CHAPTER 12
AN OPERATIONAL EARLY WARNING AGRICULTURAL WEATHER SYSTEM

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INTRODUCTION

Droughts are an important but often-ignored feature of the climate—until they occur. The rise and fall of civilizations have been linked to droughts of varying degrees of intensity or, more properly, a scarcity of food caused by drought. Droughts have existed since the beginning of recorded history, yet the impacts have changed significantly with time and societal structure (Mellor and Gavian, 1987). The nomadic people simply moved to new areas when food supplies became short. However, today most societies have established a permanent home area and have adapted to climate variability by changing customs and applying technology (irrigation, air conditioning, and so forth).

Over the years, national leaders have dealt with climate variability problems related to drought in many different ways. Yet today we cannot find many experts who can agree on a definition that adequately describes when a drought begins and ends, or what appropriate action should be taken. The disagreement is partially related to the many types of drought that can occur—hydrological, agricultural, economic, and so forth. This paper will deal with the application of known weather-plant responses to provide an early alert for potential deviations from normally expected crop development and crop yield potential, and will suggest how these data can be integrated into the non-meteorologist user community. It is not the intent of this paper to develop an acceptable definition for drought or define the most appropriate actions to be taken.

We would like to begin by briefly describing some of the recent research efforts that have led to the creation of an operational global monitoring capability, the Joint Agricultural Weather Facility (JAWF), located at the U.S. Department of Agriculture (USDA) in Washington, D.C. JAWF's approach to crop assessment is the result of the collection and implementation of ideas assembled from several research efforts undertaken during the past thirty years. The facility is staffed by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service meteorologists and USDA's agricultural meteorologists. They prepare crop condition assessments and crop yield estimates, using weather data analysis, satellite imagery interpretation, and numerical weather prediction provided by NWS meteorologists and evaluations of current weather and historical climate data by USDA's agricultural meteorologists. Knowledge of year-to-year variability in weather provides a tool that can be used in the assessment of changing crop conditions and estimates of yield variability. The assessment information is used primarily in support of USDA's agricultural economics intelligence work,

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but it is also extensively used by the agribusiness community. JAWF's biggest single challenge is to convert voluminous amounts of weather data into information that can be easily understood by the department's nonmeteorological user community. Drought occurrences, because of their destructive impacts on crops, have become one of the major focuses of JAWF. However, short-term extreme weather anomalies also play an important role in crop yield fluctuations. These short-term events must be monitored closely to identify their potential impact, which may be as damaging as the longer-term drought occurrences.

Before examining how JAWF accomplishes its crop monitoring and yield assessment work, it is useful to look briefly at selected research programs from which JAWF personnel have been able to extract and modify many useful concepts in support of assessment work.

One of the best-known efforts to systematically attempt to portray drought as a simple index number for domestic use was begun in the early 1960s by W. C. Palmer (1965a). His basic idea was to develop a series of equations that would describe the soil moisture available for plants to use during the course of the growing season. Palmer looked on drought as an accounting problem: "The amount of precipitation required for the near-normal agricultural operation of the established economy of an area during some stated period is dependent on the average climate of the area and on the prevailing meteorological conditions both during and preceding the month or period in question." His initial effort resulted in the Palmer Drought Index (PDI) and later the companion Crop Moisture Index (CMI). These indexes have now been published weekly or monthly during the summer season in the Weekly Weather and Crop Bulletin (WWCB) since the mid-1960s. The WWCB, with some variation, has been published since 1872 and is JAWF's most visible public product for use in the United States and around the world. It has also been used as a model by many nations developing their own reports.

We will discuss some of the major strengths and weaknesses of the PDI and CMI, but time does not permit an exhaustive analysis. Some recent seasonal comparisons made with field soil moisture survey results have shown the Index values to be much better than might initially be expected (personal communication, Robert Shaw, Professor Emeritus, Iowa State University, Ames). The index numbers possess some unique qualities that account for their popularity. First and most important for operational work, they can be derived and updated in a timely and economical manner using the data generated by our current national meteorological observation network. The index numbers also lend themselves to a series of statistical analyses for frequency, intensity, and duration of dry or wet periods. The assumptions used to derive the indexes have been clearly spelled out (Palmer, 1965a). Palmer, during the developmental phase, also made extensive comparisons with available soil moisture totals taken by more traditional methods. A major concern was the assignment of a soil water holding capacity, to be represented by a single value for an entire climatic division. (A climatic division is a region with nearly homogeneous climatic elements; most states have been divided into seven to ten climatic divisions.) We know that soils are highly variable across a climatic division and appropriate caution is urged in using these indexes. Users will find that the PDI changes more slowly than the CMI and is actually a better indicator for hydrological purposes than it is for crop moisture stress conditions. Recognizing this problem in the PDI, Palmer made the modification that produced the CMI, which is responsive to the changes in soil moisture conditions that are reflected by stress placed on the more shallow-rooted crops (Palmer, 1965b).

Developmental work to further improve the PDI and CMI ended in 1973, but the calculations have continued, uninterrupted, to the present. Work has continued on several other approaches to create a soil moisture index that better describes moisture stress placed on crops and/or measures intensity of drought.

The Large Area Crop Inventory Experiment (LACIE), which began in 1974, provided the next opportunity to systematically pull together ideas and research results applicable to crop-climate responses. LACIE's goal was primarily to illustrate the many potential operational uses of remotely sensed data (National Aeronautics and Space Administration, 1978). The pre-LACIE work at Purdue's Laboratory for Applications of Remote Sensing (LARS) and other universities provided a basis for the remote sensing initiative and brought the National Aeronautics and Space Administration (NASA), NOAA, and USDA into an extended cooperative program. However, the application of standard meteorological observations like those by JAWF to monitor and assess changing crop conditions and estimate crop yields as the growing season progressed became a major accomplishment of LACIE. LACIE provided a unique multidiscipline-multiagency setting in which to pursue many interesting ideas on how to evaluate and quantify crop response to various climate-weather parameters. LACIE also resulted in a systematic evaluation of past research on crop-weather relationships and provided a focus for needed future research (National Aeronautics and Space Administration, 1978).

A major obstacle to achieving the proposed goals of the LACIE research was finding adequate historical data sets, both meteorological and agronomic. Thus, a major effort was initially directed to assembling sufficiently high-quality climatic and agronomic data sets for all the major wheat-growing areas of the world. In constructing the data sets for use in model development, it was necessary to place some restriction on the model development research to ensure that the types and quality of input data would be available in real time from the World Weather Watch/Global Telecommunications System (WWW/GTS) of the World Meteorological Organization (WMO). The WWW/GTS provides data only on a synoptic scale. A study was completed to evaluate potential yield model performance bias when operated on estimated input data derived from the synoptic scale WWW/GTS data system versus data estimates derived from a much denser observation network. The denser data network used in the study for comparison was the U. S. Cooperative Observer Network, with one or more stations per county. This provides at least a tenfold increase in data points versus the synoptic scale networks. Yield model estimates derived on data for a twenty-year period from the dense United States cooperative network were compared with results from estimated data using only synoptic reports. Statistically, no differences were found in the yield estimates derived from models driven by input weather estimates made using the different data sets (Sakamoto, et al., 1978).

Tests of various methods to estimate crop growth, soil moisture, and related crop stress were also completed. This work suggested that no one model approach, be it statistical, physiological, or phenological, was clearly superior when used in the wide range of crop yield models being tested. In short, a number of different approaches with varying degrees of complexity provided reasonable and acceptable indications of the soil moisture stress being placed on the plant, crop development rate, and ultimate yield reduction observed over large areas. It must also be pointed out that like the meteorological data, all the agronomic data have a degree of unknown error. However, the agronomic data, yield, phenological information, planting dates, and so forth represent the best and most accurate information available, and thus they are used for developmental purposes and verification of test results. By drawing on the knowledge gained in LACIE and the early phases of the Agricultural and Resources Inventory Survey Through Aerospace Remote Sensing (AgRISTARS) and by making necessary modifications, the operational program at JAWF has evolved over the last six years to its present capabilities. The AgRISTARS project extended the work concepts for yield modeling developed in LACIE for wheat to other crops, including corn, soybeans, cotton, flax, sunflowers, and rice (National Aeronautics and Space Administration, 1980, 1981).

The JAWF facility was established as a world agricultural weather information center in 1978, dedicated to serve the needs of USDA's economic intelligence work. Its primary function is to conduct a daily world agricultural weather watch and assess the impact of anomalous growing-season conditions on crop and livestock production. The National Weather Service's Climate Analysis Center (NWS/CAC) and USDA's National Agricultural Statistics Service (USDA/NASS) cooperate with the USDA's World Agricultural Outlook Board (USDA/WAOB) in operating JAWF. The unit is located at USDA headquarters. JAWF receives near-real time weather data from the global station network as well as products derived from station data and estimated satellite-derived meteorological data, used for outlook and situation work by USDA agencies. Quantified agricultural weather assessments are integrated into USDA's process of systematically updating international crop production estimates at USDA's monthly interagency world crop production meetings and special briefings. JAWF's specific tasks are to:

1. Continuously monitor regional agricultural weather patterns.
2. Synthesize information on crop areas, crop calendars, and cropping patterns.
3. Identify anomalous weather and provide initial qualitative crop impact assessments.
4. Utilize crop-weather relationships to quantify agricultural weather assessments.
5. Interact with agricultural economists and statisticians to integrate quantified yield analyses into the process of commodity production estimates.
6. Provide pertinent, timely information to the secretary of agriculture and USDA staff.
7. Disseminate informative summaries of international crop-weather assessments for release via the Weekly Weather and Crop Bulletin, USDA World Crop Production Report, press releases, and special publications.

The process by which these tasks are accomplished at JAWF is reviewed below.

AGRICULTURAL WEATHER ANALYSIS

Current weather information is obtained primarily from scheduled observation reports of surface conditions received via the Global Telecommunications System (GTS). Daily summaries of global precipitation and temperature from the World Meteorological Center (WMC) Suitland Computer Facility, surface and upper air charts, polar-orbiting GOES Meteosat and GMS satellite images, and automated near real-time meteorological data products are received and processed daily at JAWF for routine monitoring and briefing purposes. Station reports of precipitation and temperature in all agricultural areas are plotted daily for review at the regular briefings.

The emphasis of JAWF's analytical capability is on macroscale (regional) applications of agricultural meteorology; it does not attempt to do microscale (field-size) applications. In regional-scale applications, agronomic and meteorological data are limited and assumptions are required. These two important facts make it imperative that the professional staff ensure that the application does not overextend the informational integrity of the data and that it provides accurate interpretations of the results with due consideration of the underlying constraints. When developing assessments for crop supply and use statistics, an accurate assessment of the direction of crop yield deviations from initial projections several months before the final harvest statistics is often as important as estimating the yield potential during the harvest season. The error in potential yield forecasts should decrease as weather factors accumulate during phenological development. Significant contributions of weather to the yield potential often become apparent by the reproductive stage. Contributions to the yield potential can extend through the harvest season, however. In 1986, persistent and heavy rains during the grain maturation and harvest periods adversely affected both quantity and quality of the wheat crops in Canada and Argentina. Thus, cumulative seasonal effects must be carefully evaluated.

Although surface station data are sparse in some crop areas, agriculturally useful information has been obtained for crop assessment by rigorous monitoring of other upper-level meteorological observations, synoptic reports, and weather satellite imagery. The ancillary information, derived from surface- and upper-level synoptic reports and weather satellite products, is extremely important. Rain-producing convective cells can develop, reach maturity, and dissipate without being detected at station sites, regardless of the density of reporting networks. Synoptic reports provide a general overview of atmospheric conditions that may be conducive to random convective activity. Satellite imagery provides either qualitative or quantitative techniques for identifying cloud coverage as well as the distribution of precipitation over a crop area. Since locally heavy convective activity is a random phenomenon, the impact on regional crop yield potential can only be evaluated by proper monitoring of all available data and information throughout the growing season.

The recent acquisition of a digital weather satellite image system has substantially improved JAWF's capability to monitor global weather systems on a near-real time basis. The system ingests, processes, and stores imagery from GOES, METEOSAT, GMS, and polar-orbiting weather satellites. Images are continuously updated in specified loops that can be magnified, enhanced, or sectorized. This system is used to document weather events and to identify the extent of likely coverage within each crop area. Information is qualitative and is used to provide additional guidance in the weather assessment. Such features as IR temperatures and cloud brightness offer valuable tools in the analysis.

JAWF uses a variety of data products to tailor the global data base to regional agricultural weather assessments. A computer episodic events program monitors the daily global station network for conditions that may develop into yield-related anomalies and identifies stations meeting criteria for specific crop seasons. Episodes of hot and/or dry summer weather, extremely cold winter weather, and temperatures above/below the spring/autumn threshold values for dormancy are flagged. The duration, intensity, and coverage of anomalous weather episodes are factors to be considered for assessment preparation as well as cropping patterns and stages of crop development.

During the summer growing season in both hemispheres, agriculturally important parameters such as vapor pressure deficits (VPD) and potential evapotranspiration (PET) are computed. The vapor pressure deficit is defined as the difference between saturation vapor pressure and the observed vapor pressure at the existing temperature. High vapor pressure deficits (low relative humidities) occur frequently during the summer months, especially in semiarid to arid regions. Numerous agricultural areas are subjected to hot, dry air masses that are generated over large arid regions and advected into the crop area by strong winds. Vapor pressure deficits become very high under these conditions. The terms *sukhovei* in the Soviet Union, *lebeche* in Spain, *sirocco* in southern Europe, and *harmatten* in West Africa are used to describe such atmospheric conditions. This phenomenon also occurs in the U.S. Great Plains, Australia's wheat belt, and South Africa's corn-growing region.

JAWF currently employs two methods to compute PET—the Thornthwaite and modified Penman methods (Palmer, 1965a; Doorenbos and Pruitt, 1977). The Thornthwaite method was developed as a function of monthly mean temperature and day length. This method offers a relatively simple procedure with minimal input, but it is not suited for short time periods. Doorenbos and Pruitt's (Doorenbos and Pruitt, 1977) modified Penman method requires empirical wind and radiation functions as well as vapor pressure deficits. The method provides more satisfactory results over short time periods of the order of days or weeks. The data necessary to compute PET by both methods are available from the global synoptic data base.

The difference between actual precipitation divided by normal precipitation and the actual PET divided by normal PET provides a relative index of moisture available to the crop. Precipitation represents the source of moisture to crops (directly during the growing season and indirectly through storage in irrigation reserves) and PET represents the potential loss of moisture through the soil-plant system. Crop moisture usage depends on specific crop type, growth stage, water availability, and atmospheric conditions. ET is much less than PET during early growth phases, but as more vigorous vegetative growth occurs, crop moisture usage substantially increases. Peak moisture requirements occur during the crucial reproductive and grain development phases. Moisture needs decrease during late filling, and a "dry-down" period helps improve quality content as the crop matures. Differences in moisture usage of specific crops by growth stage are taken into account by crop coefficients (Doorenbos and Pruitt, 1977). Actual soil moisture supplies are the result of the relationship between infiltration and runoff. A regional soil moisture budget model is currently being tested at JAWF to improve the quantification of the soil moisture status at the beginning of the growing season.

A crop calendar, which includes information such as planting, emergence, vegetative, flowering, and mature stages of development, is essential. Early in the season, assumptions may be made about the usual planting period for specific crops. Growing degree days (GDD) are computed to relate heat units accumulated during the growing season with the crop's phenological development. An automated program has the flexibility to be reinitialized when new information is received about the actual planting dates within the crop area. Stress days (temperatures above or below threshold values) are also accumulated during the growing season. Since crop cycles vary by region, relationships between growth stage and GDD have been developed over the past five years according to knowledge of specific crop areas.

A 1981 USDA publication documented cropping zones, crop statistics, and representative climatic profiles for twelve major agricultural regions (U.S. Department of Agriculture, 1981). This document served as a basic reference for more detailed regional analyses. JAWF is working on an updated version that is expected to be published in 1987. Documentation of historical weather events associated with past crop yield fluctuations provides guidance for "expected" yield deviations given similar weather occurrences. For example, soybean yields in the state of Rio Grande do Sul, Brazil, are relatively low when rainfall during either (or both) the spring planting season or summer growing season ranks in the lower 30th percentile. Timing of the rainfall and temperature patterns plays a key role in the final yield outcome. The combination of a cold, wet spring planting season and a dry summer growing season can also lead to a poor yield. These conditions occurred in 1967, 1974, and 1979 in the Canadian spring wheat belt, causing yields to fall substantially below trend projections. Cool, wet springs can delay planting, pushing critical growth phases of the crop cycle into the more vulnerable period of hot, dry summer weather. The occurrence of anomalous weather and its magnitude on crop yields will vary by region.

Various techniques have been developed to model the effects of weather on vegetative growth or the crop yield potential. These include empirical-statistical models, which use regression techniques to relate specific weather variables to crop yields. This approach does not explain cause-and-effect relationships, but it does provide a feasible statistical procedure to evaluate crop yield statistics. JAWF employs the crop-weather analysis models that simulate accumulated crop responses to selected agrometeorological variables as a function of crop phenology. Observed weather data and derived agrometeorological variables are used as input data. Statistical regression techniques are used to evaluate weighting coefficients as crop development progresses from planting to maturity. The analysis models evaluate the effects of weather on crop yields, taking into account the relative importance of weather anomalies according to both crop type and stage of crop development. Computerized estimates of yield departures from the trend provide an objective, first-iteration estimate of the yield potential. These results are compared with historical weather-yield patterns accounting for the progress of the current growing season. The final decision on the monthly estimate of the yield potential is made by the agricultural meteorologist after consideration of all other information provided by meteorologists, economists, and commodity analysts.

The crop-weather analysis approach used by JAWF's agrometeorologists has proved successful for several reasons. The basic reasons are that climatic inputs of the daily global WWW/GTS station database are used, and sufficient data are available from the global synoptic network to compute derived variables such as vapor pressure deficits, potential evapotranspiration, and growing degree days. The daily weather data input allows for adjustments in the "biological" clock of the crop's development progress to aid in monitoring the response of the plants to the observed daily weather events. Detailed information has been compiled on cropping patterns and crop calendars by geographic region in order to model phenological development. Confirmation of the status of crop development is often made by field travel surveys and by the global network of agricultural counselors of USDA's Foreign Agricultural Service. Crop coefficients weight the cumulative effect of weather on the yield potential as crops advance through stages of their development cycle. Model estimates of the crop yield potential are closely scrutinized with respect to cumulative seasonal effects to avoid spurious short-lived fluctuations.

Preplanting crop yield statistics are based on early-season projections, derived from historical trend analyses and current information regarding technological factors such as introduction of new hybrids, fertilizer purchases, and government program changes. Weather data are used to provide indications of planting conditions and subsequent crop establishment. Unusually dry weather may delay planting, as it did during the 1985-86 growing seasons for Brazilian soybeans and South African corn. However, it is generally too early in the growing season to accurately quantify the effects of weather on the crop yield potential because of the random nature of weather events over the remainder of the growing season. For example, unseasonably dry weather delayed wheat planting in both Australia and Argentina during the 1984 growing season. Very late rains extended the planting season well beyond the optimal time, and favorable growing weather yielded near or above average crop yields in both cases. The relative change in monthly yield estimates is small during the early part of the growing season because information is too incomplete to justify large deviations from the early projections. Nonweather information associated with management practices, fertilizer applications, and the introduction of new seed varieties contributed most to any potential change in these early-season estimates. Meteorological input to the yield potential is generally quantified at the national level during the flowering and filling stages of crop development.

Since 1980, JAWF has used this approach to identify weather-related crop losses that occurred in Australia in 1982; in South Africa in 1983 and 1984; in Canada in 1984 and 1985; in the United States in 1980, 1983, and, to a lesser degree, 1984; in Brazil in 1981; and in the Soviet Union and the persistently drought-plagued continent of Africa in several recent years. During the 1985-86 growing season, a prolonged drought caused substantial damage to Brazil's coffee crop and severely stressed soybeans and other summer crops in the major southern growing areas. On the other hand, favorable weather helped produce record or near-record crop yields in the United States in 1981, 1982, and 1985; in Europe in 1984; in Canada in 1983; in Australia in 1983; in Argentina in 1984; and in China in several recent years.

JAWF's yield estimations are integrated into USDA's analytical process for estimation of global area, yield, and production statistics. Non-weather-related production components, including government program changes and fertilizer purchases, are analyzed by other USDA agencies. The data are, in turn, used to evaluate global supply and use estimates. USDA's world crop forecasting process has been implemented so that annual forecasts are updated on a monthly basis. Because these frequent assessments are released to the public, they constitute a major information source for both domestic and foreign agricultural industries and governments. Both qualitative and quantitative assessments of the crop yield potential are provided in international areas for which anomalous growing season weather is identified and selected for review in the monthly meetings. USDA crop analysts evaluate JAWF's objective weather-related analysis and discuss all other interagency analyses before finalizing the monthly crop estimates.

UTILIZATION OF WEATHER ASSESSMENTS

The agricultural weather analysis provides the U.S. agricultural sector with accurate data on potential markets and on supplies of potential competitors. Daily and weekly briefings provide an opportunity for the JAWF staff to interact with USDA commodity analysts and alert them to recent and seasonal agricultural weather conditions. The commodity analysts also provide JAWF with information on crop status and crop condition, based on tours and communications with agricultural counselors assigned to U.S. embassies around the world. Weekly briefings are also given to the secretary of agriculture and his staff to provide them with an overview of global weather conditions that may affect agriculture. A monthly interagency Africa briefing is conducted to provide analysts at USDA and other interested agencies with a detailed account of current weather conditions on the famine-plagued continent.

A significant increase in the demand by commodity analysts and policy-level decision makers for near real-time weather data and assessment information of the type developed by JAWF has occurred recently. In addition to daily briefings of current global agricultural weather, alerts of anomalous conditions affecting agriculture are included in daily highlights summarizing agricultural developments for USDA officials.

SUMMARY

The ultimate goal of JAWF is to provide accurate, concise, and timely information on agricultural weather as it affects global crop production. Agriculture, one of the nation's largest industries, is still an important positive contributor toward reducing the size of the U.S. trade deficit. U.S. farmers have become increasingly dependent on highly variable world markets. Agricultural weather is one factor that affects these markets. Proper use of the global agricultural weather data base, guided by results from experimental field research, may help American agriculturalists maintain the status of a highly efficient, flexible production system capable of meeting national and international food needs.

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