation, streamflow, and/or PDSI, mainly from tree rings, are available for locations on all continents except Antarctica, with the greatest availability for the USA, northern Mexico, southern Canada, western Europe, and central and southeastern Asia. These paleodrought reconstructions are typically from 300 to 2000 yr long.

The longer window onto the past afforded by paleodrought reconstructions almost always shows drought events that are more intense, are of greater duration, and/or have a larger spatial extent than any seen during the instrumental period (Meko & Woodhouse 2011). For example, tree-ring reconstructions of Colorado River annual streamflow in the southwestern USA show a 'megadrought' during the mid-1100s in which persistently dry conditions lasted for almost 60 yr, over twice as long as any comparably dry period observed since 1900 (Meko et al. 2007). Moreover, paleodrought records tend to show that drought risk fluctuates on century time scales: in the western USA, the 20th century was generally less drought-prone than the preceding 4 to 20 centuries (Hoerling et al. 2013). From a drought-planning perspective, paleodrought records enlarge the view of what events are possible and should be prepared for, and reduce the likelihood of surprise by future events that are 'unprecedented' relative to the instrumental record. Paleodrought records can also be used to estimate historic return intervals for events that are too rare to be assessed by the instrumental period alone (Biondi et al. 2008). While paleodrought reconstructions are not available in all locations, where they are available, they provide valuable insight and are worth examining to see how they compare with the instrumental record of drought.

3.3. Seasonal climate forecasts

Instrumental climate records, supplemented by paleoclimate records, provide a good sense of the mean or climatological drought risk. A hazard analysis (as described in the above section) may also identify time-varying components of drought risk, such as changes associated with ENSO state. But, even if present in the instrumental record, it is not straightforward for drought planners to use these features in a predictive mode. Seasonal climate forecasts offer a more robust way to explicitly incorporate the evolving variation in drought risk into drought planning and response, anticipating changes before they occur.

In the past few decades, advances in our understanding of modeling, ENSO, and other persistent climate features have led to skillful operational climate forecasts on seasonal time scales (1 to 12 mo) for precipitation and temperature (Livezey & Timofeyeva 2008). The skill of these forecasts varies by region and season, with the highest skill tending to be in areas that have strong ENSO signals (Barnston et al. 2010). Seasonal climate forecasts for precipitation and temperature for 3 mo periods are now available on a near-global basis through the International Research Institute for Climate and Society, and through the meteorological agencies of 12 countries, including the USA, Canada, Russia, France, Japan, and South Africa, who contribute to the World Meteorological Office's program for long-lead forecasts.

The potential value of seasonal forecasts to drought risk management is clear: anticipating the emergence, intensification, or amelioration of drought events up to several months in advance. But adoption of seasonal climate forecasts has been slow for many applications, including drought risk management (Marshall et al. 2011). Several factors have been found to constrain the use of seasonal climate forecasts, including difficulty interpreting their probabilistic nature, insufficient perceived reliability, and mismatch with the spatial and temporal scales of decision-making (Callahan et al. 1999, Hartmann et al. 2002, Rayner et al. 2005, Lowrey et al. 2009, Bolson et al. 2013). These challenges notwithstanding, Steinemann (2006) laid out a practical method for using seasonal climate forecasts in short-term drought planning and preparedness, and demonstrated the added value of the forecasts.

3.4. Climate model projections

While instrumental records of climate are necessary for drought planning, even when supplemented by paleodrought records they may not be sufficient to fully describe all future drought risk. Anthropogenic climate change poses a considerable challenge for drought risk management. Future drought risk will reflect both natural climate variability, which is represented in instrumental and paleo records, and anthropogenically forced climate changes, which are not (Solomon et al. 2011, Deser et al. 2012). Use of climate model projections can provide insight into how drought risk may change as a result of these forced changes.

Future projections from global climate models are an attempt at numerically representing the fundamental physics of the climate system, and reflect our best knowledge of climate processes and anthropogenic climate forcings such as greenhouse gas emissions (Barsugli et al. 2009). These projections indicate that systematic shifts in drought risk will likely occur in most parts of the world over the coming decades as the effects of anthropogenic climate change are more deeply felt (Dai 2013). There is very high confidence in the projected warming of average temperatures in all regions, which will tend to increase evapotranspiration from the land surface and worsen drought conditions for a given precipitation deficit (Zhao & Dai 2015). The projections of precipitation change are generally less certain, though there is a strong model consensus of decreased future precipitation in many areas from 10° to 35° N and S, including the southwestern USA, the southern Mediterranean region, and western Australia. These areas are projected to experience the greatest shift towards increasing future drought risk (Sheffield & Wood 2008, Dai 2013).

While the broad implications of climate projections for drought risk management are clear, as with seasonal climate forecasts, incorporating this information into planning is not straightforward (Barsugli et al. 2009). For a given location and time period, there is a large range in projected future changes in climate, reflecting both unknowable future changes in the societal factors that govern greenhouse gas emissions and uncertainty regarding the physical response of the climate system to additional emissions (Mote et al. 2011). To capture the former uncertainty, several different emissions trajectories are used to drive the models, while the latter uncertainty is reflected in the spread among the several dozen climate models under a given emissions trajectory. Thus, for any planning exercise, it is important to consider multiple projections that collectively represent both types of uncertainties (Mote et al. 2011).

Climate projections need to be approached with a fundamentally different mindset to other types of climate information. The broader set of climate projections is best used to facilitate exploration of physically plausible climate futures, rather than attempting to derive a precise quantification of future risk. Scenario planning (Means et al. 2010) is one mechanism to do this, as discussed in Section 4.

3.5. Making climate information more usable for drought planning

Despite all of the types of climate data now available, and their potential utility, there are persistent barriers to integrating this information into management and planning, including lack of awareness of the data, inability to access the desired data, inadequate interpretation of the data, mismatch of temporal and/or spatial qualities of the data with the intended application, and perceived lack of utility of the data (Rayner et al. 2005, Lemos et al. 2012, Bolson et al. 2013).

To successfully bridge this 'usability gap,' it has been found that decision-makers and researchers need to work collaboratively and iteratively to develop information and tools that are directly applicable to the planning process (Lemos & Morehouse 2005, Dilling & Lemos 2011). In this model of 'co-production' of climate information and services, users can clearly voice what their needs are and researchers can develop tools specifically targeted to meet those needs. It also allows researchers greater opportunities to interact with drought and water professionals to ensure they understand the inherent uncertainties and are using the data in an appropriate and reliable manner (Bolson et al. 2013).

The acknowledged value of co-production is reflected in the rapidly increasing number of entities that serve as 'boundary organizations' (Dilling & Lemos 2011), co-producing usable climate information through both the development of new products and tools and the translation and customization of existing data. In the USA, the NOAA Regional Integrated Sciences & Assessments (RISA) program was an early pioneer of this model in the mid-1990s, along with the NDMC, Regional Climate Centers, and many state climatologists' offices. More recently, the Water Utility Climate Alliance, the US Department of Interior Climate Science Centers, the US Department of Agriculture Regional Climate Hubs, and others have brought together climate scientists with decision-makers in many sectors to identify and assess risks from climate, including drought. In Europe, the Seasonal-to-decadal climate Prediction for the improvement of European Climate Services (SPECS), European Provision of Regional Impacts Assessments on Seasonal and Decadal Timescales (EUPORIAS), and Climate Science Research Partnership (UK) are following a co-production model to improve the usefulness of climate science (Buontempo et al. 2014).

The experiences of these boundary organizations indicate that to broaden the use of climate information, e.g. in drought planning, and overcome the barriers listed above, there is no real substitute for repeated engagement between the community of technical experts and those who use the information (Ferguson et al. 2014). 'Early adopters' of new information, such as in the Colorado case study presented below, can also help convey the feasibility and benefits of using new information to their peers, and point to potential data sources and analytical approaches.

4. THE DROUGHT-PLANNING PROCESS: WHERE CLIMATE INFORMATION FITS IN

The purpose of drought planning depends on the ultimate societal objectives. In an agricultural region, this may be protection and preservation of irrigation water during the growing season, while in a more urban area, it is likely more focused on water for essential indoor use by its residents. Regardless of the objectives, effective use of the aforementioned climate data can enhance and improve overall drought preparedness.

The state of Colorado, in the southwestern USA, has taken a comprehensive approach to drought risk management and drought planning by identifying an effective and systematic means of assessing drought conditions, identifying who and what is at risk from drought events, developing mitigation strategies that reduce the risk of drought in advance, and devising response options that minimize economic stress, environmental losses, and social hardships during drought. The planning process (Colorado Water Conservation Board 2010) for drought can be broken down into 8 distinct steps (Fig. 2), 6 of which can, and should, use some level of climate information.

Step 1 lays out the plan's objectives which will differ from place to place, dependent upon the community's values and needs. This step is largely independent of climate data.

Step 2 relies upon the observed climate and paleoclimate records to examine and understand when and where drought has affected resources in the past. By examining where impacts have occurred during previous events, it is possible to not only gather information to inform a risk assessment, but also to gauge the effectiveness of adaptive risk management strategies that have been implemented previously.

Steps 3 and 4 should be informed by the information in Step 2, as existing and future vulnerabilities are identified. This is also an ideal place to incorporate climate change projections to examine how vulnerabilities may shift under a warming climate. For

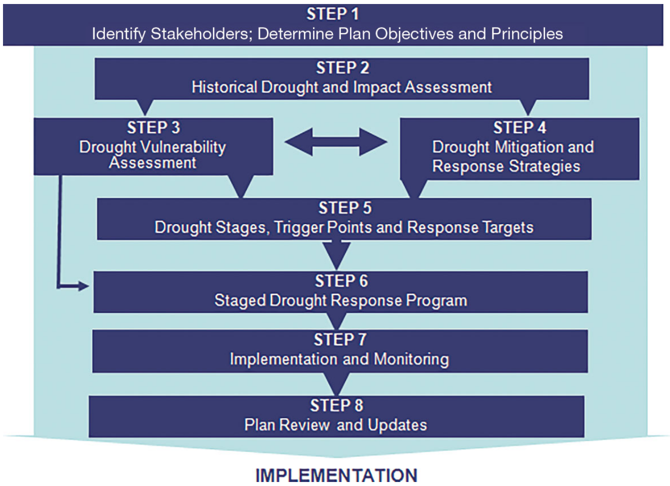

Fig. 2. Steps in the development of a drought management plan (see Section 4 for further information on the steps). Adapted from Colorado Water Conservation Board (2010)

instance, in Colorado, a recent analysis showed that under hotter and drier conditions, heavily appropriated river basins would not only be unable to meet additional future water demands, but would also be unable to meet existing needs, thereby introducing new vulnerabilities. This information will enable state and local planners, as well as water managers, to start preparing for and addressing those shortages long before the impacts are ever felt (Colorado Water Conservation Board 2015). Paleodrought information can also be used in this step to help broaden the realm of plausible future conditions based on what occurred prior to the observed record.

Based on the vulnerability assessment findings, actions and concrete mitigation strategies can be developed and implemented that will decrease the extent or severity of future impacts. For instance, if, during previous drought events, there have been severe drought impacts in a particular region with limited reservoir storage, one may be able to determine that additional storage or a revised operation of existing structures will decrease overall impacts. Similarly, if a region has proven resilient to drought events, one can examine what adaptive risk management practices are in place that may be applicable to other regions.

Step 5 addresses one of the most problematic pieces of dealing with drought response only during the onset of an event. When in crisis or response mode, actions and decisions can often become politicized and contentious, which in turn slows down response and decision-making. Identifying appropriate climate indicators to monitor drought, and agreeing upon climatic 'trigger points' (thresholds) for response prior to the onset of drought can expedite the response process and help to speed aid to those most in need.

Step 6 develops a staged drought response plan, based on the pre-determined thresholds identified in Step 5, and allows for policy makers to respond in a manner that best suits the severity, duration, and intensity of an ongoing drought event. This also incorporates activation at an early stage that slowly ramps up as an event intensifies; resulting in less shock to water users. Observed climate data can help inform policy makers about the historical context of an event, and how a current event may be similar or different. This information, along with impacts and vulnerabilities, can inform overall response strategies, and help to lessen impacts though more rapid and proactive actions.

Step 7 incorporates consistent and continual monitoring, which is critical for effective drought risk management. The use of climate data to detect the drought condition as early as possible speeds the response process, and when coupled with appropriate actions, can reduce the overall impacts. This step is also important in lengthening the record of observed data so that trends can be detected as the long-term climate shifts.

Step 8 ensures that the plan is a living document that reflects current priorities and values through regular updates and review.

4.1. Colorado: a case study of the broader use of climate information in drought and climate planning

Colorado has a long history of robust monitoring that relies upon snowpack data, forecasted and actual stream flow, SPI, PDSI, the US Drought Monitor, and experimental long-term forecasts that incorporate the potential effects of ENSO on Colorado's weather. These are reported monthly at a Water Availability Task Force meeting and summarized in a drought update that is distributed to decision-makers and stakeholders. This provides an opportunity for municipal water providers, agricultural users, government agencies, and stakeholders to collaborate on monitoring of and response to emerging conditions. These are many of the same entities actively involved in mitigation efforts.

In addition, Colorado examines vulnerabilities sector by sector at the county level in both a quantitative and qualitative manner. The vulnerability assessment directly informs decisions on mitigation strategies as it provides a means to rank or prioritize mitigation actions to provide the most relief for the least cost. In some sectors, climate data is a quantitative input to this assessment. For instance, the southeastern plains of the state are dominated by dryland farmers dependent upon natural precipitation for crop growth, rather than irrigation, yet historically this region has lacked a comprehensive network of monitoring stations. A 2010 analysis showed that this region of the state was among the most vulnerable to agricultural impacts as a result of drought. In 2011 alone, more than $110 million in lost economic activity occurred as a result of drought (Gunter et al. 2012). Since that time, the state has expended resources to increase monitoring in the region to ensure earlier detection of future droughts. The state has also upgraded monitoring stations to report data hourly, making the data more useful for agricultural producers in informing their management decisions. Increasing the user base also helps to build support for the network and justify expenditures for maintenance.

To plan for the longer term, Colorado has examined the potential impacts of climate change, including more frequent, intense, and severe droughts, using analyses of both the paleodrought record and future climate projections. This has provided insight on what droughts might look like in the future and how these events might compare to those in both the paleodrought and observed record (Colorado Water Conservation Board 2013).

Developing planning strategies takes time, and understanding the range of what may be plausible helps to ensure that planning approaches are both comprehensive and nimble enough to address a wide range of possibilities. To do this, Colorado uses a scenario planning approach in which climate is just 1 of 9 primary drivers that inform 5 future scenarios, as outlined in Table 2 (Colorado Water Conservation Board 2015). Both observed climate data and future climate projections are used to define the climate component of the scenarios. This provides policy makers with a range of potential future conditions and, through using the climate scenarios as inputs to hydrology models, their corresponding impacts on water supplies. It also illustrates how climate change, in conjunction with other uncertainties, such as population growth, land-use patterns, regulation, and energy development, can compound water supply concerns. Preparing for a broad range of possible future conditions helps to build flexibility into the planning process and ensure that the state is better prepared to address whatever future unfolds (Colorado Water Conservation Board 2015).

The incorporation of information from both paleodrought records and future climate projections in the 2013 state drought plan revision and subsequent state planning documents was built on a decade of engagement with local climate scientists, hydrologists, and consulting engineers. This included convening a technical advisory group of about 20 experts to review the proposed methodologies for climate analyses, and the state's participation in multiple climate vulnerability assessments. These activities helped build technical capacity within the state agencies to more effectively use climate information, and gave the researchers exposure to the context of planning and decision-making.

The state has also incorporated quantitative 'trigger points' that guide the activation of the staged drought response plan. These trigger points were developed by analyzing observed climate data and overlaying that information with past impacts. This provided quantitative thresholds at which certain impacts are likely to start occurring. The existence of these pre-determined decision points has helped to depoliticize the activation process and speed aid to those most impacted by drought. Without the use of long-term observed climate records, it would not have been possible to accurately develop these thresholds.

These trigger points were developed after the 2002 drought, which was the driest year in Colorado on record. In 2012, the state faced another severe statewide drought in what turned out to be the second-driest year on record, but by using the triggers, the state began responding to the drought before the impacts became as severe as in 2002. As a result of this and other changes made after the 2002 drought, the overall drought response in Colorado was more coordinated in 2012 than in 2002 (Ryan & Doesken 2013), with entities such as municipal water providers implementing response measures sooner than previously implemented, and tourism and recreation outfitters diversifying activities to offset revenue losses.

Lastly, the state details 78 specific prioritized mitigation actions that support the 8 overall goals of the drought mitigation and response plan. These have been systematically identified to reduce overall impacts of future drought events. These are updated regularly and are heavily informed by the vulnerability and impact assessments. Lead agencies are identified as potential funding sources and collaborative partners, ensuring each agency knows its responsibilities. Increased and enhanced collection of climate

Table 2. State of Colorado 2050 water planning: scenarios and primary drivers (adapted from table in Colorado Water Conservation Board 2012)

Drivers	Scenarios				
	Business as Usual Scenario	Weak Economy Scenario	Cooperative Growth Scenario	Adaptive Innovation Scenario	Hot Growth Scenario
A. Population Growth Rate/ Economic Growth Rate	Mid-range Population Growth Rate	Low Population Growth Rate	Mid-range Population Growth Rate	High Population Growth Rate	High Population Growth Rate
B. Climate Status / Water Supply	Hottest Hotter 20th Century Observed	Hottest Hotter 20th Century Observed	Hottest Hotter Between Hot and Dry and 20th Century Observed	Hottest Hotter Hot and Dry	Hottest Hotter Hot and Dry
C. Water Needs for Energy Development	Moderate (no oil shale)	Low (no oil shale)	Low (no oil shale)	Low (no oil shale)	High (oil shale)
D. Agricultural Demand and Agricultural Water Demand	Decrease in irrigated acres due to urbanization Agricultural exports and demands constant Agriculture is less able to compete with urban areas for water Agricultural water demands decreased	Decrease in irrigated acres due to urbanization Agricultural exports and demands lower Agriculture not able to compete with urban areas for water Agricultural water demands decreased	Slight decrease in irrigated acres due to urbanization Agricultural exports down and local demands up Agriculture is able to compete with urban areas for water Agricultural water demands are slightly higher	Slight decrease in irrigated acres due to urbanization Agricultural exports down and local demands up Agriculture is able to compete with urban areas for water Agricultural water demands are slightly higher	Significant decrease in irrigated acres due to urbanization Agricultural exports and demands high Competition between agriculture and urban areas is unchanged from today Agricultural water demands are higher
E. Water Efficiency Technology	Municipal & Industrial: Moderate/Passive Agriculture: same as today	Municipal & Industrial: Moderate/Passive Agriculture: same as today	Municipal & Industrial: High Agriculture: Efficiencies are implemented	Municipal & Industrial: High Agriculture: Efficiencies are implemented	Municipal & Industrial: Moderate/Passive Agriculture: same as today
F. Social/ Environmental Values	No Change	No Change	Increased Awareness Increased willingness to protect environment and watercourse recreation	Increased Awareness Increased willingness to protect environment and watercourse recreation	Full Use of Resources Low willingness to protect environment and watercourse recreation
G. Urban Land Use	No Change	No Change	Higher Density	Higher Density	Lower Density
H. Regulatory Constraints	Regulation Deregulation No Change	Regulation Deregulation No Change	Regulation Deregulation Increased	Regulation Deregulation Increased and expedited	Regulation Deregulation Reduced
I. Municipal & Industrial Water Demands	Middle of the five scenarios	Lowest of the five scenarios	Second lowest of the five scenarios	Second highest of the five scenarios	Highest of the five scenarios

Population size and growth rate; Traditional energy supply; Efficiency of water use; Levels of regulation
Precipitation levels; Alternative energy supply; Level of environmental stewardship; Municipal & industrial water demand levels
Temperature increase; Agricultural economy; Land use patterns, high versus low density for urban areas

The number of icons in each category represents the relative amount included in that scenario. For Instance, more people icons under population represents high levels of growth, more wind mills under energy development represents a high mix of alternative energy.

data is included in these mitigation actions, and as a result, the state has been able to dedicate funds to improve both.

4.2. Interconnections with other planning processes

Drought planning is most effective when it does not exist in its own silo, but rather is integrated with other long- and short-term planning efforts. Water resource plans, emergency management plans, and land-use plans are a few examples of efforts that could all be further integrated into drought planning efforts. Integrated planning is not new. Land-use plans rely on floodplain mapping, emergency management plans examine where fault lines are, water resource planning uses demographics to ensure adequate water supply. Yet, drought has not traditionally been included in this integration (Bergman 2014). Consequently, many communities lack these plans altogether, or if they exist, they are not updated as frequently as they should be. Because long intervals may be present between drought events, an outdated plan will not reflect changes in the values of a community. Integrating planning efforts will help to ensure that they are frequently updated and remain relevant.

The use of scenario planning is one way to integrate multiple planning elements into a single streamlined process. Unlike planning efforts that rely upon a predefined static future point, scenario planning recognizes that the future will be shaped by a number of diverse drivers, all of which are equally important and all of which have inherent uncertainties associated with them. The development of a scenario could use just a few drivers or it could incorporate a large number. By widening the spread of possible future conditions one prepares for, the likelihood that planning efforts are ample and appropriate for the conditions that actually unfold is increased (Colorado Water Conservation Board 2015).

4.3. Beyond Colorado

The Colorado case study indicates the value of incorporating multiple types of climate information into the drought planning process. In the USA, other similar case studies can be found at various scales, including for individual livestock producers (NDMC 2015b) and municipalities (Denver Water 2015). The NDMC recently developed a tool called the Drought Risk Atlas (http://droughtatlas.unl.edu/) designed to assist planners to better incorporate climate information into their drought planning processes at different scales. At the international level, one recent example is an effort taking place in northeast Brazil and supported by the World Bank. This effort has led to the creation of a monthly drought monitoring assessment tool and process called the Monitor de Secas do Nordeste (the Northeast Drought Monitor, or MSNE) adapted from the US Drought Monitor tool process (http://monitordesecas.ana.gov.br/). In addition to monitoring drought conditions in the 9 states across the region, drought planning at several scales within the region is simultaneously taking place with the specific intent that the drought early warning provided by the MSNE will be linked within the preparedness plans being developed (Hayes et al. 2016). These recent efforts in Brazil have relied heavily upon the lessons learned from experiences within the USA, Mexico, and Spain (Hayes et al. 2016).

5. CONCLUSIONS

While climate and weather data have long been used for drought monitoring, their use in long-term drought risk management through comprehensive long-term planning has been more recent and limited. When drought managers engage in comprehensive planning, impacts can be lessened or avoided through developing mitigation strategies that reduce the risk of drought in advance, and devising response options that minimize economic stress, environmental losses, and social hardships during drought. This straightforward planning process is applicable at any decision-making level. Additional information and research on avoided costs as a result of comprehensive planning is limited and would greatly benefit the drought planning process as well as communities' abilities to prioritize efforts.

Comprehensive drought planning helps decision-makers prepare for multiple hazards, including climate change. Broader adoption and integration of climate data in long-term drought planning and preparedness could help to increase sustainability of natural resources and could help to increase economic and societal resiliency.

LITERATURE CITED

Barnston AG, Li S, Mason SJ, DeWitt DG, Goddard L, Gong X (2010) Verification of the first 11 years of IRI's seasonal climate forecasts. J Appl Meteorol Climatol 49:493–520

Barsugli JJ, Anderson C, Smith JB, Vogel JM (2009) Options for improving climate modeling to assist water utility planning for climate change. Final Report, Water Utility Climate Alliance, San Francisco. www.wucaonline.org/assets/pdf/actions_whitepaper_120909.pdf

Bergman C (2014) Improving drought management for transboundary river basins in the United States through collaborative environmental planning. PhD dissertation, University of Nebraska-Lincoln

Biondi F, Kozubowski TJ, Panorska AK, Saito L (2008) A new stochastic model of episode peak and duration for eco-hydro-climatic applications. Ecol Modell 211:383–395

Bolson JB, Martinez CJ, Srivastava P, Breuer N, Knox P (2013) Climate information use among southeast US water managers: beyond barriers and toward opportunities. Reg Environ Change 13:141–151

Bradley RS (1991) Pre-instrumental climate: how has climate varied during the past 500 years. In: Schlesinger ME (ed) Greenhouse gas-induced climatic change: a critical appraisal of simulations and observations. Elsevier, Amsterdam, p 391–410

Buontempo C, Hewitt CD, Doblas-Reyes FJ, Dessai S (2014) Climate service development, delivery and use in Europe at monthly to inter-annual timescales. Clim Risk Manage 6:1–5

Callahan B, Miles E, Fluharty D (1999) Policy implications of climate forecasts for water resources management in the Pacific Northwest. Policy Sci 32:269–293

Colorado Water Conservation Board (2010) Municipal drought management plan guidance document. Denver, CO. http://cwcb.state.co.us/technical-resources/drought-planning-toolbox/Documents/DroughtPlanningResources/MunicipalDroughtMgmtPlanGuidanceDocFull.pdf

Colorado Water Conservation Board (2012) Draft scenarios. Colarado's water supply future. Interbasin Compact Committee Annual Report, Denver, CO. p 7–8. http://www2.cde.state.co.us/artemis/nrserials/nr1251internet/nr1251 2012internet.pdf

Colorado Water Conservation Board (2013) Colorado drought mitigation and response plan. Denver, CO. http://cwcbweblink.state.co.us/WebLink/0/doc/173111/Electronic.aspx?searchid=45a1d11c-9ccf-474b-bed4-2bccb2988870

Colorado Water Conservation Board (2015) Colorado's water plan. Denver, CO. http://coloradowaterplan.com/

Dai A (2013) Increasing drought under global warming in observations and models. Nat Clim Change 3:52–58

Denver Water (2016) Planning for an uncertain future. www.denverwater.org/SupplyPlanning/DroughtInformation/UncertainFuture/ (site regularly updated; data accessed 2015)

Deser C, Phillips A, Bourdette V, Teng H (2012) Uncertainty in climate change projections: the role of internal variability. Clim Dyn 38:527–546

Dilling L, Lemos MC (2011) Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. Glob Environ Change 21:680–689

Ferguson DB, Rice J, Woodhouse C (2014) Linking environmental research and practice: lessons from the integration of climate science and water management in the western United States. Climate Assessment for the Southwest, University of Arizona, Tucson, AZ. www.climas.arizona.edu/publication/report/linking-environmental-research-and-practice

Geological Society of America (GSA) (2007) Managing drought: a roadmap for change in the United States. Conf Rep 'Managing drought and water scarcity in vulnerable environments', 18–20 Sept, 2006. The Geological Society of America, Longmont, CO. www.geosociety.org/meetings/06drought/roadmapHi.pdf

Gleick P (2014) Water, drought, climate change, and conflict in Syria. Weather Clim Soc 6:331–340

Gunter A, Goemans C, Pritchett J, Thilmany D (2012) The economic impact of the 2011 drought on southern Colorado: a combined input-output and EDMP analysis. Colorado Water Conservation Board Project Report http://cwcbweblink.state.co.us/WebLink/0/doc/168084/Electronic.aspx?searchid=f52adb2f-1a9c-4bca-91aa-5b5ec2c368cd

Hartmann HC, Pagano TC, Sorooshian S, Bales R (2002) Confidence builders: evaluating seasonal climate forecasts from user perspectives. Bull Am Meteorol Soc 83: 683–698

Hayes MJ, Wilhelmi O, Knutson C (2004) Reducing drought risk: bridging theory and practice. Nat Hazards Rev 5: 106–113

Hayes M, Pérez ML, Andreu J, Svoboda M, Fuchs B, Cortés FA, Engle N (2016) Perspectives from the outside: contributions to the drought paradigm shift in Brazil from Spain, Mexico, and the United States. In: De Nys E, Engle N, Magalhães AR (eds) Drought in Brazil: proactive management and policy. CRC Press, Boca Raton, FL, p 81–90

Hoerling MP, Dettinger M, Wolter K, Lukas J and others (2013) Present weather and climate: evolving conditions. In: Garfin G, Jardine A, Merideth R, Black M, LeRoy S (eds) Assessment of climate change in the southwest United States: a report prepared for the National Climate Assessment. Southwest Climate Alliance, Island Press, Washington, DC, p 74–100

Howitt RE, Medellín-Azuara J, MacEwan D, Lund JR, Sumner DA (2014) Economic analysis of the 2014 drought for California agriculture. Center for Watershed Sciences, University of California, Davis. http://watershed.ucdavis.edu/files/biblio/DroughtReport_23July2014_0.pdf

Howitt RE, MacEwan D, Medellín-Azuara J, Lund JR, Sumner DA (2015) Economic analysis of the 2015 drought for California agriculture. Center for Watershed Sciences, University of California, Davis, CA. http://watershed.ucdavis.edu/files/biblio/Final_Drought%20Report_08182015_Full_Report_WithAppendices.pdf

Lemos MC, Morehouse BJ (2005) The co-production of science and policy in integrated climate assessments. Glob Environ Change 15:57–68

Lemos MC, Kirchhoff CJ, Ramprasad V (2012) Narrowing the climate information usability gap. Nat Clim Change 2:789–794

Livezey RE, Timofeyeva MM (2008) The first decade of long-lead US seasonal forecasts: insights from a skill analysis. Bull Am Meteorol Soc 89:843–854

Lowrey J, Ray A, Webb R (2009) Factors influencing the use of climate information by Colorado municipal water managers. Clim Res 40:103–119

Marshall NA, Gordon IJ, Ash AJ (2011) The reluctance of resource-users to adopt seasonal climate forecasts to enhance resilience to climate variability on the rangelands. Clim Change 107:511–529

Means EG III, Laugier MC, Daw JA, Kaatz L, Waage M (2010) Decision support planning methods: incorporating climate change uncertainties into water planning. Final report January 2010. Water Utility Climate Alliance, San Francisco. http://www.wucaonline.org/assets/pdf/actions_whitepaper_012110.pdf

Meko DM, Woodhouse CA (2011) Dendroclimatology, dendrohydrology, and water resources management. In: Hughes MK, Swetnam TW, Diaz HF (eds) Tree rings and climate: progress and prospects. Springer, New York, NY, p 231–261

Meko DM, Woodhouse CA, Baisan CA, Knight T, Lukas J, Hughes MK, Salzer MW (2007) Medieval drought in the Upper Colorado River Basin. Geophys Res Lett 34: L10705, doi:10.1029/2007GL029988

Mote P, Brekke L, Duffy PB, Maurer E (2011) Guidelines for constructing climate scenarios. Eos Trans AGU 92: 257–258

Multihazard Mitigation Council (2005) Natural hazard mitigation saves: an independent study to assess the future savings from mitigation activities. Vol 1, Findings, conclusions and recommendations. National Institute of Building Sciences, Washington, DC. http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/MMC/hms_vol1.pdf

National Drought Mitigation Center (NDMC) (2011) Drought-ready communities: a guide to community drought preparedness. http://drought.unl.edu/portals/0/docs/DRC_Guide.pdf

NDMC (2015a) US drought monitor classification scheme. http://droughtmonitor.unl.edu/AboutUs/ClassificationScheme.aspx

NDMC (2015b) Sample drought plan—south central Kansas. http://drought.unl.edu/ranchplan/WriteaPlan/SampleDroughtPlans/SouthCentralKansasAlexanderRanch.aspx

NOAA (National Oceanic and Atmospheric Administration) (2016) Climate reconstructions. World Data Center for Paleoclimatology. www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/climate-reconstruction (accessed 22 April 2016)

NRC (National Research Council) (1998) Decade-to-century-scale climate variability and change: a science strategy. Panel on Climate Variability on Decade-to-Century Time Scales, Board on Atmospheric Sciences and Climate, Commission on Geosciences, Environment, and Resources, National Research Council. National Academy Press, Washington, DC, doi:10.17226/6129

Rayner S, Lach D, Ingram H (2005) Weather forecasts are for wimps: why water resource managers do not use climate forecasts. Clim Change 69:197–227

Ryan W, Doesken N (2013) Drought of 2012 in Colorado. Climatology Report 13-01. Dept. of Atmos. Sci., Colorado State University. http://ccc.atmos.colostate.edu/pdfs/climo_rpt_13_1.pdf

Sheffield J, Wood EF (2008) Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim Dyn 31:79–105

Solomon A, Goddard L, Kumar A, Carton J and others (2011) Distinguishing the roles of natural and anthropogenically forced decadal climate variability: implications for prediction. Bull Am Meteorol Soc 92:141–156

Steinemann A (2003) Drought indicators and triggers: a stochastic approach to evaluation. J Am Water Resour Assoc 39:1217–1234

Steinemann A (2006) Using climate forecasts for drought water management. J Appl Meteorol Climatol 45: 1353–1361

Steinemann A, Cavalcanti L (2006) Developing multiple indicators and triggers for drought plans. J Water Resour Plan Manage 132:164–174

Steinemann A, Hayes M, Cavalcanti L (2005) Drought indicators and triggers. In: Wilhite D (ed) Drought and water crises: science, technology, and management issues. CRC Press, Boca Raton, FL, p 71–92

Svoboda M, LeComte D, Hayes M, Heim R and others (2002) The Drought Monitor. Bull Am Meteorol Soc 83: 1181–1189

Svoboda MD, Fuchs BA, Poulsen CC, Nothwehr JR (2015) The drought risk atlas: enhancing decision support for drought risk management in the United States. J Hydrol (Amst) 526:274–286

Wilhite DA, Buchanan-Smith M (2005) Drought as hazard: understanding the natural and social context. In: Wilhite D (ed) Drought and water crises: science, technology, and management issues. CRC Press, Boca Raton, FL, p 3–29

Wilhite DA, Botterill L, Monnik K (2005) National drought policy: lessons learned from Australia, South Africa, and the United States. In: Wilhite D (ed) Drought and water crises: science, technology, and management issues. CRC Press, Boca Raton, FL, p 137–172

Wilhite DA, Sivakumar MVK, Pulwarty R (2014) Managing drought risk in a changing climate: the role of national drought policy. Weather Clim Extrem 3:4–13

Woodhouse CA, Overpeck JT (1998) 2000 years of drought variability in the central United States. Bull Am Meteorol Soc 79:2693–2714

World Economic Forum (WEF) (2014) Global Risks 2014, 9th edn. World Economic Forum, Geneva. http://www3.weforum.org/docs/WEF_GlobalRisks_Report_2014.pdf

Zhao T, Dai A (2015) The magnitude and causes of global drought changes in the twenty-first century under a low–moderate emissions scenario. J Clim 28:4490–4512

Editorial responsibility: Donald Wilhite (Guest Editor), Lincoln, Nebraska, USA

Submitted: January 4, 2016; Accepted: May 24, 2016
Proofs received from author(s): August 17, 2016