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PROCEEDINGS OF THE WMO/UNESCO SUB-FORUM ON SCIENCE AND TECHNOLOGY IN SUPPORT OF NATURAL DISASTER REDUCTION

Geneva, 6-8 July 1999

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Cover: *Floods (Haque/Bangladesh) and earthquakes (IDNDR) are a few of the natural disasters that strike communities and countries worldwide with devastating consequences. The International Decade for Natural Disaster Reduction has made great strides in mitigating the impacts of these disasters*.

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NOTE

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FOREWORD

The International Decade for Natural Disaster Reduction (IDNDR) is about to come to a close, but it really represents a beginning that has brought together very different groups that have, up to now, played parallel but separate roles in mitigating and preventing natural disasters. During the decade, the role of science and technology clearly assumed their place as important components for the next phase in our ability to assess risk and vulnerability; provide preparedness and prevention including early warning; and in enhancing awareness and educating the public. Over 99 per cent of all natural disasters are a result of hazards occurring in the earth's fluid and solid environment. The programmes of UNESCO and WMO address the relevant science for these environment sectors that include the earth’s geosphere, atmosphere, and hydrosphere (rivers and oceans). Both UNESCO and WMO have provided strong support as part of the framework partners under the IDNDR in planning and implementation of science and technology programmes for natural disaster reduction as a part of needed capacities for sustainable development. As a part of this partnership, UNESCO and WMO jointly convened a Sub-Forum on the Science and Technology Support to Natural Disaster Reduction as a part of the overall IDNDR Programme Forum. The Sub-Forum presentations and resulting discussions, as reflected in an agreed statement by the participants, are provided in this special report as a contribution of the two agencies in the closing of the Decade. On behalf of the Member States of UNESCO and Members of WMO, we would like to express our appreciation to the many participants in the Sub-Forum and especially to the panelists and scientists that contributed long hours to the excellent presentations. We particularly would like to thank the three panel chairs, Dr John Rodda, Dr Richard Hallgren, and Dr Soren Malling for their efforts in guiding the preparation and approval of the Sub-Forum statement. Finally, We wish to thank and acknowledge the excellent work of Dr Wolfgang Eder and Dr John Zillman in convening the Sub-Forum.

Director-General	Secretary-General
UNESCO	WMO

INTRODUCTION

Increasing evidence continues to show that the world is increasingly being threatened by natural disasters that have long-term negative social, economic and environmental consequences on vulnerable societies worldwide. Most of these disasters are a result of natural hazards from phenomena either of meteorological, hydrological, oceanographic, or geophysical origin or are events that are strongly influenced in terms of development, intensity and impact from these same phenomena. The global intergovernmental cooperation in the understanding these natural hazards as well as the application of the relevant sciences, including early warning, to reduce impacts of these natural disasters rests largely within the programmes of UNESCO and WMO.

Both of these UN Specialized Agencies have been major framework partners of the IDNDR and have provided significant scientific and technological support for use in natural disaster reduction. The Science sector of UNESCO, including its Intergovernmental Oceanographic Commission (IOC), has provided a global framework for most all of the research and application of the geophysics including vulcanology, seismology, and other terrestrial and earth-related sciences. In addition, the IOC serves as a major International focus for ocean research and applications including the management of the Tsunami Warning System for the Pacific Ocean. The WMO has long served as the UN organization responsible for atmospheric science and its applications primarily in terms of weather and climate. The World Weather Watch, including its programmes of Tropical Cyclone Warning and Public Weather Services provide the majority of information and data used by all countries of the world in providing early warning capability. Similarly, the data from these activities also serve as a basis for the understanding of climate both in terms of global changes and in seasonal and inter-annual fluctuations that often are manifested in phenomena such as *El Niño* and *La Niña*. UNESCO and WMO jointly share the responsibility for Hydrological Sciences within the UN framework. UNESCO continues to pursue the understanding of the basic science aspects through activities such as the International Hydrological Programme (IHP) and WMO has responsibilities related to applications and operations through its Hydrology and Water Resources Programme.

Both UNESCO and WMO, in addition to their normal programmes, have implemented special IDNDR scientific activities and projects throughout the IDNDR decade. It is both the normal programmes and these special projects that motivated both agencies to jointly convene a special Sub-Forum on Science and Technology in Support of Natural Disaster Reduction as part of an overall Programme Forum closing event of the IDNDR.

The Sub-Forum on Science and Technology in Support of Natural Disaster Reduction (Geneva, July 6–9, 1999) was jointly organized by WMO and UNESCO. It formed a major component of the 1999 IDNDR Programme Forum "Partnerships for a Safer World in the 21st Century", a keynote event of the concluding phase of the International Decade for Natural Disaster Reduction.

The Sub-forum's objectives were to review the current state of science and technology in support of natural disaster reduction, to identify needs for additional research and capacity building efforts and to consider ways to further enhance science and technology support for global natural disaster reduction efforts during the 21st century.

Under the guidance of co-convenors Dr J. W. Zillman and Dr F.W. Eder, participants in the Sub-Forum addressed a broad range of meteorological, hydrological and geophysical hazards, focussing on the contributions of science and technology to mitigation of their impacts and on promising scientific and technological developments which may further contribute to this objective in future years. Presentations by invited experts were followed by panel discussions focussing on three key aspects of disaster prevention and reduction — Vulnerability and Preparedness; Warning Capacities; and Preparedness and Education. The meeting concluded with the endorsement by participants of a formal Sub-Forum Statement, which reflects the results and conclusions from their deliberations.

The specific presentations related to phenomena of meteorological, hydrological or geophysical origin or directly contributing to the development, movement, and intensity of the disaster-causing hazards. The lectures included the following topics: tropical cyclones, extratropical storms; severe convective storms and tornadoes; drought; extreme temperatures; dust and sand storms; forest and bush fires; floods; avalanches; landslides; seismic risk and earthquakes; tsunami and coastal storm surges; and volcanoes.

The presentations emphasized the need for expanding scientific knowledge and technological capacity to improve warning capability, preparedness and to mitigate the impacts of natural hazards in vulnerable regions around the globe. This theme was central to the panel discussions where participants reviewed the specific contributions that science and technology can make in the broader disaster reduction process through:

- The assessment of vulnerability and enhancement of community awareness of the nature of the risk;
- The operation of integrated warning systems; and
- Preparedness and education programs.

The Statement summarizes the major conclusions from the Sub-Forum, emphasizing that science and technology have already contributed to reducing injury and loss of life as well as economic damage losses from natural hazards and greater reductions are possible in the future. The Statement points out that an outstanding achievement of the IDNDR has been to increase cooperation between the natural and social science communities, resulting in enhanced application of science and technology to reducing the societal impacts from natural disasters. The statement also expresses concern regarding the substantial gap that still exists between the disaster reduction capabilities of developed and developing countries, drawing attention to the need to continue efforts to develop scientific and technological capacities, early warning systems and public awareness and education in all regions exposed to natural hazards.

The lectures and panel discussions of the Sub-Forum provided significant elements used within the overall IDNDR Programme Forum and resulted in key information presented and discussed at the substantive Economic and Social Council (ECOSOC) session of 1999 regarding successor arrangements for the International Decade for Natural Disaster Reduction.

STATEMENT FROM THE WMO/UNESCO SUB-FORUM ON SCIENCE AND TECHNOLOGY IN SUPPORT OF NATURAL DISASTER REDUCTION

(Geneva, 6-8 July 1999)

One of the outstanding achievements of the International Decade for Natural Disaster Reduction (IDNDR) has been its major contribution to increased interaction and cooperation between the natural and social science communities working in disaster reduction and thence to enhanced application of science and technology to reducing the large and growing social and economic cost of natural disasters around the world.

Though science and technology have already contributed much to saving human life and reducing property loss and environmental damage from most forms of natural hazard of meteorological, hydrological, oceanographic and geological origin, their potential contribution over the next decade is even greater. But only if they are systematically and wisely applied within the broader social context of an integrated approach to natural disaster reduction which is the principal legacy and proudest achievement of the IDNDR.

In order to assist the global community to build most effectively on the foundation provided by the IDNDR, the World Meteorological Organization (WMO) and the United Nations Educational, Scientific and Cultural Organization (UNESCO), as the two principal United Nations agencies concerned with the scientific and technological aspects of disaster reduction, convened a “Sub-Forum on Science and Technology in Support of Natural Disaster Reduction” as a special contribution to the 1999 IDNDR Programme Forum “Partnerships for a Safer World in the 21st Century”.

The Sub-Forum reviewed the various ways in which science and technology contribute to the disaster reduction process through, the:

- Assessment of vulnerability and enhancement of community awareness of the nature of the risk;
- Operation of integrated warning systems; and
- Preparedness and education programs.

In its review, the Sub-Forum took stock of recent progress and future prospects in each of these three aspects of the application of science and technology to reduction of the impacts of tropical cyclones, extratropical storms, storm surges, severe local storms and tornadoes, sand and dust storms, drought, extreme and persistent temperatures, fire weather, floods, landslides, avalanches, volcanoes, earthquakes and tsunamis. A synopsis of this review is contained in the Annex to this statement.

The participants in the Sub-Forum, who came from both the natural and social sciences and with both research and operational backgrounds in developing and developed countries were concerned that more could have been achieved during the IDNDR decade if the channels of communication and mutual trust that have now been achieved could have been established earlier. They were also concerned at the substantial gap that still exists between the disaster reduction capabilities of the developed and developing countries. They believe, however, that the achievements of the past decade have provided a sound foundation on which to build an effective global strategy for natural disaster reduction in the 21st century.

MAJOR ACHIEVEMENTS

Many of the most significant achievements in natural disaster reduction during the 1990s were largely a result of science and technology. Accuracy and timeliness of early warnings for many natural hazards have been improved. The ability to provide forecast time and location of landfall of tropical cyclones has been improved by 24 hours so that the accuracy of the 24-hour forecast in 1990 has been increased in 1999 to 48 hours in advance. The warning time for tornadoes in 1990 was around 8 or 9 minutes and this has nearly doubled to over 17 minutes by the end of the decade. In the past decade, information and understanding on specific natural hazards such as earthquakes and cyclones has, along with increased confidence of design engineers and insurance companies, permitted improvements in building codes and standards in many parts of the world. A related achievement has been the significant increase of available maps of risk for many countries based on scientific studies and analyses of the climatology of natural hazards.

Perhaps the most visible achievement in the 1990s has been the creation of new disaster management bodies at all levels of government that now include scientists and engineers involved in the study and prediction of natural hazards. One of the major meteorological concerns of the 1990s had to do with the longer time scales associated with seasonal to interannual climate variability and human-induced change. While the capacity to forecast these changes is still limited, the implications for natural disaster reduction are extremely significant with just a very small improvement in forecast skills likely to lead to major benefits for communities and national economies.

Another notable achievement of the decade has been the ability, by means of satellites, to detect, track and assess the intensity of tropical cyclones and major storm systems. It is almost a certainty that all tropical cyclones can now be detected at or before their development as a natural hazard.

Significant improvements have been made during the decade in the global observation system of the World Weather Watch (WWW) and the Integrated Global Ocean Services System (IGOSS). For example, the polar and geostationary satellite systems have been enhanced and the experimental buoy network in the tropical Pacific Ocean has been made operational providing essential observations for early detection of intense El Niño and subsequent La Niña phenomena. This achievement permitted prediction of drought and above-normal precipitation several months in advance in Eastern Africa, and prediction of heavy rain in California in the United States. These predictions also led to special preparedness actions resulting in significant loss reduction in the ensuing flooding.

Overall, the achievements in scientific understanding and its application during the 1990s have provided significant increases in evacuation times, better building standards, and improved risk assessment.

VULNERABILITY AND AWARENESS

The Sub-Forum agreed that vulnerability assessment and reduction should form an integral part of the follow-up to the IDNDR. This should be achieved through use of advances in engineering, as well as in the natural, social and human sciences.

Awareness raising on all types of natural disasters forms an essential element in early warning systems, particularly where warning periods are short. It encompasses the affected population as well as the political authorities concerned. Therefore, education and training of communities at large, the involvement of media and continuous interaction between scientists, sociologists, technologists and decision makers and governmental authorities are indispensable vehicles for effective implementation. The partnership of scientific and technical practitioners with those working in social and humanitarian fields is essential notably in urban areas, involving the local population as well as tourists.

In developed countries, it has been clearly demonstrated in recent years that the vulnerability of communities to natural hazards can be greatly reduced by the use of modern building standards in conjunction with risk zoning based on scientific and technical knowledge of the various hazards and their impact on the built environment. Indeed it is through such standards and risk zoning that much of the scientific and technical knowledge of the various hazard mitigation is applied in the community. In the building and construction areas these standards are being developed by the International Standards Organization (ISO). These standards have the potential to greatly reduce community vulnerability to a number of major hazards in the long-term but this will require that the development of these new international standards be given higher priority than the revision and upgrading of their individual national standards.

A related, but separate need, is the development of cost-efficient means of reducing the vulnerability of existing buildings and infrastructure and the financing of activities. This is required to address the reduction of vulnerability in the short- to medium-term. A high level of technical skills will be required to determine economic means of reducing the vulnerability, as well as a high-level of scientific and engineering expertise for the innovative methods of risk financing needed to securitize the investment in reducing the vulnerability.

INTEGRATED WARNING SYSTEMS

Early warnings are an extremely important link in the series of steps that need to be followed to reduce the social and economic impact of natural hazards. Warnings of a natural hazard such as a flood delivered in a timely and clear manner to individuals or communities adequately prepared to take action reduces the impact of the hazard.

All sectors must be involved in the warning process and serve population needs, environment and other national resources. Effective early warnings require unrestricted access to data that is freely available for exchange and they must emanate from a single officially designated authority.

Advances in science and technology during the past decade have demonstrated the improved warning capability for many natural hazards in many parts of the world. For example, warnings of drought have been issued several months in advance which proved of great value for alleviating the impacts of the drought and the likely resulting decrease in food supplies. The forecast accuracy of tracks of tropical cyclones has shown significant improvement and average forecast lead times for tornadoes and flash floods have been substantially increased with the concomitant reduction in loss of life.

Provided adequate assistance is available, many opportunities now exist, in the coming decade, to transfer these warning capabilities to areas affected by natural hazards especially in developing countries.

The warning process is underpinned internationally by the World Weather Watch and IGOSS, the Tsunami Warning System and associated research particularly the World Weather Research Program. At the national level this process includes local and regional observational systems such as coordinated hydrological networks and radar, data processing capability and most importantly it depends on well-trained meteorologists to prepare forecasts and warnings and interact with media and emergency management officials.

PREPAREDNESS AND EDUCATION

A wide range of activities and bodies is encompassed in the terms “preparedness” and “education”. They extend from the grass roots to the governmental level and involve individuals, families and communities at one end, and universities, ministries and government as a whole at the other. They take in classes, seminars, schools, links of various sorts such as between the forecasters and the audience for their forecasts; and they include research, not only into forecasting, but also into the delivery and dissemination of forecasts and warnings and the responses, perception and reactions to them.

Developed and some developing countries have extended their preparedness and the meteorological, hydrological and other geoscience products supporting it into new areas in the course of the IDNDR decade. A closer dialogue has been forged between the scientific community and stakeholders in various areas of endeavour, such as agriculture, health and transport, and good progress has been made in the dialogue with social scientists, but this area still needs more attention. Catering for preparedness of the disadvantaged and disabled has also not progressed to the desired extent and greater use of plain and meaningful language is seen as highly advantageous in the better communication of forecasts and warnings. Indeed the language of preparedness measures and forecasts determine the way these messages are accepted. In many cases the use of a dialect could improve effectiveness and credibility. Confirmation of such messages is also an important consideration. Using mobile phones and pagers to propagate these messages and means other than radio and television have distinct benefits. Education and training applied in the direction of those scientists building the preparedness measures as well as those they are designed for. Indian experience of workshops between forecasters and people using their forecasts pointed to the value of such exchanges. However, there are differences when carrying the message to adults as opposed to children.

There are advantages attached to the education of schoolchildren in disaster preparedness – their parents benefit as well and this has been made evident during the IDNDR. Developing countries trying to build their preparedness face enormous costs and also the much greater costs of reconstruction in the wake of a disaster.

FUTURE ACTIONS

The Sub-Forum recognized that, as a result of demographic pressures and concentration and other factors, our societies are becoming more and more vulnerable and that our protective systems are not necessarily adapted to cope. Furthermore, considering that a disaster strategy which puts emphasis solely on relief and response is short-sighted and not cost-effective, the participants agreed on the need for greater emphasis on prevention across the whole continium of hazards faced by humanity.

The Sub-Forum recalled that the 1994 Yokohoma World Conference on Natural Disaster Reduction called for a construction of a “Culture of Prevention” which should be based on improved short-term and long-term monitoring mechanisms. Mitigation, preparedness and prevention measures must be proactive rather than reactive; they must provide the correct treatment while there is still time. Prevention must be rooted ultimately in culture and education which finds its expression in our everyday social behaviour. Hence, the threat of potentially irreversible events includes an ethical dimension which should be reflected in training, organization and motivation of communities at risk.

Capacity building and education at all levels have an important role to play in the development of a culture of prevention by ensuring a two-way flow of information between decision makers and communities at risk.

The Sub-Forum emphasized the need for capacity-building in vulnerability and risk assessment, early warning of both short-lived natural disasters and long-term hazards associated with environmental change, improved preparedness, adaptation, mitigation of their adverse effects and the integration of disaster management into overall national socio-economic development planning.

The participants agreed that a focussed ongoing coordination structure is needed within the UN system in order to strengthen further the already close cooperation among intergovernmental and non-governmental scientific and technical bodies committed to natural disaster reduction. Such a mechanism is necessary to foster and sustain the vital international and national effort on the application of the natural and social sciences and technology in support of natural disaster reduction, particularly through the implementation of the relevant programmes of UNESCO and WMO.

EXTRATROPICAL STORMS OF THE DECADE - A BRIEF REVIEW

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ABSTRACT

Large-scale, mid-latitude storms are responsible for a variety of extreme weather. They are the main cause of blizzards, freezing rain and heavy snowfall in winter and can cause intense rainfall, hailstorms, or spawn tornado families in summer. The 1990s have seen an increase in the cost of natural disasters resulting from extratropical storm activity, both in terms of financial costs and human lives, despite improvements in risk forecasting. The following are examples of large-scale disasters caused by extratropical weather events. The 1998 flooding of the Yangtze River in China claimed 3 700 lives as excessive rainfall inundated the area for 60 days. The floods dislocated 223 million people and cost US $30 billion in damages, making it the most costly disaster of 1998. The Ice Storm that hit the Eastern provinces of Canada and Northern parts of the New England States of the United States of America in January 1998 coated every exposed surface with a layer of ice about 70 mm thick. This ice storm was the worst to hit Canada in recent history. Prolonged freezing rain brought down millions of trees, over a thousand hydro towers and more than 100 000 km of power lines. The storm claimed at least 25 lives and nearly 3 million people went without electricity or heat and about 100 000 people took refuge in shelters. The resulting damages cost close to US $2 billion. While El Niño and other phenomena may intensify weather conditions, the greater problem may be that more people are living in vulnerable areas and take insufficient precautions, despite great advancements in public safety warnings. In the past decade, there have been more natural disasters that have caused at least US $1 billion in damages than in any previous decade. In the past year alone, the world's economy has suffered over an estimated US $89 billion in losses from natural disasters, which have claimed over 32 000 lives. The impacts from many storms would have been much greater had they not been so well forecast. Using computer models, many storms can be predicted well ahead of time, helping to mitigate their impacts. Rescue and relief operations witnessed around the world have been impressive and have contributed greatly to reducing the effects of severe storms.

1. INTRODUCTION

From fall through to winter and well into spring, extratropical storms dominate the weather outside of the tropics. Although mid-latitude cyclones can be present at any time of the year, they are most severe in the winter. They move generally from west to east across the oceans and continents.

The extratropical storm's centre is an area of low atmospheric pressure with winds going counter-clockwise in the Northern Hemisphere and clockwise south of the equator. The winds pull cold air from polar regions toward the equator and bring warm air toward the poles. The clash of warm and cold air leads to widespread precipitation. An extratropical storm has a narrow region called a "dry slot" spiralling into the storm's low pressure centre from the north. This intrusion of dry air is within a cold air mass astride warm moist air on the storm's east and south sides. The temperature difference between the two air masses intensifies the storm. A cold front marks the leading edge of the advancing cold air on the storm's western side, while the warm front leads the warm air's move north along and into the storm's eastern side. Thunderstorms can develop along or ahead of the cold front but do not surround the system's centre as in a tropical cyclone.

Large-scale extratropical storms are responsible for a variety of summer and winter weather. In winter, they are the major cause of blizzards, freezing rain and heavy snowfall. In summer, they can cause intense rainfall activity over wide-spread areas, spawn tornado families and produce numerous hailstorms. The impact of an extratropical storm can be from either a series of events causing cumulative effects due to a change in atmospheric circulation or from one single event.

This paper is a review of a sampling of severe extratropical storms that occurred in various parts of the globe in the 1990s. It demonstrates both the impacts of a single event and the cumulative effects of these storms.

2. EXTRATROPICAL WINTER STORMS

Various types of severe winter weather are the direct result of conditions associated with each portion of a mature, mid-latitude cyclone. The strong winds and cold air behind the cold front produce severe wind-chill. Blowing snow and high wind-chill factors are the main components for blizzard conditions. Heavy precipitation over widespread areas, in the form of snow, sleet and/or freezing rain, is found along and north of a warm front to the east of a low pressure cell. The storms can move at up to 80 km/h in the developing stages or can stall in the mature stages, often depositing large amounts of precipitation in their wake.

2.1 THE STORMY ATLANTIC - 1990

During January and February of 1990, the North Atlantic bred a number of very intense storm systems that struck northern Europe with hurricane-force winds. These winter storms favoured a track across the northern and central Europe, in contrast to the usual branch pattern over the Mediterranean Sea and the North Sea. Storms penetrated well into Europe in the absence of any blocking anticyclone. The first major storm was actually traced back to a frontal system that crossed the United States of America from 18 to 21 January. The storm ultimately deepened to 948 mb over the North Sea, just east of England, on 25 January. Winds of up to 200 km/h lashed Britain, paralysing all transportation and knocking out power and phone services to hundreds of thousands of households and offices. Winds downed trees, blew roofs off buildings, and knocked over trucks, causing an epic traffic jam during the London evening rush hour. At least 45 deaths in Britain were blamed on the storm, with an early damage estimate placed at US $1.33 billion. The storm winds also caused destruction elsewhere in Europe, with a total of 93 deaths.

Only four days later, on 29 January, a second storm struck southwestern England, toppling trees and causing landslides and floods. A third major storm struck on 3 and 4 February leaving a trail of destruction over much of northern Europe. The latter was one of France’s worst storms in recent decades; high winds killed 23 people and injured dozens more. The windstorm lashed Germany on the morning of 4 February, killing 7 and injuring more than 50. It uprooted thousands of trees and tore off hundreds of roofs.

The last of the major storms to strike Europe hit on 26 and 27 February. Winds of up to 160 km/h struck the Welsh coast, and winds nearly as strong assaulted the continent. In Austria, winds damaged 4 million m^3 of trees, nearly a quarter of the annual timber harvest. In Germany, the tree damage reached 64 million m^3, more than twice the average annual number of trees normally cut-down. A total of 63 fatalities occurred across Europe. In addition, at least 25 forest workers died in accidents during the clean-up effort.

2.2 THE “STORM OF THE CENTURY” — 1993

The winter storm that hit the East coast of the United States of America on March 13, 1993 was termed the “Storm of the Century” by the media. Heavy snow and strong winds covered a very wide area, breaking dozens of monthly snowfall and daily minimum temperature records from the Gulf Coast to New England.

The storm experienced an explosive drop in central pressure, from 1000 mb on the morning of 12 March in the western Gulf to 960 mb over Chesapeake Bay on the evening of 13 March. As the storm swept over the Gulf Coast, it lashed Florida with a 2.7 m storm surge, similar to a hurricane, and 176 km per hour winds. The following day Richmond and Norfolk, Virginia, and Washington, D.C. all reported record low pressures of 951 mb.

The effects were felt from Cuba to Canada, with a total death toll of 243. In addition, 3 million people were left without power and thousands more were isolated by record snowfall. The storm caused US $1.6 billion in insured property damage and, at the time, was the most costly non-tropical storm on record and the fourth costliest U.S. catastrophe.

It was the first time a single snowstorm closed each major airport on the East Coast of the U.S.A. Cities from Boston to Washington received 18 to 30 cm of snow. Not far inland, snow depths exceeded 30 cm from Alabama through the Appalachians and Piedmont to Canada. Mountainous areas of Maryland, West Virginia and North Carolina reported over 100 cm of snow, while locations with the lake effect exceeded 60 to 90 cm. Syracuse's 109 cm was the greatest single daily snowfall since records began in 1902. Snow fell as far south as the Florida panhandle. Birmingham, Alabama set records for 24 hour snowfall (33 cm), single storm snowfall, monthly snowfall, and snow depth!

The bitter cold that followed the storm, broke or tied at least 68 low-temperature records on Sunday, March 14 and another 72 on Monday. The Sunday low temperature of –6°C at Mobile, Alabama not only broke the daily record by 13°C but also set the March record.

The impacts from the storm would have been much greater had it struck during the week and not been so well forecast. The National Weather Service forecasters, using computer models, predicted this storm of historic magnitude at least two days in advance. On 11 March the National Meteorological Center map showed the location of the storm 48 hours ahead.

2.3 CALIFORNIA WINTER STORMS — 1995

During January and March of 1995, much of California was struck by extremely heavy precipitation from frequent Pacific storms, causing extensive property damage and loss of life. Estimates show that over US $3 billion in damages and 27 lives were claimed by widespread river flooding and mud slides. The American Red Cross estimates that over 10,000 homes were damaged or destroyed. In January alone, over 762 mm of rain fell on parts of northern and central California.

A much stronger than normal Pacific jet stream was displaced well south of its normal position during much of the winter and early spring of 1995. This funnelled moisture and major storm systems directly into California. The jet core and the average storm track were displaced 15 to 20° south of the normal locations during January. During the winter of 1995, the state was struck repeatedly by very strong systems loaded with Pacific moisture.

Numerous studies have noted that a moderate-to-strong El Niño event, such as occurred the winter of 1995, usually results in a stronger than normal Pacific subtropical jet stream and a very active storm track along its path. This, in turn, creates above normal precipitation in areas along the path of major storm systems. During the winter of 1995, this storm track was the major influence in steering the strong storm systems in California.

The January storms resulted in 42 California counties being declared federal disaster areas. By late March, all 58 counties in California qualified for federal disaster assistance. Pacific Gas and Electrical reported electrical outages for 1.4 million customers during January and 1.2 million during March. Thunderstorms, sometimes severe, accompanied many of the storm systems. In both months, flooding on many of the smaller streams was caused by very heavy precipitation during short time intervals, with amounts that sometimes exceeded 100 year 24 hour event records. Then, flooding on larger rivers resulted as they were fed by overflowing tributaries. The Salinas River at Chular reached a peak flow nearly double the previous record set in 1983. The Russian River swelled to almost 5 m above the flood stage. All-time high-water marks were set in many parts of Southern California.

The January storms affected northern California more severely while the March storms were concentrated more on central California. However, both months showed much above normal precipitation over most of the state. Since most of the storms occurred within relatively cool, unstable air masses, much of the precipitation above 1 525 m in elevation fell and accumulated as snow. This somewhat lessened the immediate impact of the storms in terms of flooding. The water content of the snow pack exceeded 150 per cent of normal for the

Sacramento Basin and Sierra Nevada mountains by the end of March. Some locations reported snow depths exceeding 12 m by late March.

One of the obvious impacts of unusually heavy precipitation was on agriculture. The inability to either harvest or plant severely affected many crops. Thousands of acres of Monterey County farmland were flooded. Over 3 000 people, mostly farm workers, had to be evacuated from the town of Pajaro, which was entirely flooded due to a levee break.

2.4 ICE STORM '98

Ice storms are common to the eastern provinces of Canada and the eastern states of the United States. Approximately 15 occur each year and last from a few hours to more than a day. Usually these systems fade away or are followed by a warming trend that melts the ice and alleviates any cause for concern.

The Ice Storm of January 1998 was the worst to ever hit Canada and the United States, due to the amount of ice accumulation, the duration of the storm and the population affected. Areas affected were eastern Ontario, southern Quebec, southern New Brunswick, upstate New York, northern New England, and some parts of Nova Scotia. The water equivalent of the freezing rain and ice pellets exceeded 100 mm in many areas, more than twice the yearly average.

Freezing rain coated every exposed surface with such a thick layer of ice that tree branches snapped off, trees fell down, hydro wires and towers were destroyed and all types of transportation and travel were seriously affected. The storm claimed at least 25 lives and severely inconvenienced millions. At the height of the storm, nearly 3.5 million people were without electricity or heat. Thousands had to take refuge in shelters. Falling temperatures and additional snowfall continued to hamper relief efforts after the storm. A week after the storm ended, nearly a million people were still without light or heat. The estimated costs relating to the ice storm were close to US $1.4 billion.

A northeast outflow of air, with temperatures below 0°C, from a high pressure area over Hudson Bay and northern Quebec, pushed southward to lie north of Lake Ontario by 5 January. At the same time, a weak southerly flow of warm air was being pushed into southern Ontario and southern Quebec.

This weather pattern set up the freezing rain, as warm air was forced to rise gently over denser cold air. Rain falling from the warm air mass cooled to below the freezing point as it passed through the cold air below. Super-cooled raindrops froze on contact with any cold surface in the cold air mass and ice began to accumulate.

Environment Canada played an important role in a wide range of federal support efforts related to the ice storm. Throughout the crisis, Environment Canada was able to provide Canadians with accurate and timely weather warnings and information on a 24-hour basis. The department also provided utilities, municipalities, provincial authorities, other federal departments and emergency response officials with extensive specialized weather support, as well as advice and assessments on a broad range of environmental issues related to storm damage. Meteorologists and climate experts handled over 1 000 media calls and visits to the department's national web site increased by 50 per cent to over 300 000 hits a day.

1.5 million households were without power and 100 000 people took refuge in shelters. Trees and power lines were falling and roads were blocked, which making travelling conditions hazardous. More than 22 deaths were directly attributed to the Ice Storm. As people were reluctant to vacate their homes, many were stricken with hypothermia.

3. SUMMER EXTRATROPICAL STORMS

Various types of severe summer weather are the direct result of conditions associated with each portion of a mature, mid-latitude cyclone. In summer, flooding is the major threat from extratropical storm activity. The storms produce both widespread, heavy precipitation ahead of a warm front and intense, localised rainfall (from thunderstorm activity) in front of, on the leading edge, of a cold front. Another major threat is posed by thunderstorm activity. If severe enough, it can produce multiple hailstorms and families of tornadoes dispersed over a large area.

3.1 THE GREAT FLOOD - 1993

The great flood of 1993 in the United States surpassed all floods experienced in living memory in terms of precipitation amounts, record river stages, the extent of the flooding, persons displaced, crop and property damage and flood duration.

During the spring of 1993, the record and near-record precipitation, on soil saturated from the previous seasonal precipitation, resulted in flooding along many major river systems in the Midwest, including the Mississippi and Missouri and their tributaries.

Prior to these excessive rains, however, the region was ripe for flooding as a result of above normal precipitation that was persistently observed through most of the region beginning in July 1992, generating waterlogged ground and high stream flows and reservoir levels. There had been excessive winter snow pack in the Rocky Mountains, saturated soil conditions in the Midwest and critical run-off conditions. As a result, long-term moisture surpluses occurred across a large portion of the east-central Great Plains and the middle Mississippi Valley. For some locations, rainfall totals amounted to an extra year's worth of rain over 14 months.

By March 1993 the soil remained soaked and rivers remained high, despite slightly dry conditions. United States National Weather Service hydrologists in Minneapolis alerted residents of the upper Mississippi Valley to the saturated ground on 3 March, 1993. By the end of March, the National Weather Service released a warning that widespread, serious flooding could occur in the Northeast if an extended period of warm weather was accompanied by significant rainfall. The entire eastern half of the United States faced an above average flood risk.

From April to June, the upper Mississippi Valley received an average of 410 mm of rainfall, making these three months the wettest period since records began in 1895. The average precipitation for the period is 280 mm. Wet fields delayed or prevented spring planting. Streams and rivers began to fill. With the ground unable to absorb more rain, the water flowed southward down the Mississippi toward the Gulf Mexico.

Heavy rain fell from 19 June to 21 June, concentrating on southwestern Wisconsin, southern Minnesota, southeastern South Dakota, and Iowa. Serious flooding began on the tributaries of the upper Mississippi, as well as the river itself.

An estimated 1 100 levees or floodwall failures occurred during the summer of 1993 — 70 per cent of the total number of levees along the affected rivers. The first failure came on 20 June, when, despite efforts to reinforce the levee with sandbags, the Black River broke through, flooding approximately 100 homes in Black River Fall, Wisconsin. Residents and volunteers from around the world had shovelled more than 417 million kg of fill into 26 million sandbags by the end of the summer. Despite their efforts, flood waters washed over an estimated 4 million hectares in the Mississippi River Basin, destroying or seriously damaging more than 40 000 buildings. The flood killed at least 47 people.

The flood water moved down the Mississippi from St. Paul, joined by water from tributaries in southern Minnesota, Wisconsin, Iowa, and northern Illinois. Similar waves of flood water were also flowing southward on the Des Moines and Missouri rivers, heading for the Mississippi.

Flooding was aggravated when a heavy rain fell from 25 June through to 27 June on Iowa, Missouri, and southern Illinois, adding to the water already moving down the Mississippi and other rivers. During late June and July, 305 to 457 mm of rain fell across the central part of the country. By mid-July, the US National Weather Service announced that 100 rivers were over their banks, with 14 at their highest level ever recorded.

At the beginning of the summer of 1993, the mean position of an unusually strong jet stream was dipped southward over the northern portion of the Mississippi basin, oriented south-west to north-east between the persistent low-pressure trough to the north-west and an unusually strong Bermuda High over south-eastern United States. The clockwise winds around this high-pressure area pumped humid air from the Gulf of Mexico northward along the Mississippi Valley. The high pressure also helped block an eastern movement of thunderstorm clusters from the Midwest. The unusually large contrast between low and high pressure helped to create stronger southerly winds, which brought in moisture-laden air causing record-breaking rains. The boundary between cool air and warm air remained over the upper Mississippi Valley. Warm, humid air flowed over the cool, dry air, which helped to create thunderstorms. The influence of the sea surface temperature anomaly in the tropical Pacific associated with the El Niño/Southern Oscillation (ENSO) phenomenon was also a contributing factor.

The combination of these circumstances resulted in the worst flooding in over a century in the northern Mississippi basin. Record flooding occurred at nearly 500 forecast points in a nine state region and, in some cases, surpassed old record stages by nearly 2 m. The duration of the flood was overwhelming, by 1 September 1993, some towns had experienced 153 consecutive days of flooding. The flooded region finally began drying out in early August when the upper-air pattern changed, bringing unseasonably cool and dry weather to the Midwest.

The expected return period for an event of this magnitude was calculated from precipitation probabilities. For most sites in the midwestern United States, the recurrence interval was in the 500 to 1 000 plus year range. The presence of such extremely long return periods dramatically indicates the extraordinary nature of the event.

The duration and magnitude of the flood strongly support the premise that this event was a significant climate variation. It is quite possible that one or more climate-driving forces, such as the El Niño/Southern Oscillation (ENSO) phenomenon, significantly contributed to climate variation.

3.2 PALM SUNDAY TORNADO OUTBREAK, 1994 AND THE MIDWEST TORNADO OUTBREAK, 1999

Severe thunderstorms spawned 27 tornadoes in the southeastern United States on Palm Sunday 27 March 1994. The deadliest storms occurred in Alabama, Georgia and the Carolinas. This was the deadliest tornado outbreak since May 1985, killing 42 people and injuring more than 350. With 59 tornadoes, including two tornadoes measuring F4 on the Fujita Scale, March was an above average month for the United States and total damages were estimated at US $217 million.

On that morning, a cold front curved from Ohio through central Tennessee to a low-pressure centre along the Texas coast. The front moved into northern Georgia and Alabama, then stalled while the low pressure moved along the front into central Alabama. Southerly winds exceeded 48 km/h ahead of the front, where temperatures rose above 21°C (including a record 28°C in Atlanta). In widespread heavy rain behind the front, temperatures were only in the 10-20°C range. Just a thousand metres above the ground, 97-113 km/h south-to-southwest winds brought in Gulf air. Higher up, west-to-southwest winds exceeded 160 km/h. The warm, moist Gulf inflow and the unusually strong winds favoured destructive tornadoes. Strong winds aloft steered the severe thunderstorms northeast, along and ahead of the cold front.

The most powerful and deadly tornado, an F4, touched down south of Ragland in northeastern Alabama, just before 11 a.m. The tornado destroyed houses and threw cars across the state highways. High winds shattered the windows of a church and ripped off its roof causing a brick wall to collapse, killing 20 people and injuring another 92. The tornado headed northeast to the Georgia line just before noon, having caused US $50 million in damage. Meanwhile, an F2 tornado south of Guntersville, Alabama injured 20 people and damaged over 100 houses, and an F3 tornado east of Oak Grove grew to over 800 m wide and injured 20 people.

That afternoon, the mayhem reached Georgia. A tornado picked up a mobile home and carried it 23 m, killing the elderly couple inside. Over Floyd County, the sky turned green-black by 1 p.m. Within ten minutes, severe thunderstorms hurled hailstones up to 10 cm in diameter with continuous lightning near Cave Springs. The thunderstorms shortly spawned an F4 tornado that travelled almost 80 km, killing 3 people and injuring 20. The tornado grew to over 1.6 km wide, destroying nearly 40 chicken houses and killing more than half a million chickens. Hundreds of thousands of trees were levelled, with 18–24 m pines uprooted.

An F3 tornado touched down northwest of Dawsonville, Georgia later that afternoon and travelled over 70 km, killing 3 people and injuring 45. This tornado also killed more than half a million chickens and downed hundreds of thousands of trees. It grew up to 2.4 km wide in White County. Damage was estimated at US $17 million.

At Dahlonega, an F3 tornado tracked 37 km, killing 3 people and injuring 15 as it reached 1.2 km in width and caused US $3 million in damages. The skies of Rome were tainted a green-black colour as well. In five minutes, thunderstorms whipped gusts up to 140 km/h. Another F3 tornado then touched down south of Adairsville, at 3 p.m., and travelled 64 km, killing 9 and injuring 7. Among the US $12 million in damages were more than 300 000 chickens. The tornado was 2.4 km wide in hilly Pickens County. In Hill City, it tossed a mobile home over 90m, killing all six of the family inside. The tornado was still 1.2 km wide as it climbed a plateau toward nearby Burnt and Sassafras.

An F3 tornado northeast of Clarksville, Georgia crossed into South Carolina, injuring 35 people. Up to 1.6 km wide, it descended a 150 m cliff to the base of Tallulah Falls. Some of the debris blown into the gorge was from as far as Piedmont, Alabama, more than 225 km away.

An F2 tornado north of Helena, Alabama at 5.30 p.m. injured 53 people before lifting near Meadow Brook, prefacing another round of violent storms. An F2 tornado touched down northwest of Cedartown, Georgia at 7 p.m. and travelled 34 km, injuring 30 people and causing US $7 million in damages. The tornado flattened trees on the Booze Mountain on its way to Lindale, a suburb of Rome where residents had already seen the green-black skies and continuous lightning about five minutes before. The skies roared as the tornado passed overhead while paralleled by a weaker twister about 800 m away.

The outbreak of significant tornadoes across the southeast United States on Palm Sunday was not as synoptically evident as many of the outbreak cases in the past. The outbreak occurred without the presence of a well defined surface low centre or a prominent short wave trough. Nevertheless, what did evolve into a favourable configuration for the formation of supercells and strong tornadoes were the warm sector air mass characteristics, particularly the wind fields.

A more recent tornado outbreak occurred across the midwestern United States earlier this year. Powerful storm systems pushed across Oklahoma, Kansas and Texas on the evening of 3 May 1999, spawning 76 tornadoes, obliterating towns and killing 44 people while injuring 900 others. About 4 180 homes and businesses were destroyed or heavily damaged. The tornadoes knocked out power to thousands of people.

One unusually large and powerful F5 tornado formed just outside Oklahoma city, killing 38 people and injuring hundreds as it moved north and east with winds topping 418 km/h, cutting a path over 800 m wide. The storm carved a 30 km gash through the area demolishing about 2 000 homes. About 240 km north, a tornado spawned by the same storm system tossed mobile homes, damaged houses and killed at least five people while injuring over 80 others in Wichita, Kansas.

At least 6 tornadic storms developed over a 5-hour period on the Monday evening, mainly in central and north-east Oklahoma. Cars were tossed across highways and crushed. Houses were smashed into piles of splintered timbers and brick. The ground was scoured bare in places and stripped of trees. The estimated damage was in the hundreds of millions of US dollars. Several tornadoes may have been 1.6 km wide with winds up to 420km/h, measuring an F4 on the Fujita scale.

Eleven counties in Oklahoma and one in Kansas were declared federal disaster areas. five people were still missing in rural Oklahoma two days following the devastating tornado outbreak. A cold rain fell as residents began to pick through the wreckage of their homes and bulldozers were brought in to clear away debris.

3.3 SAGUENAY RIVER FLOODING — 1996

Another type of flooding event, the flash flood, was exemplified by the Saguenay River flooding in 1996. One July weekend, torrential rains gave rise to one of the worse flooding events in Canadian history. The floods left at least 10 people dead, 1 350 homes destroyed, while 16 000 people had to be evacuated from their houses. Material losses were estimated at almost US $545 million, making this one of Canada's most costly natural disasters.

The morning of 19 July 1996, a low pressure system located over southern Ontario was on the verge of rapid and intense development. In the following 24 hours, the system intensified as a fall-like low pressure system as it moved towards the Quebec — New Brunswick border before slowing down and becoming almost stationary over the mouth of the St. Lawrence River. The largest zone of accumulation occurred just south of the Jonquière-Chicoutimi-La Baie area of the Saguenay Valley, where in excess of 200 mm of rain fell, most within a 36 hour period. Rainfall amounts were also impressive in Saguenay-Lac Saint-Jean and Parc-des-Laurentides areas on the northern shore of the Saint-Lawrence River, west of Sept-Iles. Over these areas, the topography and wind circulation generated from the storm produced locally higher rainfall amounts due to lifting. The decline of the low pressure system over eastern Quebec allowed the precipitation area linked with this system to persist over the most affected areas.

The Saguenay floods caused extensive erosion along some major river reaches resulting in major channel widening and bank erosion, breaching of dams and dykes and damage to bridges and roads.

Many precipitation records were established during this weekend. For many sites across the province of Quebec, the total rainfall amounts from the storm exceeded the amounts that normally fall during the month of July. The 18 July to 21 July 1996 torrential rains were the most extreme, in intensity and area, for the province of Quebec in over a century.

3.4 YANGTZE RIVER FLOODS — 1998

The summer flooding of 1998 in China killed 4 150 people as heavy rains inundated the Yangtze River Valley for more than 60 days. The floods affected 223 million people (1/5th of the population of China), inundated 25 million hectares of cropland and cost US $30 billion in damages, making it the most costly disaster of 1998 and causing the worst flooding in over 44 years. The flooding caused severe damage to critical facilities such as health clinics, schools, water supplies and other infrastructure such as roads, bridges, and irrigation systems, as well as industrial facilities. During June and July, locations near the Yangtze River reported over 750 mm of rain, with isolated amounts greater than 1 270 mm.

The cause of the disaster was excessive rainfall (which according to Chinese meteorologists was ascribed to the worldwide El Niño phenomenon followed by La Niña); the melting of lasting and deep snow accumulated in Qinghai — the Tibet plateau in southwest China; a weak Asian monsoon; unusual sub-tropical high pressure systems on the west Pacific Ocean; and a decrease in the number of typhoons.

Though heavy summer rains are common in southern China, the Yangtze River Basin has lost 85 per cent of its forest cover from logging and agriculture in recent years, leaving many steep hillsides bare and causing rainfall to run quickly into the river rather than being absorbed. This has led to more devastating land-slides and floods. The heavy damming of the river has greatly increased the speed and severity of the resulting run-off. At the same time, growing population pressures have led many to settle on vulnerable flood plains and hillsides, now increasingly inhabited. The frequency of floods has increased from once every twenty years in earlier centuries to nine out of ten years.

Given the magnitude of the disaster, which was unprecedented over the last few decades, the rescue and relief operations mounted by the Chinese Government at all levels were impressive. The massive mobilisation of farmers and villagers by the police and army reduced the suffering and loss of human lives. The Government provided emergency relief efficiently and effectively.

China's advanced prevention policy, based on timely predictions, forecasting, and early warnings, greatly contributed to mitigating the outcome of the flood. The State Council of China has recognized the role of human activities in worsening 'natural' disasters. It has banned logging in the upper Yangtze watershed, prohibited additional land reclamation projects in the river's flood plain and has earmarked US $2 billion to reforest the watershed.

3.5 THE SYDNEY HAILSTORM — 14 APRIL 1999

A severe thunderstorm, which struck the eastern suburbs of Sydney, Australia on 14 April, 1999 caused extensive damage estimated at US $1 billion, making it possibly Australia's most costly natural disaster. The storm's damage surpassed that of the Newcastle earthquake of 1989 and Tropical Cyclone Tracy of 1974 in Darwin. The storm tore across the city overnight, damaging thousands of homes and cars, cutting power supplies and phone lines and briefly grounding planes. Plummeting chunks of ice damaged roofs, battered cars, and knocked out traffic lights. Up to 15 000 homes lost power. Lightning sparked at least 25 electrical fires. Dozens of people were treated for cuts from broken glass and other injuries. Others were injured the following day as they tried to make repairs.

The storm was highly unusual in meteorological terms. Not only did it produce hailstones up to 9 cm in diameter, but it occurred at a time of year when severe thunderstorms are normally rare. The storm took a highly unusual track, moving from land to sea, back to land, and finally out to sea, lasting a total of $5\frac{1}{2}$ hours.

A thunderstorm began to form about 115 km to the south-southwest of Sydney in the late afternoon. The storm subsequently developed into a supercell, a rare but unusually severe type of thunderstorm whose structure, behaviour, intensity and longevity is quite different to ordinary thunderstorms. By about 6 p.m., the storm moved up the New South Wales coastline with the western edge producing substantial amounts of hail in the Wollongong area. The storm then moved out to sea but continued to track north-northeast, parallel to the coast, before crossing inland again near Helensburgh. As the storm neared Sydney, it split into 2 sections. The weaker of the two cells moved out towards the sea and the stronger cell moved on towards the city centre. Lightning, thunder and rain was reported around the inner city areas of Sydney. The storm continued on to devastate Sydney's eastern suburbs. The storm eventually moved out to sea and had dissipated by 10 p.m.

The storm was triggered by a relatively warm autumn day that saw temperatures peaking at 26.2°C, about 2°C above normal. As the warm air rose, it carried large amounts of moisture high into the atmosphere where it met cold air, causing the vapour to suddenly freeze.

No public severe weather warning was issued for the Sydney hailstorm. The Australian Weather Bureau had been expecting a storm that would probably produce small hailstones but when it failed to occur by 3.30 p.m., they downgraded the probability of it hitting the city at all. Forecasters expected that the upper winds would steer any thunderstorms from the south of Sydney to the north-east and out to sea. They never envisaged that any thunderstorms that might occur would produce such severe weather. The storm had been drifting out to sea but caught the Australian Weather Bureau by surprise when it suddenly cut inland.

All units of the State Emergency Service were sent out to assess the disaster situation and to start the necessary repairs. Several days into the storm clean-up, a windstorm hit the area, bringing rain and 100 km/h plus winds that damaged some of the emergency repairs.

4. CONCLUSION

The 1990s have seen an increase in the cost of natural disasters resulting from extratropical storm activity, both in terms of financial costs and human lives, despite improvements in risk forecasting. While El Niño and other phenomena may intensify weather conditions, the greater problem may be that more people are living in vulnerable areas and take insufficient precautions despite great advancements in public safety warnings. In the past decade, there have been more natural disasters that have caused at least US $1 billion in damages than in any previous decade. In the past year alone, the world's economy has registered over an estimated US $89 billion in losses from natural disasters, while claiming over 32 000 lives.

The impacts from many storms would have been much greater had they not been so well forecast. Using computer models, many storms can be predicted well ahead of time, helping to mitigate the impacts. The accuracy in forecasting has improved significantly over the years. There is now the potential to predict storms well ahead of time, helping to mitigate the impacts. The quality of a 48-hour forecast in 1999 has surpassed that of the 36-hour forecast in 1990. As well, today's meteorologists are now issuing 120-hour forecasts with the same accuracy as the 96-hour forecasts from the beginning of the decade.

Rescue and relief operations launched around the world have been impressive and greatly contributed to reducing the effects of severe storms.

REFERENCES

Abramovitz, J.N., Dunn, S. November 11, 1998: *Record year for weather-related disasters*, Worldwatch Institute. <http://www.worldwatch.org/alerts/981127.html>

Brooks, G.R., Lawrence, D.E.: *Geomorphic effects and impacts from July 1996: Severe flooding in the saguenay area, Quebec*, Natural Resources Canada. <http://sts.gsc.nrcan.gc.ca/page1/geoh/saguenay/saguenay.htm>

Bureau of Meteorology, 1999: *Report by the director of meteorology on the bureau of meteorology's forecasting and warning performance for the Sydney hailstorm of 14 April 1999*. Melbourne, Australia: Commonwealth of Australia.

Crowther, H.G.: *Tornadoes*. Weatherwise February/March 1995. pp. 43-51.

Discovery Channel Online. April 15, 1999: *Hailstorm Batters Sydney*, Discovery Channel Online. <http://www.discovery.com/news/earthalert/990412/index/hail_index.html>

Environment Canada. July 31, 1998: *Quebec's torrential rains July 18 to 21, 1996*, Environment Canada. <http://www.qc.ec.gc.ca/atmos/saguenay/indexe.html>

Environment Canada. April 16, 1999: *Ice Storm '98*, Environment Canada. <http://www1.tor.ec.gc.ca/nwsd/OtherPub/ice_storm/index_e.cfm>

Environmental Adaptation Research Group, Environment Canada and The Institute for Environmental Studies, University of Toronto. 1997: *Coping with natural hazards in Canada: scientific, government and insurance industry perspectives*. The Round Table on Environmental Risk, Natural Hazards and the Insurance Industry. Toronto, Canada.

Gaddy, S.G. April 21, 1995: *The Palm Sunday tornado outbreak of 27 March 1994*, Penn State. <http://www.ems.psu.edu/~diercks/gaddy.html>.

Hales, John E. and Michael D. Vescio. 1996: *The March 1994 tornado outbreak in the Southeast U.S.: The Forecast Process from an SPC Perspective*. San Francisco, California: 18th AMS Conference on Severe Local Storms.

Le Comte, D.: *...and around the world*. Weatherwise, February 1991. pp. 13-15.

Le Comte, D. : *Highlights around the world*. Weatherwise, February/March 1993. pp. 14-17.

Le Comte, D.: *Highlights in the United States*. Weatherwise, February/March 1994. pp.12-17.

Le Comte, D.: *Going to extremes: 1995 was wild and woolly for the United States*. Weatherwise, February/March 1995. pp. 14-17

Le Comte, D.: *1996 Weather highlights around the world*. Weatherwise, February/March 1997. pp. 25-27.

Le Comte, D.: *Weather around the world*. Weatherwise, March/April 1999. pp. 29-33.

Lott, N., Sittel, M. 1995: *A California cloudburst*, National Oceanic and Atmospheric Administration. <http://www.ncdc.noaa.gov>.

Macey, R. 1999, April 15: *Hailstorm's sudden blast takes bureau by surprise*. The Sydney Morning Herald.

United Nations Disaster Assessment and Coordination Team (UNDAC)/UN Inter-Agency Mission, 1998: *1998 Floods in the People's Republic of China*. World Health Institute. Geneva, Switzerland.

Williams, J.: *The great flood*. Weatherwise February/March 1994. pp. 18-22.

World Meteorological Organization, 1995: *The Global Climate System review: Climate System Monitoring June 1991–November 1993*. Geneva: World Meteorological Organization.

SEVERE LOCAL STORMS

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ABSTRACT

Severe weather associated with thunderstorms (tornadoes, hail, high winds, and flash floods) is reviewed with emphasis on the processes that are responsible. The basis for forecasting severe thunderstorms is reviewed. The parts of the world that are most vulnerable to various kinds of severe weather and the nature of the threats are described. The current state of the climatology of severe thunderstorms and problems and importance of improving climatological information are described. The lack of high-quality climatological information makes it very difficult to determine differences in event occurrence during different periods of the El Niño-Southern Oscillation (ENSO) in most of the world and almost impossible to detect changes associated with global climate change. It is argued, however, that the threats from severe thunderstorms are generally underestimated in many parts of the world.

In general, the effects of severe local storms are concentrated in a small number of events. Death tolls and damage in “average” years are typically smaller than the totals from individual events in other years. As a result, maintaining public awareness and preparedness activities is difficult since the threat of rare, extremely damaging events, is small at any individual location and time.

1. INTRODUCTION

Severe weather associated with thunderstorms affects almost all of the planet and represents a significant threat to life and property in many locations. The definition of what is considered “severe” depends on operational forecasting considerations that vary from country to country but, typically, includes phenomena such as tornadoes, large hail (usually of diameter at least approximately 2 cm), strong convective wind gusts (usually approximately 90 km hr^{-1} or more), and extremely heavy precipitation associated with flash floods (frequently 50 mm hr^{-1} at a single location). Criteria associated with heavy precipitation vary from country to country and, in some nations, even within regions. In the USA, for instance, flash flooding is not considered a severe thunderstorm event, and in Canada the objective definition of heavy precipitation is different in different regions.

Increasing population and increased dependence of society on complex infrastructure have led to an increased exposure and threat from severe local storms. This increased exposure has been counterbalanced by an increasing awareness of the threats and improved scientific understanding and technology that allows for better anticipation of the threats. These opposing forces make changes in the actual effects difficult to ascertain, especially in developing countries.

In this paper, we will briefly describe the nature of the various threats and areas of vulnerability and efforts to prepare for and forecast them. Because the greatest efforts to measure the occurrence of severe weather and forecast it have, historically, occurred in North America and particularly in the USA, the greatest focus will be on that geographic region. However, where possible, some indication of the threats in other areas will be given (e.g., Figure 1).

2. NATURE OF THREATS

2.1 TORNADOES

Tornadoes have been observed on every continent except Antarctica although they are most common in North America, particularly the Great Plains of the USA (Fujita, 1972, 1973; and see Altinger de Schwarzkopf and Rosso, 1982; Peterson, 1992; Dessens and Snow, 1989; Zixiu *et al.*, 1993; Dotzek *et al.*, 1998; Hanstrum *et al.* 1998 for details of many individual countries.) Maps of events and threats ranging from worldwide (Figures 2 and 3) to continental (Figure 4) and for individual countries or regions (Figures 5-8) have been produced. Increased efforts to collect information about tornadoes in North America have led to an increase in the number of reports, with an average of 1 200-1 400 tornadoes reported annually in the USA in recent years, compared to only 600-700 just 50 years ago. Climatologies of tornado occurrence in the USA have identified the temporal and spatial structure of the threat (e.g., Kelly *et al.*, 1979; Brooks 1999) (Figure 9). Reported property damage, adjusted for inflation, has also increased in that time. It is important to note that the number of strong and violent tornadoes reported has increased at a much slower rate and the annual death toll in the USA has dropped considerably during that time (Figure 10). While individual tornadoes producing 40 or more fatalities used to occur in the USA on an almost annual basis, none has occurred in the last 20 years. The decrease in fatalities has been the result of many factors, including improvements in our scientific understanding of the kinds of thunderstorms that produce the strongest tornadoes and the environmental conditions in which they form, improvements in the technology to detect tornadic storms, and an aggressive program to communicate information about weather conditions and preparedness (Doswell *et al.*, 1999).

Basic research over a period of nearly 40 years has improved our understanding of tornadic storms (Church *et al.*, 1993). In the early 1960s, Browning (1964) identified a class of storm now known as a supercell, which rotates throughout its depth (Rotunno, 1993). Almost all supercells produce some kind of severe weather and it is believed that almost all strong and violent tornadoes come from supercells (Doswell and Burgess, 1993). Investigations of radiosonde observations have identified characteristics of the environments in which tornadic storms form (e.g., Darkow, 1969; Schaefer and Livingston, 1988; Davies and Johns, 1993; Brooks *et al.*, 1994a). These characteristics can then be used to help in forecasting situations in which tornadoes are likely. Further, studies of the observations and numerical modelling of thunderstorms (e.g., Weisman and Klemp, 1982, 1984) have led to conceptual models of the formation of tornadoes (Doswell and Burgess, 1993; Brooks *et al.*, 1994b) that have focused attention on what information is important to consider in tornado forecasting and warning situations.

The use of radar and, in particular, deployment of operational Doppler radars, allowing for the estimation of winds within thunderstorms, has led to large improvements in warnings for tornadoes in the USA. Identification of significant features in radar reflectivity and velocity patterns, associated with tornadic thunderstorms, provides operational weather forecasters with guidance about storms that are likely to produce tornadoes (Burgess and Lemon, 1990). Lead times for warnings for tornadoes have increased from an average of almost zero to more than ten minutes during the last decade.

Preparedness efforts have grown in the USA since 1925. Studies of the effects of tornadoes on structures and human beings have led to general safety advice about the construction of tornado-resistant structures and where people should go in case of the approach of a tornado. (The basic advice can be summarized as “getting as low as possible in as small a room as possible in the center of a well-built building, with as many solid walls between people and the tornado as possible”). Storm “spotters” are trained to identify important features of potentially tornadic thunderstorms and communicate that information to civil defence and National Weather Service personnel (Doswell *et al.*, 1999). Warnings of tornadic storms are communicated via special weather radios, broadcast media and in many areas, via civil defence sirens.

The results of these efforts can be seen in the effects of the 3 May 1999 Oklahoma City area tornado. It destroyed more homes (perhaps up to 8 000) than any tornado in US history and may well have produced the largest area of violent tornado damage in a heavily populated region ever recorded. Despite that, only 38 fatalities were associated directly with the tornado. When the long-term changes in death rates due to tornadoes and the relationship between property damage and fatalities are considered, estimates can be made of the number of fatalities that would have occurred in the absence of improvements in the overall system. Both techniques [use of historical death rates (Figure 11) and damage/death relationships (Figure 12)] yield estimates of more than 600

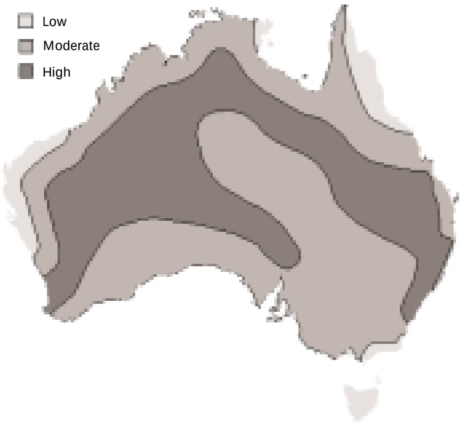


Figure 1: General description of overall severe weather threat in Australia (Australian Bureau of Meteorology).

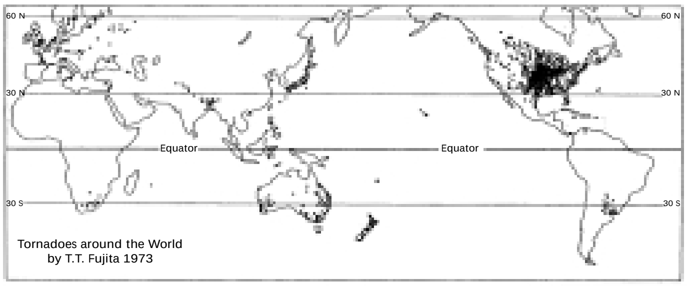


Figure 2: Reported tornado locations around the world (Fujita, 1973).

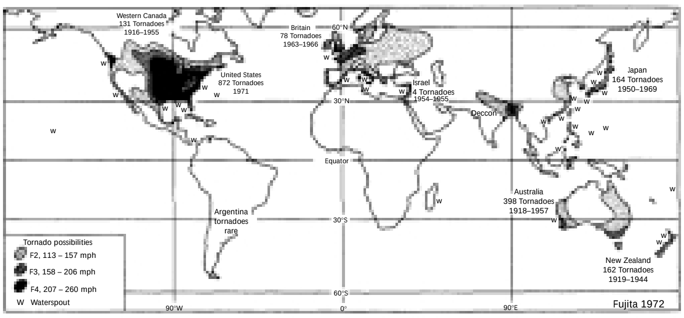


Figure 3: Estimate of maximum tornado damage around the world (Fujita, 1972).

Figure 4: Reported locations of tornadoes in Europe from the end of World War I until 1980 (Peterson, 1982).

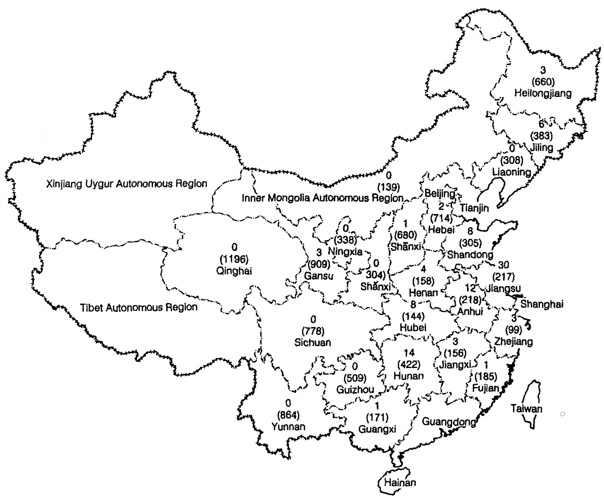


Figure 5: Reported number of days with tornadoes in China by province from 1971-1991. Numbers in parentheses are number of days with hail during period. (Zixiu *et al.*, 1993).

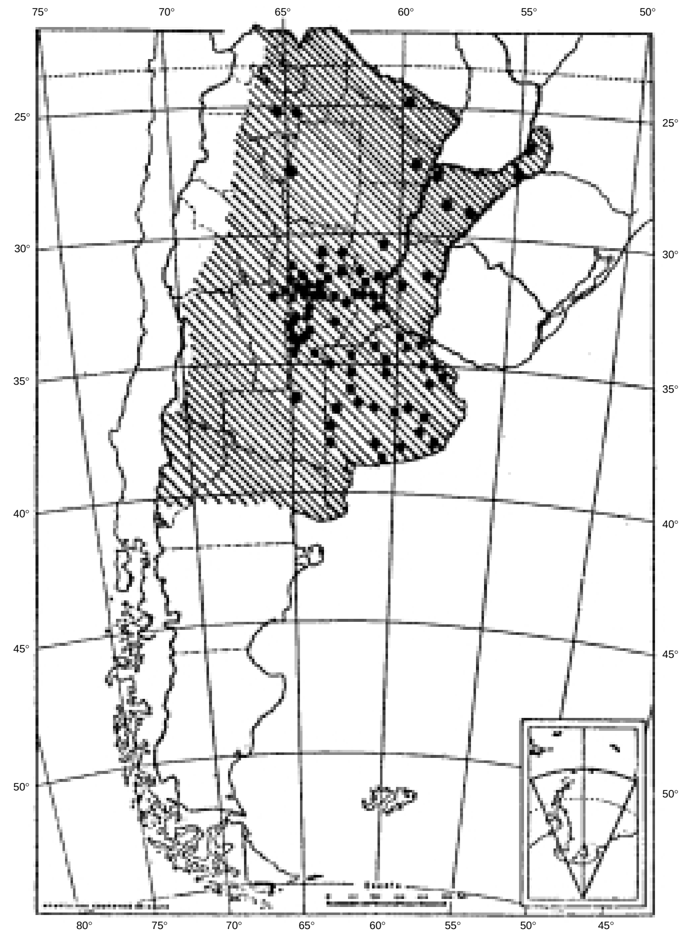


Figure 6: Reported locations of tornadoes in Argentina from 1930-1979 (Altinger and Schwarzkopf and Rosso, 1982).

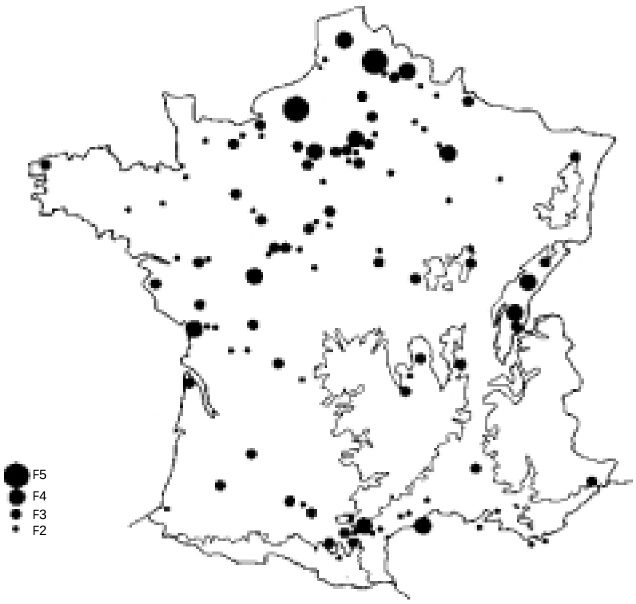


Figure 7: Reported locations of significant tornadoes in France from 1680-1989 by damage evaluated according to the Fujita scale (Dessens and Snow, 1993).

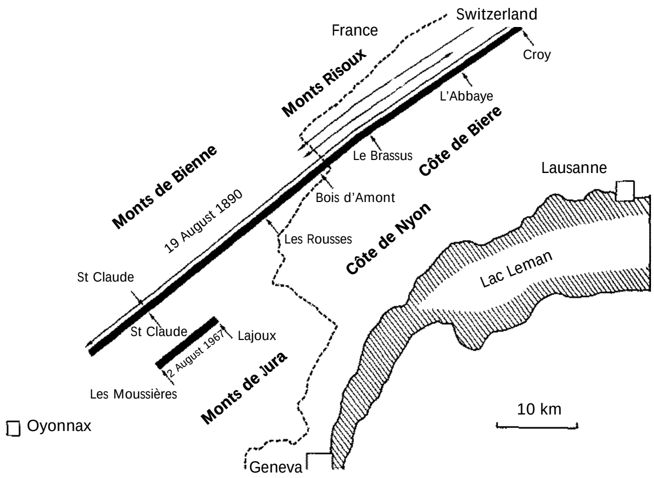


Figure 8: Approximate damage paths of tornadoes north of Geneva, Switzerland from 1680-1989 (Dessens and Snow, 1993).

fatalities in the Oklahoma City event for a pre-warning/preparedness-era tornado similar to the one that occurred in May (Doswell *et al.* 1999). In particular, there were no fatalities between the ages of 4 and 24 (Figure 13). Given the long-term record of deaths by age in tornadoes, the probability of zero deaths in that age group is approximately 1 in 5 000. It seems likely that education about safety in schools has been very successful in preparing young people to know what to do in threatening weather situations in that area of the USA.

The rarity of tornadoes in other regions of the world does not mean that the effects are small when events occur there. Landfalling tropical cyclones often produce tornadoes (McCaul, 1993; Zixiu *et al.*, 1993). Historically, devastating tornadoes have struck Europe approximately once every 20 years (Wegener, 1917; van Everdingen, 1925; Peterson, 1982; Dessens and Snow, 1989, 1993). In the last 20 years, individual tornadoes with hundreds of fatalities have occurred in Russia, northeast of Moscow, and in Bangladesh. It is perhaps significant that the largest events have produced fatalities of the same order of magnitude as the largest death tolls in US history and the “pre-warning/preparedness-era” Oklahoma City tornado. While it seems that strong and violent tornadoes are much less common in other parts of the world compared to the USA, it also appears likely that

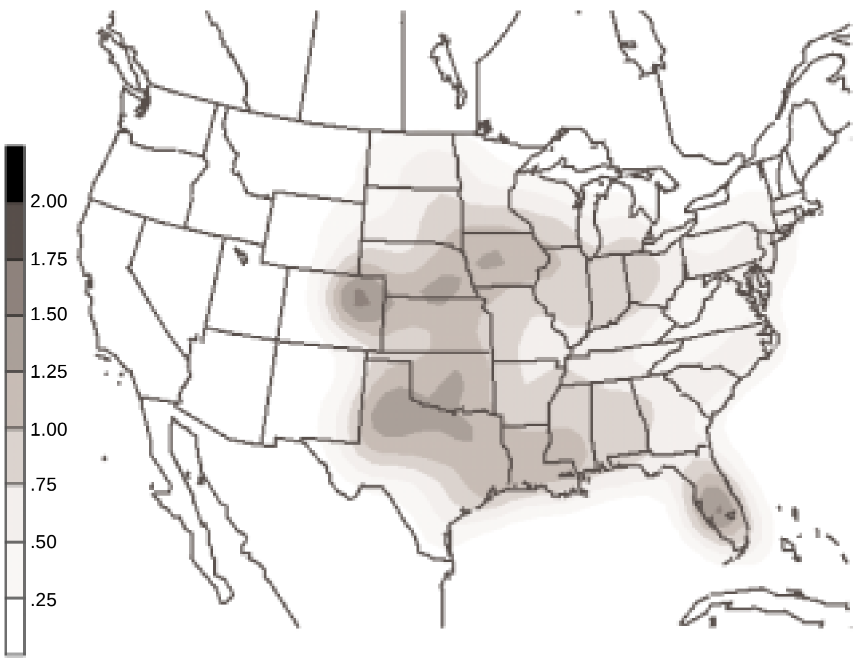


Figure 9: The mean number of days per year with a tornado touching down within 40 km of any location in the United States based on data from 1980-1994 (Brooks, 1999).

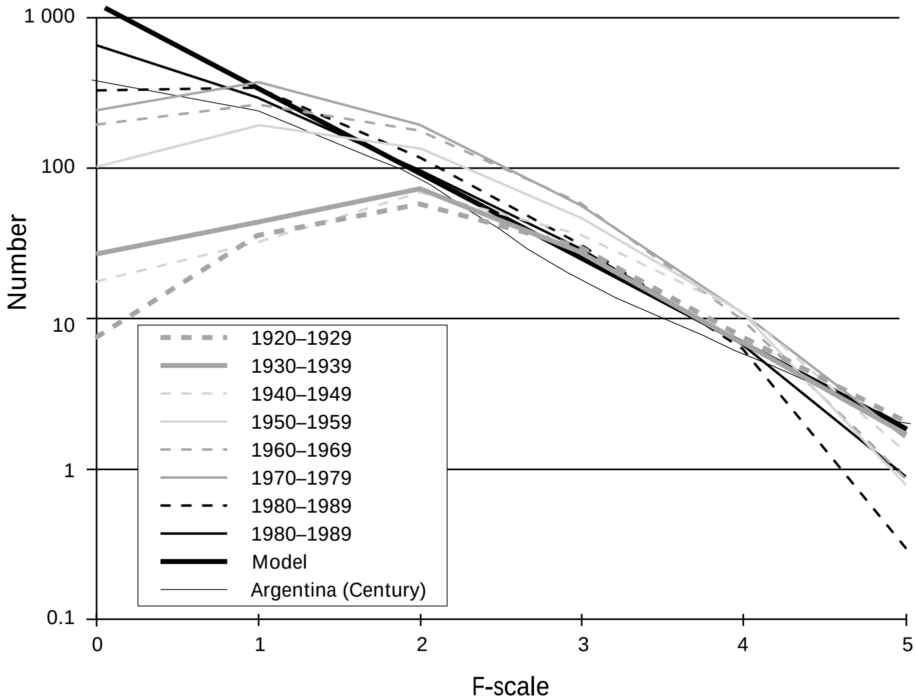


Figure 10: Mean annual number of tornadoes reported in the USA by damage rating per decade since 1920. A simple statistical model estimating the 'true' number of tornadoes expected per year is given in the thick black line (model). For comparison, the distribution of tornadoes in Argentina per 100 years is included. (Based on data of Altinger de Schwarzkopf and Rosso (1982) for 1930-1979.

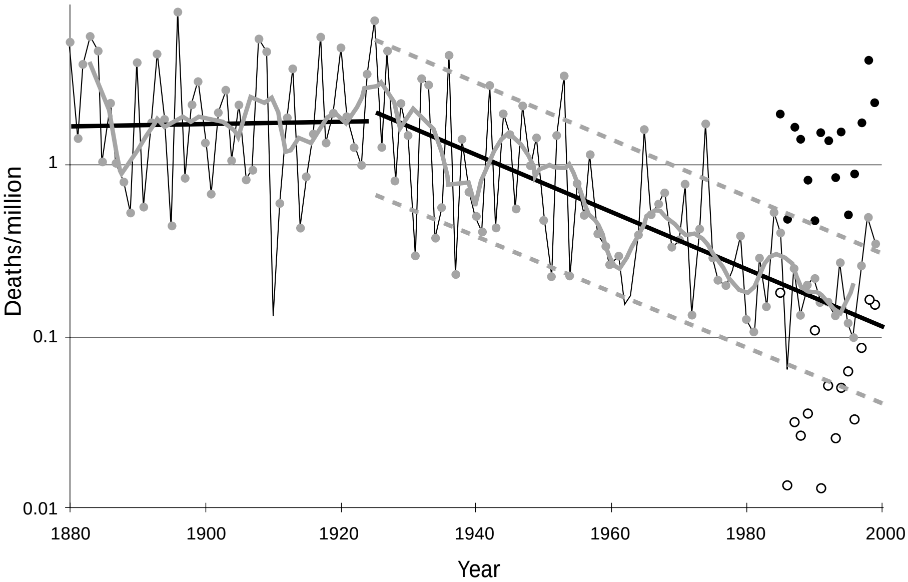


Figure 11: Annual death rates from tornadoes per million people in the USA from 1880 to the end of June 1999 on a logarithmic scale. Raw data shown by the dots, with light (linear fit) smoothing of data shown by the flowing thick median line. The dotted lines indicate 10th and 90th percentiles of annual death rates since 1925. The blank circles show death rates for residents of mobile homes since 1985 and the filled circles represent permanent homes.

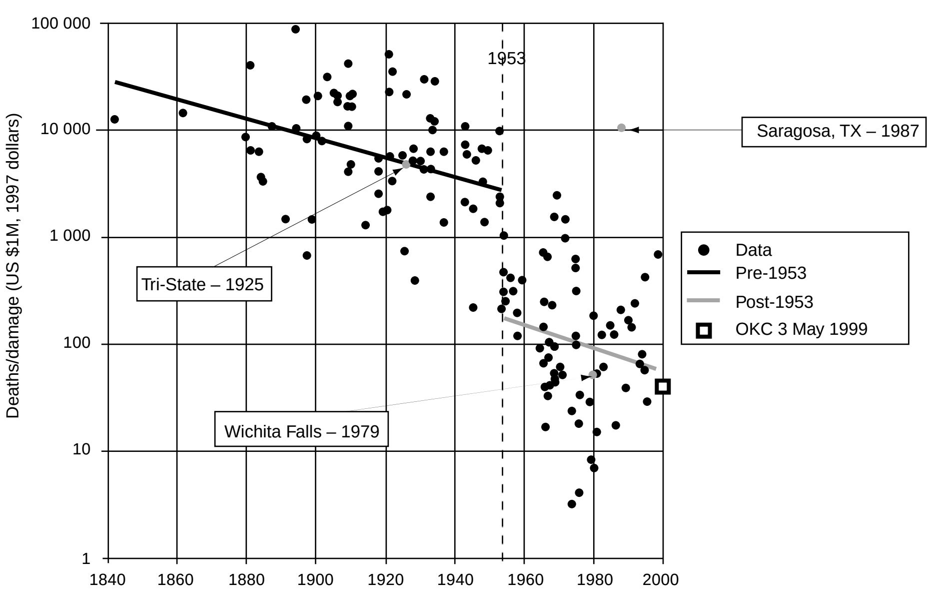


Figure 12: Rates of deaths in major US tornadoes per millions of dollars of damage (inflation-adjusted) since 1840. Linear fits to data in period before (after) 1953, when warning and preparedness activities began, shown by the darker (lighter) line. The black square shows the 3 May 1999 Oklahoma city tornado (adapted from Doswell *et al.*, 1999).

tornadoes are vastly underreported in the rest of the world. The prime evidence for this is that the majority of reported tornadoes in many parts of the world are fatality-producing events or are especially newsworthy (such as the 1998 tornado in Umtata, South Africa, while the South African President was visiting the town). This situation is similar to that in the USA in the mid-19th century when only approximately 25 tornadoes per year were reported. In some parts of Europe, such as Finland (J. Tettinen, personal communication), tornadoes were almost never reported until the last few years, when increased public attention has led to increased reporting.

2.2 HAIL

The exact definition of the nature of severe hail is troublesome. For some agricultural interests during certain periods of the year, even 1 cm diameter hail may be devastating. For urban areas, it may take much larger hail, say 4 cm in diameter, to cause problems. The distribution of regions prone to these levels of threat is very different. The smaller limit occurs in much of the temperate world during the warm season (Figure 14). Larger hail is typically limited to the central part of North America (Kelly *et al.*, 1985) and regions near major mountain ranges in the rest of the world (e.g., the Himalayas and Alps [Houze *et al.*, 1993]). It has been suggested that extremely large hail is much more likely in supercell thunderstorms than in “ordinary” thunderstorms (Rasmussen and Blanchard, 1998). This is consistent with the observed distribution of tornadoes, presumably associated with supercells, in the central part of the USA. The lack of a relationship when hail of any size is considered has been pointed out for China by Zixiu *et al.* (1993). They show that the frequency of hail is maximized in the high plateau regions of western China (Figure 15), while tornadoes are more common in the eastern part of the country, particularly in the Yangtze River valley (Figure 5). The high plateaus and other regions downwind of mountains may produce large hail because of the steep tropospheric lapse rates that develop as air comes over mountains.

Unfortunately, observations of hail have not been consistent through the years. In the USA, the number of reports of severe hail (approximately 2 cm or larger) has increased by an order of magnitude in the past 30 years. Most of the increase has been in the smaller end of the severe range. As a result, attempts to develop a climatology based on the reports face significant challenges. Researchers are faced with the dilemma of having small sample sizes or an non-homogeneous record (Figure 16, Brooks, 1999). Efforts to use insurance losses are complicated by the issue of what causes the losses (agricultural vs. urban interests) and the temporal non-homogeneity of the insured base. Nevertheless, in the last 15 years, extremely large losses (greater than US $500 million) have been associated with hailstorms in areas such as Munich in Germany, and Denver (Colorado) and the Dallas-Fort Worth region (Texas) in the USA.

2.3 DAMAGING CONVECTIVE WIND GUSTS

Strong winds associated with thunderstorms are a common feature. Little has been done to document their climatological occurrence (Figure 17) until recent years (e.g., Kelly *et al.*, 1985, Johns and Hirt, 1987, Brooks, 1999) although they are almost certainly the most common severe weather event. Damaging straight-line thunderstorm wind gusts are usually associated with cold air outflow as the downdraft reaches the ground. Fujita and Byers (1977) were the first to use the term downburst to describe very strong wind gusts produced by thunderstorms. Factors that influence the generation of damaging wind gusts at the surface include: negative buoyancy enhanced by evaporative cooling within unsaturated air, precipitation loading within the downdraft, and downward transfer of horizontal momentum by the downdraft (e.g., Kamburova and Ludlam, 1966). Again, aspects of these processes are dependent on stormscale microphysics including drop size distribution and liquid water content per unit volume, which cannot be determined from standard observing systems.

Strong winds can occur in a variety of situations (for reviews, see Doswell, 1994 and Wakimoto, 1998). They can be associated with small, short-lived downdrafts and even when they are relatively weak (say less than 25 m s^{-1}), they can be

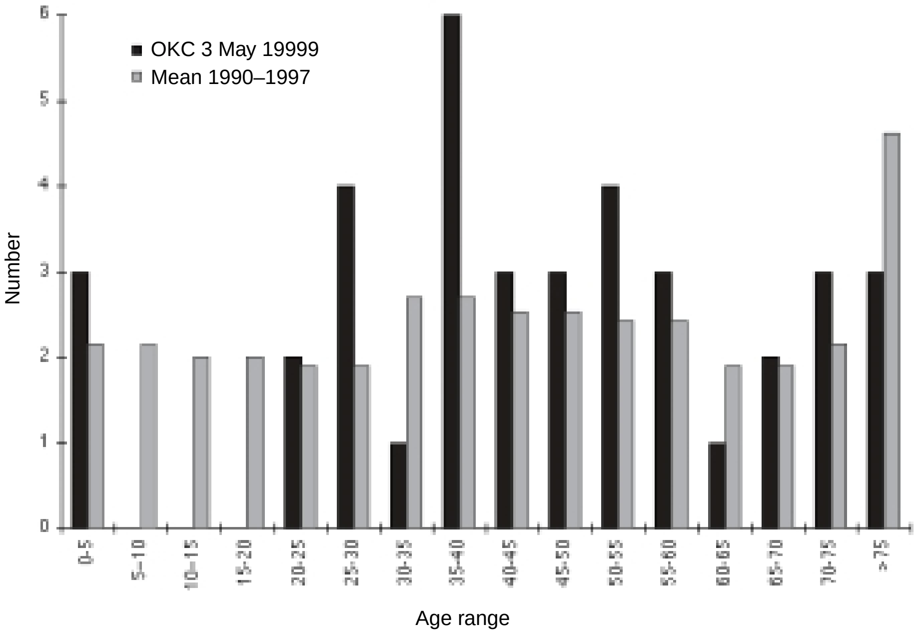


Figure 13. Number of deaths by 5-year age bins on 3 May 1999 during the Oklahoma City tornado and mean number of deaths expected for number of fatalities in tornado (based on all tornadoes) in the USA from 1990-1997.

a significant hazard to aviation (Fujita and Byers, 1977; Fujita and Caracena, 1977; Caracena *et al.*, 1989). Considerable effort has been expended in the last twenty years to decrease commercial aircraft accidents due to thunderstorm downdrafts. Radar detection and education of the aviation industry about the threats seems to have limited the number of accidents in the last decade, after several occurred from the early 1970s through the mid-1980s.

Brooks and Doswell (1993) modelled numerically a situation in which a supercell thunderstorm can produce a relatively wide (10–20 km), long (50–100 km) swath of extremely high winds (50 m s^{-1}). The winds occur in association with high-precipitation supercells (Moller *et al.*, 1990) when the storm-relative flow at mid-levels is very weak. Such storms have been observed (Cummine *et al.* 1992; Smith 1993; Conway *et al.*, 1996) and have caused significant damage over areas up to 2000 km^2.

Even larger areas can be affected by high winds when organized systems of thunderstorms occur. In the USA, widespread convective wind events are sometimes referred to as *derechos* (Johns and Hirt, 1987). They occur in association with mesoscale convective systems, which are composed of a number of individual thunderstorms. Often, they are arranged as a squall line, producing a wide area of high winds with new convective cells initiated on the leading edge of the outflow from earlier cells. The system may maintain itself for many hours, provided sufficient low-level moisture and mid-level unstable air can be found as the system moves along.

2.4 FLASH FLOODS

Flash floods are the most widespread severe local storm phenomenon associated with large loss of life. They occur all over the world (e.g., Sénési *et al.*, 1996; Li *et al.*, 1997; Bauer-Messmer *et al.*, 1997; Doswell *et al.*, 1998), especially in regions of complex terrain. They are the most difficult to forecast, in part because they involve both meteorological and hydrological aspects (Maddox *et al.*, 1978, 1979; Doswell *et al.*, 1996). Determining their effects is complicated further by interactions with people and buildings (Petersen *et al.*, 1999). If a flash flood occurs in a location where it doesn’t impact societal structures, it is unlikely to be reported. On the other hand, relatively minor precipitation events may produce significant flooding if antecedent conditions exacerbate the flooding, as occurred in the Shadyside, Ohio flood of 1990 with saturated soils (Doswell *et al.*, 1996) or in the Buffalo Creek, Colorado flood of 1996 when a forest fire cleared vegetation from the area a couple of months before the rain event.

Great loss of life has been associated with flash flooding, even in developed nations. Recently, a campground in Biescas in the Spanish Pyrenees was flooded

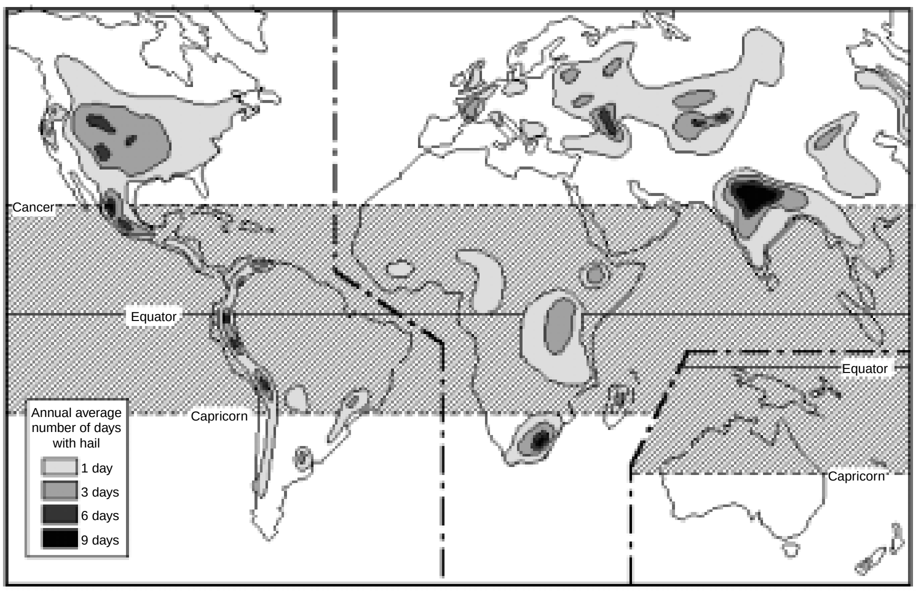


Figure 14. Number of days with hail per year around the world. Hatched region indicates tropics. (Adapted from Munich Re, 1984).

Figure 15. Number of days with hail per year in China. (Zixiu *et al.*, 1993).

and caused more than 80 deaths. In 1998, 11 hikers were killed by a flash flood in a "slot canyon" in northern Arizona when rain from a storm tens of km away from the canyon was funnelled into the canyon. The three biggest convective-weather death toll single events in the USA (with the exception of aircraft crashes) in the last 40 years have all been flash floods (235 fatalities in Rapid City, South Dakota in 1973, 145 fatalities in Big Thompson Canyon, Colorado in 1976, and 77 fatalities in Johnstown, Pennsylvania in 1977). Death tolls in developing countries are frequently difficult to estimate.

Flash floods are distinguished from riparine floods by the extremely rapid rate of rise of river levels. While riparine floods may have river stages rising by tens of cm per day, flash floods are associated with river stages rising by tens of cm per hour or, in extreme cases, per minute. Because of their very small basins, small streams can produce flash floods as they can carry up to 100 times their normal capacity in such floods. Even in the USA, this can cause problems in operational practice since these small basins may not be mapped as well as larger basins, particularly for comparison to radar estimates of precipitation. As a result, forecasters may be unaware of the nature of the threat even if accurate estimates of rainfall are available.

Detection of heavy precipitation is also complicated. Direct estimates from radar can be complicated by the presence of hail (e.g., Zrnic *et al.*, 1993) or by intervening

Figure 16. Same as Figure 9 except for hail at least $\frac{3}{4}$ inch (19 mm) in diameter.

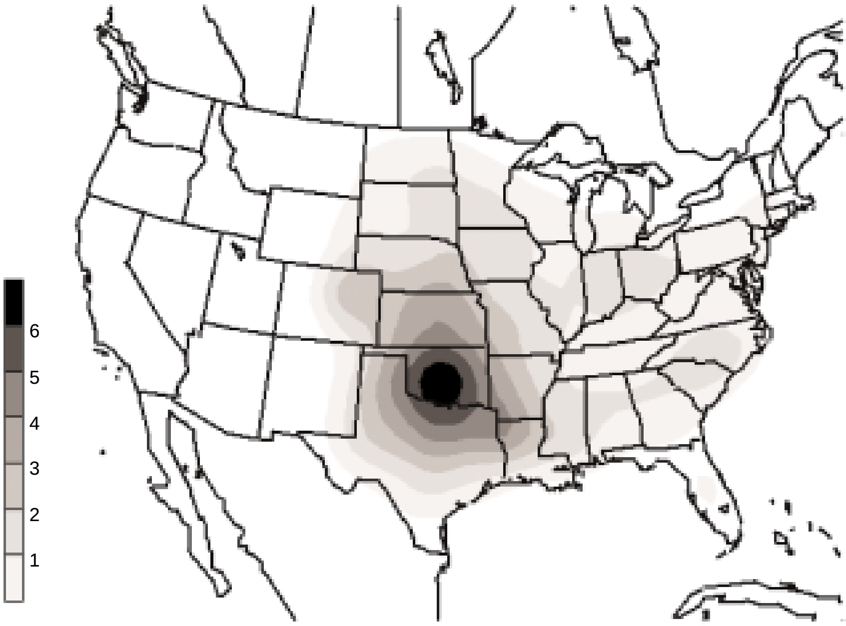
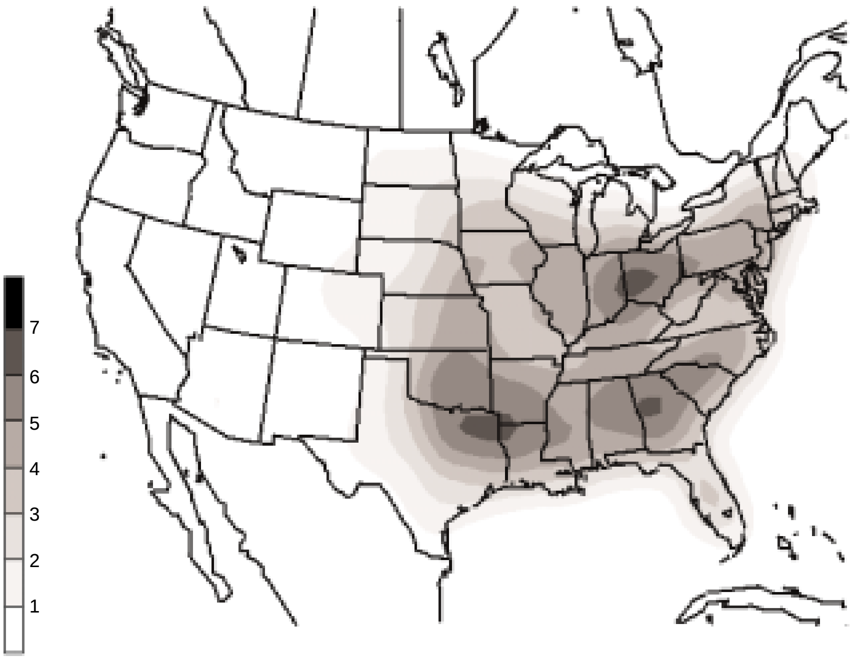


Figure 17. Same as Figure 9 except for thunderstorm wind gusts at least 50 kts (25 m s^{-1}).



radar echoes and signal processing problems (e.g., Ryzhkov *et al.*, 1997). Polarimetric estimates (Jameson, 1991) have shown some promise to improve the situation but their use is still in the experimental stage. Even with good radar estimates, the use of rainfall estimates for actual heavy precipitation calculations can be complicated by hydrological model uncertainties (Vieux and Bedient, 1998).

The threat from flash floods has increased in some regions because of the increased use of mountainous regions for recreation. Excellent examples include the Big Thompson canyon (Colorado) and Biescas floods (Spanish Pyrenees). Public response to flash flood forecasts is frequently poorer than for other weather hazards forecasts, such as for tornadoes. Most people have experienced heavy rain events and fail to realize until it is too late that what they were experiencing was more dangerous than they imagined. Further, heavy rain often makes travel difficult by washing out roads and bridges, which makes escape and rescue difficult.

3. FORECASTING SEVERE LOCAL STORMS

In regions affected most frequently by severe local storms, the operational prediction of severe weather has developed into a specialized sub-discipline of weather forecasting, over the past 50 years. In most countries, such as Canada, China, and the United Kingdom, regional or provincial weather centres issue forecasts and warnings for all severe local storms within their geographic area of responsibility. In the USA, however, responsibility for the prediction of most severe local storms (tornadoes, large hail, damaging convective wind gusts) has, since the early 1950s, been centralized at a single national center of expertise (now called the Storm Prediction Center). The actual detection and subsequent issuance of short-term warnings for individual severe local storms is handled by local Weather Forecast Offices (WFO) whose areas of responsibility typically cover relatively small parts of one or more states. For flash flood events in the USA, the WFOs issue watches and warnings, aided by guidance from two national centres (the Hydrometeorological Prediction Center and the Storm Prediction Center).

The concept known as “ready-set-go” has been applied to the forecast and warning program in the USA. This is based on sociological studies that have determined that most people will not go to a place of safety at the first mention of an approaching severe local storm but will, instead, seek additional information to confirm the existence of a hazardous weather threat. Thus, a series of forecast products are communicated to emergency preparedness managers and the public starting with outlooks for possible severe storms covering relatively large areas, that are issued 1–2 days ahead of time. If the severe local storm threat increases and storms are likely to develop over more confined regions, severe thunderstorm or tornado watches are issued with temporal/spatial characteristics of approximately 6 hr/40 000 km^2. When a severe local storm is indicated by radar or reported by storm spotters, a warning is issued with approximate temporal/spatial characteristics of 1 hr/one county.

In its simplest terms, the prediction of severe local storms must first begin with the determination of thunderstorm potential. In general, this requires three ingredients: 1) sufficient moisture in the lower and/or middle troposphere; 2) lapse rates that are steep enough to result in substantial Convective Available Potential Energy (CAPE); and 3) sufficient lifting of the parcel for it to reach the Level of Free Convection (LFC) so it can become positively buoyant with respect to the ambient environment. The upward motion needed to release the instability is typically mesoscale in character (Doswell, 1987), and most often involves low-level convergence along air mass discontinuities such as fronts, drylines, convective outflow boundaries, sea- and lake-breeze fronts and narrow zones of differential heating associated with edges of cloud shields. Once it is determined that thunderstorms are possible, the forecaster can then examine the probability of severe thunderstorm development. Typically, the forecasting process involves aspects of climatology, synoptic/mesoscale pattern recognition and meteorological parameter assessment. The first two components are closely linked, since pattern recognition procedures need to be periodically updated as the apparent climatology of severe local storms is subject to changes. The final process (parameter assessment) is probably changing the most rapidly as advances in technology (e.g., observing systems and computer workstations) and scientific understanding of severe storms and their interaction with the synoptic environment result in new ways to examine convective potential.

The organization and intensity of deep convection is largely determined by two factors: 1) instability or buoyancy; and 2) vertical wind shear. Given that increasing amounts of these two general ingredients are expected to be present, the likelihood of severe local storms increases. However, since the different types of severe local storms appear to result from variations in both synoptic/mesoscale environments and different stormscale physical processes, the prediction process must eventually examine a variety of environmental characteristics in order to assess the most likely type(s) of severe weather that may occur.

3.1 PREDICTION OF TORNADOES

Since the most significant tornadoes are almost always associated with supercell thunderstorms, the operational prediction of tornadoes at this time is largely an exercise in forecasting the likelihood of supercell formation (Johns and Doswell, 1992, Doswell *et al.*, 1993, Moller *et al.*, 1994). In the 1970s, early studies of tornadoes using a prototype Doppler radar indicated that most supercells produced tornadoes. However, experience gained with a much large database from a nation wide network of Doppler radars in the USA over the last decade strongly suggests that only a small percentage of supercell thunderstorms (less than 20 per cent) are associated actually with tornadoes. Thus, an additional task in tornado forecasting involves assessing the probability of tornadic supercell occurrence as opposed to non-tornadic supercell occurrence.

Theoretical (Lilly, 1982; Davies-Jones, 1984), numerical modelling (Weisman and Klemp, 1982, 1984; Brooks *et al.*, 1993, 1994), and observational studies (e.g., Davies-Jones *et al.*, 1990, Johns *et al.*, 1993) have demonstrated the relationship of various measures of vertical wind shear, such as mean shear in the lowest 4-6 km AGL, and storm-relative helicity (a measure of streamwise helicity that can be ingested into the updraft of a thunderstorm), to assess the potential for supercell development. While low-level shear is related to mid-level storm rotation (mesocyclone aloft), it has been suggested that the character of the storm-relative mid-level winds is linked to baroclinic processes associated with low-level rotation in supercell thunderstorms (Brooks *et al.*, 1994). Thus, once it has been determined that supercells may form, forecasters typically examine the strength of the storm-relative mid-level winds, either directly (Mead, 1997, Thompson, 1998) or indirectly using the shear term of Weisman and Klemp‘s Bulk Richardson Number (Stensrud *et al.*, 1997), to obtain information on the potential for tornadic supercells to develop.

Tornadoes can also develop in association with non-supercell thunderstorms, although these tornadoes are typically weak and do not last very long. This class of tornadoes is thought to develop when horizontal shear lines become coincident with convective updrafts, and the horizontal vorticity along the shear line is tilted and stretched vertically (e.g., Brady and Szoke, 1988, Wakimoto and Wilson, 1989). These tornadoes typically occur in weakly sheared environments along low-level boundaries associated with sea breeze fronts, convective outflows, and terrain-induced convergence lines. Reliable forecast techniques for non-supercell tornadoes have not been established at this time.

3.2 HAILSTONE DEVELOPMENT

The physics of hail development is quite complex, involving a variety of factors that relate to updraft strength, storm-scale wind structures and circulation, cloud microphysics and environmental effects on hailstones as they fall toward the ground. Many of the details needed to quantify these processes occur on scales that are not observed, which contributes to the difficulty in making accurate hail forecasts. Of the factors mentioned, simple measures of updraft strength and environmental effects related to the depth and mean temperature of the melting layer between the hailstones freezing level and the ground have been typically applied to hail size algorithms through the years (e.g., Fawbush and Miller, 1953, Foster and Bates, 1956, Prosser and Foster, 1966). The magnitude of the potential buoyancy (CAPE) has been used to infer updraft strength, while the height of the 0°C wet-bulb temperature has been related to the likelihood of large hail reaching the ground (Miller, 1972). Since non-hydrostatic pressure perturbations have been shown to have a notable effect on updraft strength in supercells (Brooks and Wilhelmson, 1993; McCaul and Weisman, 1996), it is not surprising that these techniques have proven to be ineffective in reliably predicting hailstone size (Doswell *et al.*, 1982). More recent hail size algorithms have been proposed (e.g., Moore and Pino, 1990), but additional research is needed to test the validity of these techniques using large data samples thoroughly.

3.3 DAMAGING CONVECTIVE WIND GUSTS

It has been observed that strong convective wind gusts can be generated in different types of synoptic environments. Environments characterized by weak forcing for upward vertical motion typically display weak wind shear, but it is not uncommon for thunderstorms in these environments to produce strong wind gusts. In most cases, the vertical thermodynamic structure is critical in providing clues that identify the wind gust potential in weakly sheared environments. Small-scale downbursts called microbursts can be produced where the low-levels are very dry (such as in the arid regions of western USA or northwest China), as well as in regions characterized by very moist low-level conditions (such as in the southeast

USA). In most instances, the convection embedded in weak shear is of a "pulse" nature and lasts for only short periods of time, making forecast and warning operations very challenging. The dry microburst is associated with a deep, dry adiabatic surface-based mixed layer with moisture confined to a layer in the middle-levels (e.g., Wakimoto, 1985). Conversely, the wet microburst tends to develop within a deep surface-based moist layer that contains some dry air aloft, such that the theta-e lapse rate between the surface and middle levels exceeds 20°C (Atkins and Wakimoto, 1991). In most instances microbursts affect only small areas for a short period of time but, on a few occasions, they have been known to produce extremely strong wind gusts in excess of 50 m s^{-1}.

When the vertical shear becomes stronger (on the order of 15–20 m/s in the lowest 6 km) the prediction of damaging wind gusts becomes somewhat more complex since the synoptic pattern and the thermodynamic and kinematic profiles become increasingly important. Observational studies based on radar reflectivity have documented the relationship between bow-shaped convective elements called bow echoes (Fujita, 1978; Przybylinski, 1995) and the occurrence of damaging wind gusts. Bow echoes may occur as isolated thunderstorm cells, or comprise elements of extensive squall lines. When a larger-scale bow echo or a series of bow echoes produce a succession of downbursts over a widespread region, this is termed a *derecho* (Johns and Hirt, 1987).

Derechos can occur at all times of the year in the USA. They were first studied extensively during the warm season when it was determined that they were associated with specific synoptic environments characterized by extreme instability near east-west oriented surface fronts along the southern edge of stronger westerly winds aloft with unidirectional flow above the boundary layer (e.g., Johns *et al.*, 1990). In these scenarios, bow echoes travel rapidly eastward along the surface boundary, occasionally propagating a short distance into the warm sector. The southward extent of bow echo development is usually limited by a capping inversion, so that extensive meridionally oriented squall lines do not form. More recently, *derechos* have been found to also occur during cooler parts of the year in association with energetic baroclinic waves. In these cases, squall lines tend to form along or ahead of the cold front with a series of bow echoes embedded within the line. Potential buoyancy is usually much less in these situations but the winds aloft are quite strong and the overall pattern bears a resemblance to more classic tornado outbreak patterns (e.g, Barnes and Newton, 1986).

Although the climatology and synoptic patterns associated with *derechos* are reasonably well-known (Johns and Hirt, 1987; Duke and Rogash, 1992; Johns 1993), details of meteorological parameters essential for widespread bow echo development are not well established. Weisman (1993) has conducted cloud modelling experiments that suggest that bow echos form in environments with large instability where the vertical shear is strongest in the lowest 2–3 km. However, a recent observational study by Evans (1998) examining proximity soundings associated with more than 70 bow echoes shows a very wide range of buoyancy and shear combinations can support bow echo development, suggesting additional complexity in the prediction of these hazardous convective systems.

3.4 FLASH FLOODS

The forecasting of flash floods involves not only the determination of heavy precipitation falling over the same area, but must also consider hydrologic influences such as topography and land types, as well as antecedent precipitation that affects soil moisture conditions. Thus, the forecaster must be very familiar with terrain features such as canyons and details of river and small stream basins that can enhance the chances of flash floods even during short periods of heavy rainfall rates.

The primary meteorological considerations require examination of processes that result in heavy rainfall rates that are sustained over one area during a given period of time. Chappell (1986) notes that this tends to occur most frequently when quasi-stationary mesoscale convective systems develop and individual storm cells within the MCS track repeatedly over the same area. The ingredients needed to produce moist, deep convection in flash flood situations are similar to those needed for other types of severe storms (e.g., large quantities of moisture, instability, and a lifting mechanism to release the instability), but a key difference often involves special characteristics of the vertical wind profile over a region that results in slow-moving convective cells and/or a quasi-stationary MCS. MCS movement can be thought of as the sum of advective and propagational components, where advection is proportional to the mean wind through a deep tropospheric layer and propagation is associated with the development of new updrafts where the low level moist inflow is maximized (Corfidi *et al*., 1996). When the advective and propagational components are in near balance, a quasi-stationary MCS is likely to develop. Of course, other factors such as precipitation efficiency of the convective cells play a role in the magnitude of the rainfall rate (e.g., Fankhauser, 1988), but the complexity of this process makes it quite difficult to apply in operational forecasting. Numerical guidance often provides little help on the appropriate scale and convective schemes used in such models are sensitive to small changes in their parameters (Spencer and Stensrud, 1998).

A particularly difficult forecast problem occurs when combinations of severe storm effects occur almost simultaneously, such as when tornadoes and flash flooding occur in the same area (e.g, Maddox and Dietrich, 1981, Schwartz *et al*., 1990). This places tremendous pressure on the local forecasters charged with forecast and warning responsibility and on emergency managers responsible for preparedness efforts. In these types of situations, it is not uncommon for storms to produce hail and tornadoes early in their life cycle, then result in flash flood producing rains shortly thereafter when the primary meteorological focus may still be on tornadoes.

The use of an ingredients-based methodology in the forecasting of severe local storms has allowed forecasters to apply scientific findings in a rational and orderly manner. It encourages the understanding of physical processes that can be used to link larger-scale parameters that can be observed to storm-scale processes that result in convectively generated weather hazards. [For more detailed information the reader is encouraged to consult comprehensive review articles on severe local storm forecasting by Maddox *et al*. (1979) Funk (1991), Johns and Doswell (1992), Doswell *et al*. (1993), and Doswell *et al*. (1996).] Although these basic principles were first intended to be used with observational data, they can also be applied to numerical weather prediction model output in order to extend the time range of useful forecasts of severe storms. However, it then becomes important to know the strengths and weaknesses of operational models regarding their ability to predict parameters important to the forecast process (Cortinas and Stensrud, 1995; Weiss, 1996). Mesoscale models are now routinely run in many national weather services around the world and this has resulted in improved predictions of synoptic patterns and meteorological features such as low level jets in the 1–2 day forecast period. However, as the resolution of operational models has increased into the 20–40 km range, we have seen slow improvements in the models ability to accurately forecast the 4-D evolution of thermodynamic profiles, especially water vapour, which is a key component in the forecasting of convection (e.g, Emanuel *et al*., 1995, Weiss *et al*., 1998). This not only reflects the difficulties in properly incorporating physical processes of increased complexity (such as the parameterization of convection) but also is a result of model resolution increasing much faster than the resolution of most observational data sources, so that it is becoming increasingly difficult to both calibrate and validate mesoscale models.

Accordingly, we have seen substantial improvements in the forecasting of severe local storms, especially in the detection/warning phase (e.g., Bieringer and Ray, 1996). In the USA the deployment of Doppler radars and automated radar analysis techniques have allowed forecasters to interrogate potentially severe thunderstorms in ways never before possible (see the June 1998 special issue of *Weather and Forecasting*). Coupled with real-time information from storm spotters, the radar data has given forecasters the ability literally to see the end result on the stormscale of a myriad of atmospheric processes and scale interactions, many of which we do not fully understand. And although our ability to predict the potential for severe storm development up to 2 days in advance has steadily improved over the last decade, limitations in our scientific understanding of processes affecting convective initiation and evolution remain apparent.

4. POSSIBLE RELATIONSHIPS TO EL NIÑO/SOUTHERN OSCILLATION (ENSO)

Unfortunately, the large changes in the reporting database of severe weather make it impossible to determine any influence of the phase of ENSO on the number and severity of most events, particularly in mid-latitudes. Heavy precipitation leading to flash floods in tropical environments is the one exception, where the large-scale changes in the general circulation lead to the enhancement of heavy precipitation, particularly in mountainous terrain of coastal areas of South America when the upward branch of the Southern Oscillation is in the eastern Pacific. Heavy precipitation along the California coast of the USA also increases in El Niño winters, leading to flooding and landslides there. Although connections between severe weather occurrence, particularly tornadoes, in specific regions of the USA have been hypothesized, the small sample size and large temporal changes in overall reporting patterns render those relationships statistically insignificant or, at best, marginally significant.

5. CONCLUDING THOUGHTS

It seems clear that organized systems for documenting the occurrence of severe weather are lacking in many parts of the world. The large changes in numbers of reports in recent years make it difficult to determine the true nature of the threat, particularly for non-tornadic severe weather; this is also also applied to the USA in spite of its having one of the most complete systems. This situation also means that it is effectively impossible to determine changes in severe weather occurrence that might be associated with climatic signals, such as ENSO or global climate change. It is possible that an estimate of the current climatological likelihood of severe weather could be made by the use of meteorological covariates (Brown and Murphy, 1996), where the climatology of well-observed parameters (such as information from radiosonde observations) associated with the occurrence of various kinds of severe weather is created, with the strength of the relationship between the observed covariate and the meteorological event of interest becoming the limiting factor in the estimates of the meteorological event. Conceptually, it should be possible to make estimates of various potential covariates from the relatively high-quality North American database and then apply the covariates to the rest of the world.

Despite imperfect information about the occurrence of severe local storms, the effects of these storms on human populations and societies can be estimated. In developed nations, particularly in North America, rates of fatalities associated with severe local storms have dropped from the level they reached earlier in the century. The declining death rates are associated with improved forecasting and detection of events, improved awareness in the general public and improved communication of meteorological and safety information. Reported property damage has been increasing, although much of this is due to the increased property value. However, increasing populations and recreational activities in vulnerable regions, such as mountainous terrain prone to flash flooding, makes even developed countries exposed to the possibility of disasters with significant loss of life.

Public awareness of severe local storms has been increasing around the world, particularly in developed nations, as a result of improved communication, especially television. It is likely that our understanding of the distribution of threats will improve greatly in the near future. Technological and scientific advances over the last few decades have led to decreases in fatalities from severe local storms in North America. Transfer of those advances to other parts of the world could lead to similar decreases in other parts of the world which are also vulnerable to severe local storms. Even though North America may have the greatest threat from severe local storms, the experience there indicates that the greatest loss of life in tornadoes, for example, occurs in regions where tornadoes are relatively rare. Thus, governmental and societal institutions need to be prepared to respond to rare events in order to avoid catastrophic loss of life.

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REFERENCES

Altinger de Schwarzkopf, M. L., and L. C. Rosso, 1982: Severe storms and tornadoes in Argentina. *Preprints*, 12th Conf. Severe Local Storms (San Antonio, Texas), American Meteorological Society, pp. 59-62.

Atkins, N. T., and R. M. Wakimoto, 1991: Wet microburst activity over the southeastern United States: Implications for forecasting. *Weather Forecasting*, 6, pp. 470-482.

Barnes, S. L., and C. W. Newton, 1982: Thunderstorms in the synoptic setting. *Thunderstorms: A Social, Scientific and Technological Documentary. Vol. 2: Thunderstorm Morphology and Dynamics*. E. Kessler, Ed., NOAA/Environmental Research Laboratories, pp. 109-173.

Bauer-Messmer, B., J. A. Smith, M. L. Baeck, and W Zhao, 1997: Heavy rainfall: Contrasting two concurrent Great Plains thunderstorms. *Weather Forecasting*, 12, pp. 785–798.

Bieringer, P., and P. S. Ray, 1996: A comparison of tornado warning lead times with and without NEXRAD Doppler radar. *Weather Forecasting*, 11, pp. 47-52.

Brady, R.H., and E.J. Szoke, 1988: The landspout — A common type of northeast Colorado tornado. *Preprints*, 15th Conf. Severe Local Storms (Baltimore, Maryland), American Meteorological Society, pp. 312-315.

Brooks, H. E., 1999: Severe weather climatological probabilities. <http://www.nssl.noaa.gov/~brooks/threatanim.html>

Brooks, H. E. and R. B. Wilhelmson, 1993: Helicity and updraft intensity in numerically modelled supercells. *Journal of Atmospheric Science*, 50, pp. 1824-1833.

Brooks, H. E. and C.A. Doswell III, 1993: Extreme winds in high-precipitation supercells. *Preprints*, 17th Conf. Severe Local Storms (St. Louis, Missouri), American Meteorological Society, pp. 173-177.

Brooks, H. E., C.A. Doswell III and R. Davies-Jones, 1993: Environmental helicity and the maintenance and evolution of low-level mesocyclones. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 97-104.

Brooks, H. E., C.A. Doswell III and J. Cooper, 1994a: On the environments of tornadic and non-tornadic mesocyclones. *Weather Forecasting*, 10, pp. 606-618.

Brooks, H. E., C.A. Doswell III and R. B. Wilhelmson, 1994b: On the role of mid-tropospheric winds in the evolution and maintenance of low-level mesocyclones. *Monthly Weather Review*, 122, pp. 126-136.

Brown, B. G. and A. H. Murphy, 1996: Verification of aircraft icing forecasts: the use of standard measures and meteorological covariates. *Preprints*, 13th Conf. on Probability and Statistics in the Atmospheric Sciences (San Francisco, California), American Meteorological Society, pp. 251-252.

Browning, K.A, 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. *Journal of Atmospheric Sciences*, 21, pp. 634-639.

Burgess, D. W., and L. R. Lemon, 1990: Severe thunderstorm detection by radar. *Radar in Meteorology*, D. Atlas, Ed., American Meteorological Society, Boston, MA, pp. 619-647.

Caracena, F., R.L. Holle, and C.A. Doswell III, 1989: *Microbursts: A Handbook for Visual Identification*. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, 35 pp.

Chappell, C.F., 1986: Quasi-stationary convective events. *Mesoscale Meteorology and Forecasting* (P.S. Ray, Ed.), American Meteorological Society, pp. 289-310.

Church, C., D. W. Burgess, R. Davies-Jones, and C.A. Doswell III (Eds.) 1993: *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), Amer. Geophys. Union, 637 pp.

Conway, J. W., K. Hondl, and H. E. Brooks, 1996: The Lahoma ok supercell: A study of non-tornadic vs tornadic mesocyclones. *Preprints*, 18th Conf. on Severe Local Storms (San Francisco, California) American Meteorological Society, pp. 52-56.

Corfidi, S.F., J.H. Merritt and J.M Fritsch, 1996: Predicting the movement of mesoscale convective complexes. *Weather Forecasting*, 11, pp. 41-46.

Cortinas, J. V. Jr., and D. J. Stensrud, 1995: The importance of understanding mesoscale model parameterization schemes for weather forecasting. *Weather Forecasting*, 10, pp. 716-740.

Cummine, J., P. McCarthy, and M. Leduc, 1992: Blowdown over northwestern Ontario. *Preprints*, 4th Workshop on Operational Meteorology (Whistler, British Columbia, Canada), Atmos. Environ. Service/Canadian Meteor. and Oceanogr. Soc., pp. 311-317.

Darkow, G.L., 1969: An analysis of over sixty tornado proximity soundings. *Preprints*, 6th Conf. Severe Local Storms (Chicago, Illinois), American Meteorological Society, pp. 218-221.

Davies, J. M., and R.H. Johns, 1993: Some wind and instability parameters associated with strong and violent tornadoes. 1. Wind shear and helicity. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 573-582.

Davies-Jones, R., 1984: Streamwise vorticity: The origin of updraft rotation in supercell storms. *Journal of Atmospheric Sciences*, 41, pp. 2991-3006.

Davies-Jones, R., D. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. *Preprints*, 16th Conf. on Severe Local Storms (Kananaskis Park, Alberta, Canada), American Meteorological Society, pp. 588-592.

Davies-Jones, R. and H. E. Brooks, 1993: Mesocyclogenesis from a theoretical perspective. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 105-114.

Dessens, J., and J. T. Snow, 1989: Tornadoes in France. *Weather Forecasting*, 4, pp. 110-132.

Dessens, J., and J. T. Snow, 1993: Comparative description of tornadoes in France and the United States. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 427-434.

Doswell, C. A. III, 1987: The distinction between large-scale and mesoscale contribution to severe convection: A case study example. *Weather Forecasting*, 2, pp. 3-16

Doswell, C. A. III, 1994: Extreme convective windstorms: Current understanding and research. *Report of the Proceedings (1994) of the U.S.-Spain Workshop on Natural Hazards* (Barcelona, Spain, 8-11 June 1993), J. Corominas and K.P. Georgakakos, Eds., 44-55. [Available from the Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa 52242 USA]

Doswell, C. A. III, J. T. Schaefer, D. W. McCann, T. W. Schlatter, and H. B. Wobus, 1982: Thermodynamic analysis procedures at the National Severe Storms Forecast Center. *Preprints*, 9th Conf. on Weather Forecasting and Analysis (Seattle, Washington), American Meteorological Society, pp. 304-309.

Doswell, C. A. III, and D. W. Burgess, 1993: Tornadoes and tornadic storms: A review of conceptual models. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 161-172.

Doswell, C. A. III, S.J. Weiss and R.H. Johns, 1993: Tornado forecasting: A review. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 557-571.

Doswell, C. A. III, H. E. Brooks, and R. A. Maddox, 1996: Flash-flood forecasting: An ingredients-based methodology. *Weather Forecasting*, 11, pp. 360-381.

Doswell, C. A. III, C. Ramis, R. Romero, and S. Alonso, 1998: A diagnostic study of three heavy precipitation episodes in the western Mediterranean region. *Weather Forecasting*, 13, pp. 102–124.

Doswell, C. A. III, A. R. Moller, and H. E. Brooks, 1999: Storm spotting and public awareness since the first tornado forecasts of 1948. *Weather Forecasting*, 14, pp. 544-557.

Dotzek, N., R. Hannesen, K. D. Beheng, and R. E. Peterson, 1998: Tornadoes in Germany, Austria, and Switzerland. *Preprints*, 19th Conf. on Severe Local Storms (Minneapolis, Minnesota), American Meteorological Society, pp. 93-96.

Duke, J. W., and J. A. Rogash, 1992: Multiscale review of the development and early evolution of the 9 April 1991 derecho. *Weather Forecasting*, 7, pp. 623-635.

Emanuel, K., D. Raymond, A. Betts, L. Bosart, C. Bretherton, K. Droegemeier, B. Farrell, J. M. Fritsch, R. Houze, M. LeMone, D. Lilly, R. Rotunno, M. Shapiro, R. Smith, and A. Thorpe, 1995: Report of the first prospectus development team on the U. S. Weather Research Program to NOAA and the NSF. *Bulletin of the American Meteorological Society*, 76, pp. 1194-1208.

Evans, J. S., 1998: An examination of observed shear profiles associated with long-lived bow echoes. *Preprints*, 19th Conf. on Severe Local Storms (Minneapolis, Minnesota), American Meteorological Society, pp. 30-33.

Fankhauser, J.C., 1988: Estimates of thunderstorm precipitation efficiency from field measurements in CCOPE. *Monthly Weather Review*, 116, pp. 663-684.

Fawbush, E. J., and R. C. Miller, 1953: A method for forecasting hailstone size at the earth's surface. *Bulletin of the American Meteorological Society*, 34, pp. 235-244.

Foster, D. S., and F. C. Bates, 1956: A hail size forecasting technique. *Bulletin of the American Meteorological Society*, 35, pp. 135-140.

Fujita, T.T., 1972: *Estimate of maximum wind speeds of tornadoes in southernmost Rockies*. SMRP Res. Paper No. 105, University Of Chicago.

Fujita, T.T., 1973: Tornadoes around the world. *Weatherwise*, 26, pp. 56-62, 78-83.

Fujita, T.T., 1978: *Manual of downburst identification for project NIMROD*. Satellite and Mesometeorology Res. Paper No. 156, Dept. of Geophys. Sci., Univ. of Chicago, 104 pp.

Fujita, T.T., and H.R. Byers, 1977: Spearhead echo and downburst in the crash of an airliner. *Monthly Weather Review*, 105, pp. 129-146.

Fujita, T.T., and F. Caracena, 1977: An analysis of three weather-related aircraft accidents. *Bulletin of the American Meteorological Society*, 58, pp. 1164-1181.

Funk, T. W., 1991: Forecasting techniques utilized by the forecast branch of the National Meteorological Center during a major convective rainfall event. *Weather Forecasting*, 6, pp. 548-564.

Hanstrum, B. N., G. A. Mills, and A. Watson, 1998: Australian cool season tornadoes. Part I: Synoptic climatology. *Preprints*, 19th Conf. on Severe Local Storms (Minneapolis, Minnesota), American Meteorological Society, pp. 97-100.

Houze, R. A., Jr., W. Schmid, R. G. Fovell, and H.-H. Schiesser, 1993: Hailstorms in Switzerland: Left movers, right movers, and false hooks. *Monthly Weather Review*, 121, 3345-3370.

Jameson, A.R., 1991: A comparison of microwave techniques for measuring rainfall. *Journal of Applied Meteorology*, 30, pp. 32-54.

Johns, R.H., 1993: Meteorological conditions associated with bow echo development in convective storms. *Weather Forecasting*, 8, pp. 294-299.

Johns, R.H., and W.D. Hirt, 1987: Derechos: Widespread convectively induced windstorms. *Weather Forecasting, 2, pp. 32-49*.

Johns, R.H., K. W. Howard, and R. A. Maddox, 1990: Conditions associated with long-lived derechoes–An examination of the large-scale environment. *Preprints*, 16th Conf. on Severe Local Storms (Kananaskis Park, Alberta, Canada), American Meteorological Society, pp. 408-412.

Johns, R.H., and C.A. Doswell III, 1992: Severe local storms forecasting. *Weather Forecasting*, 7, pp. 588-612.

Johns, R.H., J. M. Davies, and P. W. Leftwich, 1993: Some wind and instability parameters associated with strong and violent tornadoes. 2. Variations in the combinations of wind and instability parameters. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 583-590.

Kamburova, P.L., and F.H. Ludlam, 1966: Rainfall evaporation in thunderstorm downdraughts. *Quarterly Journal of the Royal Meteorological Society*, 92, pp. 510-518.

Kelly, D.L., J.T. Schaefer, R.P. McNulty, C.A. Doswell III and R.F. Abbey, Jr., 1979: An augmented tornado climatology. *Monthly Weather Review*, 106, pp. 1172-1183.

Kelly, D.L., J.T. Schaefer, and C.A. Doswell III, 1985: The climatology of non-tornadic severe thunderstorm events in the United States. *Monthly Weather Review*, 113, pp. 1997-2014.

Li, J., Y.-L. Chen, and W.-C. Lee, 1997: Analysis of a heavy rainfall event during TAMEX. *Monthly Weather Review*, 125, pp. 1060–1082.

Lilly, D. K., 1982: The development and maintenance of rotation in convective storms. *Intense Atmospheric Vortices*. L. Bengtsson and J. Lighthill, Eds., Springer-Verlag, pp. 149-160.

Maddox, R.A., L.R. Hoxit, C.F. Chappell, and F. Caracena, 1978: Comparison of meteorological aspects of the Big Thompson and Rapid City flash floods. *Monthly Weather Review*, 106, pp. 375-389.

Maddox, R.A., C.F. Chappell and L.R. Hoxit, 1979: Synoptic and meso-alpha aspects of flash flood events. *Bulletin of the American Meteorological Society*, 60, pp. 115-123.

Maddox, R.A., and W. Dietrich, 1981: Synoptic conditions associated with the simultaneous occurrence of significant thunderstorms and flash floods. *Preprints*, 4th Conf. on Hydrometeorology (Reno, Nevada), American Meteorological Society, pp. 181-187.

McCaul, E. W., Jr., 1993: Observations and simulations of hurricane-spawned tornadic storms. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 119-142.

McCaul, E. W., Jr. and M. L. Weisman, 1996: Simulations of shallow supercell storms in landfalling hurricane environments. *Monthly Weather Review*, 124, pp. 408-429.

Mead, C. M., 1997: The discrimination between tornadic and nontornadic supercell environments: A forecasting challenge in the southern United States. *Weather Forecasting*, 12, pp. 379–387.

Miller, R. C., 1972: *Notes on Analysis and Severe-Storm Forecasting Procedures of the Air Force Global Weather Central*. Tech. Report 200 (REV), Air Weather Service (MAC), United States Air Force.

Moller, A.R., C.A. Doswell III, and R. Przybylinski, 1990: High-precipitation supercells: A conceptual model and documentation. *Preprints*, 16th Conf. on Severe Local Storms (Kananaskis Park, Alberta, Canada), American Meteorological Society, pp. 52-57.

Moller, A.R., C.A. Doswell III, M. P. Foster, and G. R. Woodall, 1994: The operational recognition of supercell thunderstorm environments and storm structure. *Weather Forecasting*, 9, pp. 327-347.

Moore, J. T., and J. P. Pino, 1990: An interactive method for estimating maximum hailstone size from forecast soundings. *Weather Forecasting*, 5, pp. 508-525.

Munich Re, 1984: *Hailstorm*. Münchener Rückversicherungs-Gesellschaft, Munich, Germany, 56 pp.

Petersen, W. A., L. D. Carey, S. A. Rutledge, J. C. Knievel, R. H. Johnson, N. J. Doesken, T. B. McKee, T. Vonder Haar, and J. F. Weaver, 1999: Mesoscale and radar observations of the Fort Collins flash flood of 28 July 1997. *Bulletin of the American Meteorological Society*, 80, pp. 191–216.

Peterson, R. E., 1982: Tornadic activity in Europe: The last half-century. *Preprints*, 12th Conf. Severe Local Storms (San Antonio, Texas), American Meteorological Society, pp. 63-66.

Prosser, N. E., and D. S. Foster, 1966: Upper air sounding analysis by use of an electronic computer. *Journal of Applied Meteorology*, 5, pp. 296-300.

Przybylinski, R. W., 1995: The bow echo: Observations, numerical simulations, and severe weather detection methods. *Weather Forecasting*, 10, pp. 203-218.

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Weather Forecasting*, 13, pp. 1148–1164.

Ryzhkov, A., D. S. Zrnic, and D. Atlas, 1997: Polarimetrically runed R(Z) relations and comparison of radar rainfall methods. *Journal of Applied Meteorology*, 36, pp. 340–349.

Rotunno, R., 1993: Supercell thunderstorm modelling and theory. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 57-73.

Schaefer, J.T., and R.L. Livingston, 1988: The typical structure of tornado proximity soundings. *Journal of Geophysical Research*, 93, pp. 5351-5364.

Schwartz, B.E., C.F. Chappell, W.E. Togstead, and X.-P. Zhong, 1990: The Minneapolis flash flood: Meteorological analysis and operational response. *Weather Forecasting*, 5, pp. 3-21.

Sénési, S., P. Bougeault, J.-L. Chèze, P. Cosentino, and R.-M. Thepenier, 1996: The Vaison-La-Romaine flash flood: Mesoscale analysis and predictability issues. *Weather Forecasting*, 11, pp. 417-442.

Smith, B. E., 1993: The Concordia, Kansas downburst of 8 July 1992: A case study of an unusually long-lived windstorm. *Preprints*, 17th Conf. Severe Local Storms (St. Louis, Missouri), American Meteorological Society, pp. 588-592.

Spencer, P. L., and D. J. Stensrud, 1998: Simulating flash flood events: Importance of the subgrid representation of convection. *Monthly Weather Review*, 126, pp. 2884–2912.

Stensrud, D. J., J. V. Cortinas Jr., and H. E. Brooks, 1997: Discriminating between tornadic and nontornadic thunderstorms using mesoscale model output. *Weather Forecasting*, 12, pp. 613-632.

Thompson, R. L., 1998: Eta model storm-relative winds associated with tornadic and nontornadic supercells. Weather Forecasting, 13, pp. 125–137.

van Everdingen, E., 1925: The cyclone-like whirlwinds of August 10, 1925. *Proc., Royal Acad. of Amsterdam Section of the Sci.*, 25, pp. 871-889.

Vieux, B. E., and P. B. Bedient, 1998: Estimation of rainfall for flood prediction from WSR-88D reflectivity: A case study, 17–18 October 1994. *Weather Forecasting*, 13, pp. 407–415

Wakimoto, R.M., 1985: Forecasting dry microburst activity over the high plains. *Monthly Weather Review*, 113, pp. 1131-1143.

Wakimoto, R.M., 1998: Convectively driven high wind events. *Preprints*, 19th Conf. on Severe Local Storms (Minneapolis, Minnesota), American Meteorological Society, 435.

Wakimoto, R.M., and J.W. Wilson, 1989: Non-supercell tornadoes. *Monthly Weather Review*, 117, pp. 1113-1140.

Wegener, A., 1917: *Wind- und Wasserhosen in Europa*. Friedr. Vieweg und Sohn, Braunschweig, 301 pp. (In German)

Weisman, M.L., 1993: The genesis of severe, long-lived bow echoes. *Journal of Atmospheric Science*, 50, pp. 645-670.

Weisman, M.L., and J.B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. Monthly Weather Review, 110, pp. 504-520.

Weisman, M.L., and J.B. Klemp, 1984: The structure and classification of numerically simulated convective storms in directionally varying wind shears. *Monthly Weather Review*, 112, pp. 2479-2498.

Weiss, S. J., 1996: Operational evaluation of the mesoeta model for the prediction of severe local storms. *Preprints*, 18th Conf. on Severe Local Storms (San Francisco, California), American Meteorological Society, pp. 367-371.

Weiss, S. J., G. S. Manikin, and K. E. Mitchell, 1998: Eta model forecasts of low-level moisture return from the Gulf of Mexico during the cool season. *Preprints*, 19th Conf. on Severe Local Storms (Minneapolis, Minnesota), American Meteorological Society, pp. 673-676.

Zixiu, X., W. Pengyun, and L. Xuefang, 1993: Tornadoes of China. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), C. Church, Ed., Amer. Geophys. Union, pp. 435-444.

Zrnic, D.S., V.N. Bringi, N. Balakrishnan, K. Aydin, V. Chandrasekar, and J. Hubert, 1993: Polarimetric measurements in a severe hailstorm. *Monthly Weather Review*, 121, pp. 2223-2238.

DROUGHT MONITORING AND PREDICTION FOR DISASTER PREPAREDNESS

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ABSTRACT

The overall theme of the forum is to address the roles of science and technology in natural disaster reduction. This review will be devoted to drought early warning and preparedness. The review will highlight, among others, what we must know in order to reduce the impacts of droughts; the current state, achievements and limitations of science and technology; and a way forward into the next century. The first part addresses the various definitions that have been used for the term drought. The devastating socio-economic impacts of droughts are highlighted in the second section, with special reference to Africa where drought has been associated with many socio-economic miseries. Section 2 also highlights the potential use of drought monitoring and prediction products in early warning and reduction of the negative drought impacts.

Recent drought monitoring and prediction efforts are addressed in section three, with special reference to the use of El Niño and the Southern Oscillation (ENSO). Section 3 further highlights the need to take full advantage of any existing information regarding the climatology of past droughts. This requires policies that will ensure optimum utilization of any positive water stress including the availability of adequate water resources during the normal and wet rainfall years in planning for the drought years.

Specific success stories regarding the use of ENSO indicators in drought monitoring and prediction over some parts of the tropics are also presented in section 3, with special reference to the recent worldwide regional climate outlook fora. The last part of this review is, however, devoted to the limitations of current drought monitoring and prediction science and technology. Enhanced sectoral demands and challenges of drought monitoring/prediction science and technology in drought early warning and disaster preparedness during the next century are also addressed in the last part of the review.

1. DROUGHT DEFINITIONS

Drought is quite different from many other natural disasters, as unlike many others that have immediate impacts such as flash floods, drought creeps very slowly and the impacts are cumulative. Yet the impacts are sometimes more devastating (Table 1). It is, moreover, sometimes very difficult to accurately detect the onset of droughts, and some relief efforts often wait for the first victims before initiating relief emergencies. In general terms, drought may be considered as the situation where water demand for any particular system use significantly exceeds water supply from the traditional water sources for the system. Due to significant differences in the levels of water requirements by the different water use systems, various definitions have been presented for the term drought. These definitions range across hydrological, agricultural, meteorological and many other sectoral water uses (Ogallo, 1993). Precipitation is the major factor that often determines water availability from most natural sources of water, including water that may be available from underground aquifers, rivers, lakes, etc. Meteorological drought is, therefore, often presented simply as the situation when precipitation received at any location is significantly below the normal expectation for that specific location. Various measures of central tendency have been used to quantify the normal precipitation expectation at specific locations. These have included arithmetic mean, quartile / tercile / decile / percentile limits, among many other measures.

Too much and too little precipitation (floods and droughts) are often associated with various socio-economic disasters. Some of these impacts are highlighted in the second part of this review.

Table 1. Effects of the 1982-83 ENSO (NOAA, Published by the New York Times, 2 August 1983)

Location	*Phenomenon*	*Victims*	*Damage in US $*
United States			
Mountain and Pacific States	storms	45 dead	1.1 billion
Gulf States	flooding	50 dead	1.2 billion
Hawaii	hurricane	1 dead	230 million
Northeastern US	storms	6 dead	–
Cuba	flooding	15 dead	170 million
Mexico- Central America	drought	–	600 million
Ecuador-Northern Peru	flooding	600 dead	650 million
Southern Peru-Western Bolivia	drought	–	240 million
Southern Brazil- Northern Argentina, Eastern Paraguay	flooding	170 dead , 600 000 evacuated	3 billion
Bolivia	flooding	50 dead, 26 000 homeless	300 million
Tahiti	hurricane	1 dead	50 million
Australia	drought, fires	71 dead, 8 000 homeless	2.5 billion
Indonesia	drought	340 dead	500 million
Philippines	drought	–	450 million
South China	wet weather	600 dead	600 million
Southern India, Sri Lanka	drought	–	150 million
Middle East , chiefly Lebanon	cold, snow	65 dead	50 million
Southern Africa	drought	Disease, starvation	1 billion
Iberian Peninsula, Northern Africa	drought	–	200 million
Western Europe	flooding	25 dead	200 million

2. RECURRENCE OF DROUGHTS AND THE ASSOCIATED SOCIO-ECONOMIC IMPACTS OF DROUGHTS

Recurrences of extreme precipitation anomalies leading to the availability of too much or too little water are normal components of natural climate variability, as can be observed over many parts of the world. Year-to-year anomalies in regional precipitation have been associated with anomalies in the systems that control regional precipitation, including sea surface temperature [SST] anomalies, ENSO signals, etc. Some examples of the extreme anomalies which have been observed in past regional precipitation patterns will be reviewed in this section.

Past recurrences of too much or too little water have often been associated with far-reaching socio-economic and environmental implications. The adverse impacts of droughts and floods often include loss of life and property, mass migration of people and animals, environmental refugees, shortages of food, energy, water and many other basic needs of mankind. They have also been associated with environmental degradation, and a drop in gross value production for most precipitation dependent national domestic sectors, among many other environmental and socio-economic disasters. The degree of vulnerability to such natural disasters has, however, been highest in the developing countries, especially in Africa where droughts and floods have often been associated with severe socio-economic havoc in many countries.

In advanced countries, reduction in the degree of vulnerability of society to natural disasters like floods and droughts has been achieved not only through applications of advanced science and technology, but also through optimum use of available records in risk zoning over a given time and the development of realistic disaster preparedness policies, which include trying to give early warning of such natural disasters through monitoring and prediction efforts. The current state of science and technology cannot, however, adequately meet the unique demands of many users, among the questions asked are: how much rainfall will be received during the next season ? when will it start and end ? what will be the distribution of the dry and wet spells ?

3. DROUGHT MONITORING AND PREDICTION

Historical records are crucial in the zoning of drought risks and the general assessment of the vulnerability of any precipitation dependent socio-economic activity to various levels of drought stress. Such records are also needed in order to study the complex linkages between water stress and specific socio-economic activities. Furthermore, historical records can provide information about past droughts and how previous generations coped with them. Important lessons could be learnt from such coping strategies. It should also be noted that past data are fundamental in the development of sound disaster preparedness policies. Several databases are now available, these include re-analysis data, proxy climate data, data obtained from special research programmes (e.g., TOGA in 1985-94) and remote sensing data. The importance of real-time/ near real-time monitoring of the drought conditions will also be highlighted in this section, including initiatives by WWW, GCOS, GOOS, GTOS, etc.

Past records have shown that droughts are recurrent in all parts of the world. The drought impacts, however, vary significantly in both space and time. In some years, new drought stress records have been set. The most unique drought has, however, been observed over Sahel Africa where a significant decrease in rainfall trends has been observed at many locations since the late 1960s. The region has strong SST and ENSO variability signals. Linkages between ENSO and droughts have been subjects of many recent studies. Many such studies have also examined the existence of any significant changes in the traditional space-time patterns of the extreme precipitation events like droughts and floods (IPCC, 1995).

As has been highlighted in the previous sections, drought creeps in slowly and the impacts are generally cumulative. Therefore, the best approach to drought disaster preparedness would be through monitoring and early warning of any impending drought conditions. This would require timely availability of accurate and high-quality drought products. The last part of the review will address the current state of drought monitoring and prediction science and technology, with special reference to the recent use of ENSO and SST-related predictors over parts of global tropics. Some success stories regarding drought early warning will also be included in the review based on the recent worldwide climate outlook fora which have been organized by WMO/CLIPS, IRI, NOAA/OGP, national/regional climate centres, together with many other partners.

4. SECTORAL DEMANDS AND CHALLENGES OF DROUGHT MONITORING/ PREDICTION SCIENCE AND TECHNOLOGY IN THE NEXT CENTURY

With the economic challenges of the next century, including globalization, together with the rapid growth in global population levels, increased number of human settlements and expensive investments and structures would be expected in areas that are more vulnerable to natural disasters. The level of environmental degradation is also expected to increase, together with the demands for basic needs like food, water, settlement, energy, etc. This will require enhanced and integrated applications of climate information and prediction services. Key challenges to drought early warning in the next century will be highlighted in the final part of this review, including the required levels operational of seasonal climate prediction science and technology. Such challenges include data related problems, the capacity of the developing countries (hardware, software, and skilled multidisciplinary human resources) to monitor, process data/information and timely predict/early warning of the impending disasters, research to understand the complex linkages between water stress and various precipitation dependent socio-economic sectors, transfer of appropriate technology, enhanced seasonal prediction capacity including the ability to downscale prediction products to sectoral application levels, the education of the public and sectoral users about early warning information and products, networking and timely exchange of information/products, closer interface between producers of climate prediction products and the specific sectoral users, realistic and integrated disaster preparedness policies, availability of resources, etc.

REFERENCES

IPCC, 1995: *Climate Change 1995 - The Science of Climate Change. Contribution of Working Group 1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Ogallo L.A., 1993: *Climate variations, drought and desertification* (Second Edition). WMO No. 653, World Meteorological Organization, Geneva, Switzerland. pp. 45.

METEOROLOGY AS AN AID IN FIGHTING AND PREVENTING FOREST FIRES

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ABSTRACT

Techniques already exist for estimating the meteorological risk of forest fire. These take the form of indices based on measurements and forecasts of meteorological parameters and, for certain types of vegetation, on remote sensing. Provision of such information to forest fire agencies requires only modest technical efforts by meteorological services, where effective and reliable meteorological observation networks exist. Close cooperation between meteorological services and agencies established to prevent and fight fire is the key to effective fire prevention and response.

1. INTRODUCTION

No region of the world is unaffected by forest fires. Forests were catching fire even before humans appeared on the scene and nature took its time in restoring the plant cover. These fires were mainly caused by lightning and must have affected enormous areas. Nowadays, however, most fires are started by human activities, though lightning is still the primary cause in some regions. Fire is, for example, one of the techniques used to promote the growth of crops or pastures. Under controlled conditions, it can also be used in forest management though, sadly, it is sometimes used for other purposes.

Reducing the overall number of forest fire outbreaks is a non-meteorological challenge and is, consequently, beyond the scope of the present discussion. This presentation focuses, instead, on techniques for determining the risk of a fire spreading. The paper begins with an overview of the theory relating to the spread of forest fires. This is followed by a description of the physical phenomena involved, in order to distinguish clearly between the various methods that apply to different types of plant cover and climate. Finally, operational techniques are discussed which can help meteorological services to establish effective cooperation with fire prevention and fire fighting agencies.

2. SPREADING OF FIRES

The following three components are needed if a fire is to spread (Trabaud, 1989):

- Fuel (plant cover), which must be sufficiently dry;
- Oxygen (supplied by the wind), to promote combustion;
- A local heat source (lightning, match, etc.), to act as a catalyst.

2.1 LAYERS OF PLANT COVER

Generally speaking, plant cover can be divided into a number of layers based on the height of the plants concerned:

- A litter layer made up of dead plant debris at ground level;
- A herbaceous layer comprising herbaceous plants whose state depends on climatic conditions since their roots draw water only from the surface layer. Such plants are green during wet periods and when in active growth but dry out where they stand after reaching maturity and during dry periods;
- A shrub layer composed of plants which contain a greater amount of inflammable material and do not dry out completely. They can grow to a height of a few metres;
- An arboreal layer made up of trees.

In some regions (e.g. large forests), a layer of humus (i.e. decomposed plant material lying under the litter layer) must also be taken into account as it can be an important vector in the spread of fires. The physical processes governing the spread of ground fires are peculiar to such fires. These spread slowly, give off little smoke, are very difficult to extinguish and often follow surface fires.

In certain forms of plant cover, some of the above layers may be missing. For example, there is no litter layer in arid steppe areas and no shrub layer in savanna areas.

2.2 PROCESSES GOVERNING THE SPREAD OF A SURFACE FIRE

SPREAD OF A FOREST FIRE
Arboreal layer
Burning fragments are projected ahead of the fire
Shrub layer
Herbaceous layer
Litter layer

Plants burn in two stages:

- Pyrolysis: the plant loses its water through evaporation caused by heat supplied by the burning of neighbouring plants or by ignition. This is the “endothermic” stage.
- Combustion: This is the “exothermic” stage.

Fire can only spread if the heat generated during combustion is greater than that absorbed during pyrolysis. Hence, no combustion can take place when plants are very green (i.e. have high water content). Fire starts in the litter layer, which is generally dry enough to ignite unless there has been early morning dew or recent rain. The burning litter then generates the heat needed to cause pyrolysis of the herbaceous layer. Provided that this layer is not too wet, it will then ignite and cause pyrolysis in the shrub layer. This, in turn, leads to ignition in the arboreal layer, if one is present. Burning fragments then fall to the ground, setting more of the litter layer on fire. Subsequently, the fire spreads at a rate which depends on the dryness of the vegetation, the wind speed, the air temperature and the structure of the plant cover.

3. ASSESSING THE FIRE RISK

Obviously, it will never be possible to foresee exactly where and when fires will break out and, in consequence, fire will remain an unpredictable hazard. Since much information is now available on periods and areas of greatest risk, however, outbreaks of fire can be anticipated, information can be made available to the populations concerned and preventive measures can even be taken. Different methods will be used to determine risk level, depending on the type of plant cover and climatic conditions.

No universal method for meteorological assessment of fire risk can be proposed as the best for all countries. A study carried out in four Mediterranean countries in Europe (south-eastern France, Greece, Italy and Portugal) (Viegas, Sol *et al*, 1994), for example, compared methods used for the meteorological assessment of fire risk. This study showed that the same method did not always give the best results even though the plant cover was of the same type (Mediterranean vegetation). Results depended on the country concerned and the type of fire (e.g. such as summer fires in flat country, winter fires, hill fires). Results also depend on whether the aim is to prevent a fire from breaking out or from spreading and becoming a major forest fire.

WMO recently distributed a related questionnaire to the countries in its Regional Association VI (Europe). Analysis of the 31 responses received clearly reveals the diversity of methods used to assess the fire risk. Despite this caution, the following sections provide some guidance to assist countries with no experience in the field to take an effective approach to the problem and circumvent long periods of preliminary research.

3.1 TIME-SCALE CONSIDERATIONS

There should be a clear indication of the time-scale involved.

3.1.1 THE "CLIMATIC" SCALE

This entails a clear understanding of seasons of greatest fire risk, in climatological terms. Here, the contribution made by the meteorological service will be linked to its knowledge of the climate and possible climatic variations, such as those caused by phenomena like El Niño. This knowledge facilitates the precise identification of high-risk periods so that effective information can be made available to prevent the outbreak of fires.

The climatic fire scale is governed by the phenological stages of the various layers of vegetation. Shrubs dormant in winter, for example, can be as likely to catch fire as plants suffering from water stress in summer while frost will increase the amount of dead, highly inflammable, vegetation. For this reason, knowledge of variations in plant phenology and their propensity for catching fire is a prerequisite to any study on the subject. Such knowledge will, for example, prevent the identification of plants that are green and in full growth as being in a period of high risk. The danger index is often wrongly assessed during such periods.

3.1.2 The Short and Medium Scale

Forecasts of periods of high-risk, made several days in advance, can be of assistance in placing fire-fighting teams on maximum alert, gaining precious time in the event of fire and warning populations of potential danger. Forecasts of variations in the fire-risk level should be made on a daily basis in order to define the areas at greatest risk due to wind and dryness. Methods such as risk index, water balance calculations and remote sensing play an extremely useful role in such instances.

3.1.3 The Nowcasting Scale

This scale applies when a fire is in progress and calculations of the level of risk are no longer useful. The main task at this stage is to determine how the wind will affect the fire and its progress during the coming hours, in order to anticipate how the fire will spread. Provision of this type of assistance is a routine task for meteorological services. The challenge lies in quickly establishing effective and practicable links between fire-fighting teams and meteorological services.

3.2 OVERALL RISK/METEOROLOGICALLY ASSESSED RISK

Determination of the overall fire risk involves three types of factors:

- Operational components such as the availability of fire-fighting personnel, risk factors for the outbreak of fire and others. An understanding of farming, woodland and pastoral practices is included in this component and be must taken into account in any system of fire prevention;
- Condition of the plant cover; This component does not, strictly speaking, concern meteorological services; and
- Weather conditions.

GENERAL FIRE RISK

Operational Components	Condition of Plant Cover	Weather Conditions (Field of Action of a Meteorological Service)

3.3 CONDITION OF PLANT COVER

The condition of plant cover in relation to the outbreak and spread of fire, may be indicated by a number of parameters such as water content and flammability interval (i.e. time taken to catch fire). It is, however, extremely difficult to provide these indices in real time since *in situ* measurements are demanding (due to personnel requirements, difficult sampling techniques, plant destruction, plant representativity, etc.) and can only be applied to a restricted number of species in all the vegetation layers. Some countries measure the water content of the litter on a daily basis. However, this technique only provides information on the risk of the outbreak of fire from one day to the next and does not make it possible to forecast the fire-risk level several days in advance. The role played here by remote sensing is discussed later in this paper.

Due to the absence of any simple real-time means of ascertaining the condition of plant cover, meteorological assessment of risk has to take plant cover condition into account more or less directly. This is why such assessments are included in the field of action of meteorological services.

We shall now turn to the meteorological assessment of fire risk, indirectly including the condition of the plant cover.

4. METEOROLOGICAL ASSESSMENT OF FIRE RISK

How can fire risk be assessed in meteorological terms? A number of approaches are possible:

- The conventional approach using indices calculated from meteorological measurements. These include simulations of the condition of plant cover;
- The mixed approach using plant cover measurements and weather forecasts;
- The remote-sensing approach where the condition of plant cover is determined from satellite measurements. This approach should be used in conjunction with weather forecasts.

It is important to note that the meaning of fire-risk indices has to be properly understood (i.e. do they imply risk of outbreak, risk of spread or both?).

4.1 THE CONVENTIONAL APPROACH: METEOROLOGICAL INDICES OF FIRE RISK

Numerous methods have been proposed for determining fire risk levels from meteorological measurements alone. In the study cited earlier, for example, Viegas and Sol identified over a dozen methods used in the Mediterranean region of Europe alone.

4.1.1 Parameters Required

All methods require virtually the same meteorological parameters:

- wind forecast;
- air temperature and humidity forecast;
- cloud cover forecast or, for some methods, radiation forecast;
- measurements of rainfall (accumulated over 24 hours), wind, temperature and sometimes humidity (at least minimum and maximum).

The simplest of these methods only require wind, temperature and humidity forecasts. Another method combines the wind-speed forecast with the water balance derived from measurements of precipitation and mean temperature. Still others require information on the number of days that have elapsed since the previous significant rainfall.

The observed parameters (rainfall, temperature, etc) are used to monitor soil moisture reservoirs (or Sub-Indices) which represent the amount of water available to the plant cover. The Canadian method (Van Wagner, 1987) uses three Sub-Indices for this purpose; one of very low inertia which relates to the water content in the litter and small, dead plants (important for the outbreak of fire) and two others known as the Dryness Index and the Humus Index, which relate to upper layers (important for the spread of fire). While these reservoirs (or sub-indices) are clearly less useful than measurements taken directly from the plant cover, they can be calculated from simple meteorological parameters. Generally speaking, the simplest methods – those based on the temperature and humidity of the litter cover and on wind speed – are used to calculate the risk of outbreaks of fire while methods that investigate the reservoirs are used to predict the spread of fire.

It is important to note that reliable and continuous measurements of meteorological parameters, taken every day throughout the year, are absolutely essential to the calculation of sub-indices. Any interruption in observations will break the calculation chain. Gaps in the information are, however, acceptable during some periods of the year such as the rainy season or the early part of the fire-risk season when reservoirs are saturated with water. The availability of real-time measurements will sometimes determine which method is to be used. If humidity measurements and forecasts are not available, for example, a method will have to be selected that does not rely on these measurements.

4.1.2 Location and Density of Meteorological Measurements

Meteorological measurements used in the calculation of sub-indices representing the condition of the plant cover need not necessarily be taken in woodland or among the plant cover under direct threat. Measurements taken nearby will serve perfectly well, even those from an airport site. It is essential, however, that the same meteorological stations be used each time so that the climatology of the Indices can be determined, Indices can be calibrated against fires and subsequent comparisons of risk levels can be undertaken on a daily or annual basis. In addition, measurements taken in woodland do not provide a good assessment of the wind, which is an essential component in the spread of fires.

The density of the observational network will depend on the variability of weather conditions in the area concerned. It will be greatest in the case of rainfall measurements. In south-eastern France, which is a very mountainous area, station density, for example, averages one every 500 km^2. The fine-tuning of forecasts in spatial terms is determined by network density. Expansion of the measurement network to improve assessment of fire risk will teach meteorologists to recognize and thus to forecast mesoscale phenomena.

4.1.3 Choice of Method

As explained earlier, the choice of method will depend on which meteorological components are available and there is no need to create a new method to suit each country. It is suggested, however, that the Canadian method, the Fire-Weather Index (Van Wagner, 1987), be tried first. Even though it was developed in Canadian forests, this method gave the most consistent results in Mediterranean plant cover (garrigue, maquis, broad-leaf and coniferous forest) during the comparative study mentioned earlier. Its only disadvantage is that it requires humidity measurements and forecasts and computer facilities.

4.2 THE MIXED APPROACH: PLANT COVER MEASUREMENTS AND WEATHER FORECASTS

This approach requires considerable infrastructure (Valette, 1994). Samples of litter or living plants are collected by forestry staff who then weigh and kiln them. Only then can these samples be used, in combination with meteorological measurements and weather forecasts, for the meteorological assessment of fire-risk. The quality of the sub-indices indicating the condition of the plant cover is necessarily of the same order as the accuracy and representativity of the samples.

The results obtained from the mixed approach are only valid for one day. Thus, its capability for advance warning is very limited. For this reason, we do not recommend this approach if a reliable network of meteorological measurements is available.

4.3 THE REMOTE-SENSING APPROACH

Many articles in the scientific literature outline the virtues of remote sensing for the prevention or forecasting of forest fires (Deshayes *et al*, 1998). This approach uses easily repeatable measurements for direct assessment of the condition of the plant cover. Satellite images provide information on a much smaller scale than meteorological or forestry measuring station networks. In addition, the cost of such images is insignificant so long as forecasters restrict themselves to images with a resolution in the order of $1km^2$, quite sufficient for the purpose at hand. Furthermore, satellites pass overhead frequently enough to take pictures at intervals that meet operational needs.

Current satellites make the Normalized Differential Vegetation Index (NDVI) and the surface temperature available for determining the water balance of plant cover. In theory, stress in the plant cover can be determined by the combination of these two products. The author, however, takes the somewhat more cautious view that any attempt to make generalizations covering all plant species should be avoided.

4.3.1 Forested Areas

Programmes currently in operation in Europe make use of remote sensing output. Satellites, however, largely see the upper surface of forest areas while the lower layers are the main vectors of fire and determine the ferocity of the blaze. Tracking temporal variations in the stress in plant cover during the main fire-risk season is currently more difficult by remote sensing than it is by using dryness sub-indices determined from meteorological observations. In the Mediterranean zone, for example, remote sensing clearly shows differences between the end of the spring growth period (i.e. the beginning of the fire season) and the period of maximum water stress (i.e. later summer, before the onset of the heavy autumnal rains). Fluctuations from one week to the next or during the period just before the rainy season are, however, difficult to track. On the other hand, remote sensing provides improved insight into the spatial distribution of the risk since the grid interval is well below that of any meteorological network. The task then is to incorporate remote sensing images in a Geographical Information System which also makes it possible to combine information on plant cover with operational components, relief, fire outbreaks and other data.

The latest satellite products, such as those from active on-board sensors that can penetrate masking cloud and the various vegetation layers, may shortly offer a new operational approach and related research is under way.

4.3.2 Prairies and Savanna

Remote sensing provides a clear indication of the onset of the fire-risk season for areas in which the herbaceous layer is the predominant plant cover (i.e. savanna), through a rapid and quite perceptible change in the vegetation index. In this case, remote sensing data are more informative than any sub-index or soil moisture reservoir. The fire-risk season is thus clearly marked and it is possible to monitor the gradual geographical spread of areas likely to catch fire. In consequence, fire prevention campaigns can be targeted more accurately in both space and time. Furthermore, related indices, such as the Fire Outbreak Index associated with the wind forecast, can be safely applied to areas where the goal is, for example, to burn off grass. It is important to note here that remote sensing has been used for some time for agricultural activities such as monitoring crop growth and forecasting harvest dates.

4.3.3 Meteorological Assessment of Fire Risk

Even though remote sensing gives an improved indication of the water stress of plant cover, it must still be used in conjunction with weather forecasts to provide adequate warning to services responsible for fire fighting, fire prevention and informing the public. Traditional meteorological risk indices, familiar to the fire-fighting services of some countries, comprise a combination of meteorological forecasts and plant cover sub-indices. The goal now is to add the Normalized Differential Vegetation Index (NDVI), surface temperature, and any other parameters detected by remote sensing to these indices.

5. FIRES STARTED BY LIGHTNING

Fire-fighting services should be informed, in real time, of lightning strikes observed during periods when fires are likely (i.e. in terms of the meteorological fire-risk indices). Fire may break out some hours after a strike (after smouldering in the humus layer) even if the thunderstorm is not a dry one.

The parts of the world in which fires are started by lighting would do well to install networks for the detection of lightning strikes to ground, if such facilities are not already in place. Such detection networks would make it possible to dispatch fire-fighting teams to affected locations. A lightning strike detection network of this kind also has many other meteorological applications.

6. METEOROLOGICAL ASSISTANCE

As previously discussed, meteorological methods for forecasting fire-risk already exist, though some research may be required to adapt them to the meteorological and plant conditions prevailing in each country and to the measurement networks available. Like any other meteorological product, however, such forecasts are only useful when applied within an operational framework. The following sections address this aspect.

6.1 COOPERATION AMONG SERVICES

A very close relationship and a high-level of trust must be established between the meteorological service and the agencies responsible for fire prevention and fire fighting. Meteorological services should work in cooperation with the forestry service when undertaking studies to determine the best method for determining fire-risk level. They should, as a minimum, obtain available fire statistics in order to gain insight into the problems facing the country such as the causes of fires, fire and vegetation types, phenological stages and seasons. They should, moreover, also ascertain whether fires are linked to climatic incidents such as El Niño events.

Having acquired knowledge of wind and rainfall patterns, meteorologists would then be in a position to upgrade observation networks in the area and to provide input for the calculation of indices. In some instances, the observation network can be upgraded by the forestry service itself. In other countries, the forestry service may choose to determine the fire-risk level using conventional meteorological forecasting parameters. Regardless of which approach is chosen, the essential point is that there should be complete cooperation with meteorological and fire-fighting services exchanging information whenever necessary. Meteorological assistance may even include making a forecaster available for the duration of a fire to provide direct assistance to the fire-fighting service. This form of assistance, which has been practiced in France for 20 years, generates a high level of mutual understanding, inspires an essential climate of trust and is also a highly economical way of operating for all services concerned (Sol, 1994). Moreover, it should not be forgotten that fire-risk forecasting only just falls within (and may even be beyond!) the scope of meteorological services. This provides a further reason why the agencies concerned, whether they are meteorological, forestry or fire-fighting services, must work in cooperation, as they have much to learn from one another.

6.1 PREVENTION

The best means of prevention generally entail keeping people informed, especially those who start fires for agricultural or pastoral purposes or who use the countryside for recreational activities.

Such information should be transmitted in two forms:

- Ongoing background information that educates the public about fire hazards. In this context, the information provided by the meteorological service is primarily climatic;
- More detailed information during high-risk periods. Such information should be conveyed by the most appropriate media to warn concerned population groups of the abnormally high levels of risk. In the meteorological context, such information concerns the short- and medium-term.

Meteorological services are most involved with the second element above.

7. CONCLUSION

In conclusion, meteorological services should cooperate fully and openly with the services responsible for preventing and fighting forest fires. Even where the meteorological network is not very well-developed, easily applicable methods exist for forecasting periods of highest fire risk. Utilizing these methods, a system of preventive measures can be established to improve the means of coping with fires. In addition, information provided by the media during periods of high fire risk will reduce the number of outbreaks. A small number of accurate forecasts of high fire-risk levels are virtually all that is required to gain the level of trust discussed in this paper. These forecasts should be provided a few days in advance and, with recent improvements in the quality of medium-term forecasts, such a service is now within our capabilities.

REFERENCES

World Meteorological Organization: *Météorologie et incendies de forêts*. Report of the Technical Meeting held by WMO in Rabat, Morocco, 25–30 November 1991.

Deshayes M., Chuviecco E., Cocero D., Karteris M., Koustsias N., Stach N.: *Evaluation of different NOAA-AVHRR derived indices for fuel moisture content estimation: interest for short-term fire risk assessment*. Proceedings of the III International Conference on Forest Fire Research – Luso-Coimbra, Portugal, Vol I, pp 1149-1167.

Reis R.M.M., 1998: *Scales for the assessment of forest fire danger*. Proceedings of the 3rd International Conference on Forest Fire Research – Luso-Coimbra, Portugal, Vol I, pp 1235-1243.

Sol B., 1993: *Weather forecasts for forest fires: the economic impact*. Proceedings of the 2nd International Conference on Forest Fire Research – Coimbra, Portugal, Vol I, A07, pp 131-137.

Trabaud L., 1989: Les feux de forêts – mécanismes, comportement et environnement. *France Sélection*. 278 pages.

Valette J.-C., Sol B., Moro C., 1994: *Flammability parameters and soil water reserve to improve the forecast of the meteorological forest fire danger index*. Proceedings of the 2nd International Conference on Forest Fire Research – Coimbra, Portugal, Vol II, pp 611–624.

Van Wagner C.E., 1987: *Development and structure of the Canadian Forest Fire Weather Index System*. Agric.Can., Can. For. Serv., Ottawa ON For. Tech. Rep. 35.

Viegas D.X., Sol B., Bovio G., Nosenzo A. and Ferreira A., 1994: *Comparative study of various methods of fire danger evaluation in southern Europe*. Proceedings of the 2nd International Conference on Forest Fire Research – Coimbra, Portugal, Vol II, C05, pp 571 – 590.

IMPACTS OF EXTREME AND PERSISTENT TEMPERATURES — COLD WAVES AND HEAT WAVES

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1. INTRODUCTION

The most extensive source of data on natural disasters is held by the insurance industry where the most important occurrences around the world are registered according to the number of deaths and the economic and insured damages incurred. Munich Reinsurance (or “Munich Re”), the world’s biggest reinsurance company, has documented the 163 largest natural disasters that have occurred since 1960 in their “MRNatCatSERVICE” (1999a). Natural disasters are considered “large” when they considerably exceed self-help capabilities in the region concerned, making supra-regional or international help necessary. This is usually the case when the number of deaths are in the thousands and the number of homeless are counted in the hundreds of thousands, or when substantial economic damage is caused.

Vulcanoes	5
Earthquakes	45
Tropical cyclones	49
Tornados	7
Hail storms	7
Floods	27
Winter storms	11
Ice storm/blizzards	6
Fires	4
Droughts/heat	2

Figure 1. The biggest natural disasters 1960 – 1998. (MRNatCatSERVICE, Munich Re, 1999a).

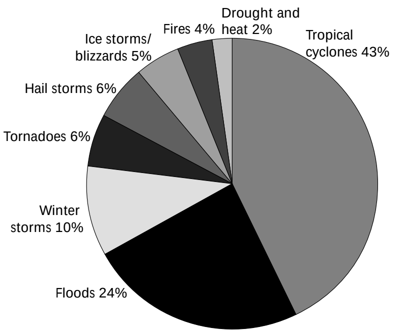


Figure 2. The biggest meteorologically induced natural disasters 1960 – 1998. (MRNatCatSERVICE, Munich Re, 1999a).

Forty-five of these disasters were associated with earthquakes and 5 with volcanic eruptions i.e. about a third were not weather-related (see Figure 1). Only 1.2 per cent of the 163 disasters were caused by extreme heat and 10.4 per cent by extreme cold, making them very rare occurrences among the great catastrophes (For the 113 disasters caused by meteorological conditions, the corresponding percentages are 1.8 per cent and 15.0 per cent). Winter damage is not caused by low temperatures, but rather by freezing rain, heavy snowfall and high wind speeds that occur in such climatic conditions.

The insurance industry classifies disasters caused by atmospheric conditions as the result of “storm”, “flooding” and “others”, a classification system that is, at times, ambiguous. It is unclear, for example, whether flooding in Bangladesh, is caused by a typhoon, counts as a “storm” or “flooding”. Equally, the data rarely indicate “cold” or “storm” as the cause of damage where ice storms or blizzards are concerned. Similar ambiguity also arises with drought and heat. According to insurance industry definitions, the issues addressed in this paper fall into the category classified as “others” (see Figure 2).

The occurrences identified in this paper are based on reviews of various information sources such as Climatic Perspectives, Transactions of the American Geophysical Union, Frankfurter Allgemeine Zeitung, Lloyd’s List, Neue Züricher Zeitung, Monthly Weather Report, Property Claim Services, Online-Reuters, dpa, Süddeutsche Zeitung, Weekly Climate Bulletin, World Insurance Report, and others, supplied by the MRNatCatSERVICE of Munich Reinsurance (1999a-d). Only confirmed, cross-checked (usually) reports on the extent of damage, obtained from a reliable source, are accepted. For example, the plausibility of damage estimate is checked by the projection of total damage from the insured losses and the insurance density.

Sporadic worldwide information on drought/heat is available from 1910 onwards and more or less regularly since 1979. Reports on damage due to winter conditions begin in 1958, and have been available on a regular basis since 1971. Complete information is available since 1986.

2. EXTREME TEMPERATURE EVENTS

2.1 COLD WAVES

2.1.1 Overview

The MRNatCatSERVICE lists 294 cases of winter damage (Munich Re 1999b). The description of associated meteorological conditions is not restricted to information on temperature, but also covers cold waves, unusually low temperatures, heavy snow falls, icing, dense fog, snow drifts, high wind speeds, severe precipitations, blizzards, frosts, freak snowstorms with typhoon force winds, snow pressure, freezing rains, ice rains, snowdrifts, snow depth, avalanches, torrential rain, persistent snow storms and floodings. Expressions such as heaviest or worst snowstorm, coldest winter or month, greatest depth of snow, longest duration for over a period of years, are also often used.

The following countries were affected by these conditions (frequency in brackets): Afghanistan (1), Albania (1), Algeria (1), Argentina (2), Australia (1), Austria (8), Bangladesh (11), Belgium (1), Belize (1), Brazil (4), Bulgaria (5), Byelorussia (1), Canada (25), Chile (1), China (3), Croatia (2), Czech Republic (1), Denmark (1), Estonia (1), European Region (5), Finland (3), France (11), Georgia (1), Germany (25), Greece (2) Guatemala (1), Hungary (3), India (13), Iran (2), Israel (2), Italy (11), Japan (5), Jordan (5), Kazakhstan (1), Korea, Republic of (1), Latvia (1), Lebanon (3), Malawi (1), Mexico (8), Moldavia (2), Mongolia (1), Namibia (1), Netherlands (2), New Zealand (4), Nigeria (1), Pakistan (2), Peru (2), Philippines (1), Poland (10), Portugal (4), Romania (9), Russia (12), Slovenia (2), South Africa (11), Spain (9), Sweden (6), Switzerland (8), Syria (2), Turkey (10), Ukraine (8), United Kingdom (5), United States of America (48), Yugoslavia (1). Of these 62 countries, about a third (21) experienced only a single extreme event while the statistics indicate that ten countries experienced 10 or more extreme occurrences. The US experienced 48, followed by Canada and Germany with 25 each, India with 13, Bangladesh, France, Italy and South Africa with 11 and Poland and Turkey with 10 cases. Countries also frequently experienced a series of disastrous events in the course of a single winter season.

Statistics display a wide range of damage types. There are various causes of death (e.g. 298 deaths in central and eastern Europe between 16 November – 18 December 1998 or 275 deaths in India between January/February 1992) and injuries from direct exposure to cold (e.g. as a result of an interruption of energy supplies), as a result of traffic accidents or avalanches and from being cut off from medical care.

Although there is generally a higher human mortality rate in the cold season in all climates, excess mortality can also be associated with cold spells in moderate climates (Jendritzky *et al.*, 1998) (Figure 3). Mortality increases within 2–3 days of the onset of a cold spell. This higher mortality rate lasts for some time and it is not completely compensated by subsequent reduced mortality. The medical causes of death are many. Direct influence of cold on the coronary circulation system and via the respiratory system is only one factor. Influenza and other infectious diseases, especially diseases of the respiratory system, are frequent causes of high winter mortality.

Damage to infrastructure ranges from the breakdown of power plants, power-supply and telecommunication systems and drinking water supplies (due to frozen pipelines), reduced oil and gas production and, in some areas, the isolation of human settlements from the outside world for weeks on end. Transportation on road, rail, water and air transport systems are hampered, with consequent reductions in economic activity and in the delivery of supplies to the population. Road traffic accidents increase. Agriculture and forestry are

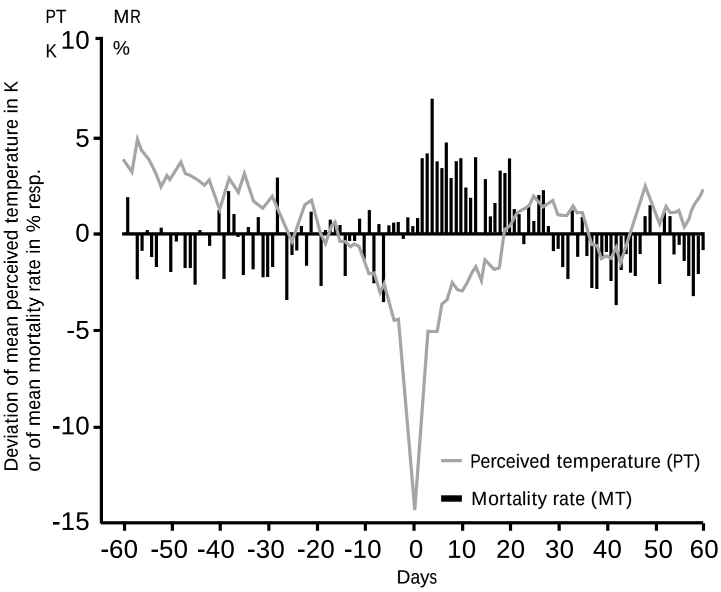


Figure 3. Extreme cold stress events. Averaged time series of mortality rate (MR), in per cent and perceived temperature (PT) (based on a complete thermophysiologically significant heat budget model of a human being) centred 60 days around the lowest PT value of each year related to their respective 30-day mean before the PT peak. Data 1968 – 1993 south-west Germany (Jendritzky *et al.*, 1998).

confronted with a loss of profits, even extending to total losses of field crops, fruit and vegetables. Examples include the loss of the grape harvest in large parts of France on 20 – 21 April 1991, 40 per cent of the Brazilian coffee harvest destroyed between 25 June – 25 July 1994, and huge losses of livestock in China with 1 million animals dying in 1986. Ice and snow also cause forest damage and the collapse of roofs.

Economic damage is enormous but is often difficult to estimate. Fairly reliable figures can, however, be derived for areas with high insurance density (Munich Re, 1999b). 14 countries or regions show economic losses greater than US $100 000 million, of which 6 have losses of more than US $1 million. Of the latter, 4 occurrences relate to the US (1977, 1994, 1996, 1998) and 2 to Canada (1992/93, 1998). The highest liquidated damages (US $4 million) resulted from extreme winter conditions in the northeastern USA, during January – March 1994, which experienced heavy snow, and rain and temperatures down to –40°C, resulting in the loss of 190 lives.

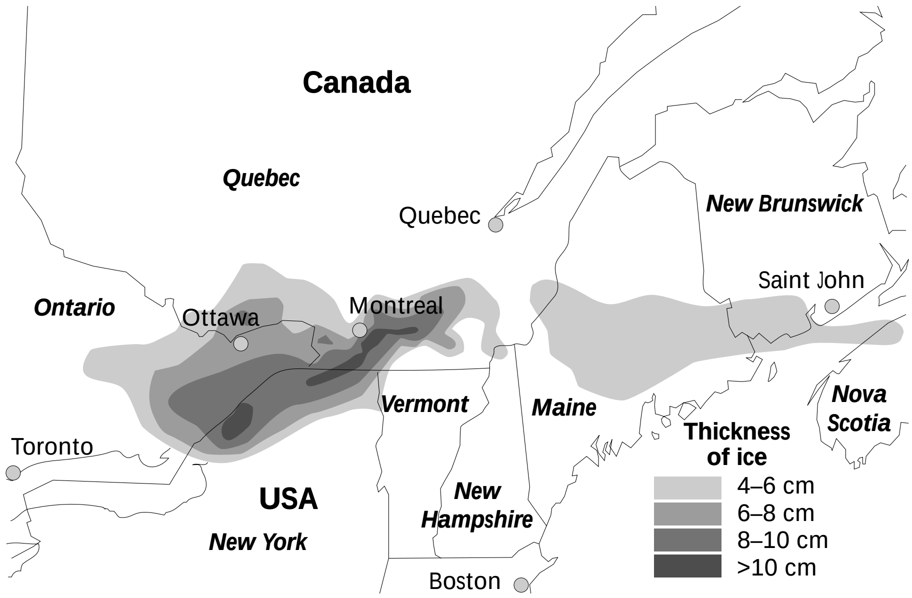
2.1.2 The 1998 Ice Storm in Canada and the US

The high damage potential of storms, ice and snow, even in moderate latitudes, is illustrated by the worst ice storm catastrophe in Canada's history, which occurred on 5–10 January 1998 (Savage 1998). Ice and snow storms (blizzards) belong meteorologically to the extratropical storms that originate in the transitional area between the subtropical and polar climatic zones, i.e. around 35–70° latitude. In this region, polar outbreaks of cold air encounter warm subtropical air and heavy precipitation often occurs along the boundary between these two air masses.

In January 1998, this situation prevailed in eastern Canada and in northeastern US. Very mild and moist air had advanced as far as the southern New England states, in advance of a cyclone moving up from the southwest. Cold arctic air was pushed south against this warm air by a powerful high pressure area over the Hudson Bay. Snow (mainly) fell to the north of the resulting sharp temperature gradient while to the south rain or sleet occurred which, with temperatures around freezing point, was transformed instantaneously to sheer ice on the deep-frozen ground and other surfaces. The landscape was slowly paralyzed under a continuously growing armour of ice that reached a thickness of up to 10 cm after six days, weighing up to approximately 100 kg/m^2 in some regions (Figure 4).

Ice storms are not an infrequent occurrence in North America. In November 1921, for example, a similar severe storm produced 8 cm of ice while in January – February 1951, 10 cm of ice covered a record geographical expanse extending from New England to Texas. The severity of ice storms depends largely on the rate of accumulation of ice, the duration of the event and the location and extent of

Figure 4. The January 1998 ice storm in eastern North America.



the area affected. Between January 5–10, 1998, the total water equivalent of precipitation exceeded 85 mm in Ottawa, 73 mm in Kingston, 108 mm in Cornwall and 100 mm in Montreal (Savage 1998). Most of the precipitation fell as freezing rain and ice pellets with some snow. A representative temperature during the period was –10°C.

The extent of the area affected by this ice storm was enormous. At the peak of the storm, however, the area of freezing precipitation extended from Muskoka and Kitchener in Ontario through eastern Ontario, western Quebec and the Eastern Townships to the Fundy coasts of New Brunswick and Nova Scotia. In the US, icing coated northern New York and parts of New England. The area affected by freezing rain, therefore, extended for about 2 000 km in an east-west direction and 400 km in a north-south direction, a total area of approximately 800 000 km^2, while an armour of ice more than 4 cm thick covered a region of almost 100 000 km^2.

The reason that this occurrence turned into a catastrophe was, firstly, its unusually long duration of around a week*. The number of hours of freezing rain and drizzle was in excess of 80, nearly double the normal annual total. Secondly, the thickness of the ice layer and its enormous expanse, covering one of the largest populated and urbanized areas of North America, left more than four million people freezing in the dark for hours or days.

* Though it did not rain continuously throughout this period

The following statistics provide an insight into the impact of the storm (Munich Re, 1999c, Savage 1998):

Deaths: 23 (Canada: 16, USA: 7);
Injured: several (!!);
Evacuated: 100 000.

Power breakdowns: More than 4 million people without electricity and heating (On 22 January 1998, 800 000 people were still without electricity in Canada).
120 000 km of power and communication lines destroyed (including 130 major transmission towers each worth US $100 000.
and about 30 000 wooden utility poles costing US $3 000 each). The damage was so severe in eastern Ontario and southern Quebec that major rebuilding of the electrical grid had to be undertaken.

Damage: Houses damaged by fire, broken pipes, destroyed roofs; many cars damaged; 2 oil refineries, copper and aluminium plants, factories, businesses and shops affected (business interruptions, loss of income).

Infrastructure: Highways, roads, bridges closed; roads and bridges damaged; railroads blocked, signalling systems frozen, train services suspended; air traffic affected; subway systems disrupted; airlines and railways discouraged travel into the area.

Miscellaneous: Water treatment plants affected; drinking water supply failure. Residents were urged to boil water for 24 to 48 hours.

Forestry and Agricultural losses: Major losses to forests, hundreds of thousands or even millions of trees downed or severely damaged; losses to livestock and dairy farms, milk processing plants closed. Many Quebec maple syrup producers (who account for 70 per cent of the world supply) were ruined with much of their sugar bush permanently destroyed.

Resources mobility: 14 000 troops, including 2 300 reservists, deployed to help with clean up, evacuation and security.

Insurance claims lodged 612 000 single damage claims were filed with insurance companies. The most frequent claims were for:

Food which had gone bad, in refrigerators without electricity supply (Insured up to US $1000 in many household policies);
Burst water pipes caused by freezing due to the failure of heating systems;
Roof damage due to ice pressure and fallen trees;
Procurement of electric generators to prevent potential damage;
Additional living costs such as for hotel accommodation;

Total economic damage: Canada: US $1 500 million
USA: US $1 000 million

Insured goods: Canada: US $950 million
USA: US $200 million

Had this storm tracked 100 km farther east or west of its actual path, the disruptive effect would have been far less crippling.

2.2 HEAT WAVES

2.2.1 Overview

A distinction is not usually made between droughts and heat waves in the data tabulated by the MRNatCatSERVICE, (Munich Re. 1999d). In total, 347 such cases are listed and most of them are categorized under the drought heading, starting with a reference to the 1910-1914 drought in the Sahel region. However, 46 of these cases are clearly identified as “heat waves”, 12 as “drought/heat waves” and in 17 droughts there is explicit mention of high temperatures, often in relation to their unusual duration.

According to the above listing, the following countries were affected by heat waves, drought/heat waves or high temperatures (frequency in brackets): Australia (5), Bangladesh (1), Canada (1), China (4), Croatia (1), Cyprus (1), Denmark (1), Egypt (1), Germany (3), Greece (2), Hungary (1), India (8), Japan (2), Kazakhstan (1), Korea, Republic of (3), Morocco (2), Mexico (5), Moldavia (1), Mozambique (1), Namibia (1), Pakistan (6), Peru (1), Romania (3), South Africa (2), Spain (1), Swaziland (1), Turkey (1), Ukraine (1), Uruguay (1), United States of America (8), Venezuela (1), Vietnam (2), Zambia (1), Zimbabwe (1). Thirty-four of these countries appear in the statistics several times. In particular, India and the USA have each experienced 8 occurrences, Pakistan 6, Australia and Mexico 5, China 4 and Germany, the Republic of Korea, and Romania each had 3 heat waves.

The damage resulting from heat waves ranges from losses of agricultural products and livestock (causing food shortage, hunger and bankruptcy of farmers) to forest and bush fires, power failures and power cuts due to water shortage and inadequate supplies of fresh drinking water. At times, droughts associated with heat waves can cause immense damage to the economy. In 1988 in the USA, for example, economic damage amounted to US $13 000 million during a drought extending from Ohio to California. Temperatures were around 40°C, 30 states were affected and a state of emergency was declared in 12 states. Temperatures in Texas reached 38°C on 29 consecutive days during 1988, 130 people died and US $4 275 million in damages resulted. Similarly, in 1996, US $1 200 million in losses occurred in Mexico and US $2 400 million in the USA, while in 1992, losses estimated at US $1 000 million were experienced in the states of southern Africa.

Exactly half of the 76 reports on heat waves identified earlier contain reports of deaths and a lesser number refer to injured persons. During 13 of these occurrences more than 100 persons died. The highest single number of deaths, 3 028, was reported from India in 1998, followed by approximately 2 000 in Greece in 1987 (Katsouyanni *et al.*, 1988) and 1 444 in China in 1988. In China, many people were, apparently, killed by a sudden rise in water level in dried-out river beds. India, Pakistan and Bangladesh are particularly susceptible to heat waves and several hundred people died in the droughts that occurred in 1988, 1991, 1992 and 1994. The July 1995 heat wave in the Midwest of the USA had the gravest consequences with 670 deaths (up to 830 according to other sources!), of which 375 (some sources say 525) occurred in Chicago (CDC 1995, Kunkel *et al.*, 1996, Changnon *et al.*, 1996) (see 2.2.2).

Available insurance data do not permit clear identification of the exact cause of death (heat, hunger, other causes) because of the ambiguity between drought and heat wave. This presents a fundamental difficulty in the case of pure heat waves where the deviation of daily mortality from the expected value in the period under consideration can be calculated (excess mortality). All countries with adequate hygiene and an efficient health system show minimum mortality in the summer months as previously feared summer infections are now under control. Heat waves, however, occur during this period and anyone without air-conditioning buildings heat up (the urban heat island). The people who die in such conditions are mainly elderly people with limited adaptability (U.S. Senate Special Committee on Aging 1983). The reference to the thermal properties of buildings and air-conditioning also illustrates the socio-economic dimension of the problem.

As a general rule, excess mortality represents a displacement of the death date of susceptible persons by a few days or weeks ("harvesting") (Figure 5). This is subsequently compensated for in the mortality time series by reduced mortality. There are studies, however, which show that this compensation is incomplete i.e. people die who would have lived longer without the additional stress of the heat wave (Kalkstein 1993, 1995). It has not been clarified whether a threshold has to be crossed to cause this biological stress (Figure 6). In essence, the term heat wave has not yet been quantitatively defined. A generally applicable definition cannot be found since, with the exception of intensity and duration, the regional climate and frequency of occurrence within the summer season will certainly play a role.

A US survey by Changnon et al. (1996) on the relationship between deaths and weather since the beginning of this century is of interest in the present context. This study shows that the number of deaths during heat waves (annual mean 1 000; extreme values from 9500 to 10 000) exceeds the number during all other extreme weather conditions such as hurricanes (annual average 38-63; extreme values 1 836-6 000), heavy rains/floods (100-160; 732-2 200), tornadoes (82-130; 322-739), winter storms (130-200; 270-500), lightning (100-154; unknown), winter storms (60-115; 105), and hail (1; 22)*.

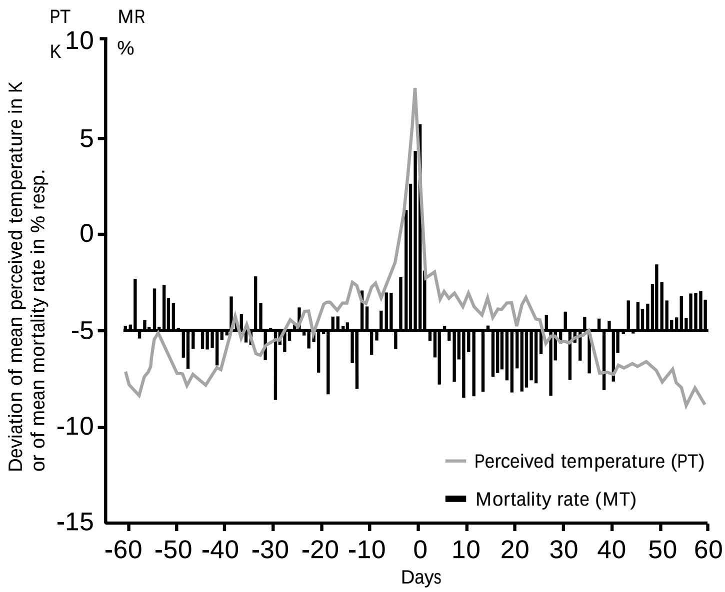


Figure 5. Extreme heat load events. Averaged time series of mortality rate (MR) in per cent and perceived temperature (PT) (based on a complete thermo-physiologically significant heat budget model of a human being) centred 60 days around the highest PT value of each year related to their respective 30 day mean before the PT peak. Data 1968 – 1993 southwest Germany (Jendritzky *et al.*, 1998).

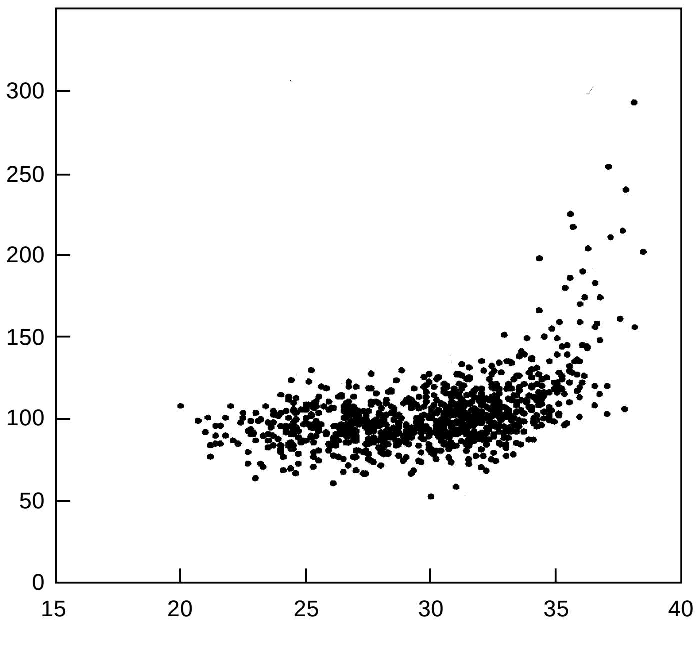


Figure 6). Relationship between maximum temperature and mortality in Shanghai, China, showing a threshold (Kalkstein 1993).

* The values quoted are based on data for different base periods and from different sources and should only be considered as relative measures

2.2.2 The 1995 Heat Wave in Chicago

A severe 5-day heat wave hit the central United States in July 1995, extending from 11–17 July (for details see Changnon et al. 1996 and Livezey and Tinker 1996). Apparent temperatures* exceeded 40°C during daytime and, probably even more serious, nocturnal temperatures in urban areas remained above 30°C. The urban heat island was insignificant during the daytime but substantial at night (Figure 7). This severe heat wave caused 830 deaths, with 87 per cent occurring in the Midwest including 525 in Chicago alone. Deaths commenced one or two days after the heat wave, with most occurring in the 4-day period between 13–16 July. Seventy three per cent of those who died from heat-related causes were persons aged 65 or older (Whitman 1995). Most deaths occurred in homes without air conditioning or where the residents did not operate air conditioning or fans because they were unable to afford them.

Some confusion exists regarding the precise number of deaths. Firstly, there is no general definition of a death due to heat. Heat stroke is clear as a cause of death, but affected individuals also often suffer from other health problems. Thus, questions arise as to whether heat is the primary cause of death or only a contributing factor? An additional problem is caused by the 1 to 2 day delay in reporting deaths, due to overloaded medical examiners. A study of excess deaths during heat waves, probably the best measure of heat-related deaths, suggests that actual heat-related deaths are generally underestimated by a factor of ten (Avery 1988) !

The 1995 heat wave also caused many other types of impacts. Energy usage increased enormously, reaching an all-time record high. 40 000 people were affected by a massive power failure during periods of peak stress. Energy use led to an increase in electricity bills, a problem for low-income families. Hospitals in the Chicago area became overloaded and the number of ambulances was completely insufficient to handle the crisis as thousands were taken to local hospitals. Highways and railroads were damaged and companies reported that productivity was greatly reduced. About 850 dairy cows died, milk production declined and major flocks of poultry were killed.

An assessment of the reasons for the severity of the heat-wave (Changnon *et al.* 1996) revealed that many factors were to blame:

- An inadequate local heat wave warning system, though the National Weather Service issued accurate short- and medium-range forecasts;
- The urban heat island;
- The inability of many people to properly ventilate their residences, due to fear of crime or a lack or resources for fans or air conditioning;
- Power failures; and
- Inadequate ambulance service and hospital facilities.

These contributing factors indicate a lack of preparedness at various levels. The social and demographic factors (i.e. increased population in urban areas, a generally older population, reduced home/apartment ventilation for fear of crime, ignorance, high electricity bills, changing ethnicity) would indicate increased likelihood of heat deaths in large urban areas (Changnon *et al.*, 1996).

* An index based on air temperature and relative humidity, which reflects the heat dissipation of a human body (Steadman, 1979)

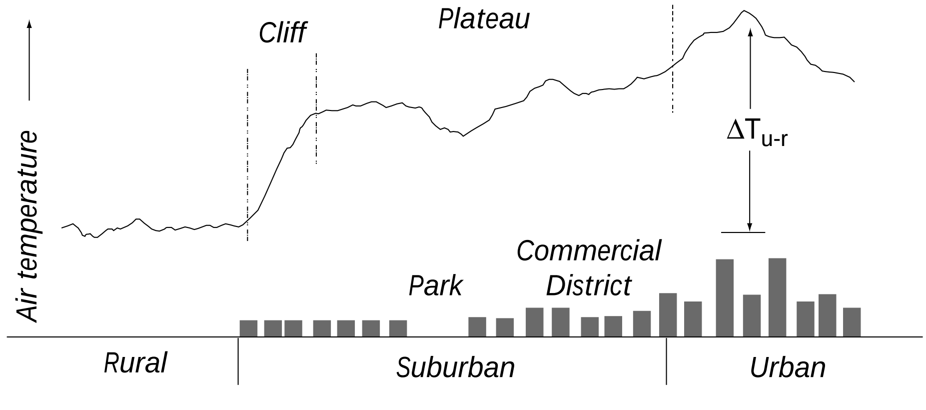


Figure 7. The urban heat island effect on night-time minimum temperatures.

3. THE METEOROLOGICAL AND CLIMATOLOGICAL CONTEXT

Weather-related disasters are concentrated in a few extreme events. The examples in Chapter 2 indicate that the worst disasters in winter are rarely related to extremely low temperatures but to particular meteorological conditions. In the 1998 winter storm in Canada, a jet stream brought an abundant amount of rain northward which, for five days, fell through a shallow layer of cold air at the surface, producing super-cooled water droplets which froze on impact on all surfaces.

Regional effects are significant for heat waves, such as the moisture uptake of the air-mass and cloud cover as it affects nocturnal cooling. In addition, the urban heat island effect contributes to the adverse affects of the high minimum temperatures. Thus with heat waves, various conditions must come together in order to produce extreme impacts.

There are meteorological teleconnections associated with ENSO events due to the response of the global atmospheric circulation and these alter weather patterns worldwide (Leathers 1994). The 1997-98 El Niño, the “climate event of the century”, for example, caused sweltering summer heat in from the Indian subcontinent to China, including the most severe heat-wave this century (Shabbar 1998). Temperatures reached 49°C in India and 3 028 individuals died. On the other hand Livezey and Tinker (1996) found little support for ENSO as a contributing mechanism for the Chicago heat wave 1995. There is no evidence that ice storms in eastern Canada are more frequent during El Niño winters though the 1998 ice storm may have had an “El Niño signature” (Shabbar 1998). Whatever the case, Canada’s worst ice storm occurred while the region was experiencing a warmer winter with less rain or snow than usual. While the effects of El Niño are more direct and dramatic in the tropics, La Niña effects seem to be more distinct in the northern hemisphere winter. This is evidenced by the extreme low winter temperatures associated with La Niña events.

Because natural climate variability is extremely high, it is impossible to tie individual events directly to a specific global force such as climate change. There is, furthermore, no consensus as yet concerning the suggested linkages between climate change and intense El Niños. It is expected that in a warmer world with intensification of the hydrological cycle, extreme events should become more frequent. It is not, however, clear what this means with respect to extreme temperatures. Temperatures close to freezing point and additional precipitation are likely to occur frequently during warmer winters. Consequently, the frequency of ice storms could increase. Simple displacement of the climatological temperature distribution of a given site or area to a higher mean as climate warms would suggest an increase in heat wave events and a decrease in cold spells. Equally, a change in the direction of increasing variability could result in more extremes of both types (Figure 8).

Every National Meteorological Service should be in a position to forecast threatening conditions in order to protect life and property. Using state-of-the-art NWP models, extreme temperature events cannot be forecast beyond the theoretical limit of dynamic predictability of 2 weeks and, in practical terms, beyond about 1 week (Livezey and Tinker 1996). Investigation of the adequacy of the

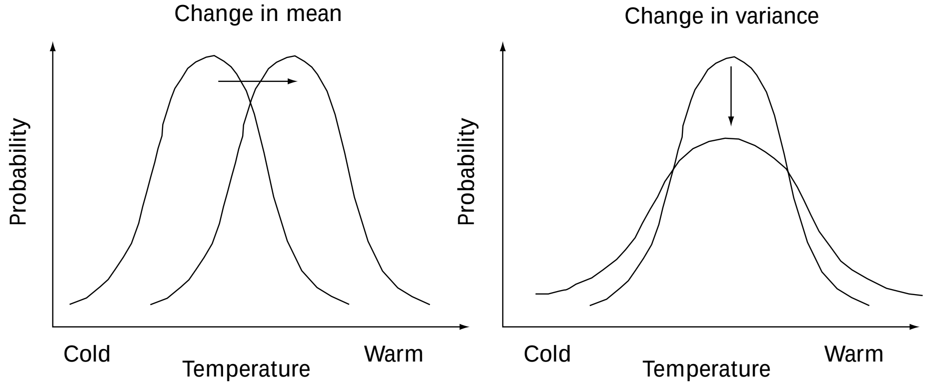


Figure 8. Possible changes in frequency distribution of temperature (Maskell et al., 1993).

1995 Chicago heat wave forecast clearly showed that the forecasting was accurate and its onset was recognized several days in advance (Changnon *et al.*, 1996).

4. VULNERABILITY

The MRNatCatSERVICE statistics on extreme weather events, referenced in sections 2.1.1 and 2.2.1, certainly contain errors, particularly during the earlier years of record. This database, nevertheless, permits some general conclusions to be drawn. Countries at different stages of development are represented in the statistics. While developed, newly industrialized and developing countries are all affected by cold wave or heat wave events, some higher risk areas can be identified. These include the middle latitudes of North America, central and southern Europe, South-East Asia from Pakistan to India and Bangladesh to China, the southern region of Africa and, mainly in summer, Australia. For a variety of reasons, vulnerability differs from country to country.

Modern industrial societies usually show a high sensitivity to disasters because they depend strongly on undisturbed, ongoing access to a well-developed infrastructure, particularly transportation and electricity. More and more people live in expanding urban areas with high settlement density where values are often concentrated in high risk locations. Intensive forms of agriculture and livestock farming are carried out. Emergency preparedness is usually underdeveloped due to lack of awareness, particularly in moderate climates, and most people do not understand the danger presented by different weather conditions (Changnon *et al.*, 1996).

People in less developed countries are also increasingly concentrated in rapidly growing urban agglomerations or megacities. Their vulnerability is, to a greater extent, determined by the lack of financial resources, inadequate infrastructure, accelerating deterioration of natural resources and wars. While economic losses and insured losses are usually much higher in developed countries, data frequently indicate a greater number of deaths in the less developed regions.

Cooperative action involving all levels of government, private companies (e.g. insurance industry) and non-profit institutions, and associations and the natural and technological community is necessary in order to reduce loss of life and damage to property caused by the impact of natural disasters. As mitigation is understood as the cornerstone of emergency management, a good example has been set in North America by the US Federal Emergency Management Agency (FEMA) and Emergency Preparedness Canada (EPC). These agencies have developed mitigation strategies “to protect the nation's critical infrastructure from all types of hazards through a comprehensive, risk-based, emergency management program of mitigation, preparedness, response and recovery” (FEMA). The aim is to bring about a safer and more disaster-resistant country.

5. THE WATCH/WARNING CONCEPT

Although short- and medium-range weather forecasting has, in general, improved significantly in recent years, the results are better at the macro- and meso-scales than at the micro-scale. For heat waves, however, the superimposed micro-scale urban heat island effects are more significant than the regional pattern (Riebsame *et al.*, 1991), taking into account local socio-economic and demographic factors. This illustrates that meteorological assessments must be tailored to the specific problem being addressed (e.g. adequate criteria have to be established for warnings). Similar guidance applies to monitoring of the preceding weather situation in order to alert responsible agencies and the public, well in advance, that conditions are favourable for the development of an extreme event.

An accurate and adequate meteorological forecast by the National Meteorological Service (NMS) is a prerequisite for providing warnings. In addition, the interface between the NMS and the emergency response decision maker (e.g. in the health department) must be formally established, in advance. Clear definition of responsibilities is necessary to ensure criteria are met, to establish the progression from watch through warning to emergency, and to alert all affected agencies and the public on the basis of a prepared plan. The heat watch/warning system, first established in Philadelphia (Kalkstein 1995) and presently being implemented in some other large cities outside the USA, under the umbrella of WMO, WHO and UNEP, is an excellent example of such an integrated procedure (Figure 9).

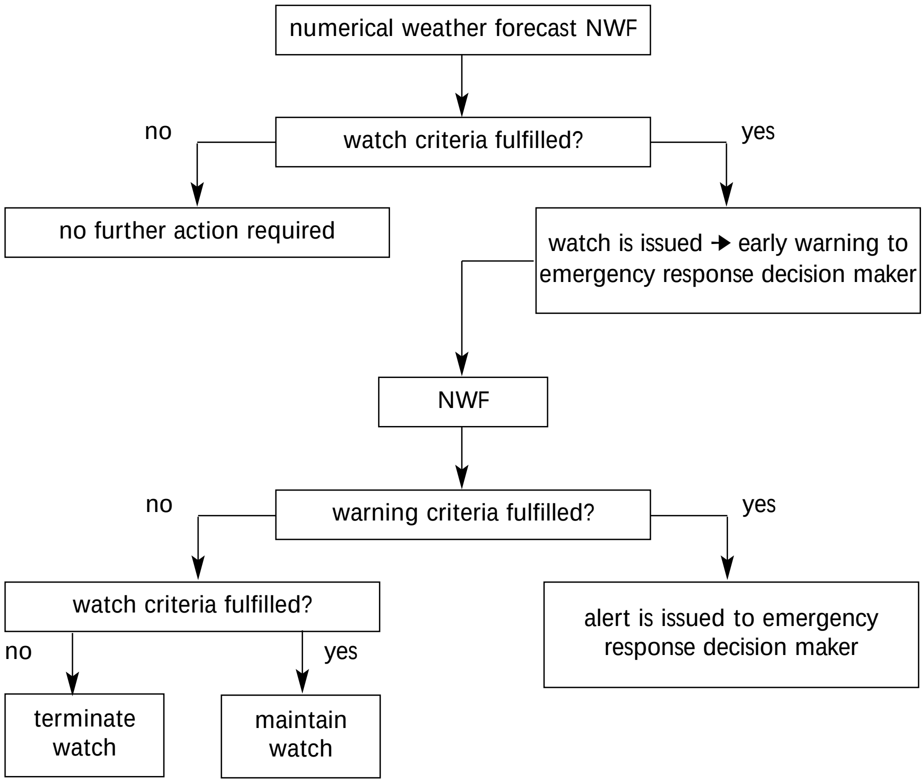


Figure 9. Flow diagram illustrating the heat watch/warning decision process.

REFERENCES

Avery, W.M., 1988: *Heat death toll in 1988*. Center for Environmental Physiology, 4 pp.

centres for Disease Control and Prevention, 1995: *Heat-related mortality*, Chicago, July 1995. Morbidity and Mortality Weekly Report, 44 (11 August), pp. 1-4.

Changnon, S.A., Kunkel, K.E., Reinke, B.C., 1996: *Impacts and responses to the 1995 heat wave: A call to action*. Bulletin American Meteorological Society, Volume 77, No. 7, pp. 1497-1506.

Jendritzky, G., Bucher, K., Bendisch, F., Walther, H., 1998: *The mortality climate study of the Deutscher Wetterdienst*. In: Preprints of the 13th Conference on Biometeorology and Aerobiology in Albuquerque 2-6 Nov. 1998, American Meteorological Society, pp. 297-300.

Kalkstein, L.S., 1993: *Health and climate change: direct impacts in cities*. The Lancet, 342, pp. 1397-1399.

Kalkstein, L.S., 1995: *The impact of climate on human mortality: Present realities and future implications*. Preprints, Ninth Conf. on Applied Climatology, Dallas, TX. American Meteorological Society, pp. 217-227.

Katsouyanni, K. Trichopoulos, D., Zavitsanos, X., and Touloumi, G., 1988: *The 1987 Athens heat wave*. The Lancet. Sept. 3, 573.

Kunkel, K.E., Changnon, S.A., Reinke, B.C. and Arritt, R.W., 1996: The July 1995 heat wave in the central United States. *Bulletin of the Meteorological Society*, 77, pp. 1507-1518.

Leathers D.J., 1994: *Global meteorological teleconnections associated with El Niño/Southern oscillation events*. In: The Oceans Physical-Chemical Dynamics and Human Impact. Majumdar, S.K., Miller, E.W., Forbes, G.S., Schmalz, R.F., and Panal, A.A. (eds.), The Pennsylvania Academy of Science.

Livezey, R. E., Tinker, R., 1996: Some meteorological, climatological, and micro-climatological considerations of the severe U.S. heat wave of mid-July 1995. *Bulletin of the American Meteorological Society*, Volume 77, No. 9, pp. 2043-2054.

Maskell, K., Mintzer, I.M., Callandar, B.A., 1993: *Basic science of climate change*. The Lancet, 342, pp. 1-5.

Munich Re, 1999a: *Some of the largest natural disasters since 1960*. MRNatCatSERVICE (A. Wirtz, pers. comm.) Munich Reinsurance Company, Munich, Germany.

Munich Re, 1999b: *Cold waves and winter damage*. MRNatCatSERVICE (A. Wirtz, pers. comm.) Munich Reinsurance Company, Munich, Germany.

Munich Re, 1999c: *Topics: natural disasters 1998. Annual Review* (in German) Munich Reinsurance Company, Munich, Germany.

Munich Re, 1999d: *Droughts and heat waves*. MRNatCatSERVICE (A. Wirtz, pers. comm.) Munich Reinsurance Company, Munich, Germany.

Riebsame, W.E., Changnon, S.A. and Karl, T.R., 1991: *Drought and natural resources management in the United States: impacts and implications of the 1987-1989 Drought*. Westview Press, 174 pp.

Savage, S., 1998: *The worst ice storms in Canadian history* ? Environment Canada. <http://www.tor.ec.gc.ca/events/icestorms98/icestorm 98_the_worst_e.html>.

Schabbar, A., 1998: *Is there a link to El Niño*? Environment Canada. <http://www.tor.ec.gc.ca/events/icestorms98/icestorms 98_elnino_link_e.html>.

Steadman, R.G., 1979: The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. *Journal of Applied Meteorology*, 18, pp. 861-873.

U.S. Senate Special Committee on Aging, 1983: *Heat stress and older Americans: Problems and solutions*. U.S. Government Printing Office, Washington, D.C., 14 pp.

Whitman, S., 1995: Mortality and the mid-July heat wave in Chicago. Chicago Department of Public Health, 32 pp.

DUST AND SAND STORMS — CHARACTERISTICS, VULNERABILITY, AWARENESS AND PREPAREDNESS

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ABSTRACT

This paper provides a review and analysis of dust storm phenomena in many parts of the world. The study investigates their types, general characteristics, hazards, preparedness and their relation to atmospheric elements. A suggested mechanism of dust storm formation is discussed as well as a detailed study of dust storms of desert depression type, including some case studies. The results show the importance of descending motion for true dust storms and that the transverse indirect circulation may play an important role in these phenomena. The relationship between dust storms over China and the suppression of the Walker cell, as a result of El Niño events, is also discussed.

1. INTRODUCTION

Among different weather phenomena which occur in sub-tropical areas, a sand storm is certainly the most unpleasant one for the population in the area, most hazardous for the health, transport and navigation, most widely known and, at the same time, the most mysterious for meteorologists in terms of its general characteristics, causes and development. Many countries suffer from these phenomena, such as the prairie regions of the United States of America, Mexico, northwest India, North Africa, the Middle East, Argentina and Australia. However, to date, no comprehensive study of sand and dust storms has been carried out for many of these regions and most of the present studies are either descriptive or statistical. Usually, this phenomenon has a local name: Chili in Tunisia, Ghibli in Libya, Samum in Sardinia, Levech in Spain, Sirocco in Italy, Andhi in India, Haboob in Sudan and Khamsin in Egypt.

2. DEFINITIONS

Terminology for the occurrence of dust and sand within the atmosphere is, as yet, not completely established. Although the unit particles composing sand and dust are similar and belong to the same order of matter as dry opaque particles, their behaviour in windy conditions is different. Dust consists of smaller and lighter particles than sand. Once raised from the ground, dust particles are, owing to their lightness, liable to become subject to upward or other irregular currents in the air where they remain in suspension until such time as air movement moderates. Dust travels in clouds, often at height, and is liable to dispersal over great distance. Certain local unidirectional winds are especially effective in this dispersal, such as the Harmattan that carries dust south into Nigeria and the west coast of northern Africa. On particular occasions, dust has been recorded streaking across Europe from the Sahara as far north as Sweden. We may ignore the distinction between sand and dust, as the terms “sand storm” and “dust storm” are frequently used indiscriminately in the literature, and use the name "dust storm" for any rapidly moving air which contains large amounts of dry opaque particles and reduces visibility to less than 1 000 meters. However, we exclude “sand devils” which are small whirlwinds that appear with a weak general wind while true dust storms are associated with high wind velocities. Frequently, sand is driven along the ground by a strong wind without being lifted into the higher air layers; this may be called “sand drift”. The most impressive phenomenon associated with the transport of dust and sand is the occasional occurrence of a “dust wall” which rises from the ground to considerable altitude and has a well-defined outline (Haboob in Sudan).

3. GENERAL CHARACTERISTICS OF DUST STORMS

3.1 ANNUAL FREQUENCY

Dust storms are markedly seasonal in their occurrence. In most of the regions, the annual distribution of dust storms shows that such storms are more prevalent in spring. In some areas, however, such as North Africa and the southern prairie states of the USA, the time of greatest frequency is late winter and early spring while in Australia and southern Iraq dust storms most commonly occur during late spring and summer (Figure 1).

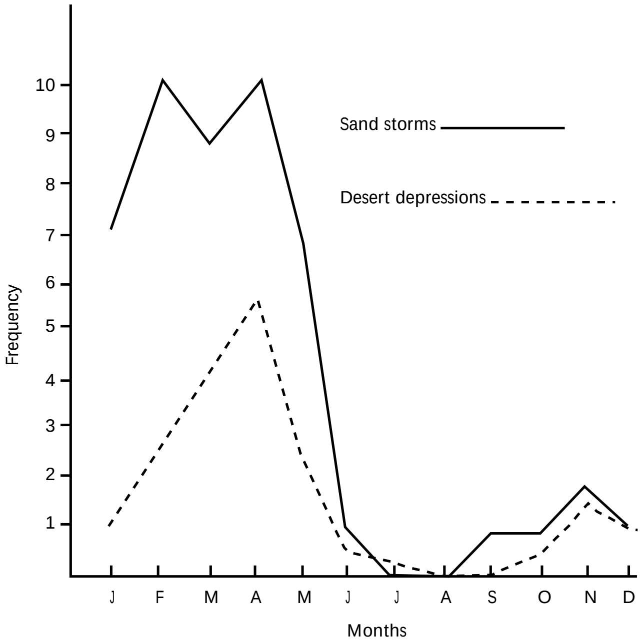


Figure 1. The mean frequency of sandstorms and desert depressions in Egypt (1956–1957) (After El-Saggagh; 1970).

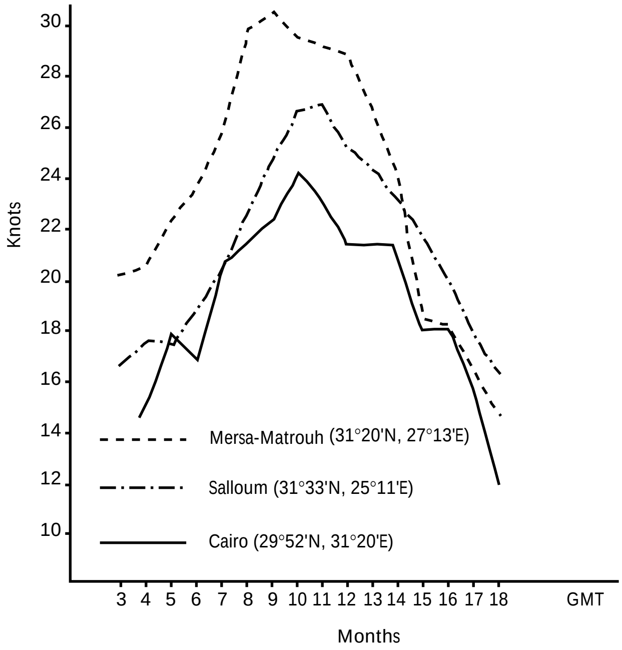


Figure 2. Diurnal variation of mean surface wind during the days when desert depressions exist at three stations in Egypt (1954–1957) (After El Sabbagh; 1971)).

3.2 DAILY VARIATION

Although dust storms are not completely absent at night, they occur mainly during daylight hours (Figure 2).

3.3 THE RELATION TO WEATHER ELEMENTS

3.3.1 Temperature

The relation between dust storms and temperature conditions is not very close. 117 cases of dust storms occurring over Cairo during the period 1968–1990 have been studied. 50 per cent of these cases were accompanied by temperatures from +2 to +13°C above normal. In 30 per cent of these cases, the temperature was 2 to 10°C below normal. The rest of the cases were within 2°C of the normal. Most of the cold dust storms occurred in winter.

3.3.2 Humidity

Dust storms are generally associated with relatively dry air. A close relationship was found between the temperature and the relative humidity of storms. The cases with above normal temperature had a very low minimum relative humidity which was less than 5 per cent in some cases and never exceeded 30 per cent. On the other hand, the relative humidity in cold storms ranged between 20 per cent and 50 per cent.

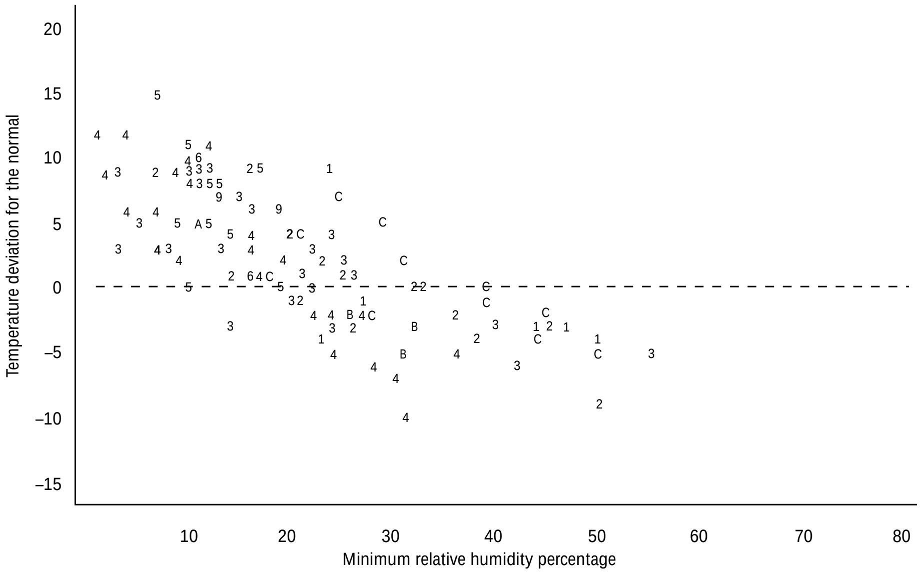


Figure 3. Scattergram for duststorms over Cairo for 117 cases (1968–1990) the plotted numbers (1, 2, ... A, B, C) indicate months of duststorm occurence (Jan, Feb, ... Dec).

Table 1
Surface wind speed (knots)

15-19	20-24	25-29	30-34	35-39	40-44	45-49	
	1	4	2	3	0	0	SS 10
Jan.	81	43	18	2	0	0	RS
	176	56	16	0	0	0	Wind without SS
	3	0	11	5	0	0	SS 19
Feb.	89	50	21	5	0	0	RS
	225	63	14	0	0	0	Wind without SS
	2	8	8	5	3	1	SS 27
Mar.	74	69	20	6	3	1	RS
	244	55	15	1	0	0	Wind without SS
	1	13	9	4	0	0	SS 27
Apr.	96	59	22	4	0	0	RS
	284	62	14	0	0	0	Wind without SS
	1	5	3	2	0	0	SS 11
May	68	40	6	2	0	0	RS
	382	53	6	0	0	0	Wind without SS
	0	1	2	0	0	0	SS 3
Jun.	31	9	2	0	0	0	RS
	317	17	0	1	0	0	Wind without SS
	0	0	0	0	0	0	SS
Jul.	7	0	0	0	0	0	RS
	125	1	0	0	0	0	Wind without SS
	0	0	0	0	0	0	SS
Aug.	8	1	0	0	0	0	RS
	111	1	0	0	0	0	Wind without SS
	0	2	0	0	0	0	SS 2
Sept.	12	7	0	0	0	0	RS
	177	10	0	0	0	0	Wind without SS
	0	1	0	0	0	0	SS 1
Oct	30	17	1	0	0	0	RS
	202	22	1	0	0	0	Wind without SS
	0	1	2	0	0	0	SS 3
Nov.	48	14	4	0	0	0	RS
	144	15	2	0	0	0	Wind without SS

3.3.3 Wind

A strong wind is a necessary but not a sufficient condition for dust storms. Table 1 shows the frequency distribution of the wind force for each month and the occurrences of dust storms (SS), rising sand (RS) and wind with no dust storm. It is clear that the frequency of occurrence of dust storms rises with an increase in wind force. However, in some areas, dust storms did not occur in spite of strong winds of more than 30 knots while dust storms were reported with winds of less than 20 knots.

4. THE MECHANISM OF DUST LIFTING

We must note the fundamental difference between the transport of dust along the ground, sand drift, and the transport of dust which extends into the layers at some distance from the ground. Strong wind may be a sufficient condition for sand drift, but it is not the only factor affecting the formation of the sandstorms. F. Loewe in his remarkable and comprehensive study of dust storms in Australia 1943 wrote that:

> "It is essential for the development of true dust storms that the air should, in places, be descending in order to impinge upon the ground and scrape up the sand locally, which is then distributed by turbulence through the atmosphere".

This statement could be considered as the pivotal idea for all types of sandstorms. This means that in our discussion of different types of sandstorms we should search for the factors that cause descending motion.

5. TYPES OF SAND STORMS

5.1 FÖHN WIND TYPE

"Föhn" is the name given by the Germans to a current of dynamically heated, subsiding air occurring in the Alps and descending from the high plateau and mountain. This type of wind may cause dust storms in the area near the high plateaux of Utah, Nevada and northern Arizona and in mountainous areas of western Saudi Arabia. A sharp inversion is usually formed between this air and the radiation-cooled shielding layer of the desert basins.

It must not be inferred that every Föhn wind produces a dust storm. The majority of them do not produce more than local dust, either because the dust supply is limited or because the wind strikes the ground only in certain well-exposed places because it is prevented from doing so elsewhere by the shielding layer of cold air. In addition, the Föhn current may be too stable or the wind may not be strong enough to carry dust in any appreciable quantity.

5.2 COLD FRONT TYPE

Belt dust storms, which accompany cold fronts, are common in many areas such as the Middle East, the USA and Australia. The width of such dust storms is in the order of 20 – 40 km and their length, which extends along the cold front, may be of order of few hundred km. As a well-marked cold front moves, the nose of the front establishes itself and turbulence increases with increasing instability and vertical wind shear. This type of dust storm is not a dry one and is sometimes accompanied by a marked increase in relative humidity and a fall in temperature.

Under favourable conditions, the dust raised by a cold front over North Africa may advance south up to 5 N of the equator, following the clockwise circulation of the great desert anticyclone, and may spread over a wide area causing the well-known “Harmattan haze” in central and west Africa.

5.3 THUNDERSTORM TYPE

Dust storms of this type are associated with the development of thundery activity, the downdrafts from which may create turbulent squalls which, on descending steeply to the ground, raise dust causing localized dust storms. The dust raised by the squalls is carried away from the storm edges, resulting in dust storms far from, and mainly ahead of, the thunderstorm cell. Haboob, is a well-known dust storm phenomena in Sudan which is associated with thunderstorms or Cumulonimbus clouds. Haboob may occur at any time of the year, but mainly between May to September.

5.4 DESERT DEPRESSION TYPE

In spring, perhaps the most important synoptic feature over the great African desert is the marked tendency for genesis of desert depressions on either synoptic or slightly sub-synoptic scales. Such depressions generally take a preferred eastward track near the North African coast, over the desert or over the southern Mediterranean. These regions, particularly in spring, are associated with boundary layer baroclinicity as a result of the pronounced contrast in surface temperature between sea and desert air. Moreover, these depressions are associated, in most cases, with strong, hot, dry, and dust laden southerly and southeasterly surface winds blowing in front of them. These winds frequently cause intense temperature and humidity anomalies as well as rising dust and severe dust storms in all of the North African countries.

The existence of a strong phase of the subtropical jet stream and its prevalence over the Sahara for the greater part of the year was considered in some studies that emphasized the role of the jet stream in the formation, evolution and propagation of these Sahara cyclones (El Tantawy, 1968). All of the cases studied, however, were found to be associated with a jet maximum in the upper troposphere. Detailed, quantitative, dynamic and energetic studies have been undertaken for particular cases of a Sahara cyclone (Hassan, 1974, Youssef, 1987). It was found that this type of relatively short wave length sub-synoptic phenomenon, which takes place over a low latitude area of specific configuration (a coastal desert area), can have a free oscillation wave with a period of the order of 24 hours. The diurnal variation in such an area may play an important role in magnifying the amplitude of such a disturbance, due to the effect of resonance (Appendix 1). In such a small active disturbance, the rapid change of mass is a more significant dominating factor than the wind change (Appendix 2). On the basis of the work of Peterssen and Smebye (1971), the cyclogenetic mechanism is very close to type B. This type B mechanism can be summarized as follows:

1. The initial synoptic conditions are a disturbance in the upper troposphere accompanied by an increase of baroclinicity.
2. Kinetic energy is imported into the cyclone domain mainly from the jet stream region.

3. Development commences when a pre-existing upper trough with strong vorticity advection on its forward side spreads over a low-level area of warm advection (or near absence of cold advection).
4. The separation between the upper trough and low-level system decreases rapidly.
5. The amount of thermal advection is small initially and increases as the low-level cyclone intensifies.
6. The amount of vorticity advection aloft is very large initially and decreases toward the time when peak intensity is reached.
7. The amount of baroclinicity in the lower troposphere is relatively small initially and increases as the storm intensifies.
8. Neither a front nor several fronts at the same time can be identified in the domain of the cyclone.
9. The disturbance is relatively fast initially with speed gradually decreasing as the cyclone approaches peak intensity.
10. Cut-off is observed regularly as the cyclone approached peak intensity.

The Sahara cyclone has, in one way or another, the first eight properties of type B. The strong vorticity advection mentioned in (3) may be in the exit region of a jet steam as well. Thus vorticity advection will cause an indirect circulation with strong descent to the right of the jet steam and strong ascent to the left. Through this mechanism, the mass adjusts itself to the local anomaly of the velocity field. The strong subsidence will carry the kinetic energy from the jet stream region to the lower layer mentioned in (2), and it will reach the earth's surface as a hot, dry and dust-laden wind. The indirect circulation will increase the baroclinicity and the thermal advection in the lower layer mentioned in (6) and (7) (Figure 4).

6. ANALYSIS OF INDIVIDUAL DUST STORMS

In the following paragraphs, the wind and vertical motion conditions associated with five synoptic situations will be discussed.

6.1 6TH APRIL 1981 (VERTICAL MOTION CALCULATED BY OMEGA EQUATION)

At 12.00 GMT on 6 April 1981, a shallow depression developed over the Egyptian western desert and was accompanied by a sandstorm. At 08.00 a.m. rising sand reported by many stations spread from the north-west to Cairo and turned into to a widespread sandstorm by midday.

By sunset, the storm moderated. The temperature over Egypt rose to approximately 10°C above its normal values and the relative humidity decreased to 10 per cent. Figures 5 and 6 show the surface charts and sectional map analysis at 1000, 700 and 500 mb covering the storm area for 12.00 GMT on 5 and 6 April 1981. The main features on the 5 April 1981 were an anticyclone centred over northern Europe, extending vertically as an upper ridge, and a cyclone over Syria, appearing as a deep active trough in the upper layers. A weak inverted trough was located on the northern coast of Libya, associated with a thermal ridge which was a part of the dominant baroclinic zone extending parallel to the southern Mediterranean coast.

During the next 24 hours, a short wave in the mid- and upper atmosphere developed. Meanwhile, this short wave trough was moving southward toward Egypt on 6 April 1981 and a closed cyclone, with a 9-mb decrease at its centre,

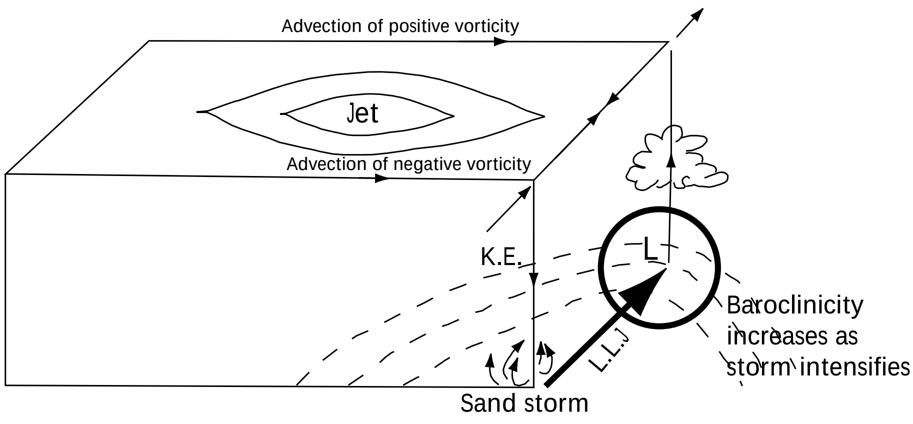


Figure 4. Schematic diagram for duststorm associated with Desert depression.

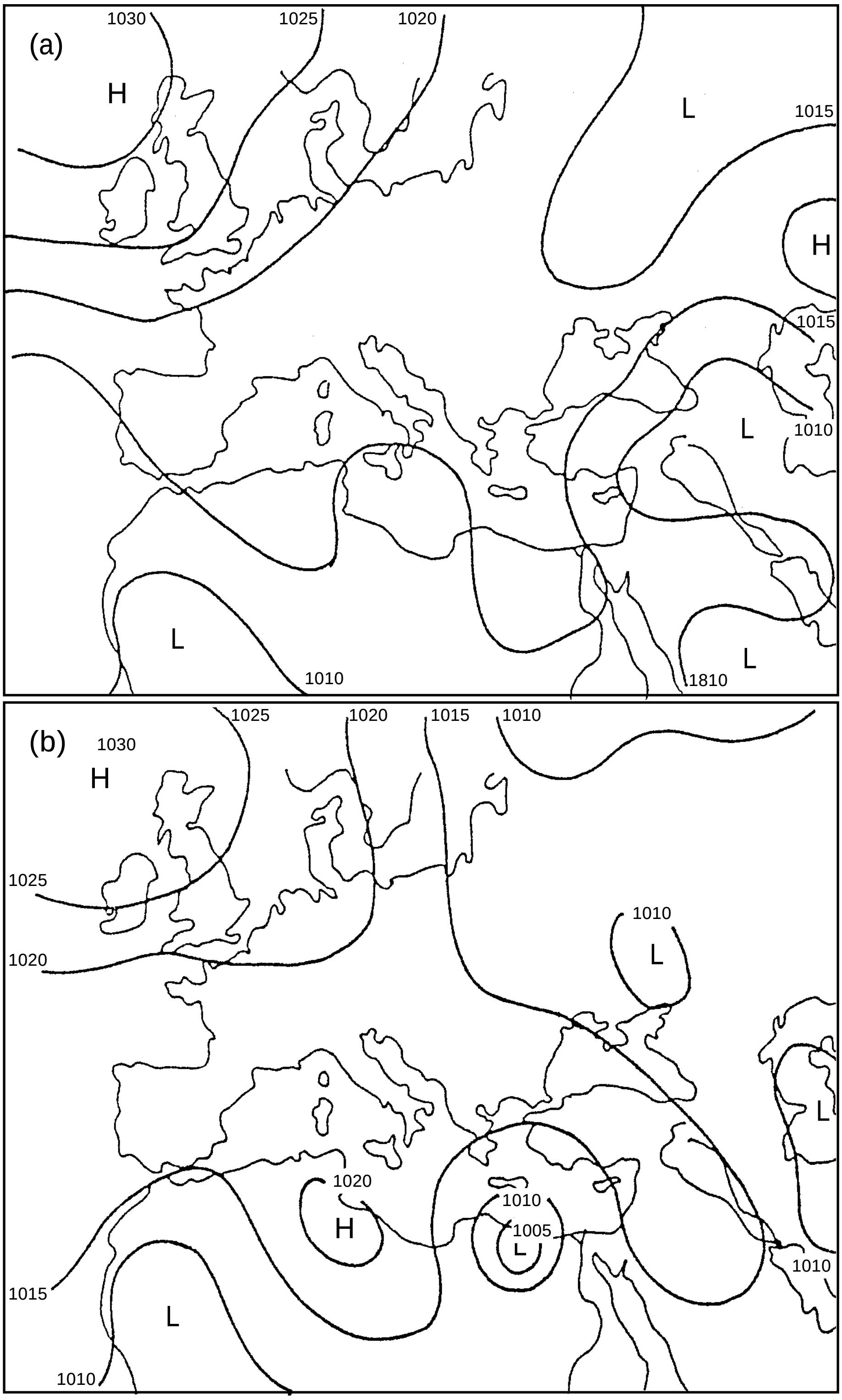


Figure 5. Sea-level pressure analysis for (a) 12.00 GMT on 5 April 1981 (b) 12.00 GMT on 6 April 1981.

then developed. The baroclinic zone, in turn, was reinforced by differential heating associated with the southerly flow. The net result was that the boundary layer air became hot and dry, while an anticyclone developed behind the depression over the Mediterranean accompanied by cold advection.

Figure 7 shows the 300 mb and 850 mb wind field at 12.00 GMT on 6 April 1981. At 300 mb, a strong westerly jet stream extended over the baroclinic zone and a jet stream had been enhanced from 18 m/sec during the previous 24 hours of the depression's development to reach a maximum of 52 m/sec with exit over north-west Egypt. An intense Low-Level Jet (LLJ) with maximum speed of 21 m/sec was apparent over the Egyptian western desert of at 12.00 GMT on 6 April

Figure 6. Height (solid line) and temperature (dashed line) analysis for 12.00 GMT on 5 April 1981 (left) and 12.00 GMT on 6 April 1981 (right). (a) 500 mb; (b) 700 mb and (c) 1000 mb.

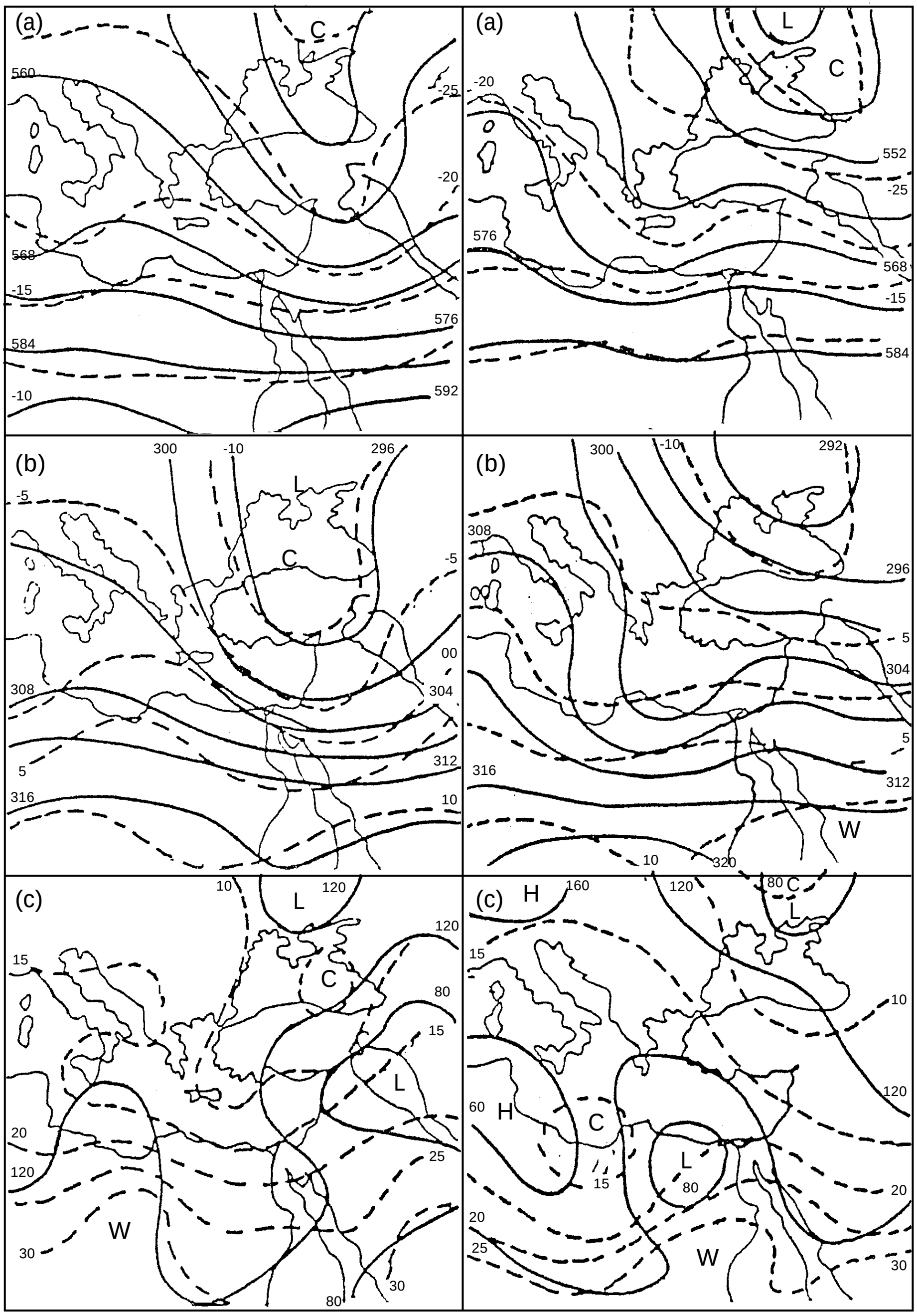


Figure 7. Isotachs at 5 knots interval at 12.00 GMT on 5 April 1981. 300 mb left and 850 mb right.

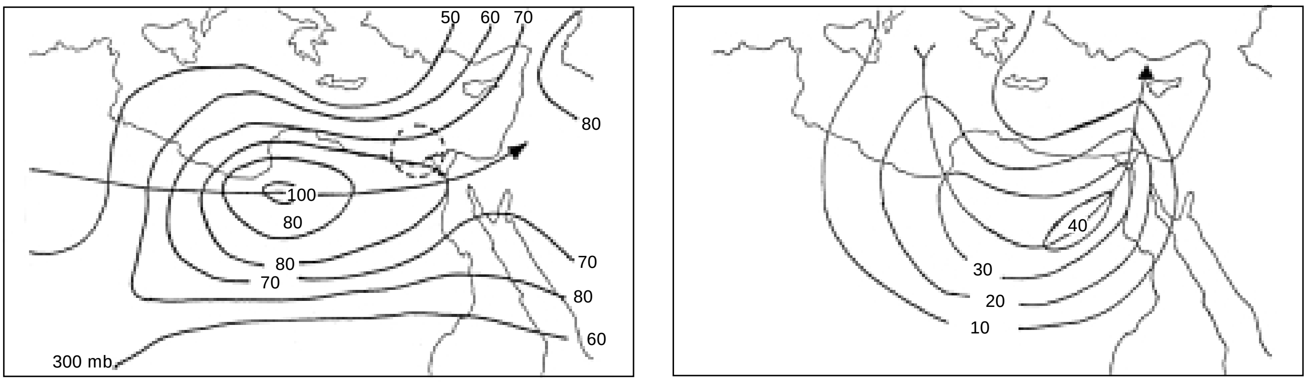
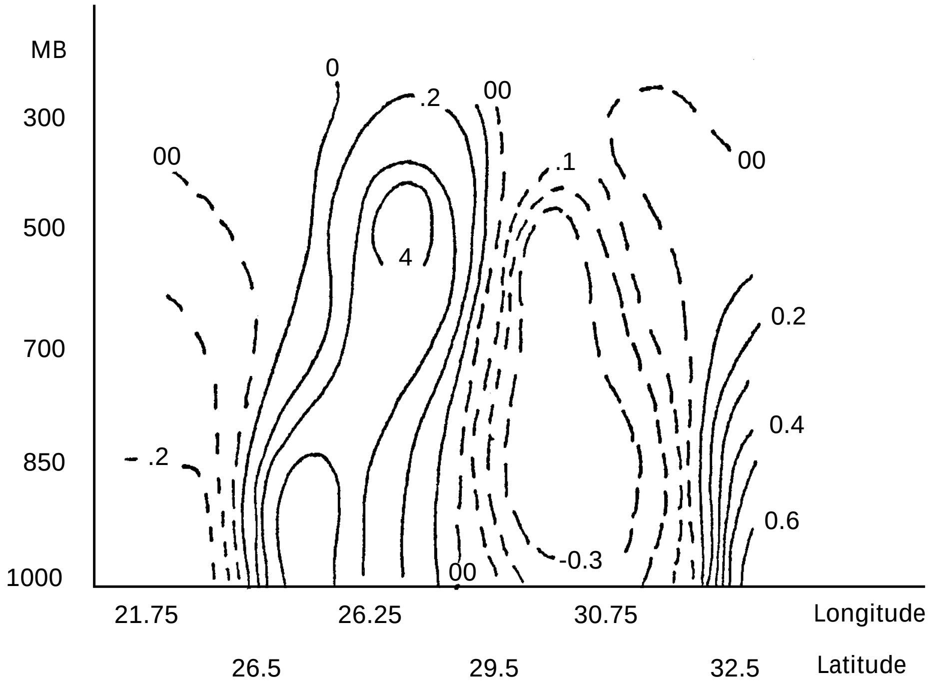


Figure 8. Cross-section along the axis of the LLJ for vertical velocity (Ps S^{-1}) at 12.00 GMT on 6 April 1981.



1981. The induced and enhanced LLJ within the indirect circulation at the exit region of the subtropical jet created an area favourable to cyclonic development.

Figure 8 shows the vertical velocity along a southwest to northeast cross section, obtained by using the omega equation method. The path of the cross-section is approximately through the exit region of the upper jet and along the axis of the low level jet. An interesting feature that appears in the cross-section is the subsidence (0.4 Ps/s) in the warmer air over desert to the right of the upper jet core behind the depression. The feed of cold air southward by the developing anticyclone and the strong subsidence produced the band of thermal gradient shown over the 1000 mb chart resulted in a pressure gradient and an LLJ. Rising motion (greater than 0.35 Ps/s) occurred in the colder air downstream of the LLJ, extending vertically to the cyclonic side of the upper jet. The pattern of vertical motion suggests the existence of an indirect circulation in the exit region of this jet.

6.2 22ND MARCH 1984, 17-18 JANUARY 1985, 20 APRIL 1986 AND 1 APRIL 1987 (VERTICAL MOTION CALCULATED BY CONTINUITY EQUATION)

Figures 9, 11, 13, and 15 represent, respectively, the four stations on 1 April 1987 (situation A), 20 April 1986 (situation B), 22 March 1984 (situation C) and 17 January 1985 (situation D). Each figure comprises four levels: (a) 200 mb, (b) 500 mb, (c) 850 mb, and (d) 1000 mb. These figures cover a relatively wide area that would fully depict all that is associated with the phenomenon within an area extending from the equator to 60°N and from 30°W to 60°E.

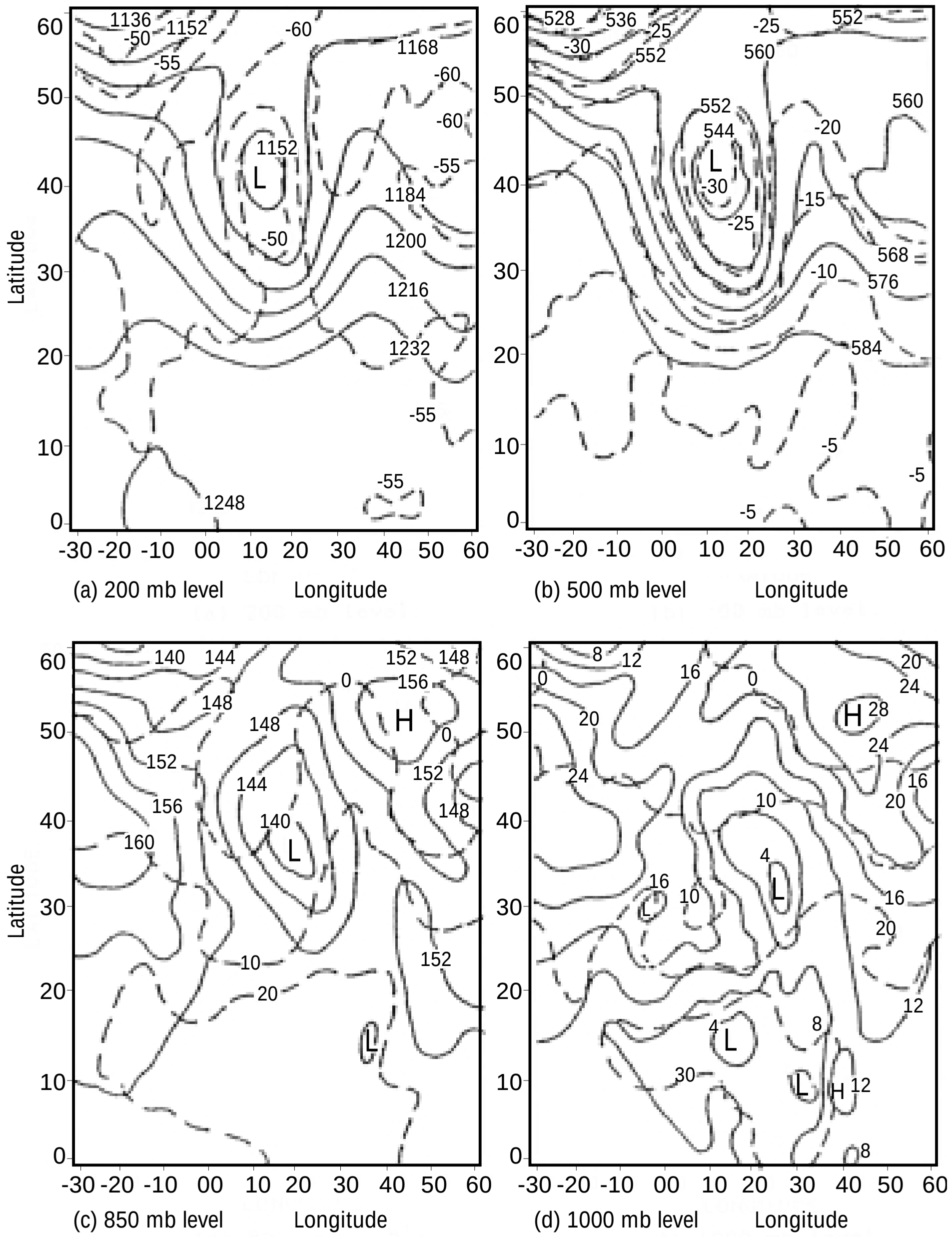
The results achieved by the continuity equation is depicted in Figure 17 which represents time sections for the four situations. Each of them covers five days except the last one which covers six days, since sand storms not only occurred on 17 January 1985 but also on 18 January 1985. These figures clearly show descending motion in the middle of each time section.

Figures 10, 12, 14 and 16 are cross-sections of wind speed for the four stations A,B,C, and D respectively. It is clearly discernible that subsidence is evident in situations in which sand storms occur (A, C and D) accompanied by relatively slow motion following the apparently semi-stationary upper jet stream with a resulting strong surface wind (as a consequence of transferring the momentum from upper levels to the surface).

7. RELATIONSHIP WITH THE EL NIÑO

Z. Fukang and Z. Wenqian (1998) suggest that, when the equatorial east Pacific Sea Surface Temperature (SST) is high, during an El Niño event, descending motion would decrease there and the Walker cell would be suppressed over Asia and the western Pacific. This is favourable to descending motion there and cold

Figure 9. Synoptic charts on 1 April 1987; geopotential heights in decameters (full lines) and isotherms in °C (dashed lines).

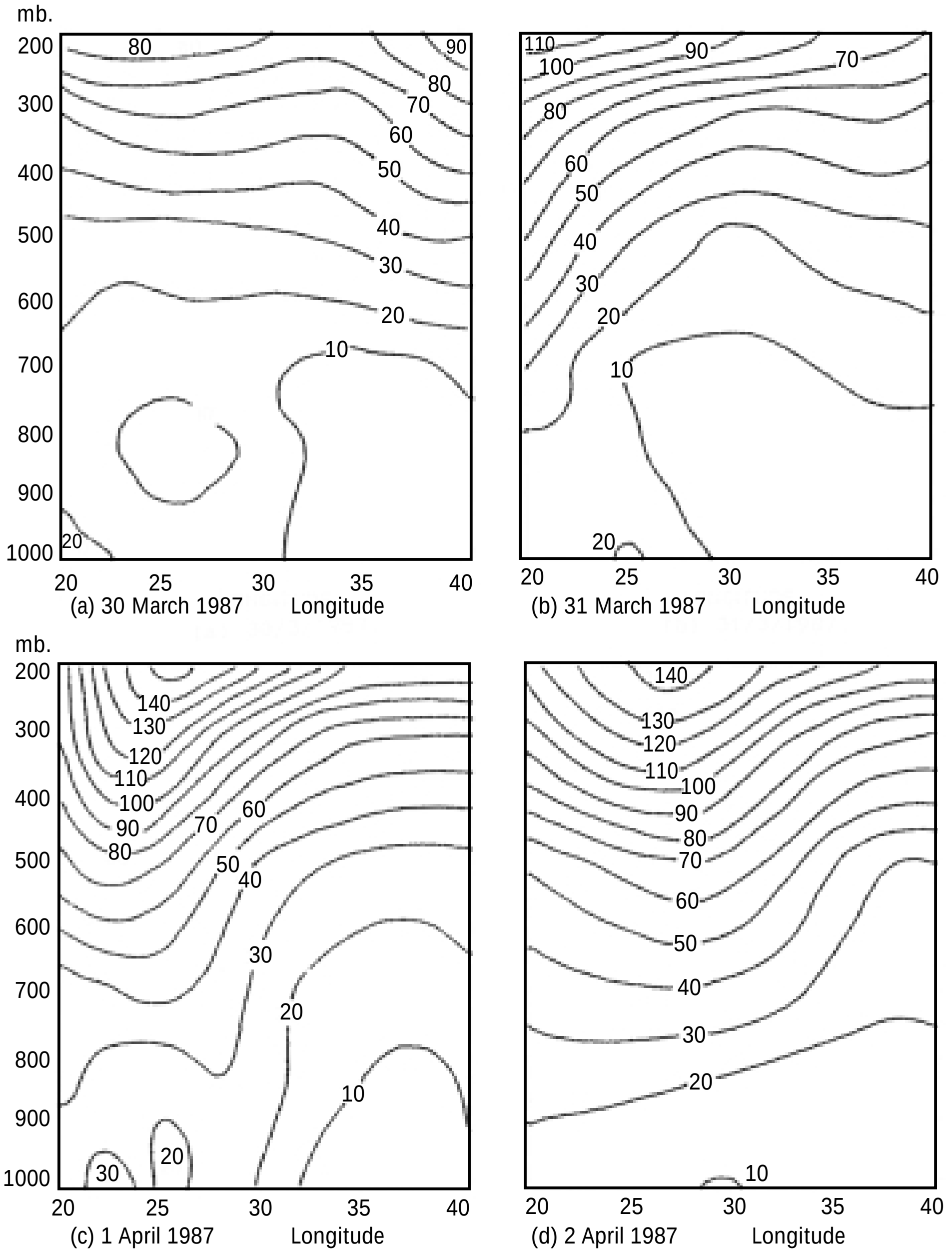


burst. Similarly, when SST is high on most parts of the Indian Ocean, the ascending motion would increase there and the Hadley cell would strengthen over Asia. This is favourable to descending motion there and cold burst as well. They conclude that an El Niño year is one of the large-scale environmental conditions for strong dust storms over Asia.

8. HAZARDS OF DUST STORMS

A violent dust storm can result in great disaster. For example, the “blackstorm”, which formed at Jingchang city in China lasted about five hours and covered about 25 x 104 km^2, created visibility conditions of less than 50 m and the ratio onset of wind speeds of more than 90 km/hr). It caused economic losses of 640 million Yuan and injured or killed about 300 persons (Xia Xucheng, Yang Genshen, 1992). Moreover, sand particles can act as condensation nuclei and cause the rather frequent phenomenon of coloured rain over the southern Balkans and, particularly, over Greece (N.G. Prezerakos, 1998). Dust particles also strongly decrease the acidity of precipitation (Loye-Pilot *et al*, 1986) and it has recently been shown that mineral dust particles in the eastern Mediterranean are often coated with sulphates.

Figure 10. Cross section of wind speed in knots, averaged between 27.5°N and 32.5°N.



REFERENCES

Alpert, P., and B. Ziv, 1989, The Sharav Cyclone: Observation and some theoretical considerations, *Journal of Geophysical Research*, 94, pp. 18493-18514.

El Sabbagh, M.K., 1971, On desert depressions and associated weather phenomena in the Middle East, *The bulletin of the 6th Arab scientific conference*.

El Tantawy, A.I., 1961, The role of jet stream in the formation and steering of desert depression. *The bulleting of the 4th Arab scientific conference*.

Fukang Z. and Z. Wenqian, 1998, *The dustorms in China*, First LAS/WMO international symposium on sand and dust storms (ISSDS-I).

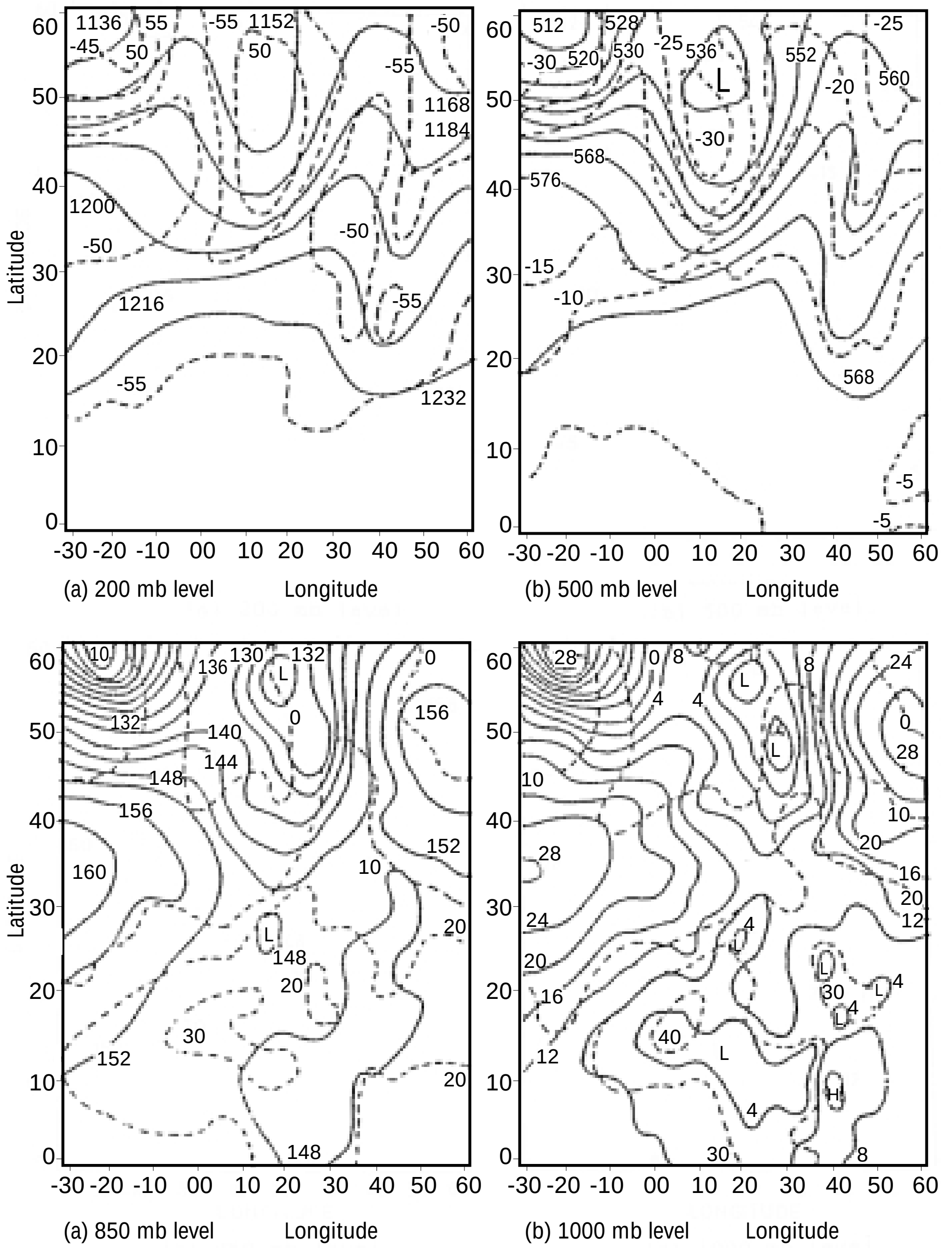
Grigoryan S.A. *et al*, 1998, *Numerical modelling of dust elevationduring storm episodes and its long-range atmospheric transport*, First LAS/WMO international symposium on sand and dust storms (ISSDS-I).

Hassan, A.A., 1974, *A diagnostic study of northern African depressions*, Ph.D. thesis, University of Reading, UK.

Loewe, F., 1943, *Dustorms in Australia*, Commonwealth of australia, Commonwealth of Meteorological Bureau, Bull No. 28.

Loye-Pilot M.D., D. Martin and M. Morelli, 1994, Influence of Saharan dust on the rain acidity and atmospheric input to the mediterranean, *Nature* 371, pp. 123-129.

Figure 11. Synoptic charts on 20 April 1986; geopotential heights in decameters (full lines) and isotherms in °C (dashed lines).



Petterssen, S., and S.J. Smebye, 1971, On the development of extratropical cyclones, *Quarterly Journal of the Royal Meteorological Society*, 97, pp. 457-482.

Prezerakos N.G., 1998, *Dust storms over Sahara desert leading to dust deposit or coloured rain in the south Balkans,* First LAS/WMO international symposium on sand and dust storms (ISSDS- I).

Washington, W.M., 1964, A note on adjustment towards geostrophic equilibrium in a simple fluid system, *Tellus*, Vol. 16 No. 4, pp. 530-534.

Xucheng X., Y. Gengshen, 1992, Blackstorm, *Science Press,* 15.

Figure 12. Cross section of wind speed in knots, averaged between 27.5°N and 32.5°N.

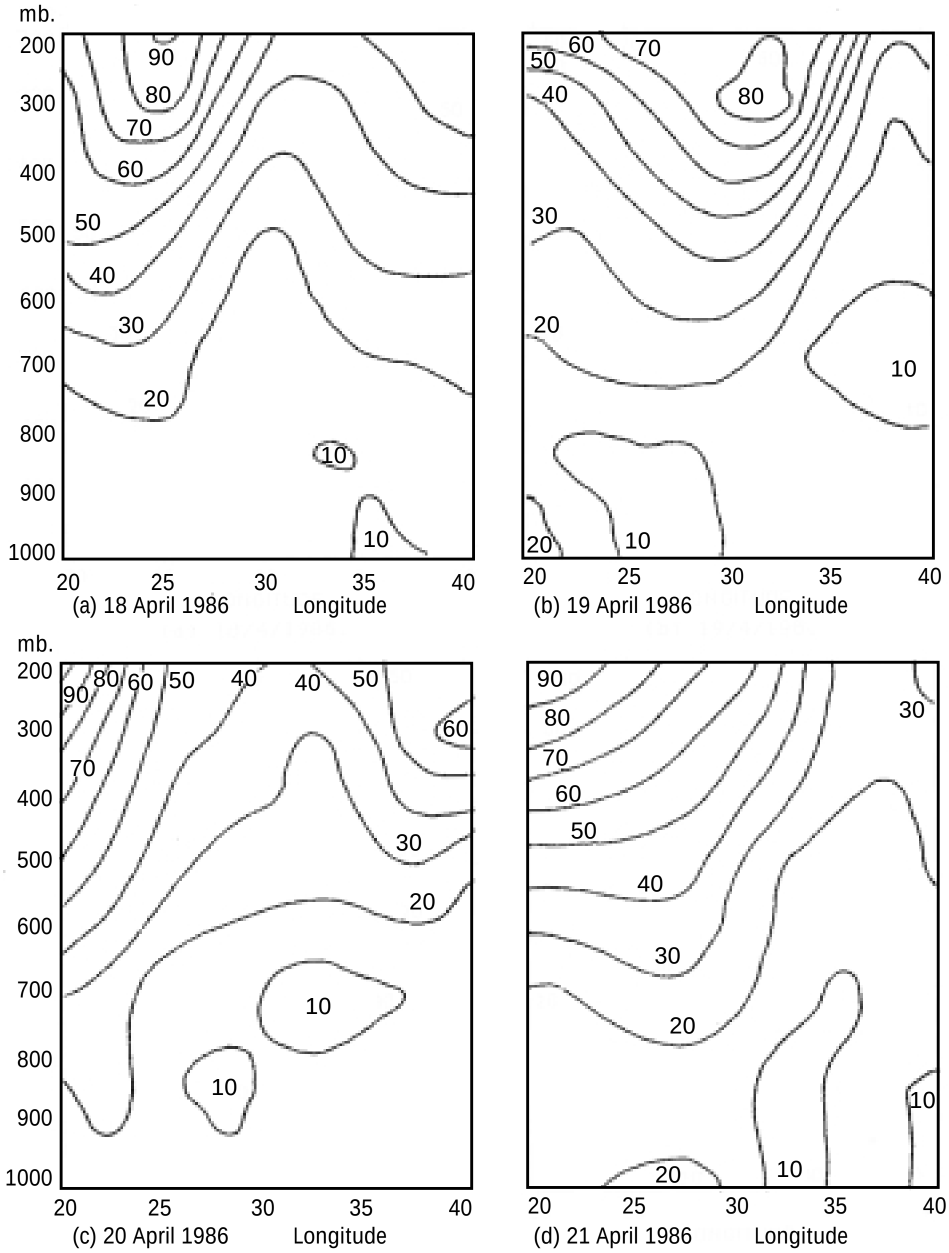


Figure 13. Synoptic charts on 22 March 1984; geopotential heights in decameters (full lines) and isotherms in °C (dashed lines).

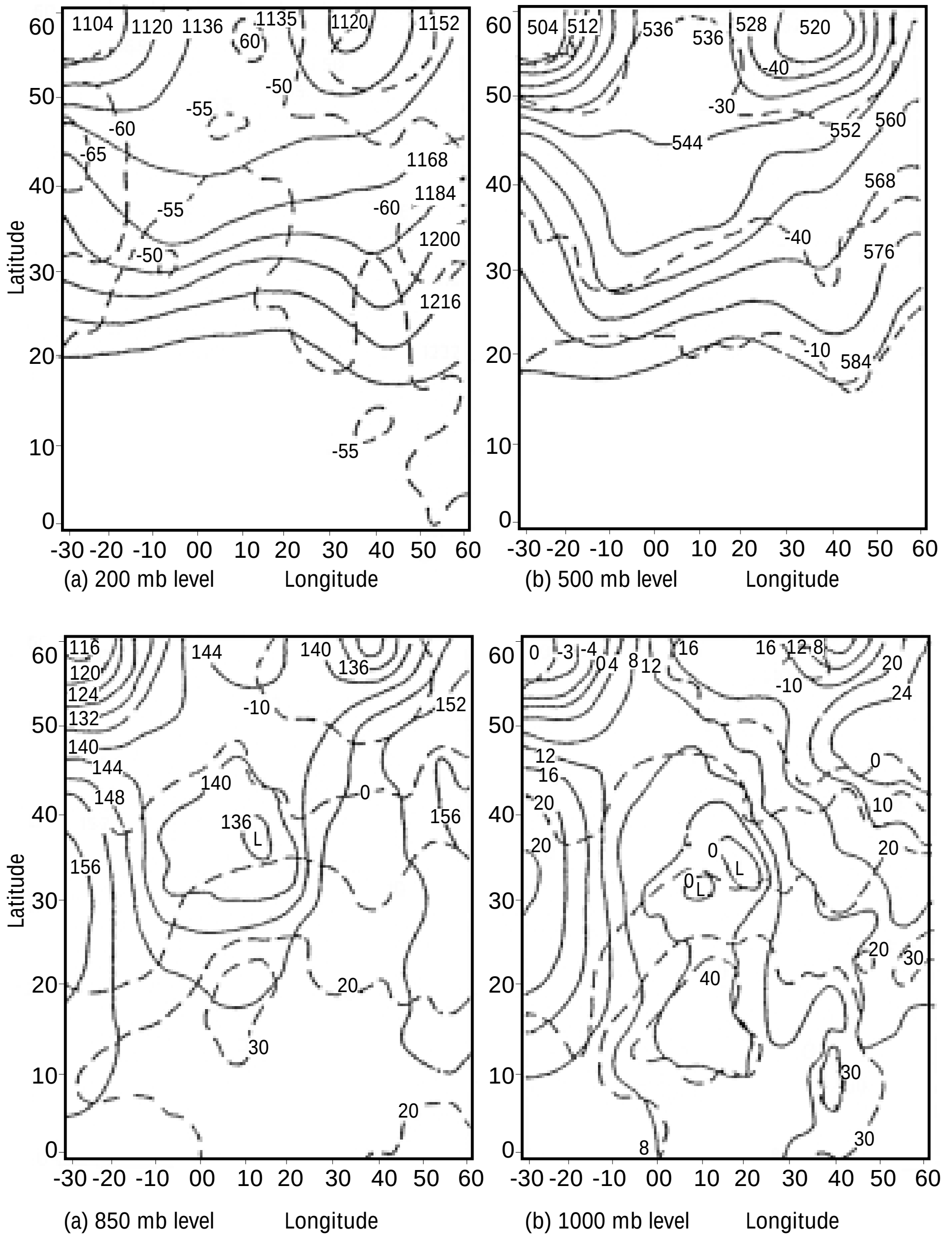


Figure 14. Cross-section of wind speed in knots, averaged between 27.5°N and 32.5°N.

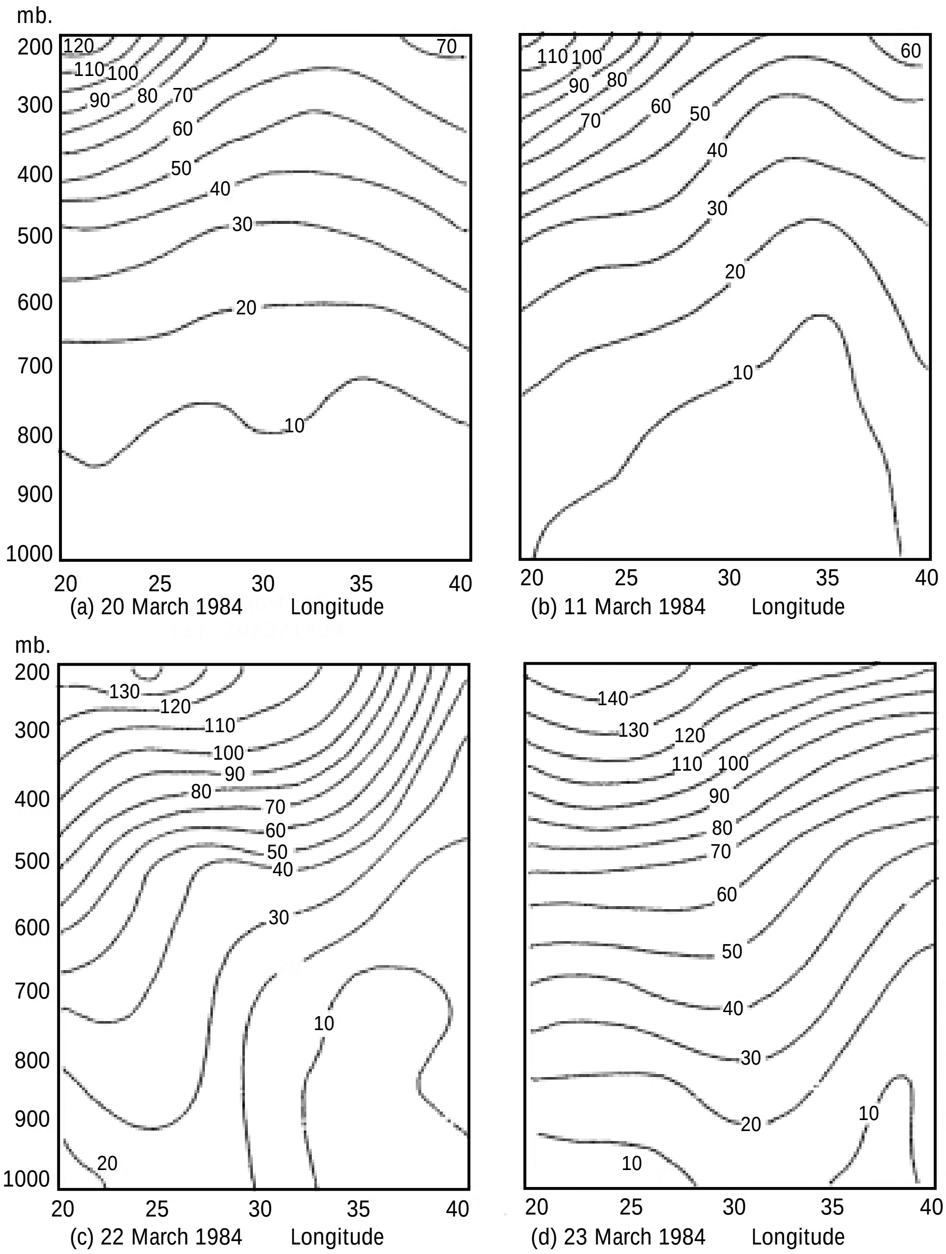


Figure 15. Synoptic charts on 17 January 1985; geopotential heights in decameters (full lines) and isotherms in °C (dashed lines).

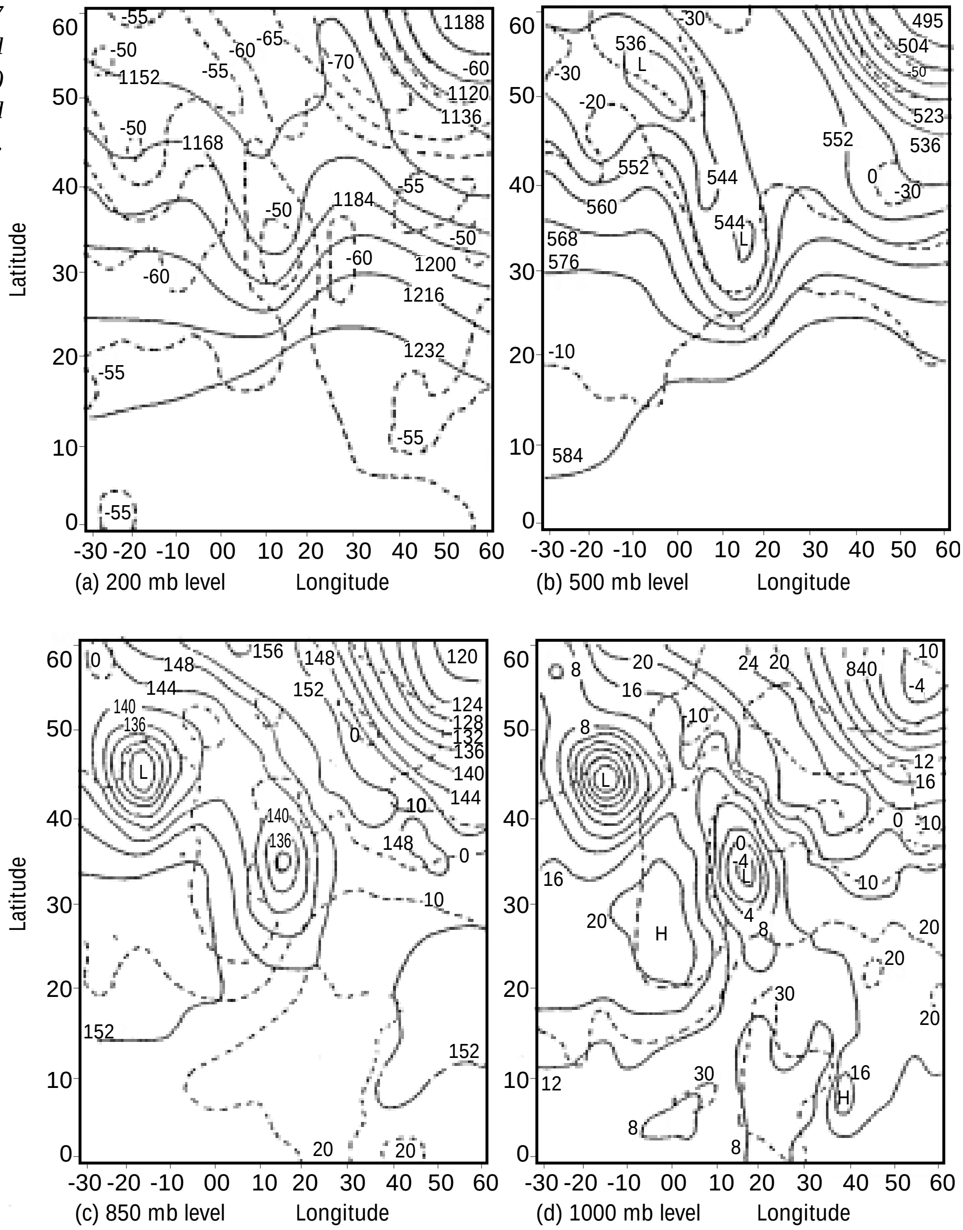


Figure 16. Cross-section of wind speed in knots, averaged between 27.5°N and 32.5°N.

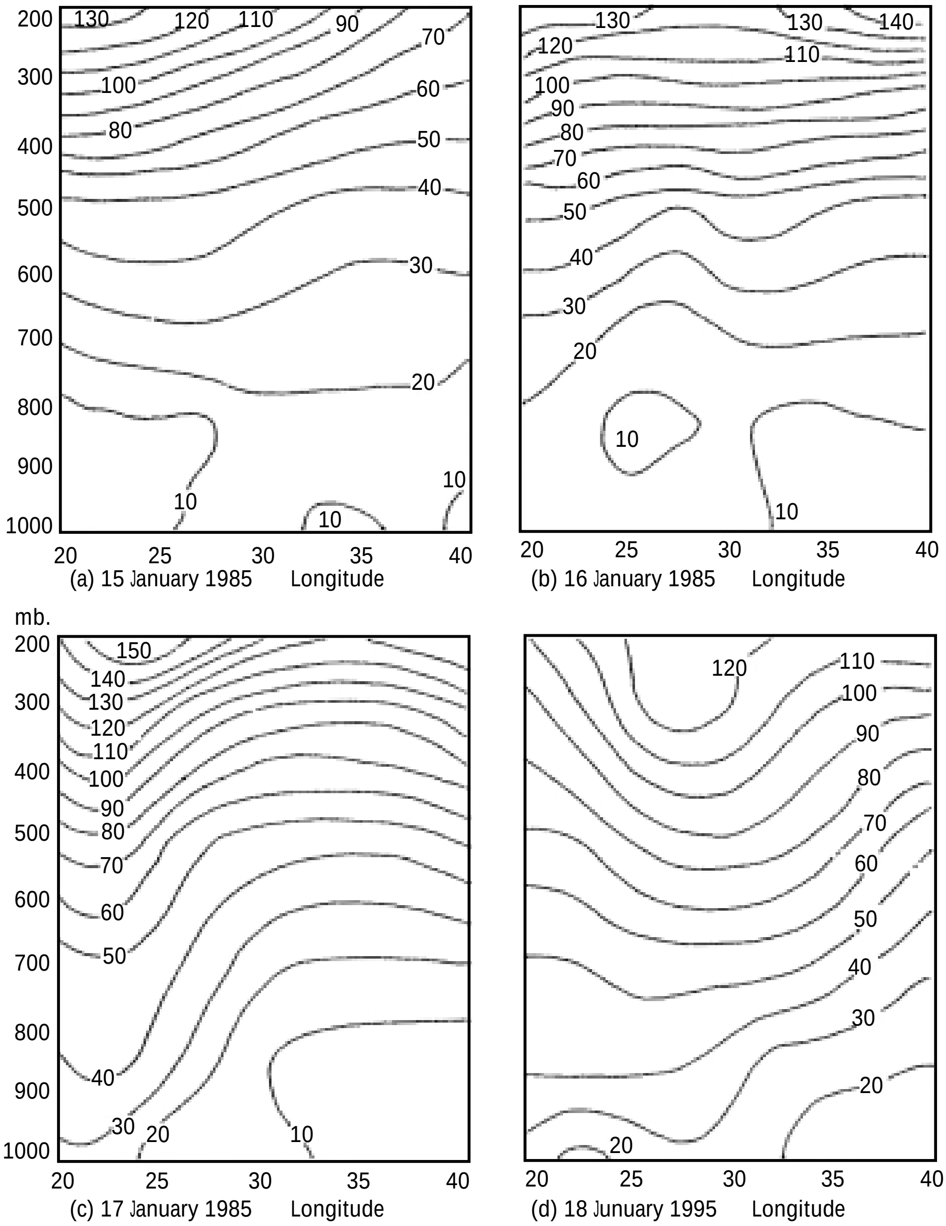
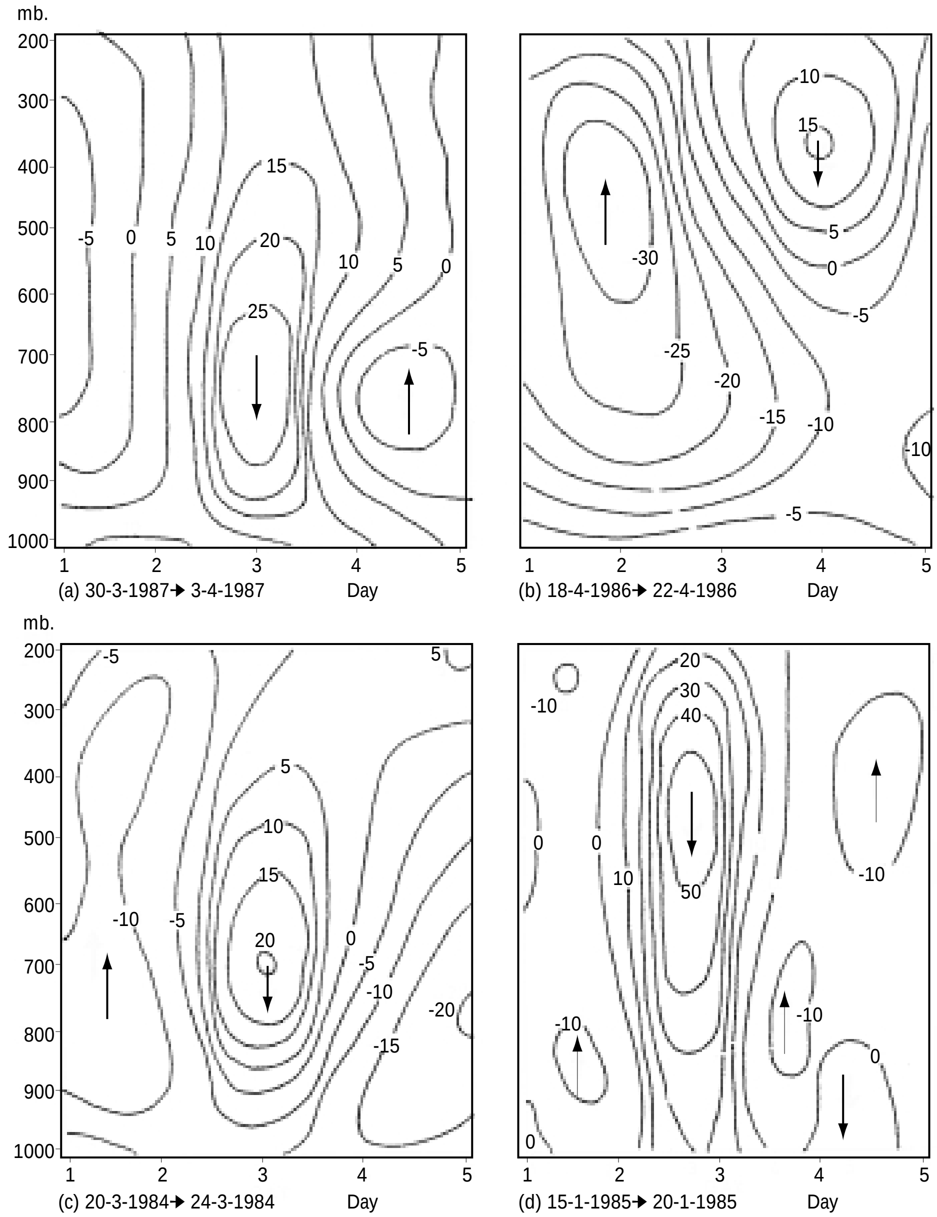


Figure 17. Time section of w. Located at 30°N and longitude averaged between 25°E and 30° E. in 10^{-4} mb/s.



APPENDIX I

FUNDAMENTAL ASPECTS OF RESONANCE

The statement of equation of motion in the form ma = net force, for unit mass and frictionless motion is

$$\frac{d^2u}{dt^2} + f^2u = Ao\ Sin\ wt \tag{I.1}$$

Where f is the natural frequency of the system (f is coriolis parameter for initial oscilation)

Ao Sin wt is the driving force with frequency w.

The general solution for 1.1

$$u = Uo\ Sin\ ft + \frac{Ao\ Sin\ wt}{f^2 - w^2} \tag{I.2}$$

The first term in (1) is the free oscilation.

The period of the free oscillation = $\frac{2TT}{f}$

The second term represents a forced oscillation with constant amplitude and with the same period as the external force.

The resonance phenomenon itself is represented by the result that amplitude becomes infinitely large at $f = w$. At latitude 30 the inertial oscilation has a period = $\frac{2TT}{2\ \Omega\ Sin\ 30} = 24$ hr.

The equation of motion for oscilation with damping

$$\frac{d^2u}{dt^2} + C\frac{du}{dt} + f^2u = Ao\ Sin\ wt$$

where $C\frac{du}{dt}$ is the damping force.

The general solution for oscilation with damping

$$u = Uo\ \bar{e}^{(C^{t/2})}\ \ Sin\left(t\sqrt{f^2 - \frac{1}{4}c^2 + \alpha_o}\right) + \frac{Ao\ Sin\left(wt - B\right)}{\sqrt{\left(f^2 - w^2\right)^2 + 4\,C^2w^2}}$$

where B is the phase angle

$$t\ and\ B = \frac{C\ W}{f^2 - W^2}$$

APPENDIX II

GEOSTROPHIC ADJUSTMENT

Geostrophic adjustment is the mutual adjustment of mass and velocity fields when an initial geostrophic imbalance exists. This process, as shown by Washington (1964), depends critically on the horizontal wave length scale L. If the scale is large compared to the radius of deformation λ [$\lambda = \left(\frac{9h}{f^2}\right)^{\frac{1}{2}}$ where H is the depth of the fluid, f coriolis parameter.
i.e., L > λ, the adjustment is affected primarily through the wind field changes, whereas for smaller scales, L < λ, the mass field changes more rapidly.

To simplify this idea the vorticity, divergence and continuity equations for shallow water incompressible fluid can be written.

$$\frac{\partial}{\partial_t}\nabla^2\Psi = -\,fD + G1 \qquad \text{(II.1)}$$

$$\frac{\partial}{\partial_t}D = f\nabla^2 - \psi\; g\nabla^2 h + G2 \qquad \text{(II.2)}$$

$$\frac{\partial}{\partial_t}h = HD \qquad \text{(II.3)}$$

Where	Ψ	the stream function
	D	the divergence field
	f	coriolis parameter
	H	vertical scale of the atmosphere
	h	perturbation of the height
	G1, G2	are the remaining functions in the equations 1, 2
	i	(lx + my)

Assuming A e
where 1, m are wave numbers

$$\therefore \nabla^2\;\Psi = -\left(1^2 + m^2\right)\Psi$$

Equations (1), (3) could be written in the form

$$\frac{\partial\Psi}{\partial_t} = L^2\; f\; D \qquad \text{(II.4)}$$

$$\frac{\partial}{\partial_t}\frac{gh}{f} = -\frac{gh}{f}D \qquad \text{(II.5)}$$

The above two equations show the rates of changes of Ψ and $^{gh}/_f$ which have been considered as measures for velocity and mass changes. The velocity and mass fields and changing in opposite directions as a response of a divergence field.

$$\text{if } f\,L^2 > \frac{gH}{f} \text{ or } L > \left(\frac{gH}{f^2}\right)^{\frac{1}{2}} = \lambda$$

The velocity changes more rapidly than the mass.
Whereas for smaller scale of L < λ the mass field changes will dominate.

APPENDIX III

MOTORISTS BEWARE!

A dust storm usually arrives suddenly in the form of all advancing wall of dust and debris which may be miles long and several thousand feet high. They strike with little warning, making driving conditions hazardous. Blinding, choking dust can quickly reduce visibility, causing accidents that may involve chain collisions, creating massive pile-ups. Dust storms usually last only a few minutes, but the actions a motorist takes during the storm may be the most important of his or her life.

DUST STORM SAFETY TIPS

- If dense dust is observed blowing across or approaching a roadway, pull your vehicle off the pavement as far as possible, stop, turn off lights, set the emergency brake, take your foot off of the brake pedal to be sure the tail lights are not illuminated.
- Don't enter the dust storm area if you can avoid it.
- If you can't pull off the roadway, proceed at a speed suitable for visibility, turn on the lights and sound the horn occasionally. Use the painted center line to help guide you. Look for a safe place to pull off the road.
- Never stop on the travelled portion of the road.

LIGHTS OUT!

In the past, motorists driving in dust storms have pulled off the roadway, leaving lights on. Vehicles approaching from the rear and using the advance car's lights as a guide have inadvertently left the road and in some instances collided with the parked vehicle. Make sure all of your lights are off when you park off the road.

HEED WARNINGS

During threatening weather listen to commercial radio or television or NOAA Weather Radio for Dust Storm Warnings. A dust storm (or sand storm) warning means: Visibility of 1/2 mile or less due to blowing dust or sand, and wind speeds of 30 miles an hour or more.

NOAA/PA 82002

MITIGATING THE EFFECTS OF EARTHQUAKES: PROBLEMS, PROGRESS AND FUTURE TRENDS

By Alan G. Green; Institute of Geophysics, Zürich

ABSTRACT

Over the past few decades, seismologists have made enormous progress in understanding the physical processes that govern the occurrence of earthquakes. For example, we now know that most earth tremors are generated by stresses that accumulate along the boundaries between the giant tectonic plates that constitute the Earth's outermost rigid layer. Seismologists have estimated the sense of ground displacement to be expected in many seismically active regions, and experience has shown that damage caused by direct shaking of the ground can be augmented markedly by such secondary effects as fires, landslides and tsunamis. Moreover, the number of fatalities and level of damage created by an earthquake are not only dependent on the size and location of the event, but they are also affected significantly by the quality of the buildings and the local ground conditions.

Nevertheless, one of the major goals of seismology, that of short-term (days to weeks) earthquake prediction, remains as elusive as ever. Although some seismologists claim that earthquakes may be predictable in the not-too-distant future, others suggest that their occurrence is essentially random and that research into earthquake prediction may be futile. By comparison, trustworthy earthquake hazard and risk assessments based on time scales of tens to hundreds of years are realizable. In many regions, these assessments are benefiting from the results of global projects aimed at:

(i) compiling dependable earthquake statistics,
(ii) ascertaining the present state of stress and strain rate,
(iii) mapping the distribution of active faults,
(iv) determining the rate of seismicity in the distant past, and
(v) estimating the expected level of ground-shaking by means of computer modelling. Furthermore, fast inexpensive computer technologies are allowing early warning and early-damage assessment strategies to be developed, such that disaster response personnel can be either forewarned of damaging waves approaching or informed where the most intense ground-shaking has occurred.

As the International Decade of Natural Disaster Reduction (IDNDR) comes to an end, it is appropriate to consider how mitigation and preparedness measures for the natural disasters that will inevitably affect our planet may be better promoted and implemented. One approach is to concentrate our efforts on the large urban centres of the developing world, where the effects of natural disasters can be devastating to the people, their economy, their culture, and their environment. Several programs aimed at improving capacities for natural disaster mitigation and preparedness in the megacities of the developing world are currently underway.

1. INTRODUCTION

Earthquakes are amongst the most damaging natural phenomena to affect the Earth. Since the beginning of this century, more than two million people have lost their lives as a direct or indirect consequence of violent shaking of the ground. Two of the three most costly natural disasters to strike our planet since 1980 were the Northridge (California) and Kobe (Japan) earthquakes. Economic losses due to the Northridge event exceeded $30 billion and those due to the Kobe exceeded $100 billion. Although these were only moderate magnitude earthquakes (Northridge: 6.8; Kobe: 6.9), they generated ground accelerations over large areas that approached or exceeded that of the Earth’s gravitational field. These events were not the so-called "Big Ones”, which will eventually strike California and Japan. The Big Ones are likely to have magnitudes greater than 8, resulting in the release of thirty times more energy than either the Northridge or Kobe earthquakes. Based on recent experiences, losses due to the Big Ones in

California and Japan are expected to exceed $300 billion and an astounding $1 000-2 000 billion, respectively.

Most of the world's earthquakes (more than 95 per cent) are focused along the boundaries of tectonic plates (Figure 1). Although it is certain that earthquakes will continue to shake these same narrow zones, we cannot predict exactly when an earthquake will happen and how much energy it will release. A relatively small number of earthquakes (less than 5 per cent) occur within the plates themselves. Some intra-plate earthquakes are associated with active volcanoes overlying mantle plumes (e.g. Hawaii in the middle of the Pacific plate), whereas others are related to rifting within the continents (e.g. East African Rift). There is also a class of intra-plate earthquake that we really do not understand. Outstanding examples are the huge earthquakes that struck Missouri and Southern Carolina (southeastern United States) during the last century.

In addition to damage caused by direct shaking of the ground during an earthquake, secondary effects such as fires (through the rupture of gas lines), landslides and tsunamis can be equally or more devastating than the earthquake itself. A major problem that invariably occurs, even in the best prepared countries and cities, is the destruction of critical communication and other lifeline systems. Roads and railways often become impassable (Figure 2), telephone systems are either broken or choked by excessive use, electricity is interrupted so that television and radio stations cannot broadcast and water systems, which are required for extinguishing fires, are broken.

2. CONSTRUCTION PRACTICES AND GROUND CONDITIONS MAKE A DIFFERENCE

Experience has demonstrated that the number of fatalities and amount of damage caused by an earthquake are not only related to its magnitude, depth and geographic coordinates, but also to the quality of the affected buildings and the nature of the ground on which they are constructed. Two comparisons illustrate well the difference that construction practices and ground conditions can make. In 1960, a magnitude 5.9 earthquake caused around 12,500 deaths in the Moroccan city of Agadir. These fatalities resulted from the collapse of primitively built stone and brick houses situated on loosely consolidated sediments. In contrast, a slightly larger earthquake of magnitude 6 within the crystalline crust of the Canadian Shield shook a large region of northeastern North America in 1988. No deaths resulted from this event. Typical houses in this region are wood-framed with relatively light roofs.

In December 1988, a magnitude 6.9 earthquake devastated a large part of northwestern Armenia. Many poorly reinforced concrete buildings completely collapsed. As a consequence, more than 25 000 people lost their lives. Nearly one year later, an earthquake with magnitude 7.1 hit the Loma Prieta area of California. It caused much damage, but the extent and number of deaths were four hundred times lower than in Armenia. The key difference between the two earthquake zones was in the quality and type of buildings.

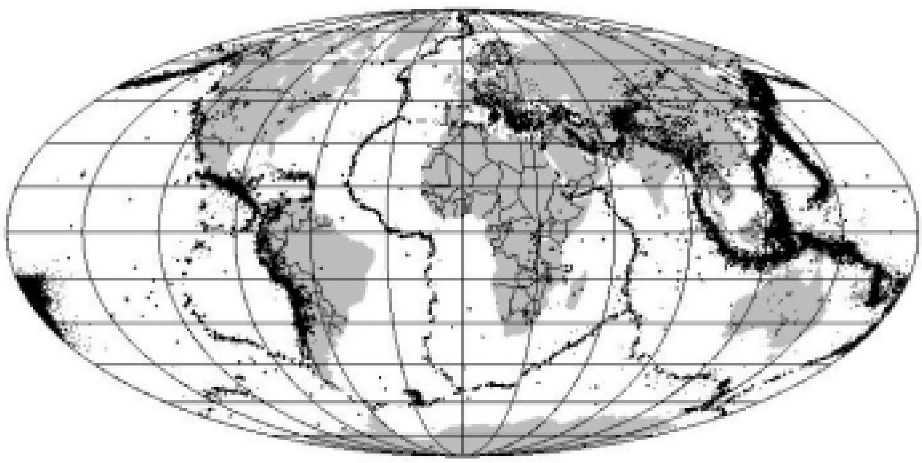


Figure 1. Earthquakes located during the period 1995-1998 by the Prototype International Data Center (Arlington, Virginia).

Figure 2. Spectacular collapse of the Hanshin Expressway as a result of the 1995 Kobe earthquake (Reproduced from the Kobe Geotechnical Collection, University of California, Berkeley).

3. EARTHQUAKE PREDICTION

Although earthquake prediction continues to be a hot topic of discussion, the optimism in the 1970s and 1980s that reliable means to predict earthquakes would soon be available has turned out to be ill-founded. Only a very few of the millions of earthquakes recorded since 1970 have been predicted ahead of their occurrence. In the context of earthquake prediction, the following physical phenomena have been investigated (Wyss, 1997; Geller, 1997):

1. Changes in seismicity patterns;
   - foreshocks — increase of seismicity prior to a major earthquake;
   - seismic quiescence — decrease of seismicity prior to a major earthquake;
   - seismic gaps — inactive segments of seismically active faults;
   - increased moment release — increase release of seismic energy over a wide area prior to a more localized major event;
   - M8 algorithm — combination of statistical parameters based on observations of seismic quiescence and increased seismicity;
2. Variations in groundwater level, chemistry and temperature;
3. Crustal deformation;
4. Temporal anomalies in the earth’s electrical, electromagnetic, magnetic, gravity and/or thermal fields;
5. Changes in seismic wave velocity;
6. Extraordinary behaviour of animals;
7. Unusual atmospheric conditions (e.g. strange noises, bright lights in the sky).

Although precursory phenomena have been observed prior to a small number of earthquakes, none of the proposed prediction techniques appears to be generally applicable. Some geoscientists have suggested that earthquakes belong to a class of physical processes governed by “self-organized criticality” and are, therefore, not predictable on a short-term basis. There is an ongoing controversy regarding the wisdom of large expenditures directed towards earthquake prediction. Competing arguments can best be summarized by the following two sets of statements:

> "Theoretical work suggests that faulting is a non-linear process which is highly sensitive to unmeasurably fine details of the state of the Earth in a large volume, not just in the immediate vicinity of the hypocentre. Any small earthquake thus has some probability of cascading into a large event. Reliable issuing of alarms of imminent large earthquakes appears to be effectively impossible." (Geller, 1997),

which has been countered by:

> "However, based on measurements of elastic strain accumulation and release before and during large earthquakes, most seismologists believe that after a maximum credible earthquake, the crustal volume in which it occurred is not capable of another until sufficient elastic strain energy has been accumulated again. This process typically takes in excess of 100 years. Thus, most seismologists believe that the random element in triggering large ruptures plays an important role, and that this impairs the capability of short-term [days to weeks] predictions, but that intermediate- and long-term predictions are not affected by this problem". (Wyss, 1997).

4. EARTHQUAKE FORECASTING: HAZARD AND RISK ASSESSMENT

Provided there are sufficient details on the history of seismicity and a thorough understanding of the prevailing tectonic regimes, the general level of seismicity to be expected across a broad area can be forecast for periods ranging from decades to centuries. This information is provided in the form of local and regional hazard maps. Hazard is defined as the probability of a certain area being affected by a potentially destructive process within a given time. For example, a typical seismic hazard map shows the maximum level of ground motion that has a certain probability (e.g. 10 per cent) of being exceeded within a defined period of time (e.g. 50 years). To improve the reliability of hazard maps, several high-profile global projects have been initiated over the past decade to:

- compile dependable earthquake statistics for most regions of the world;
- ascertain the current state of stress and strain rate;
- map the distribution of active faults throughout the continents;
- determine the timing and distribution of seismicity in the distant past by archeo- and paleoseismological investigations;
- estimate the expected level of ground shaking at various locations affected by large earthquakes via modelling studies based on detailed knowledge of the subsurface geology (Figures 3 and 4).

One highly successful international project (Global Seismic Hazard Assessment Program [GSHAP]) has involved the computation of hazard maps for most regions of the world based on relatively uniform databases, standard criteria and identical computational procedures (Giardini *et al.*, 1999). Through this project, nearly all countries now have regional seismic hazard maps, and estimates of seismic hazard are continuous across most international boundaries.

Once reliable seismic hazard maps are available, the next stage is to improve our understanding of the risk associated with earthquakes. Risk is a measure of the possibility of loss of lives, property, production capacity etc. within an area subjected to hazard. Risk is defined as the product of hazard, vulnerability and

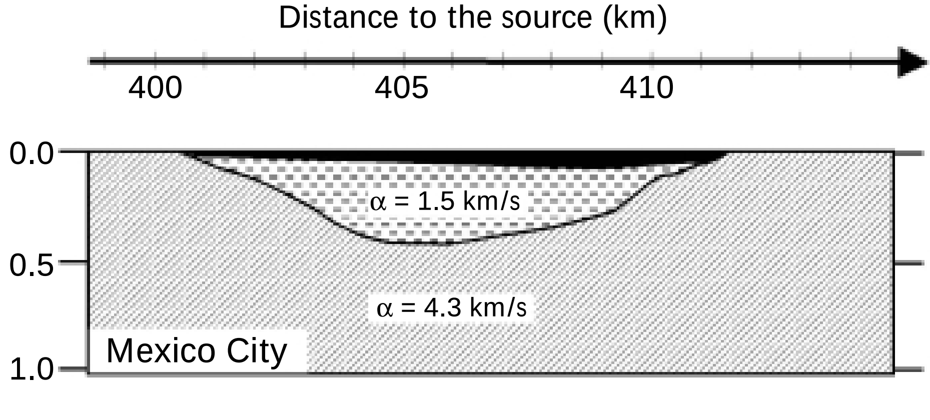


Figure 3. Simple model of the sedimentary basin underlying Mexico City. Used for the computation of ground response due to an impinging earthquake wave (modified from Fäh *et al.*, 1994).

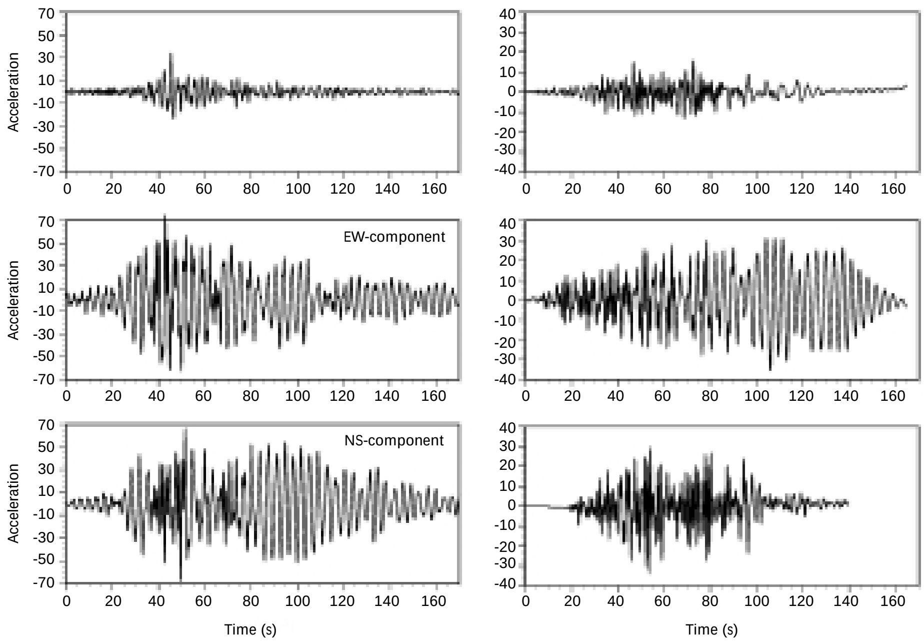


*Figure 4. For the 1985 magnitude 8 earthquake landward of the Central American Trench (see Figure 5), comparison of (A) recorded ground motion within Mexico City with (B) that predicted from the simple sedimentary basin model of Figure 3 (*modified from Fäh *et al.*, 1994).

value. To estimate risk, in addition to having sufficient hazard information at hand, we need to perform for each region a vulnerability study and a standardized inventory of populations, buildings, lifelines, transportation systems and critical facilities.

5. EARLY WARNING SYSTEMS

Although there is no general method for predicting earthquakes, there are a limited number of regions in the world where it is possible to warn urban managers and citizens of approaching seismic waves from relatively distant, but potentially damaging earthquakes. Early warning systems are comprised of:

- one or more seismographs immediately above the active earthquake zone;
- computers that can estimate very quickly (in a few seconds) the magnitudes; occurrence times and locations of earthquakes from the seismographic records;
- very fast communication links between the seismographs, computer systems and urban centres; and,
- effective means to transmit information to critical facilities and the general public.

After the onset of a large earthquake, it may take several seconds to more than a minute for dangerous shear and surface waves to hit an exposed urban center. During this time, the earthquake parameters have to be reliably determined, the information distributed, and the necessary precautionary actions implemented. In addition to enabling the public to take appropriate safety measures to protect themselves, early warning systems may be used to trigger the cessation of oil and gas flow through pipelines, the re-routing of electricity, the safe shutdown of oil refineries and nuclear power plants, the slowdown of high-speed trains, and the saving of crucial information on computer discs.

Presently, early warning systems of different sophistication and purpose are operational in three countries: Japan, Mexico and Taiwan (Lee and Espinosa-Aranda, 1999). A fourth system is currently under development in Romania (Wenzel *et al.*, 1999). Only the Mexican early warning system is capable of issuing earthquake alerts to the general public. It was developed after a magnitude 8.1 earthquake devastated a broad area of Mexico City in 1985. This earthquake actually occurred 350 km from the city, within the Central American Subduction Zone (Figure 5). Nevertheless, it resulted in 10 000 deaths within the city limits, 50 000 injuries, 250 000 homeless, and US $5 billion worth of damage. The 1985 earthquake was not an isolated event. Since the beginning of this century, 28 earthquakes with magnitudes greater than 7.7 have shaken this region (Figure 5). Earthquakes along the Central American Subduction Zone generate high-amplitude shear and surface waves that may take more than one minute to reach

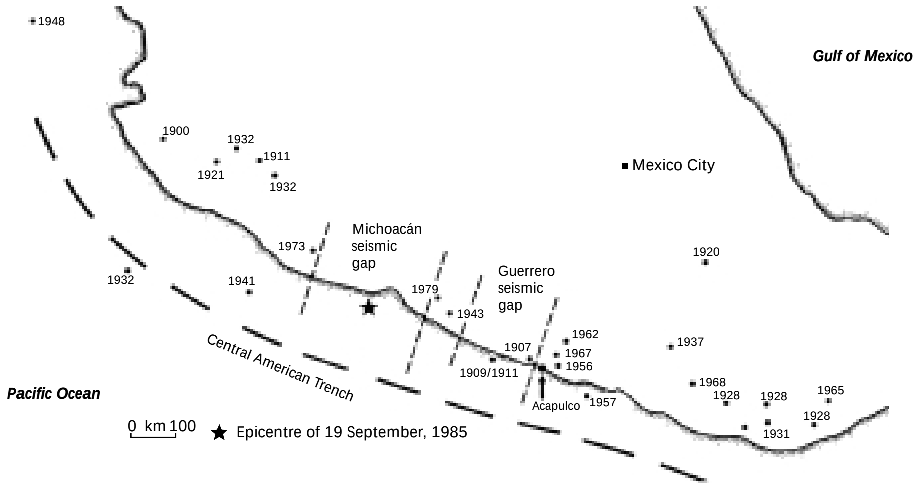


Figure 5. Map showing Mexico City relative to seismicity of the Central American Subduction Zone. Locations of earthquakes with magnitudes greater than 7.7 are displayed (Degg, 1992).

Mexico City, thus allowing adequate time for warnings to be broadcast. According to Lee and Espinosa-Aranda (1999), this system has already been responsible for one successful earthquake alert. In September 1995, it broadcast information that gave a 72-second warning to the general public of high-amplitude seismic waves arriving from a magnitude 7.3 earthquake.

Even for those cities built directly above dangerous earthquake zones, rapidly available information on the level of ground shaking affecting each region during a major earthquake may be used to implement many of the safety measures and actions mentioned above. Furthermore, such information enables disaster relief officials to direct their efforts to locations where injured citizens are likely to require emergency aid and where critical facilities are likely to have been damaged. A key element in early warning and early damage assessment strategies is the availability of real-time systems that very quickly provide earthquake parameters and supply estimates of ground-motion throughout an affected area. The introduction of inexpensive, yet very fast electronic and computer-based technologies is allowing low-cost and ever more effective systems to be developed.

6. PROMOTING EARTHQUAKE MITIGATION AND PREPAREDNESS

Effective disaster management requires that strategies for mitigation and preparedness be in place before an earthquake occurs and that swift measures for the response, recovery and reconstruction be implemented subsequent to the event (Figure 6). Immediately after a major earthquake, details of the catastrophe are likely to be newsworthy on a global scale. Typically, national and international relief agencies provide the necessary resources for rapid response and partial recovery, with emphasis on reducing the death toll, minimizing human suffering, restoring crucial lifelines and re-activating commercial activities. Funds for the reconstruction phase are generally much more difficult to obtain, and in only a few countries are appropriate mitigation and preparedness strategies in

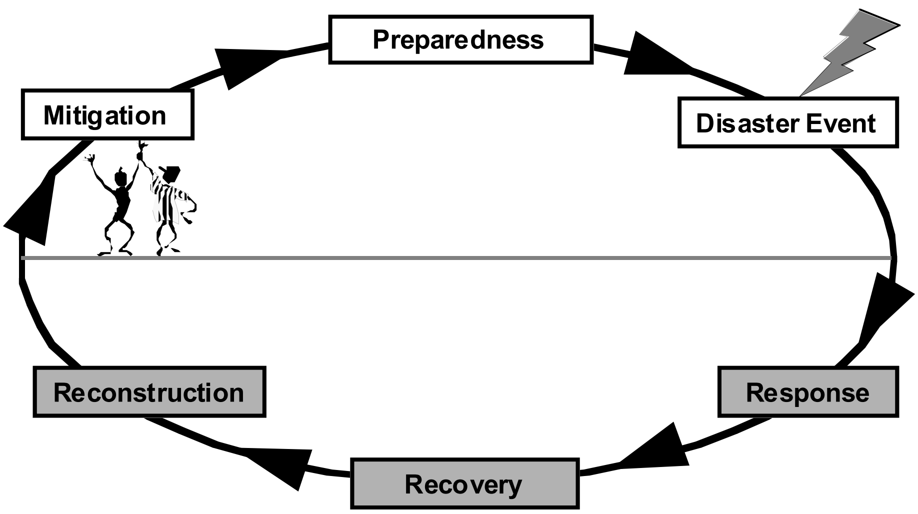


Figure 6. Cycle of disaster management (The Institution of Civil Engineers, 1995).

place. Yet, it has been estimated that for every dollar spent on the protection side of the disaster mitigation cycle (Figure 6), ten dollars are saved on the recovery side; efficient earthquake mitigation and preparedness strategies make economic sense.

A common mission of several projects contributing to the International Decade of Natural Disaster Reduction (IDNDR) is to markedly increase the resources directed towards earthquake mitigation and preparedness. Here, three international projects shall be mentioned briefly (WSSI, GHI, RADIUS) and a fourth (EMI) reviewed in a little more detail.

One of the first projects to become truly operational as a result of IDNDR was the World Seismic Safety Initiative (WSSI), which was initiated in 1992 by the International Association for Earthquake Engineering. The goals of WSSI are to:

- disseminate state-of-the-art earthquake engineering information;
- incorporate experience and research findings into recommended practices and codes;
- advance engineering knowledge through problem-focused research;
- encourage governments and financial institutions to establish policies directed towards understanding and preparing for future earthquakes.

Countries in which WSSI has been particularly active include Bangladesh, Burma, Malaysia, Nepal, Singapore, Sri Lanka, Uganda and Vietnam.

GeoHazards International (GHI) was established in 1993 as a non-profit organization dedicated to reducing earthquake-related death and injury in developing countries. Until quite recently, GHI concentrated on two high-profile development and training projects, one in Quito (Ecuador) and one in Katmandu (Nepal). Over the past two years, GHI has also been a major contributor to the IDNDR project “Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disaster (RADIUS)”. The principal objectives of the RADIUS project are to raise the awareness of earthquake risk among decision makers and the general public, and to provide them with appropriate earthquake mitigation technologies. Specific components of RADIUS include the development of:

- seismic damage scenarios for several cities;
- a practical manual for seismic damage assessment in urban areas;
- guidelines for simple assessment of seismic safety of buildings and for practical retrofitting.

Cities chosen for full-case study by RADIUS are Addis Ababa (Ethiopia), Guayaquil (Ecuador), Tashkent (Uzbekistan), Tijuana (Mexico) and Zigong (China). Also under investigation are the cities of Antofagasta (Chile), Bandung (Indonesia), Izmir (Turkey) and Skopje (TFYR Macedonia).

6.1 EARTHQUAKE AND MEGACITIES INITIATIVE (EMI)

The Earthquakes and Megacities Initiative (EMI) is an international scientific non-governmental organization dedicated to the acceleration of earthquake mitigation, preparedness and recovery of large urban centres, with emphasis on developing countries. EMI has many goals in common with other IDNDR-oriented projects. One difference is its concentration on problems associated with very large cities. Growth in world population and urbanization is truly alarming. By the year 2000 it is expected that 450 cities with populations greater 1 million inhabitants will crowd our planet. Of these, 50 cities with populations more than 3.5 million and 25 with populations greater than 8 million will compete for limited space and resources (Figure 7). More than half of these cities will be located in the developing world, of which 50 per cent will be situated in major earthquake zones (compare Figures 1 and 7). EMI's multidisciplinary scientific agenda includes four major themes:

Assess earthquake hazard by:

- modelling ground motion for realistic earthquake scenarios;
- encouraging the installation of local seismographic and strong-motion networks.

Determine vulnerability and risk by:

- reviewing the effectiveness of building codes and their implementation;
- developing methodologies for collecting standardized inventories of buildings, lifelines, transportation systems and critical facilities;

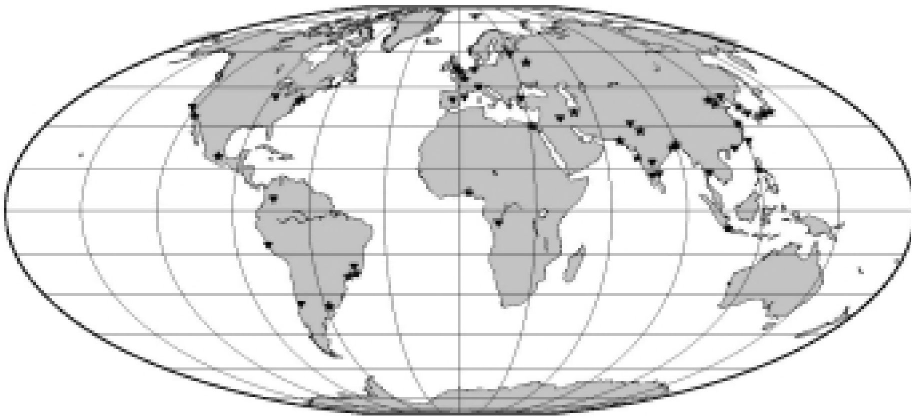


Figure 7. Map showing the locations of large urban centers: ★ — megacities with populations greater than 8 million, ▼ — large cities with populations greater than 3.5 million.

- applying damage-loss estimation models that include economic and social impact;
- modelling disaster scenarios for emergency preparedness and response.
- Evaluate options for sustainability by
- examining the effects of cultural differences in perceptions and response to risk;
- studying earthquake constraints on the long-term sustainability of megacities;
- investigating the technical, social, political, historical and economic factors that would allow earthquake mitigation measures to be integrated in urban planning policy at different government levels.

Promote earthquake mitigation and preparedness by:

- designing regional-dependent educational programs aimed at earthquake preparedness and earthquake awareness;
- promoting special procedures to protect cultural heritage items and monuments;
- advocating new construction methodologies for non-engineered buildings and new training programs for local builders;
- promoting seismic code provisions to encourage cost-effective retrofitting;
- encouraging improvements in emergency response coordination and communication.

EMI's scientific and technical agenda involves the promotion of multi-disciplinary research to evaluate the effects of earthquakes on large urban areas and to develop technologies and methods for the mitigation of such effects. In addition, EMI participants focus their efforts on specific projects expected to have a high impact in accelerating earthquake preparedness, mitigation and recovery. These activities are aimed at building and sustaining local and regional capacity of selected organizations and institutions in megacities of developing countries. EMI's capacity-building action plan for the next five years includes the Twin Cities, Regional Center and Training and Education projects.

The Twin Cities project pairs up two or more large cities in a formal exchange and development of knowledge that involves researchers, practitioners and end-users (Figure 8). Usually, one of the cities has more advanced knowledge on mitigation and preparedness procedures than the other, or has experienced a recent earthquake disaster. Exchanges between the cities are intended to result in the implementation of low-cost mitigation measures and improved emergency response. The following city grouping are currently involved in the EMI Twin Cities project: Los Angeles - Mexico City, Bogota - Managua, Naples - Cairo, Izmir – Tashkent, Tehran-Yeravan, Beijing - Manila - Kobe.

Under the auspices of the Regional centres project, megacities with active mitigation programs contribute expertise to large areas and provide the motivation to build partnerships with managers of large metropolitan centres, international development agencies and risk mitigation advocates. In contrast, the Training and Education project involves knowledge and information sharing to build local and regional capacities. The focus is on four project areas: training, establishing databases and directories of resources and activities, coordinating researcher or student exchanges to increase access to information, and running special workshops and seminars.

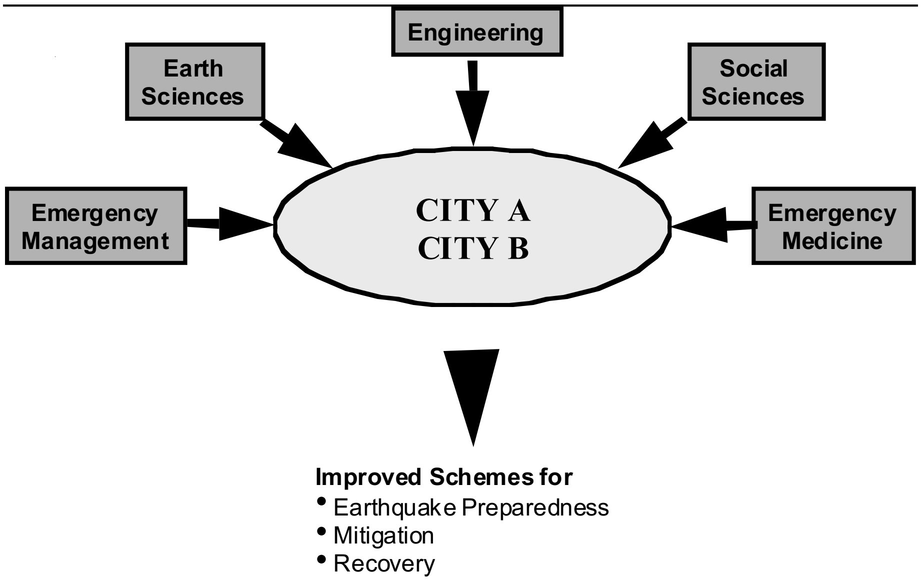


Figure 8. Concept of the Twin City project operating under the auspices of the Earthquake and Megacities Initiative.

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REFERENCES

Degg, M.R., 1992: Some implications of the 1985 Mexican earthquake for hazard assessment. In *Geohazards: Natural and Man-Made*, McCall, G.J.H., Laming D.J.C. and Scott, S.C. (Editors), Chapman and Hall, London, pp. 105-114.

Fäh, D., Suhadolc, P., Mueller, St., and Panza, G.F., 1994: A hybrid method for the estimation of ground motion in sedimentary basins: Quantitative modelling for Mexico City. *Bulletin of the Seismological Society of America*, 84, pp. 383-399.

Geller, R.J., 1997: Earthquake prediction: A critical review. *Geophysical Journal International*, 131, pp. 425-450.

Giardini, D., Grüntal, G., Shedlock, K., and Zhang, P., 1999: *Global Seismic Hazard Map*. United States Geological Survey, in press.

Lee, W.H.K., and Espinosa-Aranda, J.M., 1999 Earthquake early warning systems: Current status and perspectives. In *Proceedings of the International IDNDR Conference on Early Warning Systems for the Reduction of Natural Disasters* (EWC'98), Potsdam, Germany, in press.

The Institution of Civil Engineers, 1995: *Megacities: Reducing vulnerability to natural disasters*. Thomas Telford, London, 170 pp.

Wenzel, F., Oncescu, M.C., Baur, M., and Fiedrich, F., 1999: *An early warning system for Bucharest*. Seismological Research Letters, 70, pp. 161-169.

Wyss, M., 1997: Protection of megacities by earthquake prediction: A goal to work towards. In *Proceedings of the "First International Earthquake and Megacities Workshop*, Seeheim, Germany, Deutsches IDNDR-Komitee für Katastrophen-vorbeugung, IDNDR Series, 9, pp. 329-339.

EARTHQUAKE VULNERABILITY

By Walter W. Hays; United States Geological Survey

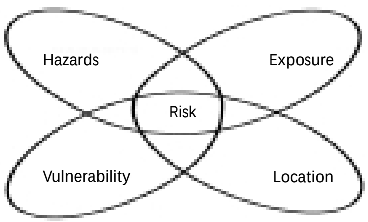
ABSTRACT

Throughout the world, each earthquake-prone community's vulnerability, or susceptibility to damage from earthquake ground shaking, ground failure, surface fault rupture, regional tectonic deformation, tsunamis and aftershocks is growing rapidly as a result of either a lack of public policy, or flaws in public policy. These mistakes have led incrementally over time to inadequate consideration by many communities of the need for planning, siting, design, construction, quality control and use. These oversights have become the root causes of unacceptable risk to individual elements of the built environment and the overall unacceptable risk to the community. The 21st century presents the most opportune moment ever to correct these flaws and to reduce community vulnerability because of advances made during the International Decade for Natural Disaster Reduction (IDNDR). For the first time, more professionals, policy makers and stakeholders are collaborating than ever before, and every earthquake-prone community has access to scientific and technical data needed to anticipate the consequences of earthquakes and to form public policy for reducing community vulnerability. The 1990s have seen an increase in the technical capacity, desire to collaborate, capability to anticipate, and political will to change public policies. Seismic zonation, a policy tool that can be used to link risk assessment and risk management, is now available to every earthquake-prone community. Seismic zonation calls for anticipation (i.e. mitigation and preparedness measures) instead of reaction (response and recovery), integration (i.e. linking risk assessment with risk management) instead of fragmentation, and public-private partnerships instead of individual efforts to promote reduction of community vulnerability as a public value. The most effective course of action now is for every earthquake-prone community to call for public policies that: 1) stop increasing the risk as new development are added to the built environment inventory, 2) start decreasing the risk to the existing built environment, and 3) continue planning for the inevitable earthquake.

1. INTRODUCTION

This paper highlights the results of a collaborative 10-year effort led by the United States Geological Survey and the United Nations Educational Scientific and Cultural Organization to promote seismic zonation [Hays, Mohammadioun, and Mohammadioun, 1998]. More than 300 professionals contributed to the effort which pointed out that the current trend of large unacceptable economic losses experienced recently in Northern California, Southern California, Japan, and other countries is a wake-up call for responsible, innovative actions to reduce community vulnerability (Figure 1). Scientists, engineers, planners, and policy makers in every earthquake-prone community of the world have an important role to play in a cooperative worldwide effort. Earthquakes are an international problem. They occur globally, impacting people, property, and infrastructure without regard to political boundaries, season, time of day, social status, and state-of-preparedness in the stricken community. The problem is exacerbated over time because of the increasing vulnerability of existing community development and new community development expanding into new geographic areas that are susceptible to ground shaking, ground failure, surface faulting, regional tectonic deformation, tsunamis, and the aftershock sequence. Over 1.6 million people died in earthquakes during the 20th century, many more were injured, and direct economic losses from a single, moderate sized earthquake reached a record high of at least US $140 billion in the 17 January 1995 Kobe, Japan earthquake. This trend, expected to continue throughout the world, has ominous social implications.

Figure 1. Schematic illustration showing the principal elements of risk: hazards, location, exposure, and vulnerability. The focus of worldwide collaboration must now be on reduction of community vulnerability, which should be seen as the key to sustainability.



Vulnerability reduction is urgent because, not only are economic losses, mortality, and morbidity increasing with time in every country, but also the

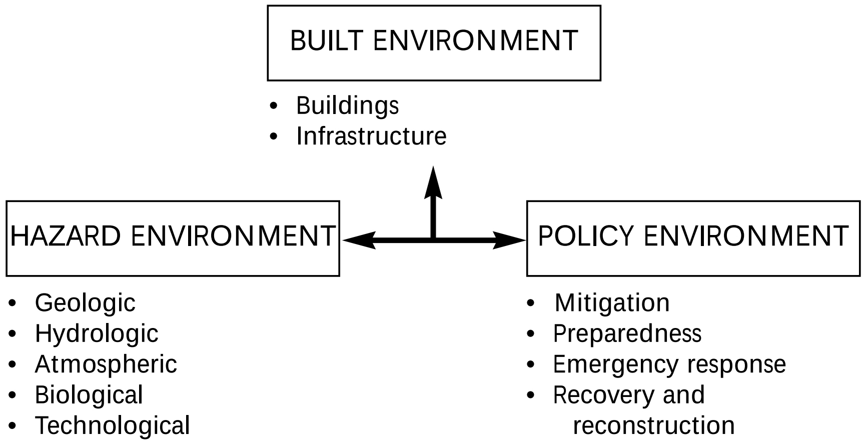


Figure 2. Reduction of community vulnerability calls for integrated strategies that consider all aspects of the community's hazard, built and policy environments.

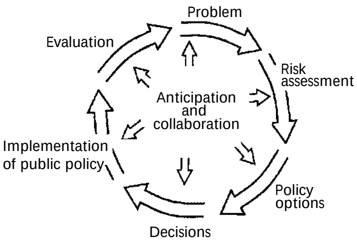


Figure 3. Scientists, engineers, planners and public officials need to collaborate as they improve their ability to anticipate what is likely to happen in the future and their capacity to work together, devising, implementing, and enforcing integrated public policies that will reduce vulnerability in each community at risk to earthquakes.

number of "surprises" is increasing. The expectation is that losses will continue to increase until earthquake-prone communities start reducing their vulnerabilities through integrated strategies for the hazard, built, and policy environments (Figure 2).

Vulnerability reduction calls for scientists, engineers, planners, and public officials to work together to anticipate what is likely to happen in the future (Figure 3), and to devise and implement integrated public policies that are designed to reduce a community's vulnerability. Anticipation of what is likely to happen and collaboration to eliminate flaws in planning, siting, design, construction, quality control and use—the sources of community vulnerability—are the keys to reduction of community vulnerability.

2. WHAT MAKES A COMMUNITY VULNERABLE TO EARTHQUAKES?

Many factors combine to make a community vulnerable to the physical effects of earthquakes. They range from the manner in which engineered and non-engineered buildings and infrastructure performing the essential functions of supply, disposal, transportation, and communication are combined to inform the community on the temporal and spatial characteristics of the earthquake hazards. To the furthest extent possible, all must be identified and incorporated in a model of the community's hazard and built environment when assessing the overall urban vulnerability and risk (Figure 4).

A community's vulnerability to the earthquake hazards of ground shaking, ground failure, surface fault rupture, regional tectonic deformation, tsunamis, and aftershocks is the result of either no public policy, or flaws in public policies related to: a) planning, b) siting, c) design, d) construction, e) quality control, and use of individual elements of the built environment (i.e. single family dwellings, commercial buildings, schools, hospitals, government buildings, highway structures, bridges, underground pipelines, dams, power plants, airports, ports, railways).

Comprehensive studies following damaging earthquakes to determine what happened before, during, and after the earthquake and to explain why it happened have isolated the principal factors that increase the vulnerability of a community. They include:

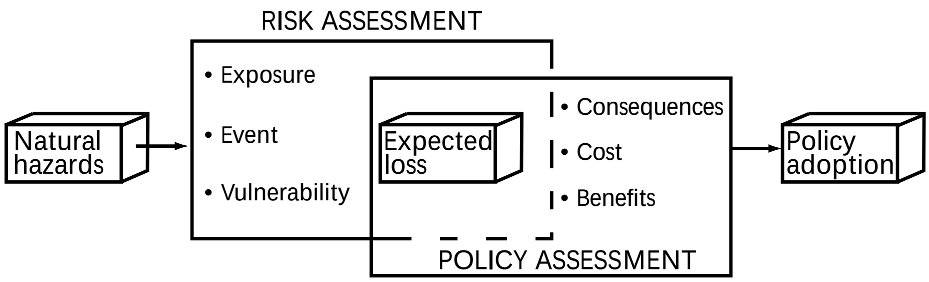


Figure 4. Elements of a model for a comprehensive risk assessment of a community.

1. Older, non-engineered residential and commercial buildings typically constructed with un-reinforced masonry or other construction materials having little or no resistance to the lateral forces of ground shaking.
2. Older infrastructure constructed at one time to conform with a seismic code or standard that is now considered to be outdated, and inadequate as a result of changes in the state-of-the art or state-of-practice.
3. Non-engineered residential and commercial buildings that are vulnerable to fire following an earthquake.
4. New buildings and/or infrastructure that have been sited, designed, and constructed without adequate consideration of the proximity to the fault.
5. Communities sited at the water's edge or in low-lying or coastal areas that are susceptible to tsunami.
6. Buildings or lifeline systems sited on or encased within poor soils that either enhance ground shaking, or fail through permanent displacements (e.g. liquefaction, lateral spreading, falls, topples, slides, and flows of soil and rock).
7. Buildings with irregular plan, and elevation and vertical and/or horizontal discontinuities in mass, strength, and stiffness.
8. Schools and hospitals—a community's "safe haven" facilities — that have been designed and constructed with materials with low resistance to lateral forces and irregular plan and elevation and vertical and horizontal discontinuities in mass, strength, and stiffness.
9. Communities with their communication facilities and disaster response control centres concentrated in the most hazardous areas instead of being widely distributed geographically to spread the risk.
10. Outdated bridges and viaducts.
11. Underground utilities providing the essential community services of supply and disposal for electricity, gas, water, and sewage that are likely to fail or be rendered unusable by ground failure.
12. Ports and harbours that are in locations susceptible to regional tectonic deformation, lateral spreads, and liquefaction.

3. WHAT DO THE "SURPRISES" THROUGHOUT THE WORLD INDICATE?

The number of "surprises" after earthquake disasters throughout the world indicate that, at present, many communities: 1) do not know that they are vulnerable; 2) do not understand why they are vulnerable; or 3) are ineffective in reducing their vulnerability. In fact, most communities are just beginning to be willing to acknowledge that they are vulnerable because of inadequate public policies to ensure comprehensive planning, siting, design, construction, and use of the built environment. The numerous so-called "surprises" that the media has highlighted in most countries during the past two decades have included the following situations:

1. Discovering after the earthquake disaster that an active fault system was located directly beneath the community or very close to the community.
2. Experiencing unanticipated damage and loss of function to essential buildings (e.g. hospitals, schools, government buildings), and lifelines (e.g. elevated highway systems, ports), especially when the scientific and technical consensus before the earthquake is that these structures have adequate earthquake resistance.
3. Discovering that portions of the community are susceptible to fire following the earthquake.
4. Experiencing thousands to tens of thousands of deaths and injuries, and thousands to hundreds of thousands left without homes and jobs.
5. Unexpected loss of community revenue, tax base, economic loss, and insured payments in the billions of dollars.
6. Discovering that the community lacks the capability for speedy emergency response and effective recovery and reconstruction.
7. Discovering after the earthquake disaster that the causes of the surprises were within the power of the community's policy makers and stakeholders (earth scientists, engineers, planners, insurers, businesses, and others) to correct before the disaster occurred.

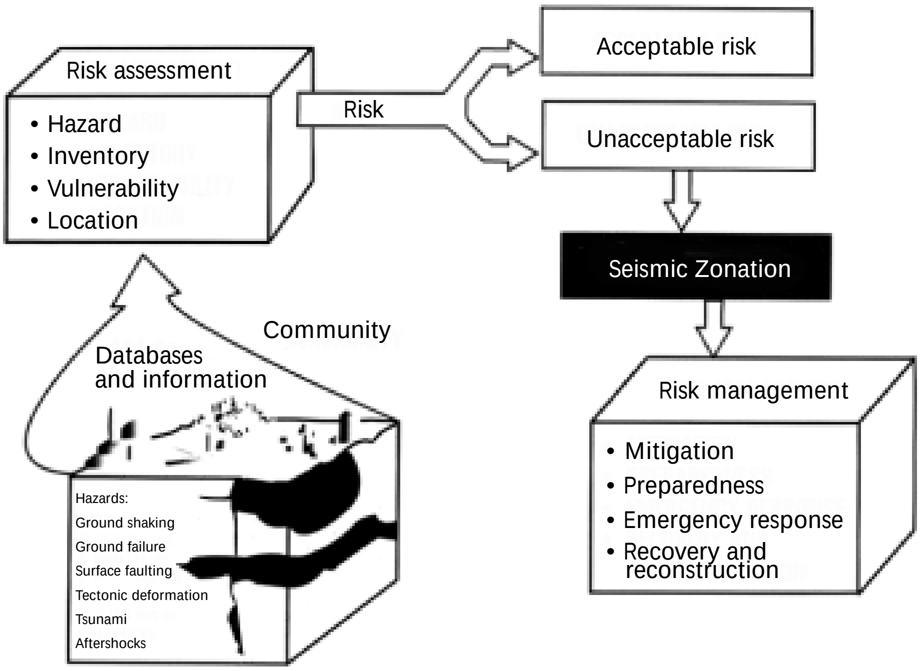


Figure 5. Schematic illustration of seismic zonation as a policy tool to link earthquake risk assessment and earthquake risk management before new community development is approved. This concept has been a legal mandate in California since 1990.

4. WHY IS SEISMIC ZONATION—A POLICY TOOL FOR INTEGRATED RISK ASSESSMENT AND RISK MANAGEMENT—URGENTLY NEEDED AND A HOPE FOR THE FUTURE?

Integrated risk assessment and risk assessment—seismic zonation—is needed if earthquake-prone communities are going to anticipate what is likely to happen and collaborate to eliminate or reduce actual and perceived vulnerabilities at the source and potential losses (see Figures 3, 4, and 5).

Each community needs to devise strategies that will: 1) stop increasing the risk as new development is added to the community's inventory of buildings and lifeline systems comprising the built environment; 2) start decreasing the risk to existing buildings and lifeline systems; and 3) continue planning for the inevitable earthquake. The need for integration of risk assessment and risk management is urgent because the number of vulnerable structures and the economic value at risk are increasing rapidly in every community throughout the world. Because of the advances made during the 1990s, and the increased availability of basic scientific and technical information, databases, hazards maps, codes and standards, and analytical tools, seismic zonation is now feasible anywhere, Moreover, it is becoming increasingly feasible technically and politically to link seismic zonation and performance codes and standards.

The two keys to linking, in the near future, seismic zonation with performance codes and standards are: 1) access to basic scientific and technical information, databases, hazards maps, codes and standards, and analytical tools; and 2) capacity to perform the assessments required to characterize a community's hazard and built environments for a risk assessment. Databases and case histories are now readily available to every earthquake-prone country, either from professionals within the country or through collaboration with professionals in other countries. The following are examples:

1. Location of the active and inactive faults
2. Geometry of the faults
3. The regional tectonic setting
4. The spatial and temporal characteristics of the seismicity
5. Rate of decay of seismic energy with distance from the point of fault rupture
6. Effects of geologic structure, tectonic setting, databases, and magnitude
7. Data on site response
8. Data on ground failure potential
9. Data on surface fault rupture potential
10. Data on flooding potential
11. Maps of the ground shaking hazard
12. Maps of ground failure hazard
13. Maps of potential surface fault rupture

14. Maps of potential regional tectonic deformation
15. Maps of potential tsunami flood wave run-up
16. Locations of the community's engineered and non-engineered buildings in relation to soil deposits and their earthquake resistance in terms of the criteria of a modern building code
17. Locations/routes of the community's lifeline systems in relation the soil deposits and the criteria of modern lifeline standards
18. Vulnerability/fragility relations for the community's buildings and lifelines

5. WHAT ARE THE GAPS IN KNOWLEDGE

Gaps in knowledge exist. The most critical gaps in knowledge that need to be filled by ongoing "works in progress" in order to improve seismic zonation as a policy tool to link risk assessments and risk management include the following:

1. The physics of the fault rupture
2. Near-source phenomena
3. Identifying tsunami sources
4. Basin effects
5. Attenuation laws for plate margin and intra-plate regions
6. Effects of soil non-linearity on site response
7. Optimum soil profile characterizations for generalized site response characterization
8. Prediction of lateral displacements associated with liquefaction-induced lateral spreading
9. Prediction of non-liquefaction related settlements and lateral displacements (e.g. in soft clay soils)
10. Tsunami modelling
11. Synthetic seismograms for specific source-path-site-structure configurations
12. Vulnerability/fragility relations for buildings of various types, materials, and functions
    1. Vulnerability/fragility relations for lifeline systems of various types, materials, and functions
    2. Implications of uncertainty in the characterizations of a community's hazard and built environments for the enactment and implementation of public policies for risk assessment and risk management

6. WHAT ARE THE PRINCIPAL OPTIONS FOR REDUCING COMMUNITY VULNERABILITY?

At present, community policy makers and community stakeholders have many options available for reducing community vulnerability, each having a wide range of potential benefit and costs. The ultimate realization of a specific benefit cost depends on the capability of the community to enact and enforce specific mitigation measures and regulations. The options and estimated ranges of benefit or cost are summarized below:

1. Insurance, with a potential benefit or cost ranging from one to one million, which spreads the risk and enhances recovery and, because of recent paradigm shifts within the insurance sector, offers hope for new mitigation incentives and initiatives.
2. Non-structural mitigation, with a potential benefit or cost ranging from one to one thousand, which protects equipment and contents, while ensuring continued use of buildings and facilities.
3. Building codes, with a potential benefit or cost ranging from one to one thousand, which prevent collapse of buildings; protects life and reduces injuries.
4. Demolition, with a potential benefit or cost ranging from one to one thousand, which eliminates collapse- hazard buildings and highway structures and reduces potential for loss of life and injuries.
5. Standards and guidelines for lifelines, with a potential benefit or cost ranging from one to one thousand, which protect community infrastructure.
6. Performance-based design, with a potential benefit or cost ranging from one to a hundred, which prevent loss of function and loss of use, especially in essential and critical facilities.
7. Training and exercises, with a potential benefit or cost ranging from one to a hundred, which expand the capability and self-reliance of professionals.
8. Retrofit, strengthening, upgrading, and repair, with a potential benefit or cost ranging from one to a hundred, which prevent collapse, eliminate vulnerabilities

caused by asymmetries, irregularities, and vertical and horizontal discontinuities in mass, stiffness, and strength in elevation and plan and reduce damage.

9. Base isolation, with a potential benefit or cost ranging from one to a hundred, which ensures continued functioning of essential and critical structures and facilities.
10. Soil remediation, with a potential benefit or cost ranging from one to a hundred, which prevents liquefaction, lateral spreading and landslides.
11. Public-private partnerships, with a potential benefit or cost ranging from one to ten, which spread responsibility.
12. Earthquake disaster scenarios, with a potential benefit or cost ranging from one to ten, which facilitate advance planning for the expected and the unexpected (i.e. "the surprises").
13. Siting criteria and land-use, with a potential benefit or cost ranging from one to ten, which avoid surface fault rupture, soil failure and soil-structure resonance.
14. Relocation and rerouting, with a potential benefit or cost ranging from one to ten, which reduce the likelihood of damage to communities, buildings, and important lifelines.
15. Protective works, with a potential benefit or cost ranging from one to ten, which prevent release of hazardous materials.
16. Changes in use and density of use, with a potential benefit/cost ranging from one to ten, which reduce the likelihood of loss of function; loss of life and injuries.

7. CONCLUSIONS

The time is right for all earthquake-prone communities to collaborate in order to increase their capacity to anticipate the consequences of earthquakes, devise and enact mitigation measures to eliminate or reduce community-specific vulnerabilities at the source, and to decrease the likelihood of an earthquake disaster. Reduction of community vulnerability, an increasingly urgent goal for every nation during the 21st century, is feasible and closer to realization now because of the scientific, technical, and political advances made during the 1990s under the auspices of the IDNDR.

The key action for the 21st century is for community professionals and community policy makers and stakeholders to anticipate the need and to collaborate in solving their problems. Seismic zonation, a policy tool to integrate risk assessment and risk management before permitting new construction, is now an option that all earthquake-prone communities can consider. The next step, a policy tool for linking seismic zonation with performance codes and standards is also feasible now and is perhaps the best way to move the state-of-the-art and the state-of-practice forward.

REFERENCE

Hays, W.W., B. Mohammadioun and J. Mohammadioun, 1998: *Seismic zonation: a framework for linking earthquake risk assessment and earthquake risk management*, Ouest Editions, Nantes, France, 147 p.

SUCCESSES AND FAILURES IN FIGHTING LANDSLIDES: SOME EXPERIENCES FROM ITALY AND ELSEWHERE

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ABSTRACT

When is an action taken to cope with a hazardous mass movement considered a success ? When is it necessary to admit failure ? This paper attempts to give an answer to these questions by examining the three main aspects of a landslide risk management programme: prediction, prevention (or mitigation) and emergency planning. Examples of successes and failures are given with reference to some of the best known case histories that have occurred, more or less recently, in Italy and elsewhere in the world. The recent developments of scientific research regarding the different aspects of landslide risk management are briefly outlined.

As far as the prediction phase is concerned, the state-of-the-art on landslide risk assessment and the basic differences between spatial and temporal prediction are briefly summarized and discussed. The GIS database of the Emilia-Romagna region, containing over 30 000 individual landslides, is presented as a successful example of a spatial prediction containing elements for temporal forecasting. The exceptional 1996 Versilia rainstorm that triggered more than 450 debris flows, causing 13 casualties, is described as a representative case of an unpredictable event.

A general framework for the main strategies and techniques employed for landslide risk prevention is proposed. A successful case history, the urban transformation accomplished in the second half of the 19th century on the San Miniato hill of Florence is presented: the architectonic transformation, of high artistic and landscape value, was combined with an effective stabilization of the hill, the instability of which was documented in a number of historic documents starting from the 11th century. The 1998 Sarno disaster is illustrated as an example of prevention failure: a series of debris flows caused 161 casualties in the suburbs of Sarno and Quindici, where uncontrolled urban development took place on areas historically exposed to high hazard.

The basic requirements of a successful emergency plan are therefore discussed, such as monitoring and warning systems and simulation techniques for risk scenario analyses. The emergency plan devised and implemented after the occurrence of the 1993 La Josefina landslide in Ecuador is presented as a success: the landslide produced a dam on the Rio Paute and the successive emergency measures managed to reduce the losses caused by the dam breaching and overtopping to a minimum. Finally, the well-known 1963 Vaiont disaster is proposed as a representative example of unsuccessful emergency planning: more than 1 700 casualties were caused by the catastrophic flood wave generated by the sudden failure of a huge mass of rock into a reservoir.

1. INTRODUCTION

Landslides and, in general, mass movements of earth receive less attention from the mass media and policy makers than other natural disasters such as earthquakes, volcanic eruptions and floods, probably because they are less impressive. However, they undeniably represent one of the major risks for the safety and welfare of people, property and wealth. Very often the damage caused by landslides is strongly underestimated, since they frequently represent a relevant part of multi-hazard disasters such as earthquake-induced failures, rainfall-induced floods and debris flows, or rock avalanches and lahars triggered by volcanic eruptions. A worldwide survey carried out by the International Association of Engineering Geology for UNESCO between 1971–1974 showed that 14 per cent of all casualties caused by natural disasters are connected with landslides. In the same period, an average of 600 people were killed by landslides each year (Varnes, 1981). This figure, however, gives only a partial idea of landslide impact on public safety, as single major events that have occurred in this century have caused, in some cases, over ten thousands victims (Schuster, 1996).

Schuster (1996) has published an updated review on the socio-economic significance of landslides showing that Japan is the most severely affected nation, suffering an estimated total loss of 4 × US $109 per year (value referred to 1990). It is followed by the United States, Italy and India, where the estimated losses ranges between 1 × US $109 and 2 × US $109 each year. These losses include both direct and indirect costs. The first involve costs of repair, replacement or maintenance of damaged property and installations. Indirect costs include loss of productivity, reduced real estate value, loss of tax revenues and other induced economic effects not directly produced by the landslides (Schuster, 1996). According to Schuster, a significant proportion of landslides affect transportation facilities or lifelines such as railways, highways, channels and pipelines, producing both Civil Protection problems and damage to economic activities. Another important aspect that must be taken into consideration relates to cultural heritage and environmental and ecological resources; the damage caused by landslides can in some cases be of inestimable value.

The mitigation of damage caused by natural disasters and risk reduction is one of the institutional duties of UNESCO. In 1976, the United Nations Disaster Relief Organization (UNDRO) promoted the constitution of a “landslide commission” within the IAEG, where a global framework for landslide hazard and risk analysis was defined (Varnes and IAEG, 1984). The 42nd General Assembly of the United Nations decided that the period between 1990–2000 would be the International Decade for Natural Disaster Reduction (IDNDR). In this context a Working Party on the World Landslide Inventory (WP/WLI) was formed by the main international geotechnical societies. With the enlargement of the International Union of Geological Sciences (IUGS), the WP/WLI was transformed into the IUGS Working Group on Landslides (IUGS/WGL). The main outcomes of this activity consist in the publication of suggested methods for landslide description and inventory (WP/WLI, 1990, 1991, 1993*a*, 1994; IUGS/WGL, 1995; Cruden and Varnes, 1996), a multilingual glossary on landslides (WP/WLI, 1993*b*), and a review of the state-of-the-art on quantitative risk assessment for slopes and landslides (Cruden and Fell, 1997).

The socio-economic significance of landslides has been recognized in recent decades, following the occurrence of several disasters. The reasons can be listed as follows:

1) landslide hazard is growing both in developing countries, due to continuous deforestation, and in industrialized countries, because of the gradual abandonment of rural areas;
2) global climate change appears to negatively affect hazard through increased annual precipitation in some countries, or higher frequency and intensity of extreme meteorological events in others;
3) the exposure of the elements at risk has risen rapidly in recent decades due to demographic growth and to increased urbanization and development; if this tendency seems to have been reversed in technologically advanced nations, it is now a major problem in developing countries where the population is growing rapidly and regional development is often uncontrolled;
4) the vulnerability of the elements at risk is also on the rise given the growing complexity of the socio-economic structure of industrialized countries; even events causing minor direct loss can generate major indirect losses linked, for example, to the interruption of productive activities, loss of competition, non-fulfilment of contracts, legal or insurance problems and even psychological effects;
5) acceptable risk thresholds have been drastically reduced in more developed nations as today’s society no longer tolerates losses from natural unexpected events.

For these reasons, the mitigation of landslide effects has, in recent decades, become even more challenging. The objective of this paper is to provide a general framework for the definition of the effectiveness of society’s fight against landslides, providing case studies of both successful achievements and distressing failures. The first step in landslide mitigation is to examine what type of phenomenon a landslide represents. A landslide is a mass of rock, debris or earth, which moves down a slope under the action of the force of gravity (Cruden, 1991). Despite this simple definition a landslide is a very complex phenomenon. It is characterized by five fundamental mechanisms of movement (fall, topple, slide, spread and flow) and their combinations (Cruden and Varnes, 1996). The material involved can range in size and consistency from hundreds of millions of cubic meters of solid rock to single particles of soil. The rate of movement ranges over ten orders of magnitude, from imperceptible creeping (velocity <10-10 m/s) to catastrophic, extremely rapid, failures (velocity >10 m/s) (IUGS/WGL, 1995). The material can move as a whole, like a solid block, or flow like a fluid depending on the water content. The activity of the movement can vary spatially and through time and between different parts of the same displaced mass (WP/WLI, 1993*a*). A landslide can occur as a first-time rupture of intact material or along a pre-existent sliding surface. The first case is less common but usually has more violent effects given the brittle characteristics of failure, whereas re-activations occur more frequently but are usually characterized by limited displacements and slow rates of movement, because of the non-brittle nature of the pre-existing slip surface (Hutchinson, 1987, 1988).

Another aspect that must be considered in a landslide risk analysis is the induced risk. A landslide, in fact, may be the triggering cause of another type of hazard: a volcanic eruption, as in the 1980 Mount St. Helen event in the state of Washington (USA); groundwater pollution, when industrial plants or waste disposals are damaged; or a flood, when the landslide causes the blockage of a stream or river channel. This last case is perhaps the most common and can produce dangerous consequences: a landslide dam represents a potential source of flood hazard since it may cause flooding both upstream, by water impoundment, and downstream, by breaching and overtopping of the dam.

The type of action that can be taken in the face of landslide hazard is the main aspect that needs to be discussed, before proceeding to the examination of successes and failures in combating landslides. Generally speaking, a hazardous phenomenon can be either forecasted, prevented and mitigated or tackled with an emergency plan. The three main phases concerning landslide risk management are the following:

(a) **prediction**: includes all the activities aimed at studying and determining the causes of landslides, at identifying the risks and at the zonation of the areas exposed to risk;

(b) **prevention**: includes all the activities aimed at avoiding or reducing to a minimum the possibility of occurrence of loss as consequence of landslide events, based on the knowledge acquired in the prediction phase;

(c) **emergency planning**: consists of the decisional and operational framework for the protective measures to put into effect in situations of crisis.

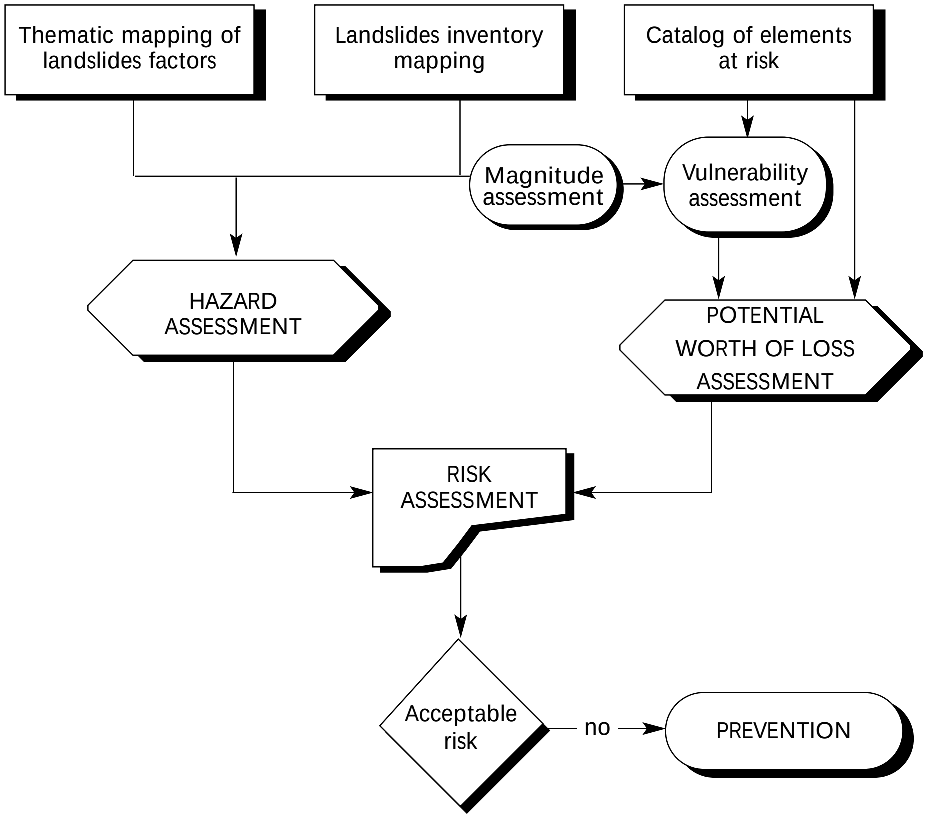
In the following sections these three aspects of landslide management will be discussed in detail. For each of them, two case studies are presented and briefly commented on: one relating to a success and one to a failure. The case studies presented are well-known events where the authors had a direct research experience and, in some cases, a direct operational responsibility as members of the National Group for Hydrogeological Disaster Prevention (GNDCI), an organization funded by the Italian Civil Protection Department, with the aim of supplying technical support to the Government in the fight against landslides and floods. Many of them are Italian examples, where the authors have gained most of their experience, but they are chosen as representative of landslide phenomena and socio-economic contexts that can be easily encountered in other parts of the World.

2. PREDICTION

A formal framework for landslide risk prediction is shown in Figure 1. The basic initial information is represented by the description of the state of nature (Einstein, 1988; Wu *et al.*, 1996) which can be divided into the following three aspects:

(a) thematic mapping of landslide factors: providing all the relevant information on slope instability causes, such as lithology, bedrock structure, debris cover, vegetation, groundwater, slope gradient and aspect, etc.;

Figure 1. Formal framework for landslide risk prediction.



(b) landslide inventory mapping: providing all the relevant information on slope instability effects, such as past landslide distribution, type of movement and of mobilized material, state, style and distribution of activity;

(c) catalogue of the elements at risk: including information on population, property, buildings, transportation infrastructures, lifelines, socio-economic activities, cultural heritage, environmental and ecological resources, classified by typology and by value.

From the combined interpretation of information regarding slope instability causes and effects, it is possible to predict landslide hazard, defined as the probability that a catastrophic phenomenon may occur in a defined area during a given period of time (Varnes and IAEG, 1984). The analysis of the characteristics of past landslides supplies indications of the geometrical and mechanical severity (magnitude or intensity) of the expected events. Cross-analysis of landslide magnitude and the type of elements at risk permits the assessment of vulnerability, which represents the degree of loss of an element or group of elements at risk, as consequence of the occurrence of a natural phenomenon of a given magnitude (Varnes and IAEG, 1984). Vulnerability, in fact, depends on the type of element at risk, in particular on its susceptibility to suffer a loss, and on the magnitude of the landslide, which is linked to its damage potential. By combining the vulnerability with the value of the elements at risk it is possible to assess the potential worth of loss (Einstein, 1988), which is independent from the probability of occurrence of the landslide event. The total risk, which expresses the expected amount of loss, is obtained by combining the potential worth of loss with landslide hazard.

Methods for the quantitative assessment of the potential worth of loss have been developed within the *Plans d'exposition aux risques* (PER) of the French Government (DRM, 1985, 1988) and formalized by Einstein (1988) in the framework of the Decision Theory. The development of methods for the quantitative assessment of landslide hazard is one of the main topics of scientific research in the field of engineering geosciences. These are usually based on GIS mapping and analysis for predictions over extensive areas and on geotechnical numerical modelling for single site predictions.

Compared to other types of natural disasters, landslides pose a series of additional problems that must be solved for a complete hazard analysis. This is due to the wide variability of slope movements in terms of type of movement, type of material, water content, and rate of movement. The following steps are necessary for a complete hazard assessment (Hartlén and Viberg, 1988).

(a) Temporal prediction: the forecasting of when a landslide will occur on a specified slope.

(b) Spatial prediction: the forecasting of where a landslide has the highest probability of occurring within a specified area.

(c) Type prediction: consists in determining the type of movement that is most likely to occur (e.g. rock fall, earth slump, etc).

(d) Magnitude prediction: this consists in determining the geometrical and mechanical severity of the expected event; the parameters to be investigated and predicted are landslide volume, rate of movement, and released energy. The magnitude closely controls the vulnerability of the elements at risk. A correct risk analysis should consider different hazard levels for events with different magnitude by evaluating frequency-magnitude relationships.

(e) Evolution prediction: is the forecasting of travel distances, retrogression limits and lateral expansion. This is another fundamental aspect as it involves the delimitation of the “hazard basin” of existing and potential landslides.

2.1 THE EMILIA-ROMAGNA REGION: A DATABASE OF 32 000 LANDSLIDES FOR PREDICTION PURPOSES

The Emilia-Romagna region, located in the northern sector of the Apennine chain, is one of the areas in Italy more extensively affected by landslides that periodically cause severe damage to property and productive activities. Amongst the most recent events having occurred on its territory, several can be singled out. The 1994 Corniglio earth slide with a volume of over 200×106 m^3 caused the loss of important food processing plants (Larini *et al.*, 1997; Gottardi *et al.*, 1998). The 1994 Silla landslide caused a prolonged interruption of activity in mechanical industrial plants (Canuti *et al.*, 1998). Finally, the 1994 San Benedetto landslide dam posed serious civil protection problems linked to the expected failure of the blockage on the Sambro river (Casagli *et al.*, 1995).

Slope instability in the region has been well-known for centuries and several historic documents report landslide problems that occurred during previous centuries. Fortunately, the majority of the landslides in the region are characterized by a slow rate of displacement. Common velocities are a few centimetres per day and only exceptionally have velocities of up to tens of meters per day been recorded. Apart from a few rare cases, therefore, landslides in the region do not pose a risk to the safety of people, but can, nonetheless, have severe consequences on the economy of the region, owing to the damage caused to urban areas, isolated buildings and, in particular, transportation facilities (Canuti *et al.*, 1999).

The vast majority of the landslides occurring in the region are re-activations of pre-existing slope movements that take place with an intermittent, irregular recurrence, usually in response to prolonged rainfall. In consequence, it is clear that a detailed inventory map of past and existing landslides, based on air-photo interpretation and on field surveys, represents the basis for a spatial and typological prediction of landslide hazard, since it permits us to detect and classify the phenomena which can be re-activated in the future. In the 1970s, the Regional Administration started a systematic inventory of landslides, covering the whole Emilia-Romagna region (which extends over an area of 12,685 km^2 excluding flood plains) at a scale of 1:25 000 and afterwards at 1:10 000. This work is now nearly complete and has lead to the detailed mapping of 32,337 individual landslides, covering a total area of 2 554 km^2 (20.1 per cent of the area of the hilly and mountainous ranges). All the data have been stored in a GIS and are now accessible to the general public by means of telematic networks.

After the series of events which affected the region between 1994-96, the Regional Civil Protection Service promoted the constitution of a technical-scientific group to develop a hazard map to be used for prediction purposes. The type of data processing adopted is not substantially different, in methodology and content, from cases cited in the scientific literature and employed for cartographic projects by other public administrations, such as the French national project ZERMOS (Humbert, 1976, 1977; Antoine, 1977) and PER (DRM, 1985, 1990). The landslides already mapped in the GIS have been classified according to their state of activity (WP/WLI, 1993*a*) and ranked in different classes of relative hazard. The next step was the zonation of slopes in which there was no evidence of past movements. These areas are susceptible to occasional first-time slides and also to re-activations of pre-existing dormant landslides that may have escaped systematic inventory, due to obliteration by geomorphic or anthropogenic activity. In these non-affected areas, the hazard ranking has been based on the areal frequency of landslides over homogeneous lithological units, following a criterion already successfully tested in other parts of the world (Radbruch-Hall *et al.*, 1976, 1982; Brabb, 1972; De Graff, 1978).

The available data on the state of nature permitted only a spatial and typological hazard prediction (Figure 2), with the assessment of the degree of relative hazard amongst different sectors of the territory. Data on landslide types and mechanisms also allowed a ranking in classes of relative magnitude, which can be used for an analysis of the vulnerability of the elements at risk and of the potential worth of loss. To also formulate a temporal hazard prediction, ongoing research is concentrated on correlating rainfall time series and historic records of landslide events. A first attempt, the results of which are shown in Figure 3, is the combination of a hydrological soil balance model with an empirical recharge model (Casagli *et al.*, 1999). The resulting hydrogeological function is empirically correlated with the recorded landslides. The results obtained are encouraging despite the well-known difficulties in modelling groundwater response to rainfall in low permeability terrain with deep-seated landslides.

A risk prediction is obtained by overlaying hazard maps and the elements at risk stored in the GIS. The results of this process provide a measure of the landslide impact on the region: 150 municipalities are affected by landslides, with 235 urban areas threatened by problems of instability. Where transportation facilities are concerned, the analysis shows that landslides threaten 11 882 km of railway tracks, 14 668 km of highways, 1 031 950 km of National and Provincial roads

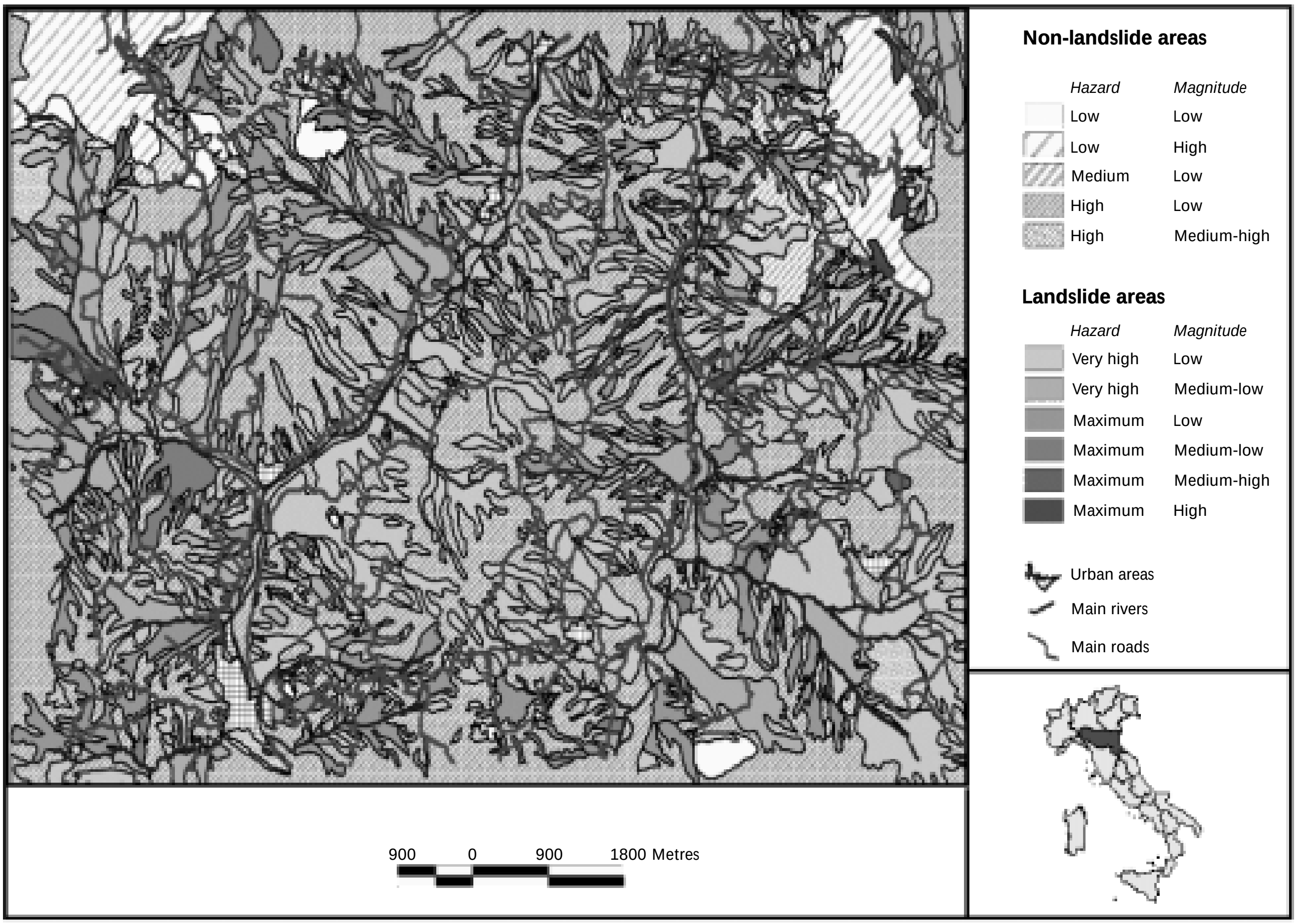


Figure 2. Example of landslide hazard and magnitude zonation from the Emilia-Romagna GIS.

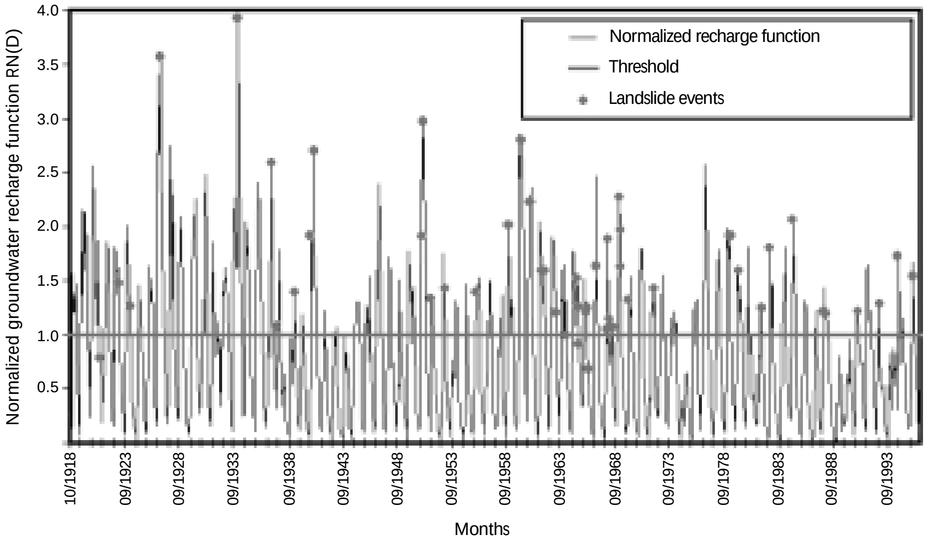


Figure 3. Preliminary results of the rainfall threshold model applied to the Reno river watershed. The groundwater function is compared with landslide reactivations in the period 1918 – 1998.

and 2 234 402 km of municipal roads (Garberi *et al.*, 1999). The Emilia-Romagna GIS on landslide hazard represents one of the most advanced tools available today for predictions over large areas. It is currently employed in planning urban development and risk mitigation measures.

The 1996 Versilia Debris-flows: an Exceptional Unpredictable Event

A meteorological event of exceptional violence and intensity took place on 19 June 1996 in the Apuane mountains, a well-known site for the extraction of high-quality marble at the northern margin of the Apennine chain. The rainstorm triggered more than 450 slope movements, causing the destruction of mountain villages, flash-floods that provoked damage along the two main rivers both in the western Versilia basin and in the eastern Garfagnana one and leaving 13 victims. A schematic reconstruction of the isohyets of the event is shown in Figure 4 together with the distribution of the slope movements. The extreme spatial concentration of the event and the high rainfall intensity are remarkable. The whole event lasted 13 hours yielding a maximum rainfall of 478 mm in Versilia and over 420 mm in Garfagnana. This underlines the exceptional nature of the event as the whole Apuane range receives a yearly mean rainfall of 1 430 mm.

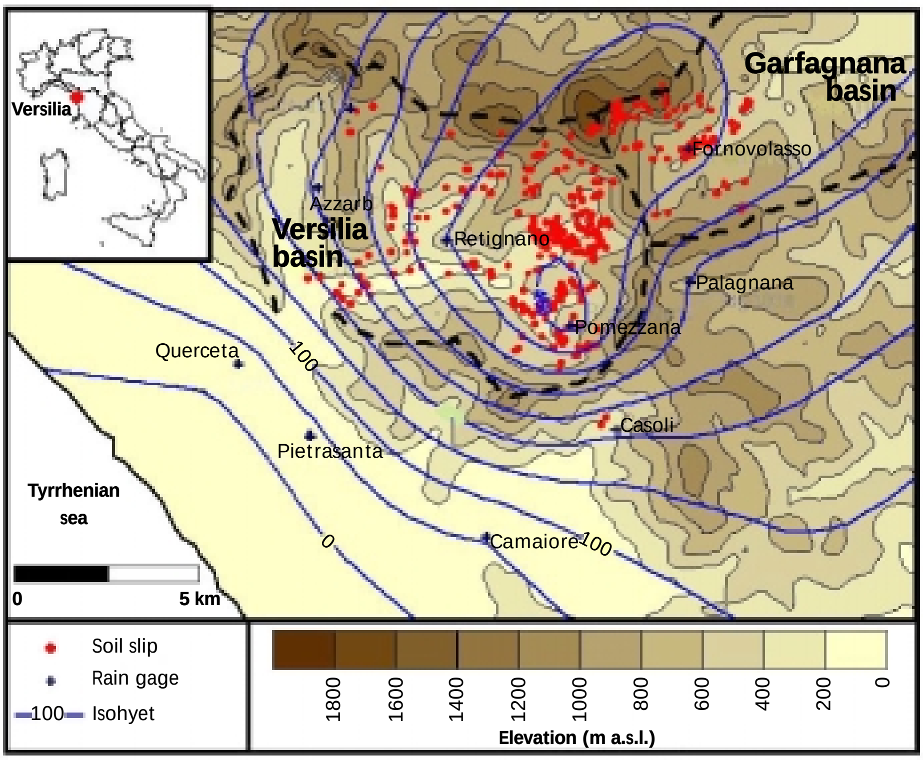


Figure 4. Isohyets of the event (relative to a duration of 13 hours) and distribution of soil slips in Versilia and Garfagnana.

The majority of the landslides are distributed around the water divide between the Garfagnana and Versilia basins, within the 400 mm isohyet, and are classifiable as soil slip - debris flows (Figure 5). In the triggering zone, they start as small first-time slides affecting only a few decimetres of superficial loose soil debris, mainly in zero-order basins or hollows (Caredio *et al.*, 1998). They rapidly evolve into open-slope debris flows and, in most cases, reach the hydrographic network, changing into channelized debris flows or hyper-concentrated flows, increasing considerably in volume during their run-out. The rainstorm migrated progressively towards the northeast, with a maximum intensity of 173mm/h in Versilia, between 05.45 and 06.45 hrs and of 152mm/h in Garfagnana, between 12.00 and 13.00 hrs. Nearly all the soil slips seem to have been triggered by the second rainfall peak that took place after 13.00 hrs.

Due to its localized, violent character the meteorological event was virtually unpredictable, at least with the climatic models used for weather forecasting in the Mediterranean basin. The Regional Agrometeorological Service weather report for the 19 June forecast only occasional rainfall of weak intensity. On the other hand, events with these characteristics are determined by the particular microclimate of this region, with its high relief close to the open sea causing the rapid uplift of masses of moist air of Atlantic origin.

Statistical analysis of the maximum rainfall heights of different duration clearly shows the exceptional nature of the meteorological event (Castelli *et al.*, 1997). For the Fornovolasco rain gauge, where a time series of rainfall intensities over a 50-year period is available, in 1952 the maximum rainfall intensity in 12 hours was 262 mm. On 19 June 1996, 416 mm of rain fell in the same period !

In Figure 6, the curves of maximum intensity in function of the duration, for three rain gauges in the region, are compared with the threshold curves for the triggering of soil slips, proposed by different authors in different parts of the world (Caine, 1980; Moser and Hohensinn, 1983; Cancelli and Nova, 1985; Wieczorek and Sarmiento, 1988; Jibson, 1989). The exceptional character of the event is confirmed by the fact that it lies well above all the thresholds proposed in literature, even for those proposed for other climatological environments such as inter-tropical regions. For this reason it is quite difficult to determine the critical rainfall duration that set off these movements.

For all the reasons exposed above, the Versilia case represents a typical example of an event for which a temporal hazard prediction is extremely difficult. Despite this fact, the effects of the phenomenon could have been less destructive if, at the very least, a spatial prediction of zones susceptible to debris mobilization had been carried out. A spatial and typological prediction would have yielded the basic tool for programming measures of risk mitigation such as, for example, forest maintenance, creek dredging, building protective structures or limitation of land use.

Figure 5. Soil slips – debris flows triggered by rainfall.

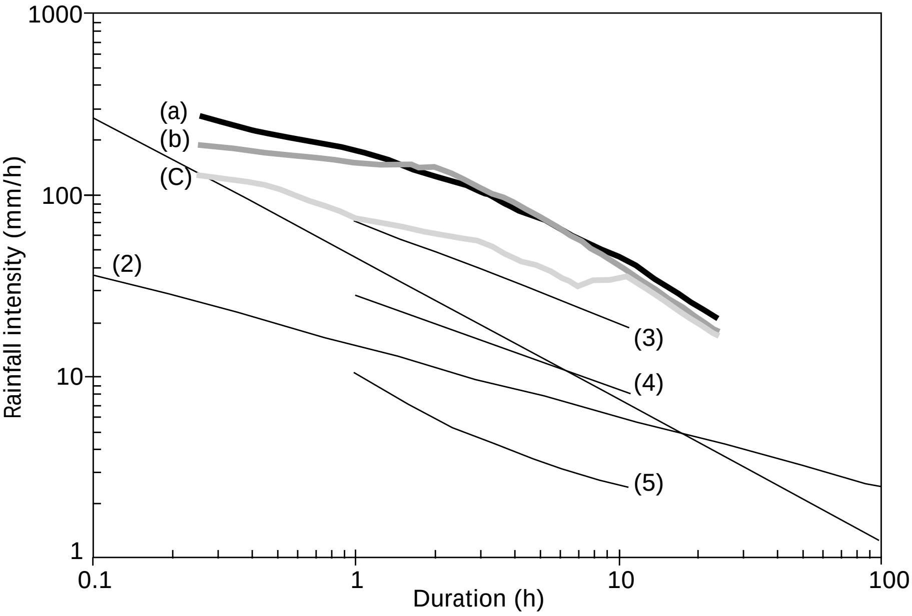


Figure 6. Comparison of the curves of maximum intensity in function of the duration for three rain gauges in the region and the thresholds of soil slip triggering proposed by different authors. (A) Pomezzana, (B) Retignano, (C) Fornovolasco. (1) Alps (Cancelli and Nova, 1985)*; (2) Worldwide* (Caine, 1980)*; (3) Puerto Rico* (Jibson, 1989)*; (4) Worldwide* (Jibson, 1989)*; (5) California* (Wieczoreck and Sarmineto, 1988).

3. PREVENTION

The prevention of landslide risk is based on the interpretation of the information collected in the prediction phase and on the establishment of a framework of measures aimed at risk mitigation. The implementation of these measures is usually the task of decision and policy makers of national or local administrations. However, the role of the scientific and technical community is of crucial importance in determining scales of priority and for the development of mitigation strategies. In areas exposed to unacceptable risk levels two general strategies are possible (Figure 7):

(a) ”allowable risk” threshold increase using information means such as mass media, danger or warning signs, promotion of insurance policies.

(b) risk reduction: obtained through measures for the prevention of landslide consequences which can be further sub-divided into the following two procedures:

(b1) hazard reduction: the probability of occurrence of landslides in a given zone can be reduced with “structural measures” in two ways:

(i) reduction of slope instability causes, such as land drainage, geo-hydrological and woodland management, reforestation, erosion control, rationalization of land use and farming practices;

(ii) direct action on slope instability effects aimed at preventing the re-activation or the expansion of pre-existing landslides; this can be achieved with

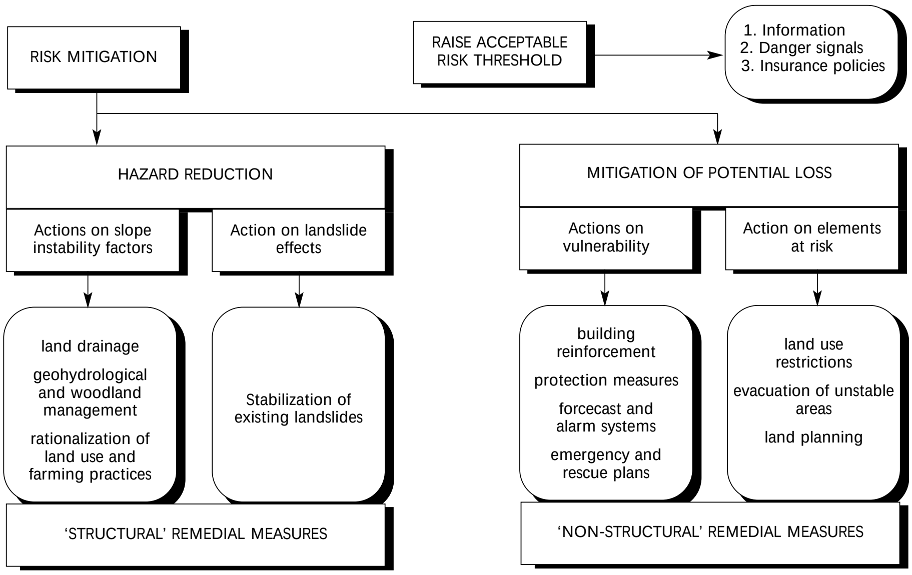


Figure 7. Formal framework for landslide risk prevention.

stabilization works, such as slope profile modification, local drainage, restraining and retaining structures, chemical or thermic treatment, grouting (Hutchinson, 1977).

(b2) mitigation of potential loss: this can be obtained with "non-structural measures" by land planners and policy makers in the following two ways:

(i) working on the vulnerability with measures aimed at lowering the probability of suffering a loss without reducing the probability of occurrence of the landslide, such as building reinforcement, protection measures (i.e. diversion and catchment structures), forecast and alarm systems, emergency and civil protection plans;

(ii) with measures for reducing the exposure of the elements at risk, such as land use restrictions, evacuation of unstable areas, land and urban planning.

The quantitative evaluation of landslide risk in the prediction phase, in terms of expected value of loss per year, permits the rational selection, on the basis of a cost-benefit analysis, of the appropriate prevention strategies. A benefit in terms of risk reduction, expressed as the decrease of the expected loss caused by landslides, can be associated to the cost of each mitigation measure.

3.1 THE SAN MINIATO LANDSLIDES IN FLORENCE: HOW SUCCESSFUL PREVENTION CAN BE COMBINED WITH A TOWN-PLANNING TRANSFORMATION

The southern extremity of the historic center of Florence, on the hydrographic left side of the Arno river, is bordered by a series of hills, known as "Colli Fiorentini", which provide suggestive panorama of the city with its artworks and monuments. The San Miniato hill (known also as Monte alle Croci or Mons Florentinus) represents the most famous of these gentle topographic features for its landscape significance and for the monuments of inestimable cultural, historic and artistic value (Figure 8). Its northern flank is cut by the "Viale dei Colli", a wide hillside boulevard which borders the southern margin of Florence, constructed between 1865 and 1876. The hilltop hosts the complex of the Romanic Basilica of San Miniato al Monte (11th c.) (Figure 9) with the annexed Palazzo dei Vescovi (14th c.), which are surrounded by the monumental cemetery of the Porte Sante (1854) and by the fortification system designed by Michelangelo Buonarroti. The fortress is connected to the "Viale dei Colli" with a monumental staircase (1865-1876) and the church of San Salvatore al Monte (1499-1504) with the contiguous San Francesco Monastery (1499-1504) are also nearby. Situated in the central portion of the slope is the famous panoramic square known as Piazzale Michelangelo (1865-1876), linked downslope to the city with the Rampe, a complex system of artificial terraces, waterfalls and masonry walls, hosting the roadway.

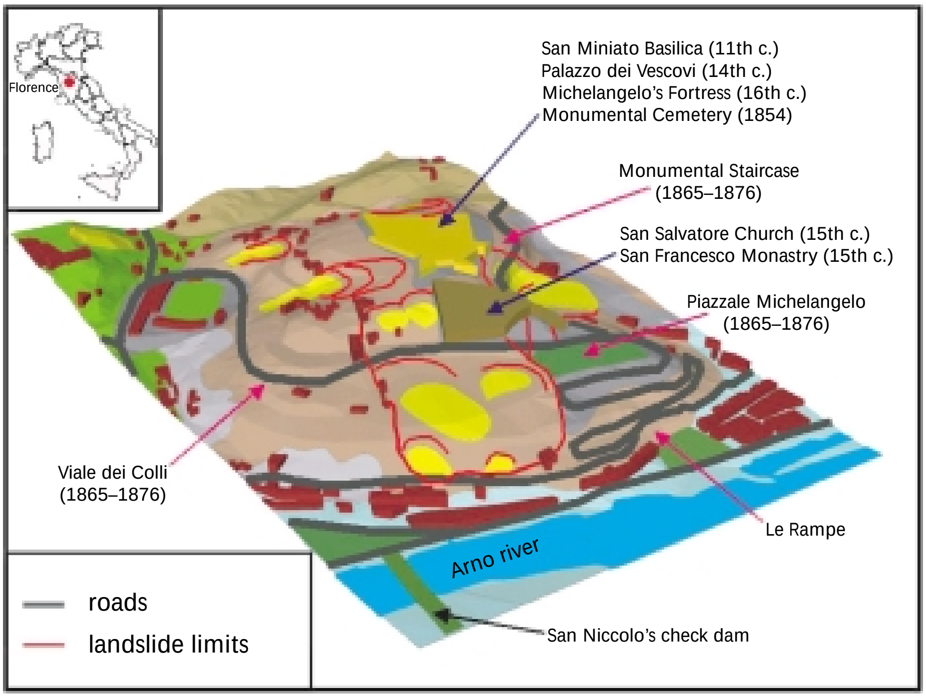


Figure 8. Isometric view of the San Miniato hill showing the main monuments and the boundaries of the dormant landslides (Computer graphics by Earth Sciences Department of the University of Siena, Italy).

Figure 9. The San Miniato Basilica (11th c.) at the top of the monumental staircase (1865-1876).

Unfortunately, the hill has always been affected by slope instability phenomena, with periodical re-activations documented in several historic documents. Most of the monuments and art works on the hill are affected by fissures which, in various circumstances during the centuries after their construction, required restoration. The first documented studies on the stability of the hill were carried out by Leonardo da Vinci in the 15th century and afterwards by various commissions appointed for the restoration works. The studies carried out in the past pointed out the presence of a generalized translational sliding of the entire hill, down the slope facing the Arno river, linked to the adversely oriented strata. Detailed geomorphological investigations showed the presence of distinct slides scattered over all the slopes of the hill (Figure 8) (Bertocci *et al.*, 1995). Their recognition and delimitation is made extremely difficult by the urbanization of the entire hill over many centuries which has led to the almost complete obliteration of the evidence of past movements. The main landslide bodies which have been detected are:

(a) the large earth slide on the northern slope which laps the Piazzale Michelangelo and the church of San Salvatore and extends over a green zone used today as a camping site;

(b) the earth slide on the western slope which affects the Monumental Staircase of San Miniato;

(c) the coalescent slides on the eastern slope which affect some private villas and some public facilities such as the Florence Orthopedic Hospital;

(d) the earth slide on the southern slope, the crown of which reaches the base of the Michelangelo bastions.

Various documents testify to the periodic re-activations of the different landslides: the main events date back to 1499, 1551, 1562, 1652, 1695, 1709 and 1853.

Between 1865 and 1876, dates which coincided with the designation of Florence as temporary Capital of the Italian Kingdom, the hill was involved in a radical town-planning transformation directed by the Architect Giuseppe Poggi. On the San Miniato hill, Poggi designed and constructed the scenic Viale dei Colli with its panoramic open squares, of which the Piazzale Michelangelo is the most famous. Among the reasons cited by Poggi to support his extremely expensive plan, was the necessity of a global geo-hydrological and hydraulic re-arrangement of the entire slope, in order to prevent the future occurrence of instability phenomena. The implementation of the project lead to a general modification of the slope profile, with excavations and fillings involving impressive earth movements, the building of drainage systems and canals which supplied water for the waterfalls and fountains, and the construction of a series of earth retaining structures along the boulevard and on the Rampe terraces (Figure 10). The most unstable zones, including the area used today as a campsite, were left green and used as public gardens.

The entire complex of works has an undoubted artistic and architectural value and represents one of the key elements of the landscape of the Florentine hills. Apart from these aesthetic aspects, it is clear that the entire works were supported by a full appreciation of the local, critical stability conditions and by the necessity of putting into effect preventive measures to protect the cultural heritage from the risk of landslides. For this reason Poggi's opera still today represents an excellent and prestigious example of appropriate land management and sustainable urban development that, unfortunately, has not always been followed in the successive periods.

3.2 THE 1988 SARNO EVENT: A DISASTER CAUSED BY THE LACK OF PREVENTIVE MEASURES

On 5 May 1998, in the Sarno area in southern Italy, 30 km east of Naples, approximately 150 shallow landslides (soil slips — debris flows) were triggered by an intense rainstorm. The mobilized material was conveyed into the hydrographic network, giving rise to large channelized debris flows that hit the urban areas of Sarno, Quindici, Siano and Bracigliano (Figure 11). This catastrophic event produced 161 casualties and heavy, widespread loss of property, services, infrastructures and economic activities. Available rainfall records show a total rainfall of 100 mm in 24 hours (4–5 May), with a peak intensity of 11 mm/h. Although

Figure 10. Original drawing of Poggi showing the Rampe plan.

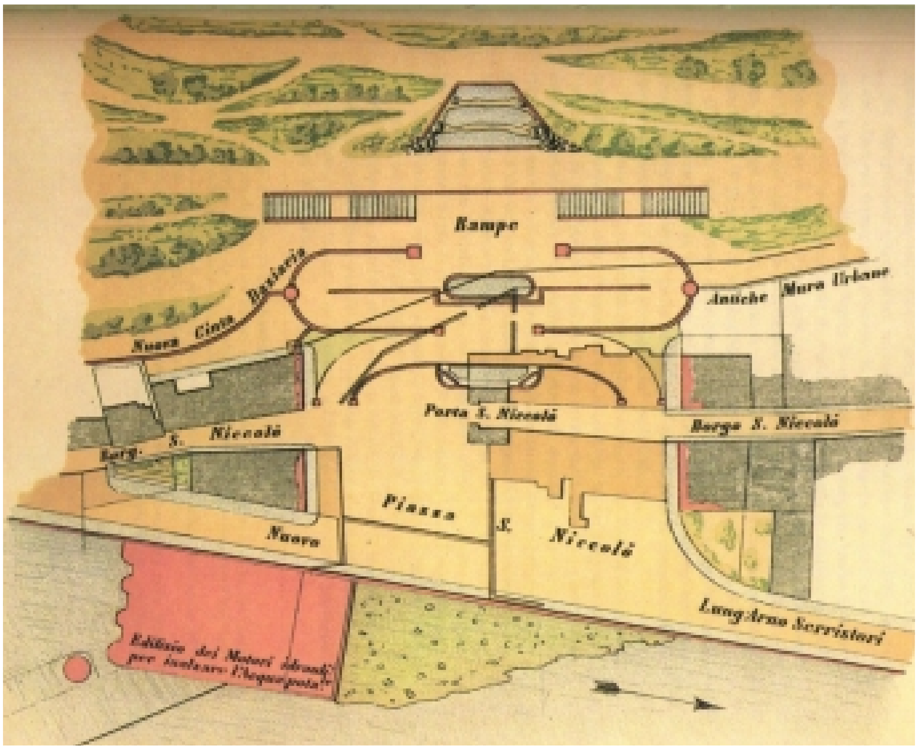


Figure 11. Debris flows reaching the suburbs of Sarno (photo courtesy of G. Falorni).

Figure 12. The channels known as Regi Lagni built in the 19th c., left in a state of abandonment (photo courtesy of P. Aleotti).

this rainfall was not exceptional. it must be noted that 175 mm of rain fell in the month of April, 147 mm of which fell in the last week preceding the triggering rainfall. Moreover, the Ponte Camerelle rain gauge is located in the lowland near the sea and its records are not representative of the precipitation on the inland slopes.

The soil slips affected a thin cover of loose or weakly cemented pyroclastic deposits (falls) from Somma-Vesuvius eruptions that overlie a karstified Mesozoic limestone bedrock. The geomorphological evolution of the slopes is determined by the mobilization of pyroclastic materials and the expansion of debris fans in the pedemont zone. The development of deeply incised gullies, first in the calcareous rock and successively in the pyroclastic deposits, has a major influence on the run-out of these phenomena. The evolution of the degree of risk in the pedemont zone is thus strictly linked to the morphological variation of the fans. In fact, the areas affected by the debris flows have migrated towards the plain as a consequence of the channel formation and of the “telescopic” development of the fans (Aleotti *et al.*, 1999).

From these considerations it is clear that the geomorphic evolution of the area has been controlled by slope movements, therefore the entire lowlands in front of the calcareous massif are intrinsically characterized by conditions of natural hazard. Moreover, several historical documents testify to the frequent occurrence of slope movements. In the last century alone, 34 landslide events have been recorded in the region (Del Prete *et al.*, 1998).

In previous centuries, during the Kingdom of Naples, before the unification of Italy, some slope instability preventive measures were carried out in the area. The channel systems of Regi Lagni, built mainly in the 14th century in order to accommodate the accumulation of material from debris flows, are worthy of note (Figure 12). Up to 50 years ago, the urbanization of the lowland area was limited to the more stable areas, where no apparent gullies were present. Rapid urban growth in the post-war period, and especially in the 1970s and the first half of the 1980s, led to a rapid, uncontrolled, expansion over areas exposed to high hazard. The damage caused by the 1998 event entirely affected the more recent suburbs of the towns (Figure 13). In recent years, the rapid increase in the vulnerability and the exposure of the elements at risk has been combined with an increase in the hazard level due to the excavation of a network of paths, built to facilitate access to nut plantations on the hill slopes (Del Prete *et al.*, 1998).

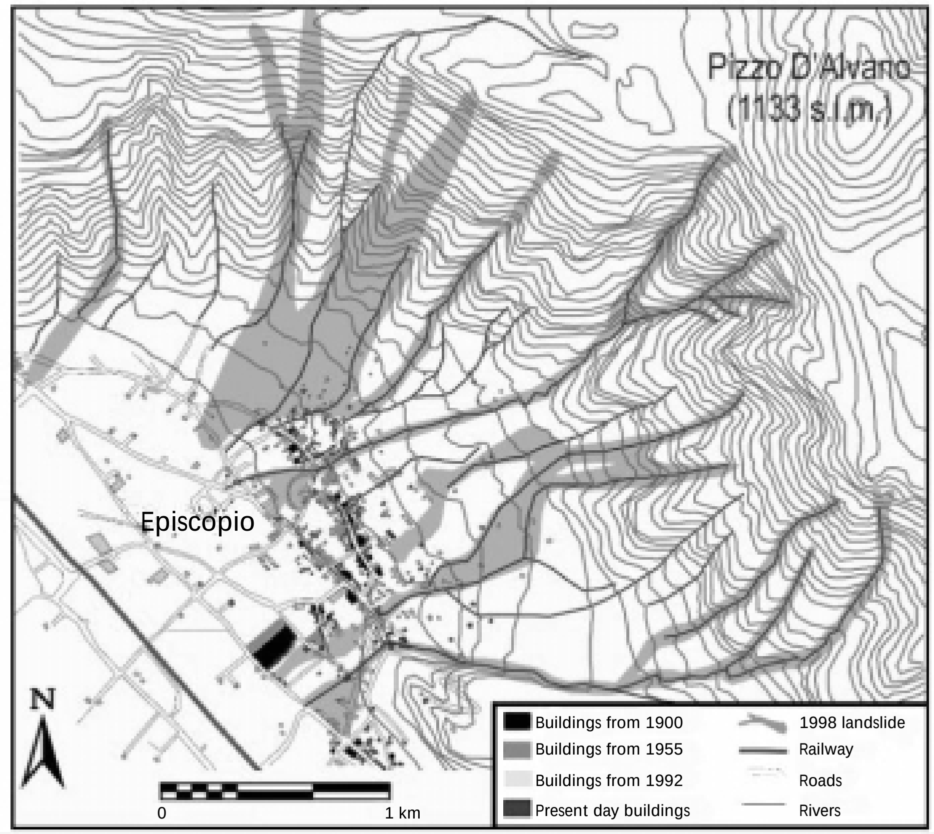


Figure 13. Map of Episcopio (suburb of Sarno) showing the age of buildings and the areas affected by debris flow propagation in 1998 (Aleotti *et al.*, in press).

The case of Sarno is an illustrative example of lack of preventive measures associated with uncontrolled urban expansion. Minimal attention to the requirements of sound urban planning and some basic geological investigations could have greatly reduced the impact of this event.

4. EMERGENCY PLANNING

An emergency plan should be prepared for all those areas exposed to an unacceptable level of risk, based on the socio-economic and cultural context of the territory. An emergency plan refers to a homogeneous area characterized by a defined landslide mechanism and should cover a sufficiently large area encompassing all the possible direct and indirect consequences. The key elements for the planning of emergency measures are scenario analyses and warning systems (Figure 14).

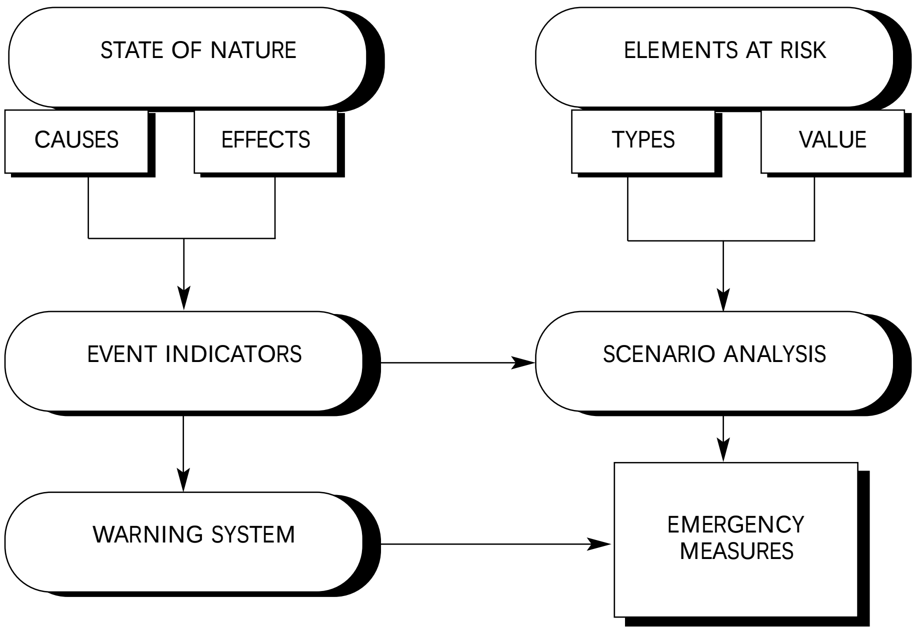


Figure 14. Formal framework for emergency management planning.

A scenario consists in a series of hypotheses which simulate the occurrence of the expected event, aimed at forecasting and preventing all the possible consequences, direct or indirect. Each scenario should be characterized by a set of measurable or observable physical parameters, defined as event indicators, which describe the relevant aspects of the state of nature. Possible event indicators include parameters which characterize the causes of the expected phenomenon (e.g. rainfall amount or intensity, seismic intensity or acceleration, external water stage), or its effects (e.g. rate of displacement, areal extension, expansion limit, mobilized run-out volume, mechanism of movement). A scenario analysis consists of a set of simulations, based on different event indicators and on the current exposure of the elements at risk. In general, several scenarios are examined with reference to situations of increasing severity up to the worst-case hypothesis (maximum expected scenario). Each scenario should include:

(a) the possible landslide mechanisms and the delimitation of the areas potentially affected by landslide evolution (retrogression limits, run-out distance, lateral spreading, etc.);

(b) the event indicators and the control points where the indicators should be observed or measured during the emergency phase;

(c) the prediction of all possible consequences, both direct (e.g. loss caused by the landslide itself) and indirect (e.g. blockage of a river channel, sliding into a reservoir, pollution produced by damage to industrial plants, escape of inflammable gas or liquids).

A successful scenario analysis requires detailed site investigations for the choice of the relevant event indicators, and powerful simulation tools for the prediction of landslide evolution and its consequences. Great advances have been made in the last few years in the numerical analysis of slope stability: limit equilibrium analyses have become routine, and more sophisticated stress-strain analyses, based on finite-element, finite-difference or distinct-elements, are today possible, given the advances in computer capabilities. Models for the prediction of landslide run-out and travel distances are becoming more and more realistic and reliable. As far as loss prediction is concerned, GIS technology provides fundamental tools for the spatial analysis of the effects of landslides on complex systems of elements at risk, making socio-economic analyses of landslide effects possible. Further research is required for a better definition of landslide mechanisms and triggering thresholds, as well as on quantitative vulnerability analyses of buildings and infrastructures.

Once defined, each scenario can be associated with a warning system, related to the monitoring of one or more of the event indicators. The warning system must include a control device of the selected relevant event indicators, so that the evolution of the expected event towards a parossistic phase can be forecast with sufficient accuracy. In general, two different control strategies are possible:

(a) monitoring of the causes of the event: regional weather forecasts, local rain gauges, piezometers, seismometers, gauges of external water levels, etc.;

(b) monitoring of the effects of the event: periodic surveys in the field, topographic surveys, fissurimeters, inclinometers, surface or deep-wire extensometers, tiltmeters, electric crack gauges, etc.

In both cases it is necessary to develop predictive models in order to choose the thresholds to be used as warning levels, taking into account, on one hand, the expected frequency and magnitude of the landslide and, on the other, the vulnerability and value of the elements at risk.

The rapid development of technology in recent years has had important effects on landslide monitoring and control. Besides making traditional methods and instrumentation much more effective and easily manageable, innovative technology is starting to produce accurate and reliable monitoring systems. Traditional equipment can now be effectively and conveniently coordinated by central units capable of acquiring, storing and managing all the collected data. GPS (Global Positioning System) technology has been successfully applied to the monitoring of landslides of different types and is gradually replacing traditional topographic surveying techniques. Radar interferometry and laser technology have been applied for the accurate monitoring of surface displacements and for the production of high-definition digital terrain models. New telecommunication technologies permit data acquisition from remote workstations, via radio or telephone modem (cable, cellular, satellite), on-line real-time alarms, remote management of the data acquisition system, real-time transmission of data and information to decision and policy makers through telematic networks.

After accurately defining the loss scenario and selecting an appropriate warning system, the operational phase of the emergency plan can be scheduled. In a successful emergency strategy, the following points should be carefully planned:

(a) measures for the prevention of the consequences described in the expected scenario, such as evacuation plans, identification of alternative transportation facilities and lifelines, removal of sources of induced risk, etc.;

(b) selection of the areas for temporary accommodations, as well as for the rescue and assistance structures;

(c) inventory of the technical, human and logistic resources to be used in the implementation of the emergency plan;

(d) information and dissemination activities on the correct conduct that the population should adopt in case of an emergency.

4.1 LA JOSEFINA LANDSLIDE DAM: AN EXAMPLE OF SUCCESSFUL EMERGENCY MANAGEMENT

On 29 March 1993, at about 22.00 hrs, a rockslide dammed the course of the Rio Paute, about 20 km northeast of Cuenca in Ecuador. The rockslide killed 35 people and produced a dam with an estimated volume of 25×106 m^3, which caused the upstream flooding of over 1 000 ha of land (Figure 15 and Figure 16). As a consequence of the event, an international scientific commission was established to manage the emergency linked to the possible failure of the landslide dam.

Both the upstream and downstream regions are densely urbanized, with major railways and highways, lifelines, productive and agricultural activities. Moreover, the Amaluza reservoir (with a total capacity of 120×106 m^3) lies about 60 km downstream, impounded by an arch-gravity dam on the Rio Paute. The emergency measures put into effect were aimed at mitigating the effects of the landslide dam breaching, considered unavoidable after a careful scenario analysis. The lake level was lowered by excavating a channel over the dam crest (Figure 17). The outflow through the channel started on 24 April and reduced the lake volume by 130×106 m^3, avoiding the upstream flooding of an additional 250 ha of land (Plaza-Nieto and Zevallos, 1994). The Amaluza reservoir was emptied to receive the flood wave and more than 20 000 people were evacuated from the area exposed to the flood.

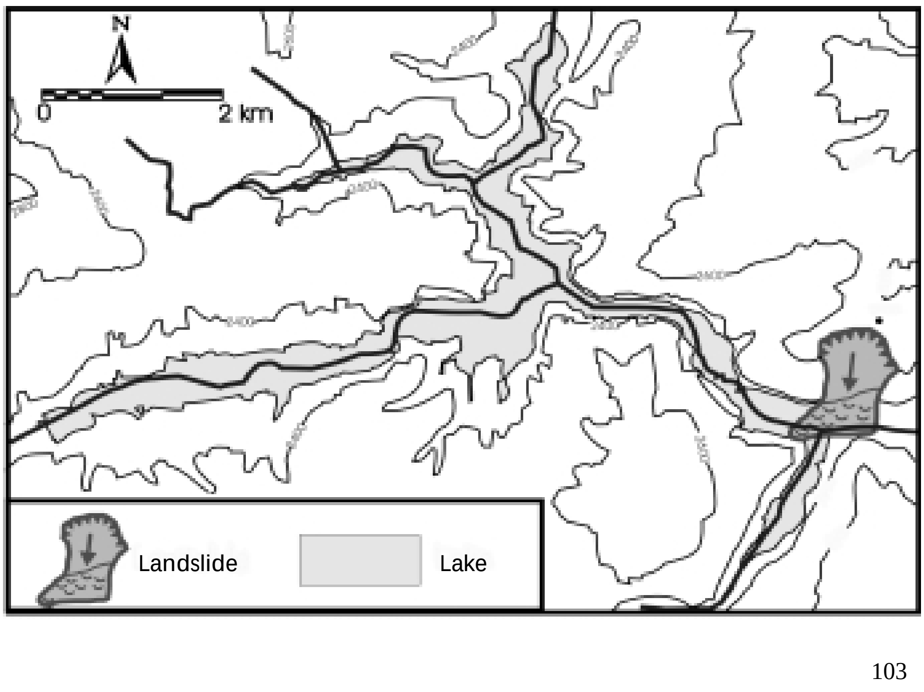


Figure 15. Map showing La Josefina landslide and the impounded lake (after Plaza-Nieto and Zevallos, 1994).

Figure 16. La Josefina rockslide and the impounded lake.

Figure 17. Outflow from the excavated channel over the dam crest.

Numerical, physical and statistically-based simulations permitted the definition of a risk scenario with the prediction of a total volume of 177 × 106 m^3 of released water and a peak discharge ranging between 2 000 and 16 000 m^3/s, depending on the grain-size distribution of the dam material. At about 0700 hrs on 1 May 1993, the dam started to breach when the lake had reached a maximum storage of 210 × 106 m^3. In 24 hours, about 185 × 106 m^3 of water were released, with an overflow peak discharge of about 10 000 m^3/s (Figure 18) (Canuti *et al.*, 1994). The flood from the rupture caused serious damage, especially for the first 20 km, destroying property, productive activities, infrastructures and services. However, thanks to the emergency measures put into effect, no human lives were lost and the Amaluza dam, despite being overtopped, did not suffer significant damage.

The work of the international scientific commission in this case was of fundamental importance in transferring the know-how and the technical support to the decision makers for the successful implementation of the emergency plan.

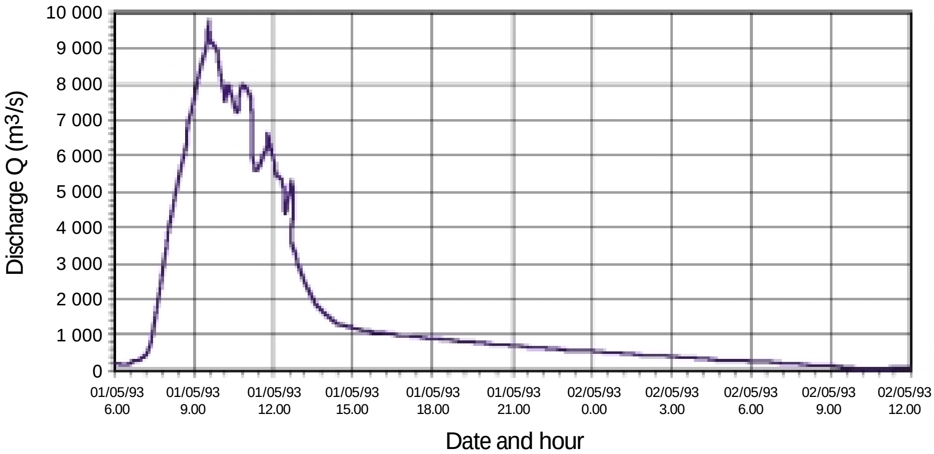


Figure 18. Hydrograph of the flood wave originated by the dam breaching (after Canuti *et al.*, 1994).

4.2 THE VAIONT SLIDE: AN EXAMPLE OF POOR MANAGEMENT LEADING TO A CATASTROPHE

The 1963 Vaiont event in northeastern Italy represents the most disastrous landslide in Europe since historic times. On 23 October 1963, a rockslide of 270 × 106 m^3 fell from the northern flank of Mount Toc (Figure 19), with a peak velocity estimated at 20-30 m/s, into the 150 × 106 m^3 reservoir of the Vaiont dam, the then highest arch dam in the world (Figure 20). The slide displaced over 50 × 106 m^3 of water, which overtopped the dam causing huge losses downstream in the Piave valley (Figure 21). Five villages were destroyed and 1 759 lives were lost. The total direct cost of the loss of property and services (excluding the value of the lives lost) was estimated to 600 × US $106 (1990 value).

The presence of a prehistoric dormant slide on the northern slope of Mount Toc was first recognized by Giudici and Semenza (1959), two years after the construction of the dam was started. The inadequacy of the geological and geophysical investigations, mainly due to the limited technological development of applied geosciences at that time, did not permit those involved to draw conclusions of the seriousness of the situation. The dam was completed and started to impound water in February 1960.

Figure 19. The Vaiont landslide: in the foreground the foot of the displaced mass and behind it the scar.

A first global re-activation of the slide occurred on 4 November 1960, three years before the catastrophe, when a crack suddenly appeared bordering the entire landslide body, thus confirming the Giudici and Semenza hypothesis (Figure 22). In the following three years, the technical commission in charge of the reservoir readied and implemented different strategies to manage the emergency situation. The scenario defined by the commission was based on the principle that the re-activation of a pre-existing slide of such relevant size would occur gradually, with progressive limited displacements and slow rates. Within this framework, Müller proposed to induce the progressive, slow mobilization of the entire mass by alternately filling and drawing down the reservoir (Müller, 1964). A bypass tunnel was excavated within the opposite bank with the aim of maintaining the reservoir functionality after the landslide (Figure 22). During the third filling phase, in October 1963, the slide velocity overcame the warning thresholds fixed by the

Figure 20. *The Vaiont dam seen from downstream.*

technical commission and a rapid draw down of the reservoir level was initiated. This triggered the sudden rapid mobilization of the entire landslide mass and caused the Vaiont catastrophe.

In the 36 years since the disaster, the scientific community has developed and disseminated knowledge which today would suggest a completely different management of the situation. The main points which can, in part, be considered as lessons learned from that disaster, are the following:

(a) studies and analyses of the stability of slopes on reservoirs are now routinely carried out in the preliminary design of dams;
(b) the dual effect of raising the external water level on a potentially unstable slope is now fully clarified and has lead to the development of the "critical pool level" concept;
(c) the decrease of the safety factor during rapid drawdown phases has been understood and can be adequately predicted;
(d) the fact that the re-activation of a pre-existing shear surface can produce large displacements and high velocities has been demonstrated by a series of case histories.

Despite advances in scientific research on the mechanisms of large landslides in rock, the Vaiont event remained poorly understood for many years and still cannot be considered fully explained today. The first studies on the Vaiont failure (Müller, 1964, 1968; Kenney, 1966, Novellier, 1967 Mencl, 1967) did not provide a satisfactory explanation of the movement mechanism. Only with the study of Hendron and Patton (1985), 22 years after the event, was a fully convincing interpretation of the landslide mechanism provided. In particular, the main points of their work can be summarized as follows:

(a) comprehension of the coupled effect of external water level and antecedent rainfall;
(b) identification of the presence of sheared argillitic inter-layers (at residual strength) within the calcareous sequence;
(c) presence of a confined aquifer under the slip surface and consequent new interpretation of the piezometric readings made before the landslide;
(d) additional friction provided by the sub-vertical fault plane on the western margin which makes a three-dimensional stability analyses necessary;
(e) the sudden acceleration is explained with a 50 per cent drop in strength caused by the generation of pore water pressure on the shear surface by frictional heating.

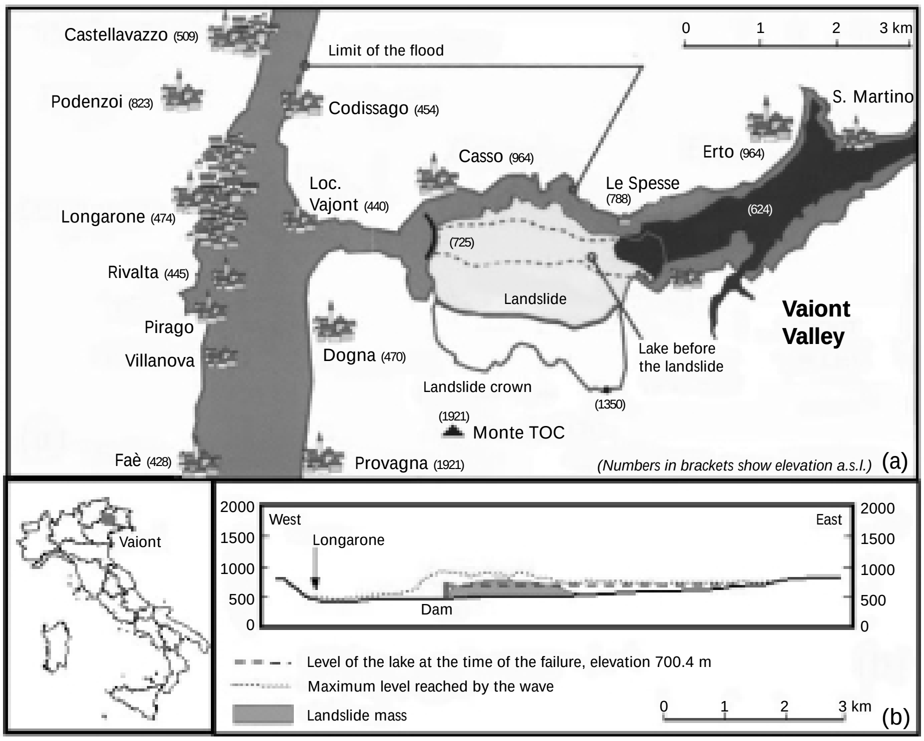
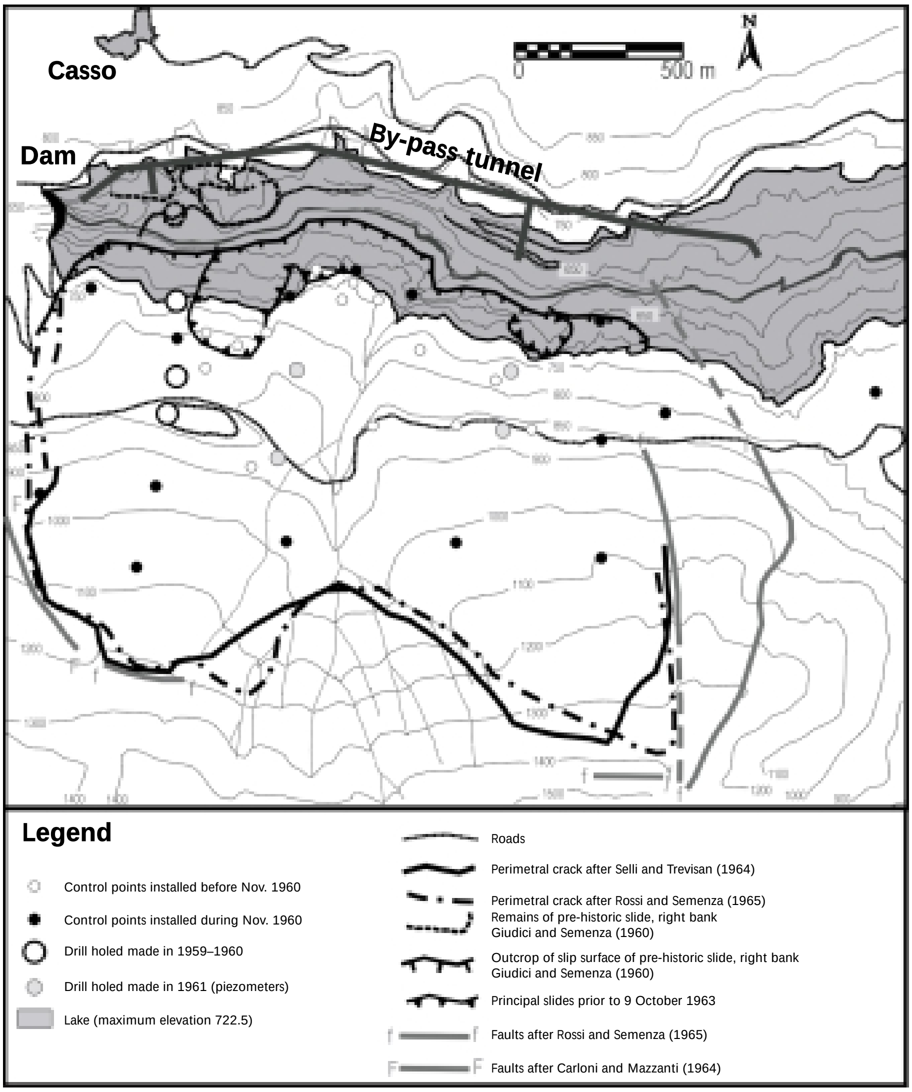


Figure 21. General plan showing the Vaiont landslide and the limit of the flood (a); schematic longitudinal section showing the original lake level and the elevation of the flood wave (b). After Selli and Trevisan (1964) and Kiersch (1964).

Figure 22. General plan of the Vaiont valley before the slide (after Hendron and Patton, 1985).



The last point is perhaps the weakest of the Hendron and Patton study, since it does not appear to be sufficiently documented nor supported by thermodynamical modelling. Hutchinson (1987) offered an alternative explanation of the sudden acceleration. The markedly non-circular shape of the slip surface (in section) did not allow the mass to slide without triggering internal deformations or ruptures. The high strength and brittleness of the Cretaceous limestone could have caused the accumulation of strains with a sudden drop in strength following the development of internal shear zones. A further decrease in strength is attributed by Hutchinson (1987) to the drop in residual strength caused by rapid shearing. This idea seems to be confirmed by high-speed ring shear tests carried out on samples from the slip surface (Tika and Hutchinson, 1999) that showed a loss of up to 60 per cent of the slow residual strength. Thirty-six years after the disaster a complete interpretation of the event seems to be close.

5. CONCLUSIONS

The actions to be carried out for coping with landslide hazard can be divided into three main phases: prediction, prevention, and emergency management. In the prediction phase, it should be considered that landslides are complex phenomena caused by many factors, such as intrinsic ground conditions, geomorphological, physical and man-made processes. All of these factors interact and can rarely be completely recognized before the occurrence of an event. Therefore the prediction, in particular the temporal prediction, is difficult and complex and can only be obtained by keeping these factors under control by monitoring systems. This can be implemented only in special cases where the value of the elements at risk justifies the expense. Particular care should be used when the territory has been strongly modified by human activity, which frequently disturbs the pre-existing conditions of natural equilibrium. Spatial hazard prediction is usually more feasible since the integrated analysis of slope stability factors, such as lithology, morphology and hydrogeology, makes landslide-prone areas readily identifiable. Landslides are dynamic processes that, in most cases, show evident traces of their presence before occurring. This is obvious in re-activations of pre-existing events, but it is also frequently true in first-time failures characterized by precursory symptoms that, if promptly detected with detailed geomorphic investigations, are of invaluable help in landslide hazard zoning. These considerations point out how landslide inventory mapping can be a powerful predictive tool. The Emilia-Romagna case is an excellent example of how the systematic collection of geologic and geomorphic data, with the aid of modern geographic information systems, can be successfully employed in the regional assessment of landslide risk. Unfortunately, man is still confronted with situations that are difficult to predict, such as in the Versilia example, that show how extreme events can escape the prediction techniques currently available and cause huge unexpected losses.

Regarding landslide risk prevention, success is linked to a clear spatial and typological prediction: when the phenomena are clearly spatially delimited and their mechanism is fully described, risk mitigation actions can be successfully implemented. Therefore prevention can be pursued, on one hand, through the mitigation of hazard, following the identification of precursory symptoms and of preparatory casual factors and, on the other, through a correct management of human activities and land use. With the combination and coordination of these actions, the success rate of preventive measures becomes satisfactory. Careful land and urban planning is of paramount importance in countries exposed to landslide hazard and the cases illustrated in this paper have shown two different approaches. These can either lead to effective slope stabilization, even promoting the re-beautification of a landscape such in the San Miniato hill example, or to a major catastrophe such as in the Sarno event where incomplete geologic and geomorphic knowledge was combined with uncontrolled urban development.

For effective management, an emergency should be accurately planned and defined before hand, integrating both elements of prediction and prevention. The implementation is usually carried out in rapid succession and under conditions of great stress. It is in this phase that the scientific community can play a fundamental role, transferring to the decision makers the necessary knowledge for successfully overcoming a crisis. The comparison between La Josefina and the Vaiont examples points out how the development of investigation and simulation techniques can help define reliable scenarios, with functional warning systems, that permit us to correctly manage emergency situations.

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REFERENCES

Aleotti P., Bastianelli L., Canuti P., Iotti A., Polloni G. and Vannocci P. (1999); *The use of airborne laser terrain mapping techniques in slope instability assessment: preliminary results in the Sarno area*. Proc. General Assembly of the European Geophysical Society. In press.

Antoine P. (1977); *Rèflexions sur la cartographie ZERMOS et bilan des expériences en cours*. BRGM Bull., Sect.III, N.1-2, pp. 9-20.

Bertocci R. and D'Amato Avanzi G. (1993); *Il contributo dell'analisi ed interpretazione dei documenti storici relativi ai dissesti che interessano la collina di S.Miniato al Monte (Firenze)*. Atti 3 congresso Giovani Ricercatori in Geologia Applicata, Potenza (in stampa)

Bertocci , R., Canuti P., Focardi P., Garzonio C.A., Trivisonno R. (1995); I problemi di stabilità della collina di San Miniato nella storia urbanistica e monumentale di Firenze. *Geologia Applicata e Idrogeologia*, Bari, 30, pp. 451-168.

Brabb E.E., Pampeyan E.H. and Bonilla M.G. (1972); *Landslide susceptibility in San Mateo County, California*. USGS Misc. Field Study Map, MF-360.

Caine N. 1980; The rainfall intensity-duration control of shallow landslides and debris flows. *Geografiska Annal*, 62A, pp. 23-27.

Cancelli A. and Nova R. (1985); *Landslides in soil and debris cover triggered by rainfall in Valtellina (Central Alps-Italy)*. Proc. IV Int. Conf. & Field Workshop on Landslides, Tokio, pp. 267-272.

Canuti P., Egidi D. and Palmieri S. (1998); *Prevenzione e gestione del rischio nella frana di Silla (Gaggio Montano, BO) del novembre 1994*. Proc. International Conference on Prevention of Hydrogeological Hazards, Alba 1996, 1, 613-624.

Canuti P., Frassoni A., Natale L. (1994); Failure of Rio Paute Landslide Dam. *Landslide News*, 8, pp. 6-7.

Canuti P. & Casagli N. (1996); *Considerazioni sulla valutazione del rischio di frana. Atti del Convegno "Fenomeni franosi e centri abitati"*. Bologna, 27 Maggio 1994. CNR-GNDCI - Regione Emilia-Romagna. 29-130.

Canuti P., Casagli N., Pellegrini M. and Tosatti G. (1999); Geo-hydrological hazard. In: G.B. Vai and P. Martini (eds.) *Apennine Book* Chpt.28. In press.

Caredio F., D'Amato Avanzi G., Puccinellic A., Trivellini M., Venutelli M. and Verani M. (1998); *La catastrofe idrogeologica del 19/6/1996 in Versilia e Garfagnana (Toscana, Italia): aspetti geomorfologici e valutazione idrauliche*. Proc. International Conference on Prevention of Hydrogeological Hazards, Alba 1996, 1, pp. 75-88.

Casagli N., Catani F. and Salvadori A. (1999); *A model for prediction of landslide triggered by prolonged rainfall in low permeability terrains*. European Geophysical Society Plinius Conference on Mediterranean storms. Maratea, Italy. 14-16 October 1999.

Casagli N., Iotti A. and Tarchiani U. (1995); *Caratteri geomorfologici e geotecnici della frana di San Benedetto Val di Sambro (BO)*. Proc. 2° International Meeting of Young Researchers in Applied Geology, Peveragno (CN). Politecnico di Torino. Dipartimento di Georisorse e Territorio. Sez.A, pp. 32-37.

Castelli F., Becchi I., Caporali E., Mazzanti B. and Castellani L. (1997); *Hydro-sedimentological analysis of the '96 Apuanian Alps flash-flood event*. Proc. XXII General Assembly of the European Geophysical Society, In press.

Cruden D. M. (1991); A simple definition of a landslide. *Bull. International Association Engineering Geology*, 43, pp. 27-29.

Cruden D.M. and Varnes D.J. (1996); Landslides types and processes. In: *Landslides: investigation and mitigation*. Transportation Research Board. National Research Council. Special Report 247. National Academy Press, Washington. Chap.3, pp. 36-75.

Cruden , D. and Fell, R. (Eds.) (1997); *Landslide risk assessment*. Proceedings of the International Workshop on Landslide Risk Assessment, Honolulu, 19-21 February 1997. Balkema, Rotterdam, 371pp.

De Graff, J.V. (1978); Regional landslide evaluation: two Utah examples. *Enviromental geology*, 2(4), pp. 203-214.

Del Prete M., Guadagno F.M. and Hawkins A.B. (1998); Preliminary report on the landslides of 5 May 1998, Campania, Italy. *Bull. Engineering Geology and the Environment*. Springer-Verlag. 57, pp. 113-129.

DRM (Délégation aux Risques Majeurs) (1985); Mise en oeuvre des Plans d'Exposition aux Risques naturels prévisibles. *Plan d'Exposition aux risques*. Rapport Administratif et technique provisoire. Premier Ministre.

DRM (Délégation aux Risques Majeurs) (1988); Evaluation de la vulnérabilité. *Plan d'Exposition aux risques*. Ministère de l'Environnement. Direction de l'Eau et de la Prévention des Pollutions et des Risques. La Documentation Française. 112pp.

DRM (Délégation aux Risques Majeurs) (1990); *Les études préliminaires à la cartographie réglementaire des risques naturels majeurs*. Secrétariat d' Ètat auprès du Premier ministre chargé de l'Environnement et de la Prévention des Risques technologiques et naturels majeurs. La Documentation Française. 143pp.

Einstein H.H. (1988); Special Lecture: *Landslide risk assessment procedure*. Proc. 5th Int. Symp. on Landslides, Lausanne, 2, pp. 1075-1090.

Garberi M.L., Palumbo A. and Pizziolo M. (1999); I numeri sulle frane. Regione Emilia-Romagna. Direzione Generale Sistemi Informativi e Telematica – Servizio Cartografico e Geologico. *Grafiche Damiani*, Bologna, 94pp.

Giudici F. and Semenza E. (1959); *Studio geologico del serbatoio del Vaiont*. Relazione inedita. SADE.

Gottardi G., Malaguti C., Marchi G., Pellegrini M., Tellini C. and Tosatti G. (1998); *Landslide risk management in large, slow mass movements: an example in the Northern Apennines (Italy)*. Proc. 2nd Internat. Conf. on Environmental Management, University of Wollongong, Australia. 2, pp. 951-962.

Hartlén J. and Viberg L. (1988); General report: *Evaluation of landslide hazard*. Proc. 5th Int. Symp. on Landslides, Lausanne, 2, pp. 1037-1058.

Hendron A. J. and Patton F. D. (1985); *The Vaiont slide, a geotechnical analysis based on new geologic observations of the failure surface*. Depart. of Army, U. S. Army Corps of Engineers, Tech. Rep. GL-85-5, p. 103.

Humbert M. (1976); Le cartographie en France des zones exposées à des risques liés aux mouvements du sol; Cartes ZERMOS. *IAEG Bull.*, 16, pp. 80-82.

Humbert M. (1977); La cartographie ZERMOS. Modalités d'établissement des cartes des zones exposées à des risques liés aux mouvements du sol et du sous-sol. *BRGM Bull.*, Serie II, sect. III, n.1/2, 5-8.

Hutchinson J.N. (1977); Assessment of the effectiveness of corrective measures in relation to geological conditions and types of slope movements. *IAEG Bull.*, 16, pp. 131-155.

Hutchinson J.N. (1987); *Mechanisms producing large displacements in landslides on pre-existing shears*. 1st Sino-British Geol. Conf., Tapei, Memoir of the Geological Survey of China, 9, pp. 175-200.

Hutchinson J.N. (1988); *General report: Morphological and geothecnical parameters of landslides in relation to geology and hydrogeology*. Proc. 5th Int. Symp. on Landslides, Lausanne, 1: pp. 3-36.

International Union of Geological Sciences Working Group on Landslides (IUGS/WGL) (1997); Quantitative risk assessment for slopes and landslides – The state-of-the-art. In Cruden, D. & Fell, R. (Eds.) *Landslide risk assessment*. Proceedings of the International Workshop on Landslide Risk Assessment, Honolulu, 19-21 February 1997. Balkema, Rotterdam, pp. 3-12.

International Union of Geological Sciences Working Group on Landslides (IUGS/WGL) (1995); A suggested method for describing the rate of movement of a landslide. *IAEG Bull.*, 52, pp. 75-78.

Jibson R.W. (1989); Debris flows in southern Puerto Rico. *Geol. Soc. Am. Spec. Pub.*, 236, pp. 1-13.

Kenney T.C. (1966); Stability of the Vaiont slide slope. *Rock Mech. Eng. Geol.*, 1, pp. 10-16.

Kiersch G.A. (1964); Vaiont Reservoir Disaster. *Civil Engineering*, March 1964, 32-39.

Larini G., Marchi G. Pellegrini M. and Tellini C. (1997); *La grande frana di Corniglio (Appennino settentrionale, Provincia di Parma) riattivata negli anni 1994-96*. Proc. International Conference on Prevention of Hydrogeological Hazards, Alba 1996, 1, pp. 505-516.

Mencl V. (1967); Mechanics of landslides with non-circular slip surface with special reference to the Vaiont slide. *Géotechnique*, 16, pp. 329-337.

Moser M. and Hohensinn F. (1983); Geotechnical aspects of soil slips in Alpine Regions. *Engineering Geology*, 19, pp. 185-211.

Müller L. (1964); The Rock Slide in the Vaiont Valley. *Rock Mech. Eng. Geol.* 2(3-4), pp. 148-212.

Müller L. (1968); New considerations on the Vaiont slide. *Rock Mech. Eng. Geol.* 6, pp. 1-91.

Novellier E. (1967); *Shear strength of bedded and jointed rock as determined from the Zalesina and Vaiont slides*. Proc. Geotechnical Conference, Oslo, 1, pp. 289-294.

Plaza-Nieto G. and Zevallos O. (1994); The 1993 La Josefina rockslide and Rio Paute landslide dam, Ecuador. *Landslide News*, 8, pp. 4-6.

Radbruch-Hall D.H., Colton R.B., Davies W.E., Lucchitta I., Skipp B.A. and Varnes D.J. (1982); *Landslide overview map of the conterminous United States*. USGS Prof. Papers 1183, US Gov. Printing Office, 25pp.

Radbruch-Hall D.H., Colton R.B., Davies W.E., Skipp B.A., Lucchitta I., and Varnes D.J. (1976); *Preliminary landslide overview map of the conterminous United States*. U.S. Geol. Survey Misc. Field Studies Map, MF-771.

Selli R. and Trevisan L. (1964); *Caratteri e interpretazione della frana del Vaiont*. Annali del Museo Geologico di Bologna, Ser.2, 32(1).

Schuster R.L. (1996); Socio-economic significance of landslides. In: *Landslides: Investigation and Mitigation*. Transportation Research Board. National Research Council. Special Report 247. National Academy Press, Washington. Chap.2, pp. 12-35.

Tika TH.E. and Hutchinson J.N. (1999); Ring shear tests from the Vaiont landslide slip surface. *Géotechnique*, 49(1), pp. 59-74.

Varnes D.J. and IAEG Comm. on Landslides (1984); *Landslide hazard zonation - a review of principles and practice*. UNESCO Paris. 63pp.

Varnes D.J. (1981); Slope-stability problems of the Circum-Pacific region as related to mineral and energy resources. In: Halbouty M.T. (ed.) *Energy resources of the Pacific Region*. American Association of Petroleum Geologist Studies in Geology, 12, pp. 489-505.

Wieczorek G.F. and Sarmiento J. (1988); Rainfall, piezometric levels and debris flows near La Honda, California, in storms between 1975 and 1983. In: *Landslides, floods and marine effects of the storm of Jan 3-5, 1982, in the S.Francisco Bay region, California*. USGS Prof. Papers., 1434, pp. 43-63.

WP/WLI - International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory (1990); A suggested method for reporting a landslide. *IAEG Bull.*, 41, pp. 5-12.

WP/WLI - International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory (1991); A suggested method for a landslide summary. *IAEG Bull.*, 43, pp. 101-110.

WP/WLI - International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory (1993a); A suggested method for describing the activity of a landslide. IAEG Bull., 47, pp. 53-57.

WP/WLI - International Geotechnical Societies' UNESCO Working Party for World Landslide Inventory (1993b); *Multilingual Glossary for Landslides*. The Canadian Geotechnical Society. BiTech Publisher Ltd., Richmond (CAN).

WP/WLI - International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory (1994) - A suggested method for reporting landslide causes. *IAEG Bull.*, 50, pp. 71-74.

Wu T.H., Tang W.H. and Einstein H.H. (1996); Landslide hazard and risk assessment. In: *Landslides: Investigation and Mitigation*. Transportation Research Board. National Research Council. Special Report 247. National Academy Press, Washington. Chap.6, pp. 106-118.

SNOW AVALANCHES

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ABSTRACT

For alpine countries, avalanches represent one of the major hazards, threatening people in villages as well as on highways and railways. Measures have to be taken to reduce the avalanche risk. Avalanche hazard mapping, as a basis for land use planning, and avalanche warning are the most cost-effective measures to reduce or even avoid avalanche exposure. Long-term technical measures, such as supporting structures, deflecting dams and afforestations, or short-term measures, such as avalanche forecasting, artificial avalanche release or evacuation, might be chosen to reduce the avalanche risk to an acceptable level. It is important to evaluate the different measures within the framework of an overall risk management procedure.

1. INTRODUCTION

In the Alps and elsewhere, expanding settlements and increasing mobility due to tourism have resulted in a growing number of structures under threat by avalanches. Eleven million people live in the Alpine region from France through Switzerland, Italy, Austria to Slovenia and this number is temporarily tripled due to winter tourism. A number of important highways and railways cross the Alps. For example over 19 000 vehicles daily cross the Gotthard Pass, a very important transit route between Italy and Germany (CIPRA, 1998). Since the catastrophic avalanche winter in 1950–51, the mobility of people in terms of vehicle-kilometres may have increased by a factor of 100. Therefore, it is no surprise that avalanche mitigation has continued to play an important role in the life of people living in the Alps. In Switzerland alone, over the past 50 years, about 1.5 billion Swiss francs have been invested in engineering construction work for avalanche protection such as snow supporting structures, deflectors or snow sheds. Together with daily avalanche forecasts, the avalanche hazard zoning and sustainable silviculture of the protection forests, has led to a high degree of safety (compared to other hazards) in densely populated mountainous areas and on roads with high volumes of traffic.

Although avalanche research and avalanche hazard mitigation have made major progress in recent decades, there are still deficiencies and not enough knowledge or suitable tools to sufficiently protect life and property. The catastrophic 1998–99 winter, with many hundreds of devastating avalanches all over the central Alps, clearly showed this. In Switzerland alone, 17 people were killed during January–February 1999, half of them in buildings and half of them on roads and in rural areas. Total damages are estimated at 1 billion Swiss francs, composed of 250 million Swiss francs in direct damages and 750 million Swiss francs in indirect damages. Neighbouring alpine countries suffered from similar experiences during this devastating period. In the European Alps, a total of 75 fatalities were counted during January–February 1999.

2. AVALANCHE HAZARD AND DAMAGE SCENARIOS

Instabilities in the snow cover and external impacts can cause avalanches on slopes with an angle of 25°–55°. Extreme weather situations with heavy snowfall over several days may lead to catastrophic avalanches threatening villages, access roads and railways. Different kinds of avalanches occur depending on the characteristics of the snow pack, the snow volume involved, the slope angle, additional loading, etc. Slab avalanches are most frequent and are typically of moderate size and involve snow masses in the order of a few 1 000 m^3 up to some 10 000 m^3. Over the long-term, on average, most fatalities are due to accidental snow slab avalanche releases, set-off locally by off-piste skiers, ski mountaineers or similar leisure activities (in Switzerland these kind of avalanches caused 24 out

Figure 1. Devastating dense flow avalanches at Evolène/Valais, Switzerland, causing 12 fatalities on 21 February 1999.

of 26 fatalities). Only very few people have been killed on open roads or in settlements (Tschirky, 1998), particularly during the last decade.

This annual statistic may drastically change during a winter period with exceptional meteorological and snow conditions, as experienced in January–February 1999. Situations with return periods of several decades may threaten a whole country, severely endangering people and their settlements, vehicles on roads and railways and forest and agricultural landscape. The devastating avalanches of January–February 1999 were mostly big powder snow and/or dense flow avalanches consisting mainly of dry, loose snow, which started to rupture spontaneously under their own weight. The rupture plane was often situated at the base of several snow layers, accumulating a 2–4 m thick snow pack. Huge snow masses up to more then 1 million m^3 were sometimes involved and the resulting avalanches advanced down to valley level, endangered settlements, roads and railways (Figures 1, 2 and 3).

These avalanches caused direct damages including fatalities, destruction of buildings, devastation of forests and crops damages. These damages, in turn, generate costs because of interrupted roads and railways, failures in electricity distribution and in communications, reduced accessibility of tourist resorts, decrease in hotel reservations, etc.

3. AVALANCHE PROTECTION MEASURES

3.1 GENERAL OVERVIEW

Several classification possibilities exist for the large variety of avalanche risk reducing measures. Most often used is a sub-division into short- and long-term protection measures (Föhn, 1994; Salm, 1994):

Short-term protection measures:
- Avalanche forecasting, warning;
- Artificial release of avalanches;
- Closure of roads and railways;
- Orientation and evacuation of people and cattle.

Long-term protection measures:
- Hazard mapping, land use planning;
- Construction measures;
  - supporting structures in zones where avalanches are triggered;
  - deviation dams in the avalanche path;
  - snow sheds (roads, railways crossing avalanche path);
  - retarding constructions (deposition zone of avalanches);
  - retaining dams (deposition zone of avalanches);
- Silvicultural measures;
  - afforestation;
  - reforestation, combined with technical measures;

Figure 2. Huge powder snow avalanche, released for research purposes at the SLF test-site Vallée de la Sionne/ Valais, Switzerland on 10 February 1999.

3.2 AVALANCHE FORECASTING

Avalanche hazard forecasting and subsequent measures, such as evacuation of people in exposed settlements, the closing of roads and railway lines and the artificial release of avalanches under controlled conditions, are called organizational or short-term measures. Efficient use of these measures requires close interaction and cooperation between all national, regional and local security commission staff members and nation-wide public avalanche awareness programmes. All Alpine countries operate national and/or regional avalanche warning centres, which forecast avalanches on a daily basis. With the introduction of the European Avalanche Hazard Scale in 1993, a common language to describe snow cover stability and the probability of an avalanche release has been found which is now being used in all European countries (Meister, 1995).

Avalanche warning has been a key task of the Swiss Federal Institute for Snow and Avalanche Research in Davos (SLF) since it was established over half a century ago. In the past, the predominant methods used for avalanche forecasting at SLF have been conventional, i.e. snow stability and avalanche hazards were predicted by synoptic methods, as in meteorology. Avalanche forecasting was mainly based on data analysis and experience and intuition, supplemented with some statistical programs.

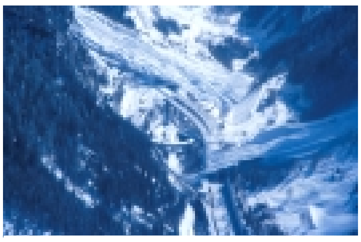


Figure 3. Situation in Goppenstein/ VS in February 1999. Several dense flow avalanches from both valley sides threaten the international Loetschberg railway, the access road, and a temporary construction site for the tunnelling work.

A paradigm shift is now slowly taking place. Information systems and computer programs are becoming more and more important, assisting the forecaster in collecting and analysing large amounts of field data (Föhn,1998; Russi *et al.*, 1998). Statistical analysis of measurements, numerical simulations of weather and snow-pack (Lehning *et al.*, 1998) and symbolic computations of the avalanche hazard are the key elements of modern avalanche forecasting. A similar approach has also been initiated in France (Brun *et al.*, 1992, Durand *et al.*,1998).

However, the forecaster with his intuition, experience and local knowledge still plays a decisive role in the forecasting process. While the computer helps to assimilate information, propose the appropriate hazard risks, support the forecaster in his decision and distribute forecasts via modern communication channels, it is still the forecasters ultimate responsibility to check and modify the computer's prediction.

A three level concept for avalanche forecasting (national, regional, local level) is being implemented within the Swiss concept "Avalanche Warning Switzerland CH 2000". The SLF provides the first two levels, the daily national bulletin and the regional bulletins, while local security commissions are responsible for the local level (regional bulletins cover an area of 1000–5000 km^2, and local bulletins an area of 100 km^2).

The overall aim of this concept is to modernize avalanche warning in Switzerland and to improve the temporal and spatial resolution of avalanche forecasting on a national, regional and local level, thereby helping to prevent avalanche accidents. Figure 4 shows the general architecture containing all major modules and information paths. Shaded boxes denote input sources and white boxes indicate computer models.

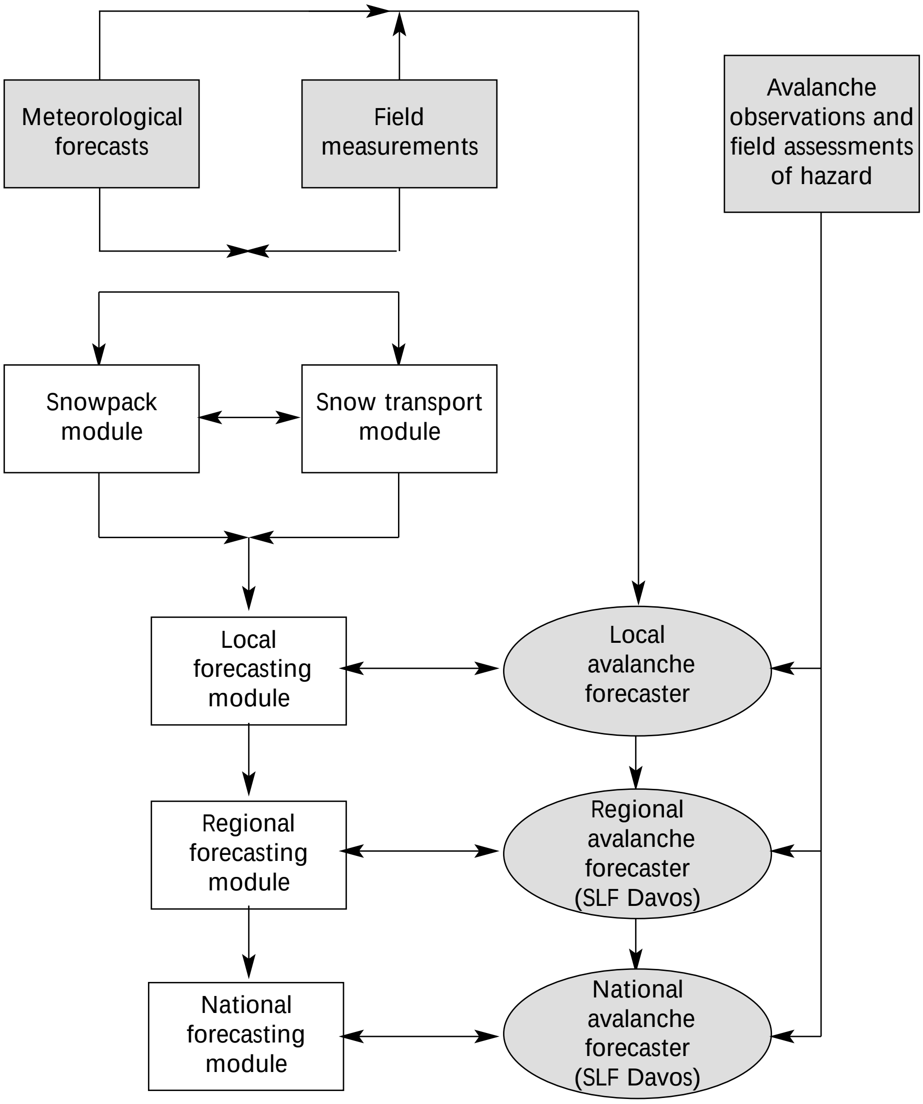


Figure 4. General architecture for the Future avalanche forecast in Switzerland (Russi et al., 1998).

The avalanche warnings (bulletins) represent an important tool for all local and regional security commissions in their risk management process, e.g. to close a road, to evacuate people or to order the artificial release of potential avalanches. Basic information for the bulletins is gathered by a network of 75 snow and avalanche observers and 60 automatic measuring stations throughout the Swiss Alps (Russi *et al.*, 1998). The forecaster's expert knowledge, supplemented by a continuously operated numerical snow pack model (Figure 5, Lehning *et al.*,1999), is used to analyse the extensive set of data. The numerical model evaluates the internal state of the snow cover (temperature, density and grain type profile, moisture content, layering, depth hoar).

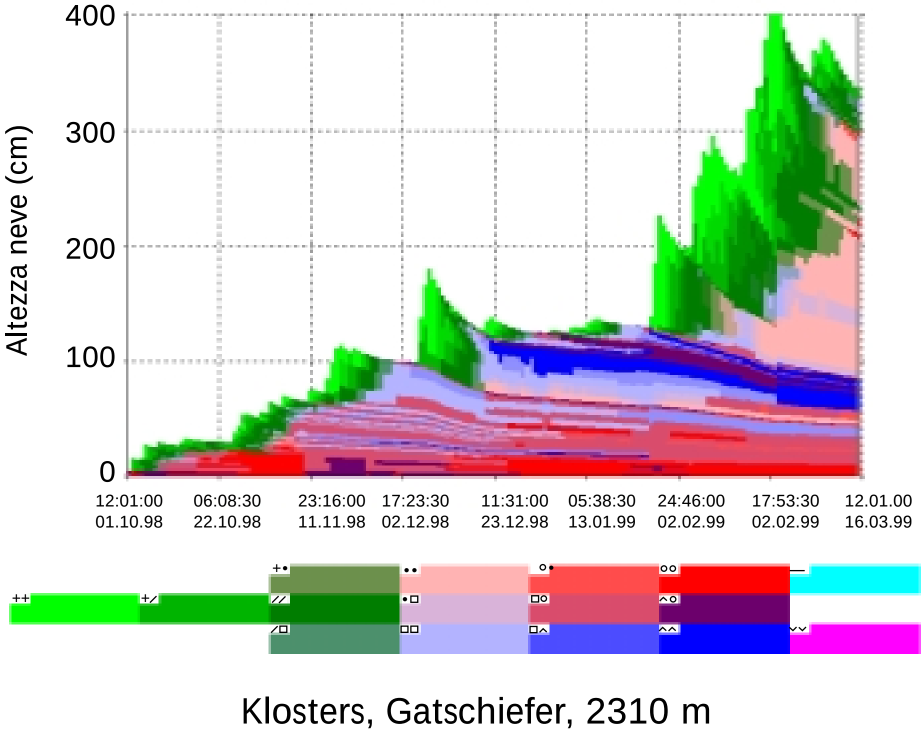
Additional software such as, for example, NXD2000 (Russi *et al.*, 1998) will provide fast and efficient decision support for the local level. Even though these models have made good progress in recent years, they cannot fulfil all requirements for precision in space and time (Buser, 1989, Föhn,1998).

While the Web is the main information channel for the general public, a service called InfoBOX was set up by the SLF three years ago. This service links together national, regional and local avalanche specialists in Switzerland. At present, about 140 specialists (i.e. people who are in charge of avalanche safety in villages or towns, in ski areas or on highways) are using the SLF InfoBOX service. Snow and weather data from automatic stations (see Figure 6) or weather forecasts can now be accessed 24 hours a day using this service.

All other short-term, temporary measures, like artificial release, traffic closure, evacuation of people and cattle, are subsequent measures in critical periods. Stoffel (1997) has discussed the different techniques for artificial avalanche release. Evacuation has to be based on well-defined warnings and evacuation procedures to prevent additional hazardous situations for the people involved. In such critical situations, the local authorities, supported by avalanche experts, have to assume grave responsibilities. The catastrophic avalanche period of February 1999 clearly showed that, in all concerned Alpine countries, there is a definite need for improved links between avalanche experts and regional and local authorities on one hand and between avalanche experts and the local avalanche commissions in the communities (which finally recommend the evacuations of endangered zones) on the other.

Figure 5 (right). Snow cover layering (seasonal snow layers with grain shapes), calculated with "Snowpack", a computer model developed at the SLF (Lehning et al, 1999).

Figure 6 (left). IMIS network. Automatic snow and weather station at Simplon Pass, Valais Switzerland.



3.2 AVALANCHE HAZARD MAPPING

Hazard maps serve as basic documents for avalanche risk evaluation, especially with respect to land-use planning (for a more detailed overview see Margreth *et al.*, 1998). In Switzerland, hazard mapping begun after two catastrophic avalanche periods in January and February 1951. The first avalanche hazard maps in Switzerland were developed for Gadmen and Wengen in the Canton of Bern, in 1954 and 1960 respectively. Dangerous zones were designated in a rather qualitative way, on the basis of previous disastrous events, without taking into account climatic factors or quantitative avalanche calculations. In the course of time, methods were improved and avalanche models introduced to calculate the dynamic behaviour (Föhn and Meister, 1982). This development led, for example, to the "Swiss guidelines for avalanche zoning" (BFF, 1984) and the "Guidelines for the calculation of dense flow avalanches" (Salm *et al.*, 1990). These two publications are, today, the most important tools for the preparation of avalanche hazard maps in Switzerland. In recent years, numerical simulation, GIS and DTM tools have led to substantial improvements (Gruber *et al.*, 1998*a, b*). The two following parameters were chosen to quantify the potential hazard for a given site:

- The expected frequency of an avalanche reaching a given site (frequency is normally expressed by the mean return period);
- The intensity of an avalanche (intensity is expressed by the avalanche pressure exerted on a wall of a building. As this pressure is assumed to increase with the square of speed and proportional to density, the kinetic energy of snow masses is also included).

Several hazard zones are defined in order to distinguish variable hazard intensities and run-out scenarios:

Red zone: Pressures of more than 30 kN/m^2 for avalanches with a return period of up to 300 years, and/ or avalanches with a return period up to 30 years, independent of pressure.

Blue zone: Pressures of less than 30 kN/m^2 for avalanches with return periods between 30 and 300 years.

Yellow zone: For powder-snow avalanches: pressure less than 3 kN/m^2, return period more than 30 years. For dry-snow avalanches: pressure unknown, return period more than 300 years.

White zone: No avalanche impacts to be expected.

Gliding Snow: Area of pronounced danger for gliding snow at locations without avalanches or with impacts larger than by avalanche effects.

The elaboration of hazard maps must follow strictly scientific criteria and methods, including expert knowledge. The goal is to determine the extreme avalanche on a reliable basis. Important tools are field visits to assess the avalanche terrain, the examination of the avalanche record as a map with all known avalanches in history, including their extent and date, additional information from competent local people or from old chronicles and checks of local climatic conditions and dynamic avalanche calculations. The dynamic calculations are used for:

- Predicting an extreme event, probably not recorded in historical records;
- Delimiting the hazard zones for the different return periods;
- Calculating run-out distances and pressures as a function of avalanche frequency.

In Switzerland, the Voellmy-Salm model has been used for more than 20 years for estimating avalanche speeds, flow heights and run-out distances of dense flow avalanches (Salm *et al.*, 1990). This model requires careful estimation of its input parameters such as fracture depth, friction parameters or avalanche size (Margreth *et al.*, 1998). The calculations have to be made with different input parameters to check the sensitivity. Critical assessment of the results is very important. It must be pointed out that dynamic calculations are just one part of hazard assessment. In recent years, many such dynamic calculation methods have been proposed, some of which are routinely and effectively used by practitioners (Harbitz *et al.*,1998). Numerical modelling methods using FE or FD techniques have set new standards in the use of avalanche dynamics models (McClung *et al.*, 1995, Bartelt *et al.*, 1997). User-friendly GIS and DTM tools are additional assets in completing and facilitating avalanche hazard mapping.

3.3 CONSTRUCTION MEASURES

Technical, long-term, avalanche defence measures are used in the starting zone to prevent the release of avalanches (supporting structures) and in the avalanche track and run-out zone (avalanche sheds, deflecting and catching dams) to reduce the damaging effect of descending avalanches.

SUPPORTING STRUCTURES

The wide application of supporting structures, which started in the last century, took a big step forward following the severe avalanche winter of 1950–51. The technology has since this period reached an advanced stage. More than 500 km of supporting steel bridges and snow nets has been built over the last 50 years (Figure 7). All the experience gained through these decades is summarized in the Swiss Guidelines (1990). The aim of supporting structures is to prevent the start of large avalanches or at least to limit snow motions so that they remain harmless. Fully developed avalanches, however, cannot be stopped and retained by supporting structures (Margreth, 1996).

The first effect of supporting structures is to create an overall increase in the stability of the inclined snow pack. The acting snow-pack forces are redistributed, compressive reaction forces are increased and shear forces, which often dominate stability, are decreased. The second effect is to limit the mass of snow put in motion, retarding and catching it. The vertical height must correspond to the extreme snow depth occurring with a return period of at least 100 years. The snow height adopted is a crucial point for the design to guarantee the effectiveness of supporting structures. In February 1999, some lines of structures, were overfilled with snow; more than 550 cm of snow was measured there at 2 500 metres above sea-level. Construction for up to 7 m of snow is technically feasible. The typical structure heights used in Switzerland vary between 3.0 m and 5.0 m.

Steel bridges and flexible snow nets are predominantly used today. The costs for supporting structures are about 1.0–1.5 million Swiss francs per hectare. Due to these high costs, supporting structures are mainly used for the protection of settlements. The structures are designed for an avalanche return period of 100 years. Maintenance of older supporting structures is, therefore, expensive and becoming more and more important.

Deflecting and catching dams

Deflecting and catching dams are relatively cheap compared to supporting structures but need enough space (with respect to volume) to be effective. Deflecting and catching dams are normally earth dams, sometimes combined with stone masonry to increase the slope-inclination on the impact side. The height of catching dams may reach 15–20 m, depending on the avalanche velocity and the snow volume to be retained. An overflow of the dam crest has to be avoided. Catching dams for avalanches may also be used to retain mudflows.

Avalanche sheds

Avalanche sheds are very effective measures to protect roads and railway lines if the avalanche track is narrow and the shed construction sufficiently long (see Figure 8). In situations where the avalanche deposition zone is widely spread, however, a shed construction would become too long. In such situations and from the perspective of integral risk management, road closures are often the only cost-effective measures. Swiss guidelines for the design of avalanche sheds (ASB/SBB, 1994) have existed for a few years. One meter of snow shed costs, on average, about 25 000 Swiss francs.

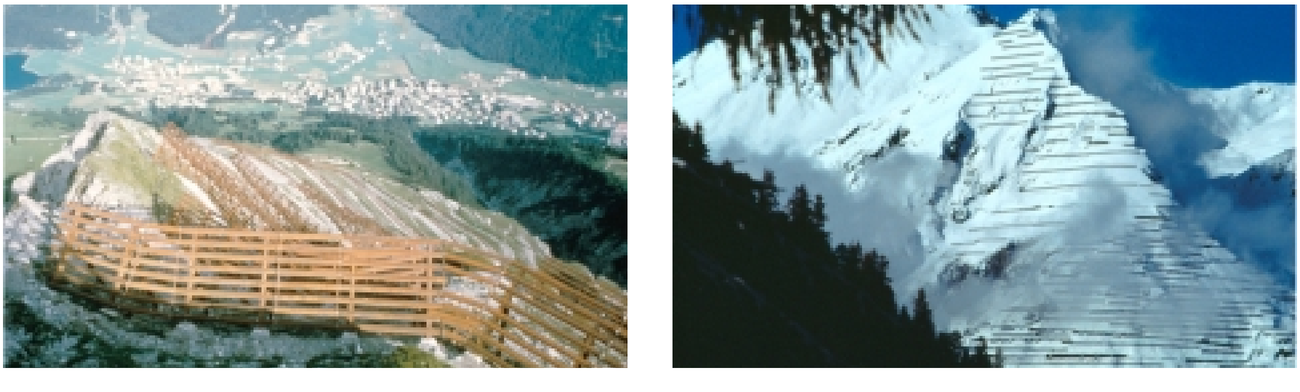


Figure 7. Steel supporting structures above Davos/Switzerland (Schiahorn). *Left side: View from above in summertime; right side: View from the opposite valley flank in wintertime.*

3.5 MOUNTAIN FORESTS

Mountain forests is the most effective and the cheapest protection for villages, roads and railways. The trees retain the snow, stabilise the snow-pack and prevent avalanches from starting. The mechanical resistance of the trees is not, however, sufficient to stop avalanches. In consequence, the protective effect of mountain forest, against avalanches, is only valid for starting zones below the timberline. In Switzerland, about 1000 km^2 of forest area serves, primarily, as avalanche and rock-fall protection. If this effect were to be replaced by technical measures, a yearly investment of 2 billion Swiss francs would be necessary.

4. AVALANCHE RISK ASSESSMENT AND MANAGEMENT

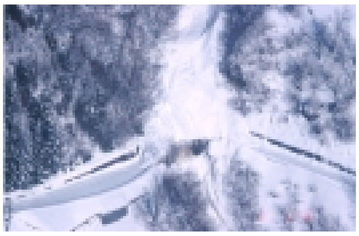


Figure 8. Example of a too short avalanche shed Bm/GL Switzerland (end of February 1999).

Figure 9. Snow deposit of an avalanche near Linthtal/GL Switzerland.

Risk management is an integral approach of human thinking and acting. It incorporates the anticipation and assessment of risk, a systematic approach to limiting the risk to an acceptable level and undertaking the necessary measures. Avalanche risk is the result of the temporal and the spatial overlapping of the two independent domains “potential avalanche danger” and “spatial area in use”. The combined probability, or the risk (R) as a product of the avalanche hazard (A), of the probability that human beings, dwellings, vehicles or other goods are endangered in a zone (Z), and of the value of or damage probability of these goods (D) has to be evaluated for each area:

$$R = A \cdot Z \cdot D$$

The avalanche danger is described by the avalanche probability and the extent of the avalanche. The spatial area in use corresponds to the probability of the presence of any objects and the value of these objects (or the number of people present).

To avoid the disastrous effects of avalanches, different kinds of preventive measures are used to reduce the avalanche risk to an acceptable level. These measures have to be seen as an integral set of possible protection measures. In most cases, a combination of the different measures is used. The optimal combination can be found by maximising the cost-effectiveness and cost-benefit of all possible avalanche control measures. Basic principles to be applied in an integral risk management approach include the identification of the avalanche danger in terms of probability of occurrence; the estimation of the risk potential based on the vulnerability of the corresponding values exposed to risk; the assessment of protection goals; and the cost-estimation for control measures (e.g. Wilhelm, 1997 and 1998, Heinimann *et al.*, 1998).

Cost-effectiveness can be expressed in terms of amount of money spent per saved life (Wilhelm, 1997). For avalanche control measures, it varies to a large extent, depending on the actual situation (1 to 20 million CHF). The whole risk management process is iterative with several assessment and control loops. For preliminary design purposes, Wilhelm (1998) has established simplified cost-effectiveness evaluation charts which will be published as a BUWAL-Guideline for the risk assessment of roads and railways.

5. RESEARCH NEEDS

5.1 PHYSICS AND MECHANICS OF SNOW

Snow as material for avalanches is a complex mixture of air, water and ice which, in our environment, is always close to its melting point and henceforth changes its physical properties continuously in time and space. This metamorphic process changes the shape of the snow particles from fine dendrites to rounded grains or other shaped particles depending on temperatures, density, solar insulation, wind, etc. These physical properties need to be known in depth if the formation of the various types of avalanches is to be predictable for detailed avalanche forecasting. Unfortunately, however, very little is known on the quantitative description of, for example, the shrinking, settling and re-crystallisation processes within the snow pack combined with the corresponding changes in mechanical properties such as shear resistance and cohesion. Consequently, the numerical simulation of snow pack layering is still lacking of many details.

5.2 AVALANCHE FORECASTING

An overview of avalanche forecasting models and methods has recently been published (Föhn,1998), and the research needs may be briefly summarized as follows. In order to increase the accuracy of avalanche forecasting in time and space, research has to concentrate on questions such as:

- How can the stability of various slopes with different aspect, altitude and slope angle be quantitatively assessed by simulation models and introduced in operational avalanche forecasting service? What are the most likely triggering mechanisms for the release of avalanches in a given situation?
- How can the known local (in hundreds of metres) and temporal (in days) variability of the snow cover on slopes and its stability be taken into account?
- How can snow drift be quantitatively described on a local to regional scale and how can this description be used to improve avalanche forecasting ?
- How can the information available on a local, regional and national scale be combined and used as input to avalanche warning models (statistical methods, expert systems, neural networks) which support the decision process?

5.3 AVALANCHE HAZARD MAPPING

Avalanche hazard mapping is very closely linked to avalanche dynamics. Various dynamic avalanche models have been developed in the last 20–40 years, based on different flow-types (hydraulic, aerosol, mixed, granular). In addition, statistical models, based on a few topographical factors and observed run-out distances, compete with the various flow-type models as far as run-out distances are concerned (Lied,1998).

Significant improvements could be obtained in the avalanche dynamics calculations which serve as a basis for hazard mapping by:

- Improved knowledge of initial conditions (fracture area and depth of sliding snow layers, quality of sliding snow, e.g. various friction coefficients), all dependent on the return period;
- Development of adequate physical models to describe the flow regime of dense-flow avalanches (Bartelt *et al.*, 1997), the snow entrainment in powder-snow avalanches (Issler, 1998) and the impact mechanisms on structures;
- Validation of physical models and numerical modelling with field and laboratory data.

Real progress will only be possible when field and laboratory data become available covering all major parameters influencing avalanche dynamics. Since 1997, therefore, the SLF operates a test-site in the Vallée de la Sionne/VS, Switzerland (Figures 2 and 10, Ammann, 1998). At this site, it is possible to study the overall dynamic behaviour of dense-flow and powder-snow avalanches and to measure avalanche impact forces along their path

5.4 TECHNICAL MEASURES AND RISK MANAGEMENT

Avalanche defence structures and dams still need improvements in:

- The design of the load bearing capacity of the foundations (anchors);
- The design of defence structures in permafrost sub-soil (Stoffel, 1995);
- The implementation of maintenance strategies for existing structures;
- The design of deflecting and retaining dams (McClung, 1995); and
- The design of reinforced structures in the blue avalanche hazard zone.

Major improvements in risk reduction may be achieved by a consequent risk management. Research efforts are needed in the following domains:

- The devastating events in January/ February 1999 showed clearly the importance of indirect damage costs. Damage patterns have changed, the increased mobility and poor public awareness are major reasons. To develop strategies to address this changed damage pattern will be an important task.
- What is the acceptable risk level. Has aversion to be taken into account;
- Development of tools to assess the cost- effectiveness of different defence strategies for settlements;
- roads, railways;
- Implementation of a strategy for the continuous education of local and regional avalanche safety managers (e.g. members of avalanche commissions).

REFERENCES

Ammann, W., 1998: *A new Swiss test-site for avalanche experiments in the Vallée de la Sionne/Valais*. Proceedings Int. Snow Science Workshop, ISSW 1998, Sunriver USA.

ASB/SBB, 1994: *Richtlinie Einwirkungen auf Lawinenschutzgalerien*. Eidg. Drucksachen- und Materialzentrale, Bern.

BFF / EISLF 1984: *Richtlinien zur Berücksichtigung der Lawinen-gefahr bei raum-wirksamen Tätigkeiten*. Bundesamt für Forst-wesen BFF, Eidgenössisches Institut für Schnee- und Lawinen-forschung EISLF; EDMZ Bern.

Bartelt, P. and Gruber, U., 1997: *Development and calibration of a Voellmy-fluid dense snow avalanche model based on a Finite Element Method*. Internal Report No. 718. Eidg. Institut für Schnee- und Lawinenforschung, Davos (unpublished).

Brun, E., Cavid, M. Sudul and G. Brunot, 1992: A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting. *Journal of Glaciology*, 38(128), pp. 13-22

Buser, O., 1989: Two years experience of operational avalanche forecasting using the nearest neighbours method. *Annals of Glaciology*, Vol. 13, pp. 31-34.

CIPRA, 1998: *Alpenreport: Daten, Fakten, Lösungsansätze*, CIPRA International (Hrsg).

Durand, Y., Giraud, G., Mérindol, L., 1998: Short-term numerical avalanche forecasting used operationally at Météo-France over the Alps and Pyrenees. *Annals of Glaciology*, Vol. 26, pp. 357-366.

Föhn, P.M.B.,1994: *Schweiz. Zeitschrift für Forstwesen*, Vol.145 (1), pp. 59-73

Föhn, P.M.B., 1998: *An overview of avalanche forecasting models and methods*. Proceedings of the Norwegian Geotechnical Institute 25 years-Anniversary Conference, Publication Nr. 203, pp. 19-27.

Föhn P.M.B. and Meister R., 1982: *Determination of avalanche magnitude and frequency by direct observations and/or with the aid of indirect snow cover data*, Mitteilungen der Forstl. Bundesversuchsanstalt Wien,144, pp. 207- 228.

Gauer, P., 1998: Blowing and drifting snow in Alpine terrain: numerical simulations and related field measurements. *Annals of Glaciology*, Vol. 26, pp. 174-178.

Gruber, U., 1998a: *Der Einsatz numerischer Simulationsmethoden in der Lawinengefahren-kartierung. Möglichkeiten und Grenzen*. PhD-thesis to be published as Mitteilung des Eidg. Institutes für Schnee- und Lawinenforschung, Davos (in press).

Gruber, U., Bartelt, P., Haefner, H., 1998b: *Avalanche hazard mapping using numerical Voellmy-fluid models*. Proceedings of the NGI Anniversary Conference. Norwegian Geotechnical Institute, pp. 117-121.

Harbitz,C.B., Issler, D. and Keylock, C. J., 1998: *Conclusions from a recent survey of avalanche computational models*. Proceedings of the 25th Anniversary Conference Norwegian Geotechnical Institute,pp. 128-139.

Heinimann, H.R., Hollenstein, K., Kienholz, H., Krummenacher, B., Mani, P., 1998: *Methoden zur Analyse und Bewertung von Naturgefahren. Umwelt-Materialien Nr. 85*. Hrsg. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, 248 S.

Issler, D., 1998: Modelling of snow entrainment and deposition in powder-snow avalanches. *Annals of Glaciology*, 26, pp. 253-258.

Lehning, M., Bartelt, P., Brown, B., 1998: *Operational use of a snowpack model for the avalanche warning service in Switzerland: Model development and first experiences*. Proceedings of the NGI, Nr. 203, pp. 169-174.

Lehning, M., Bartelt, P., Brown, R.L., Russi, T., Stöckli, U., Zimmerli, M., 1999: *Snowpack model calculations for avalanche warning based upon a new network of weather and snow stations, cold regions science and technology,* in press.

Lied, K., 1998: *Snow avalanche experience through 25 years at NGI*. Proceedings of the NGI 25-Anniversary Conference. Norwegian Geotechnical Institute, Publ. Nr 203, pp. 7-14.

Margreth, St., 1996: *Experiences on the use and the effectiveness of permanent supporting structures in Switzerland*, Proceedings International Snow Science Workshop, ISSW 96 Banff, Canadian Avalanche Society.

Margreth, St., Gruber, U., 1998: *Use of avalanche models for hazard mapping*. Proceedings 60 Jahre Schneeforschung, Eidg. Institut für Schnee- und Lawinenforschung, SLF Davos (in Druck).

Meister, R., 1994: *Country wide Avalanche Warning in Switzerland*. ISSW'94 Proceedings, pp. 58-71.

McClung, D. and Mears, A., 1995: Dry-flowing avalanche run-up and run-out. *Journal of Glaciology* 41, No. 138, pp. 359-372.

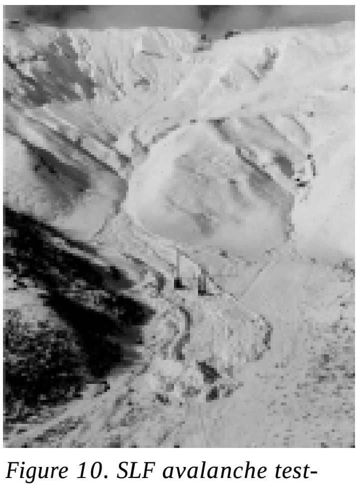


Figure 10. SLF avalanche test-site, Vallée de la Sionne. View on avalanche track with the location of the different measuring equipment.

Russi, T., Ammann, W., Brabec, B., Lehning, M., Meister, R., 1998: *Avalanche warning Switzerland CH 2000*. Proceedings Int. Snow Science Workshop, ISSW 1998, Sunriver, USA.

Salm, B., 1987: *Schnee, Lawinen und Lawinenschutz. Vorlesungsmanuskript ETH Zürich*. VAW ETHZ, Zürich.

Salm, B., Burkard, A. and Gubler, H.U., 1990: *Berechnung von Fliesslawinen. Eine Anleitung für den Praktiker mit Beispielen*. Mitteilung Nr. 47. Eidg. Institut für Schnee- und Lawinenforschung, Davos.

Salm, B., 1994: *Lawinen- Gefahr und Risiko langfristig betrachtet*. Schweiz. Zeitschrift für Forstwesen, 1994, 145(1), pp. 75- 86

Stoffel, L. 1995: *Bautechnische Grundlagen für das Erstellen von Lawinenverbauungen im alpinen Permafrost*. Mitteilungen des Eidg. Institut für Schnee- und Lawinenforschung, SLF, Davos, Nr. 52.

Stoffel, L., 1996: *Künstliche Lawinenauslösung. Hinweise für den Praktiker*. Mitteilungen des Eidg. Institutes für Schnee- und Lawinenforschung, SLF Davos, Nr. 53.

Swiss Guidelines, 1990: *Richtlinien für den Lawinenverbau im Anrissgebiet*. BUWAL, WSL, Eidg. Institut für Schnee und Lawinenforschung, SLF, Davos.

Tschirky, F., 1998: Lawinenunfälle, Vorabdruck des Winterberichtes SLF Nr. 61, SLF Davos

Wilhelm, Ch., 1997: *Wirtschaftlichkeit im Lawinenschutz. Methodik und Erhebungen zur Beurteilung von Schutzmassnahmen mittels qualitativer Risikoanalyse und ökonomischer Bewertung*. Mitteilungen des Eidg. Institutes für Schnee- und Lawinenforschung, Davos, Nr. 54.

Wilhelm, Ch., 1998: *Beurteilung der Kosten-Wirksamkeit von Lawinenschutzmassnahmen an Verkehrs-achsen*. Praxishilfe, Vollzug Umwelt, BUWAL Bern/SLF Davos.

MITIGATING THE EFFECTS OF TSUNAMIS: WHERE DO WE GO FROM HERE?

By Charles S. McCreery; Pacific Tsunami Warning Center

ABSTRACT

During the decade of the IDNDR, significant progress has been made towards more effectively mitigating the tsunami hazard, much of it though the activities of the IOC International Coordination Group for the Tsunami Warning System in the Pacific (ITSU) and its Member States. Worldwide historical tsunami data have been compiled in computer databases with graphical interfaces for more widespread access and to better assess the tsunami hazard in each coastal region. Numerical modelling of tsunamis has matured, and this technology has been transferred to many countries at risk for producing realistic tsunami run-up maps to guide coastal development and emergency planning. Warning systems have better and faster access to high-quality seismic and water level data, better techniques for evaluating tsunamis, and more effective methods for disseminating warnings. Educational materials for both children and adults have been produced in many languages. But with ever-increasing coastal development and population growth, significant challenges remain. Eleven destructive tsunamis have occurred since 1990, causing over 4 000 casualties and significant property damage. When these events are examined, it is possible to identify ways that mitigation efforts have helped, but more often how those efforts need to be expanded and improved in the future.

TSUNAMI PHENOMENON

A tsunami is a series of ocean waves generated by any sudden and large-scale disturbance of the sea or other large body of water. Earthquakes generate most tsunamis, but they can also be generated by landslides and submarine slumps, by volcanic eruptions next to or beneath the sea, and even by meteorite impacts. Recently it has been recognized that some tsunamis that accompany earthquakes are enhanced or may have been produced entirely by landslides or slumps. Tsunamis have occurred in every ocean, but are most common in the Pacific owing to its high level of seismic and volcanic activity. Most often, large tsunamis occur at subduction zones — regions where two of the earth's plates converge and one is diving beneath the other (Figure 1). When great earthquakes take place along these boundaries, the sea-floor over a very large area can be vertically and permanently displaced by as much as several meters. This deformation in turn produces an elevation or depression of the sea surface. In the process of the sea surface coming back to equilibrium, tsunami waves form and propagate away in all directions from the displacement.

Tsunami waves are distinguished from ordinary ocean wind waves by their very long period, high propagation speed, and long wavelength. Tsunami wave periods — the time between one wave crest and the next — range from about 5 to 60 minutes, depending upon the size of the disturbance that generated them. The speed a tsunami travels depends upon the depth of the ocean by the simple relationship: speed = square root (acceleration of gravity x water depth). In mid-ocean, tsunamis can travel at speeds of 800 km/hr or more — the speed of a commercial jet aircraft. As a consequence, it takes less than 24 hours for a tsunami to cross the entire Pacific basin (Figure 2). As a tsunami waves near shore, however, they slow down to the speed of the wind waves — a few tens of kilometres per hour. The wavelength of a tsunami, which is simply its speed times its period, also depends upon the ocean depth. In mid-ocean, tsunami wavelengths may be several hundred kilometres, but near shore the same waves can shorten to only a few kilometres in length as they slow down.

The height of a tsunami depends upon several factors. Near the source, the height may be several meters and it mirrors the deformation that has occurred on the ocean floor. As it moves away from the source, tsunami wave heights are reduced by the spreading of the wavefronts into ever-larger circles, thus reducing

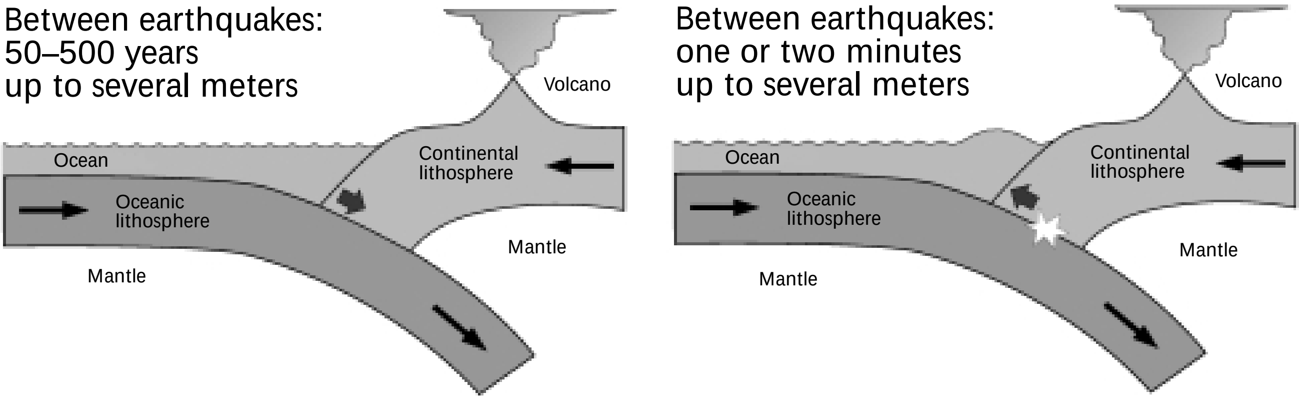


Figure 1. Most major tsunamis are generated at convergent plate boundaries where two plates of the earth's lithosphere are moving towards each other. One plate (typically the oceanic plate) is sliding beneath the other (typically the continental plate) at a rate of a few cm per year. If the contact surface is locked over a long time period, then stresses will build and the continental plate near the boundary can be bent downward by up to several meters. When this boundary slips in a great earthquake, the plate quickly rebounds, pushing up a mound of water several meters high on the ocean surface. Tsunami waves then form and move away in all directions from this mound; the ocean then settles back to a state of equilibrium.

their energy density. Even a great tsunami is often less than a meter high in the deep ocean and is undetectable as it passes beneath ships at sea. Due to its long wavelength, the energy in a tsunami wave extends all the way to the ocean floor. Consequently, as water depth and wavelength decrease when a tsunami approaches shore, its energy becomes increasingly concentrated causing the wave height to grow, sometimes to tens of meters.

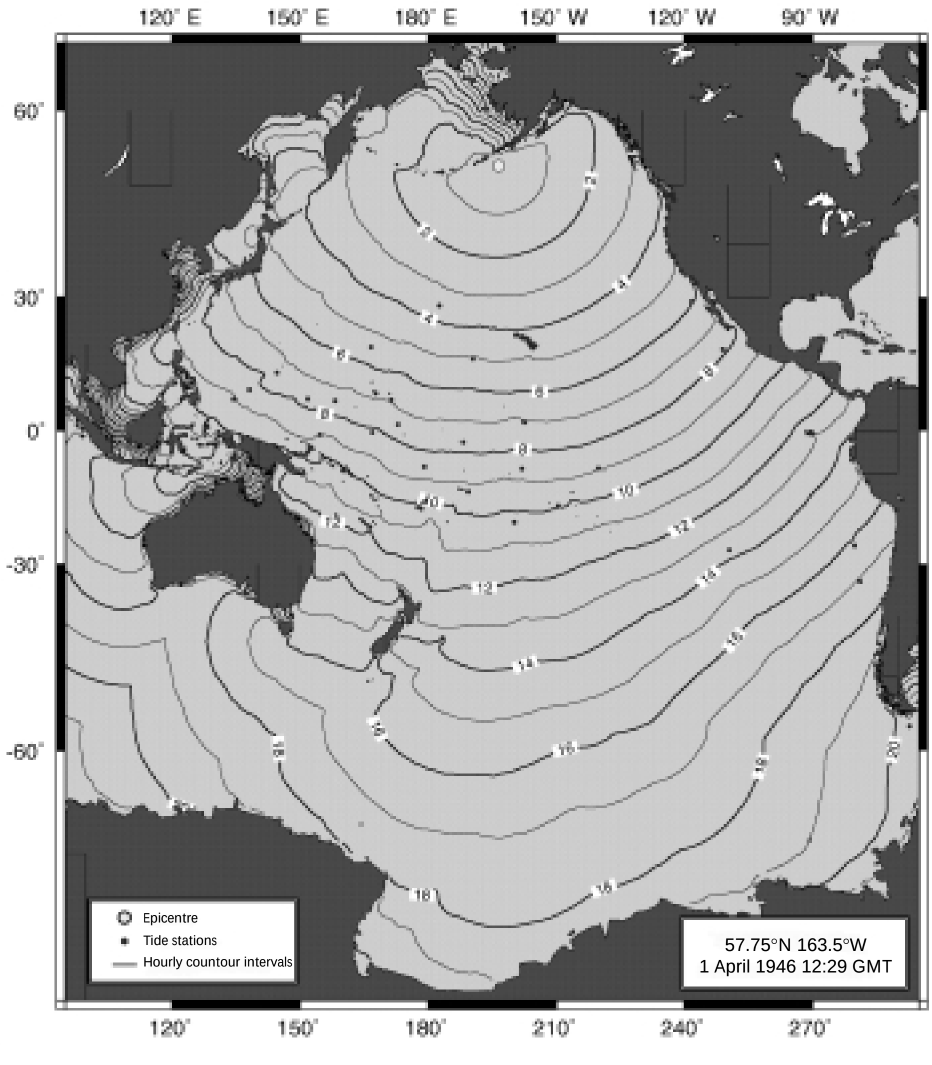


Figure 2. Estimated travel times for the very destructive tsunami generated near Unimak Island, Alaska, on 1 April 1946. The interval between contours is one hour. As illustrated by this case, a tsunami can propagate across the entire Pacific basin in less than a day. This poses a challenge for the warning system since there is only a very limited amount of time available to gather seismic and sea-level data needed for accurate tsunami forecasting, and also to disseminate a warning to all potentially affected coastal communities. Recent advances in communications technology are now being applied to help overcome this problem.

Tsunamis are a hazard because of the damage and casualties that they can cause when they strike shore. In the best of cases, a tsunami may come onshore like a series of quickly rising and falling tides and only cause a gentle repetitive flooding of low-lying coastal areas. Even this can be dangerous to persons who are caught unaware or are immobile and may be unable to escape. In the worst of cases, a tsunami can come onshore as a bore — a wall of turbulent water carrying rocks and debris that can be likened to the leading edge of a flash flood. This type of tsunami can be extremely destructive and may sweep away all but the most sturdy of structures. Large tsunamis can flood inland many hundreds of meters from the coast and run onshore to a height of 30 meters or more above normal sea-level. In addition, the danger can continue for many hours after the initial wave as following and sometimes-larger waves flood onshore and then drain offshore. Persons caught in a large tsunami have a much smaller chance to survive than in many other natural hazards. Aside from the danger of drowning, they face a significant possibility of being crushed by objects carried in the water. Children and the elderly are particularly at risk since they may have less strength, endurance and mobility.

A few tsunamis occur each year, most of them non-destructive and observed only on sea-level gauges (Figure 3). When they are destructive, tsunamis are often categorized as local, regional, or Pacific-wide, depending upon the distance they travel from the area of generation to the coasts along which they are observed or cause damage. Tsunamis that strike the closest shorelines within minutes of their generation, and whose damage is confined only to those shorelines, are categorized as local (Figure 4). Tsunamis that only cause damage within a few hundred kilometres of their source, or just within a well-defined geographic area such as a marginal sea, are categorized as regional. The largest tsunamis cross entire ocean basins and can cause damage thousands of kilometres from their source. They are known as teletsunamis, or in the Pacific where most of them occur as Pacific-wide tsunamis. A few of these occur each century (Figure 5). Destructive local, regional, and teletsunamis also occur outside the Pacific, for example in the Atlantic, Mediterranean, and Indian Oceans, but on a much less frequent basis.

During the 1990s, eleven destructive tsunamis occurred causing more than 4 000 casualties and at least several hundred million US dollars in property damage (Table 1). These tsunamis were all local or regional tsunamis. There has not been a destructive Pacific-wide tsunami since 1964 (Figure 6).

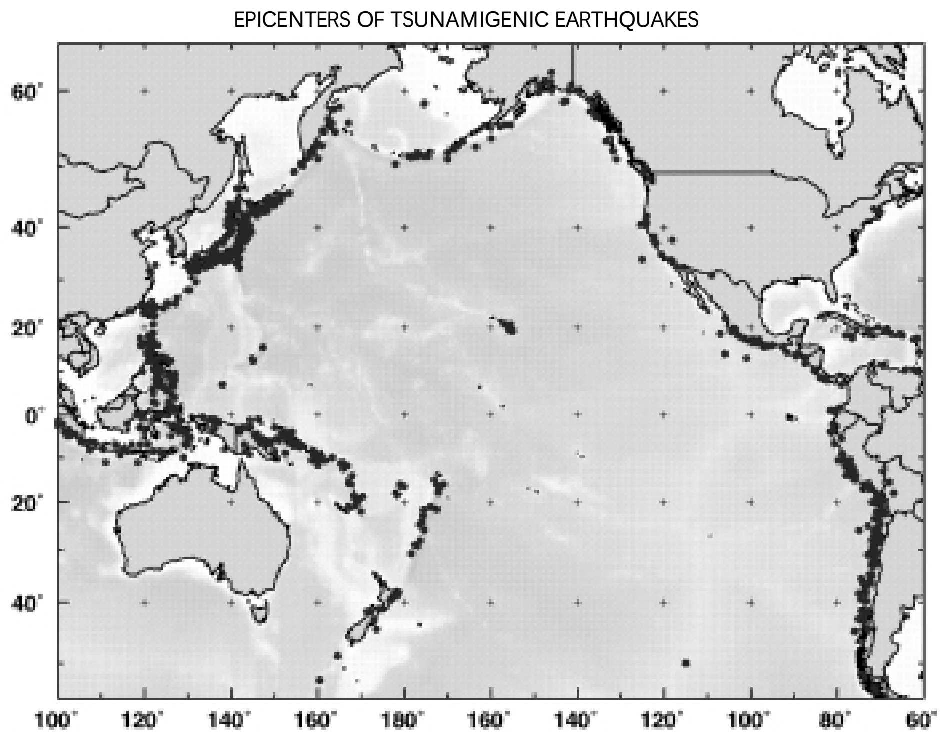


Figure 3. Tsunamigenic earthquakes (dots) occur all along the margins of the Pacific basin at the boundaries between tectonic plates. Most of the resulting tsunamis are not destructive and are often observed only on sensitive sea-level gauges. A few tsunamis occur each year in the Pacific. (Data from the historical tsunami database of the World Data Center - A.).

Table 1. Destructive tsunamis since 1990

Date	*Source Region*	*Estimated Casualties*
2 September 1992	Nicaragua	168
12 December 1992	Flores Island, Indonesia	1 000
12 July 1993	Okushiri Island, Japan	230
3 June 1994	Java Island, Indonesia	222
4 October 1994	Shikotan Island, Russia	11
14 November 1994	Philippines	74
9 October 1995	Manzanillo, Mexico	1
1 January 1996	Sulawesi, Indonesia	9
17 February 1996	Irian Jaya, Indonesia	110
23 February 1996	Peru	12
17 July 1998	Papua New Guinea	2 500

TSUNAMI MITIGATION

The great tsunami of 22 May 1960 was generated off the coast of Chile by the largest earthquake this century. It struck nearly every coastline in the Pacific and caused 61 casualties in Hawaii and nearly 200 in Japan — more than halfway around the globe. Following that event, countries around the Pacific recognized the need for a coordinated international effort to more effectively mitigate tsunamis. Consequently, in 1965, the Tsunami Warning System in the Pacific (TWSP) was formed under the auspices of the Intergovernmental Oceanographic Commission of UNESCO. It is guided by its International Coordination Group (ITSU), and now has 25 Member States. At the same time, the US National Tsunami Warning Center became the operational center for the TWSP and changed its name to the Pacific Tsunami Warning Center.

There are four key areas that have been the focus of most tsunami mitigation activities carried out by ITSU, its Member States, and other organizations. They are: 1) hazard assessment; 2) warning systems; 3) preparedness including education; and 4) research.

HAZARD ASSESSMENT

Tsunami hazard assessment is an evaluation of how often a tsunami may impact some particular coastline, and what the possible characteristics of that impact might be. Accurate hazard assessment is a very important first step to provide guidance for and help motivate the other mitigation activities needed to help protect a coastline. Data useful for hazard assessment are: 1) historical data; 2) paleotsunami data; 3) data from post-tsunami surveys; and 4) numerical model outputs.

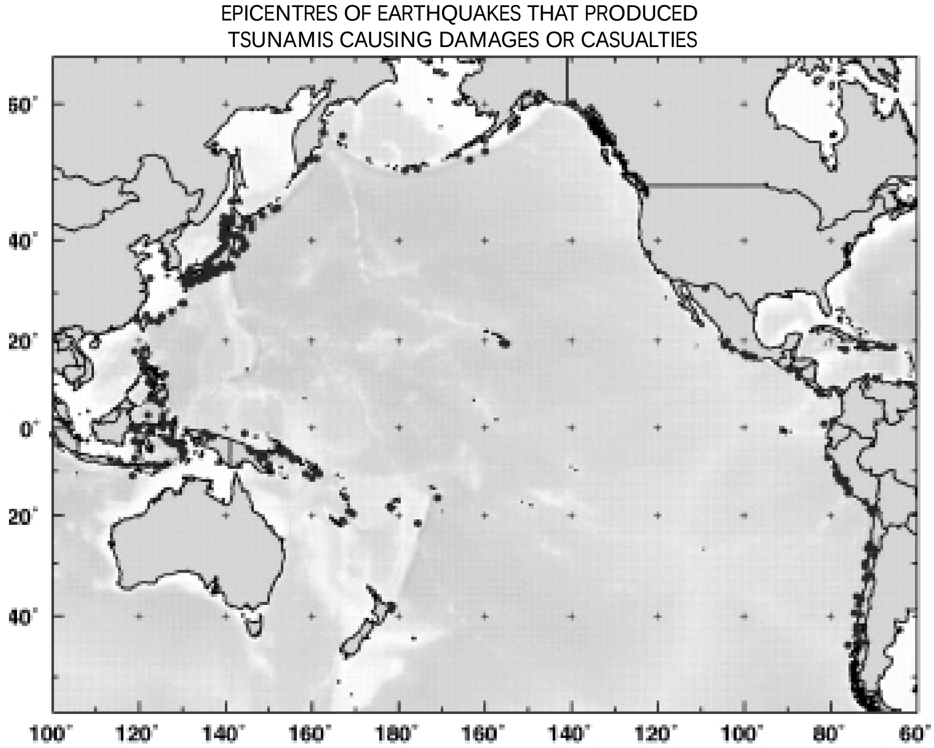


Figure 4. Destructive tsunamigenic earthquakes in the Pacific (dots) occur primarily along convergent plate boundaries associated with major subduction zones. Most destructive tsunamis are local or regional, only causing damage or casualties along coasts near the generating earthquake. (Data from the historical tsunami database of the World Data Center - A.).

Figure 5. There are only a few Pacific tsunamis in the historical record that have caused destruction far from their source. They were generated by earthquakes in northern Japan, the Kuril-Kamchatka region, the Aleutian Islands and Alaska, and off the coast of South America (dots). Although the next destructive teletsunami will likely come from one of these regions, historical records are, however, far too short to allow us to determine where they could have originated. Paleo-tsunami evidence now indicates that major teletsunamis may also be generated every few hundred years by great earthquakes that occur every few hundred years along the northwest coast of the USA and British Columbia in the otherwise quiescent Cascadia subduction zone. (Data from the historical tsunami database of the World Data Center - A.).

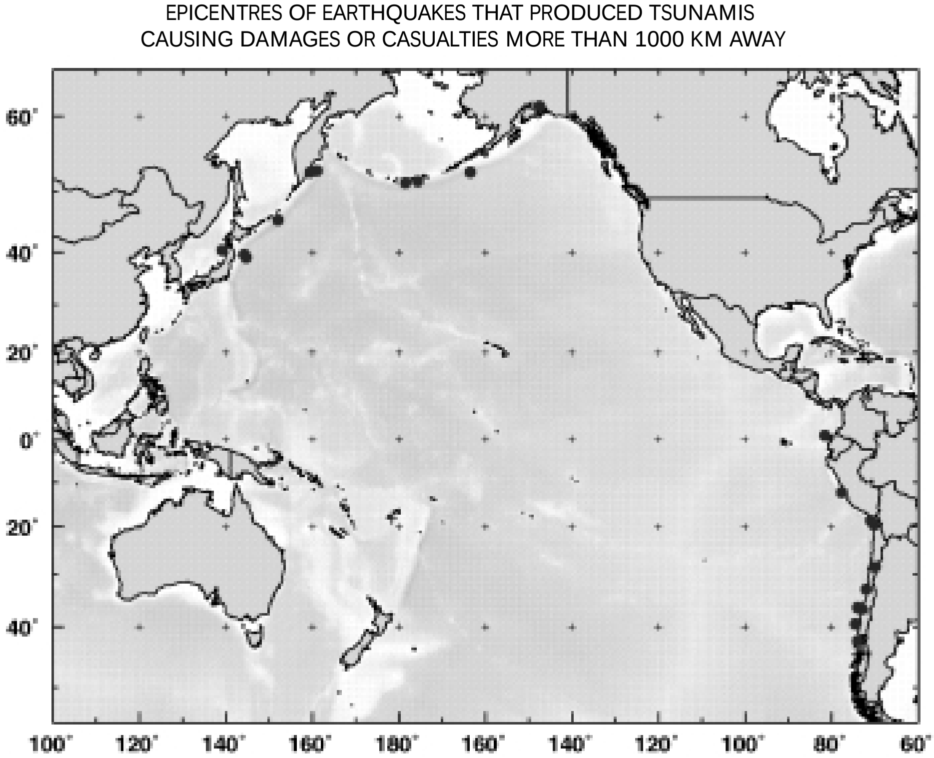
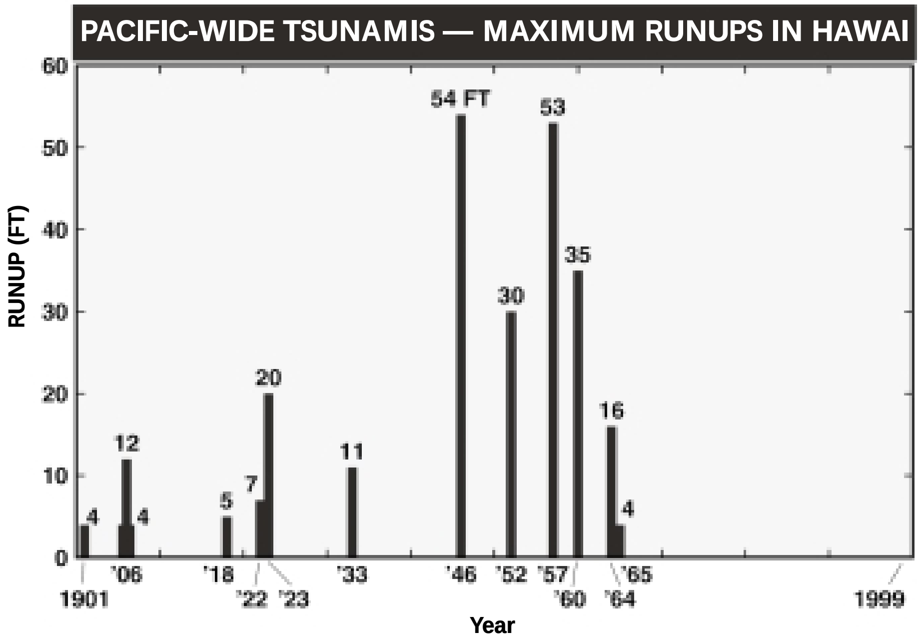


Figure 6. The Hawaiian Islands have the unfortunate distinction of being a victim to virtually every Pacific-wide destructive tsunami. Within this century Hawaii has been struck fourteen times by a tsunami with a recorded run-up over three feet, and seven times by a tsunami with a recorded run-up over ten feet. Since 1965, however, there have been no Pacific-wide destruc-tive tsunamis. Although this is a very fortunate circumstance on the one hand, it is also a cause for concern since there is now very little first-hand knowledge of this hazard among the Hawaiian public and emergency management community. This typifies the situation in most coastal communities at risk, and underscores the need for institutionalized educational programs.



Historical tsunami data have been compiled for many regions into paper catalogues. But these catalogues are not widely available, nor are they in a form that is easy to use. In recent years much of the historical data have been recompiled in at least two electronic databases — one at the World Data Center-A and one that is a part of the ITSU Historical Tsunami Database (HTDB), an interactive graphical-display computer program (Figure 7). Efforts should continue to populate these databases with all available past and current data and to check the quality of those data for accuracy.

Unfortunately, even the most complete set of historical data is often scant for most regions. In some regions such as Kamchatka and the northwest coast of the US, evidence has recently been discovered in the sediments of coastal marshes for paleotsunamis. These data offer the possibility of extending knowledge of past tsunamis back by hundreds or even thousands of years, and contributing greatly to the hazard assessment for those areas.

Just as important as investigating past tsunamis for hazard assessment is the accurate recording of tsunamis that occur now. Although there is no single organization responsible for rapidly carrying out post-tsunami surveys, the worldwide tsunami research community has done a commendable job of organizing and carrying out surveys following each of the destructive tsunamis this decade. ITSU also recently published a *Post-Tsunami Survey Field Guide* that includes information and forms describing the measurements to make and how to make them, as well as a variety of other useful information for survey participants.

For most coastal locations, the only way to accurately assess the potential for damage and flooding from a tsunami on a fine scale, though, is through the use of numerical models. Numerical modelling techniques have matured in recent years, partially as a result of repeated testing against a variety of high-quality measurements from recent tsunamis. Computer codes and training in how to use them have now been transferred to many countries at risk through the ITSU Tsunami Inundation modelling Exchange (TIME) program. Such modelling efforts should continue to be applied to produce potential run-up maps for all coastal communities at risk, in order of priority related to the level of that risk.

WARNING SYSTEMS

Warning systems provide notification to emergency managers and the public whenever a tsunami is impending so that appropriate protective action such as an evacuation can be carried out before the tsunami arrives. Real-time seismic data is used to detect the occurrence of an earthquake and then rapidly evaluate its tsunamigenic potential. Real time sea-level data is used to confirm or deny the presence of tsunami waves, and to refine tsunami forecasts.

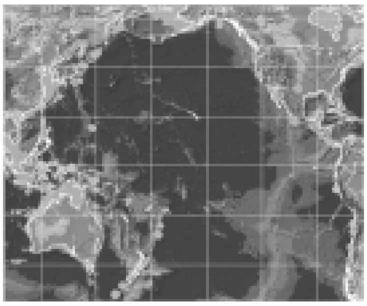


Figure 7. Map of historical tsunami data produced by the IOC/ITSU Historical Tsunami Database (HTDB) interactive graphical computer program. In this figure, the data displayed are the epicenters of all tsunamigenic earthquakes in the Pacific region for the period 1989-1997. The dot size indicates the magnitude of the earthquake, and the dot color (that would appear on the computer display) the magnitude of the tsunami. The program is also capable of displaying tsunami run-up data as well as non-tsunamigenic seismicity patterns for any selected portion of the Pacific. The HTDB was developed for use by scientists, emergency managers, and warning center operators as a tool for research, education and warning operations. It complements the tsunami database maintained by the World Data Center-A.

Recent enhancements to the worldwide seismic network, with many new stations, improvements in seismic sensors, and better real-time data transmission methods (Figure 8), and recent advances in seismic data processing techniques have resulted in improvements to the speed and accuracy of the seismic evaluation for tsunami warnings. A stand-alone system called TREMORS has been developed by France to provide earthquake parameters for tsunami warnings from a single seismic station. Better techniques for rapidly and accurately determining earthquake magnitudes and focal mechanisms are being applied. Nevertheless, it is still beyond currently available techniques to determine if and how much the ocean bottom has deformed using only the seismic data.

Real-time sea-level data must be evaluated to know whether or not a tsunami has been generated, and to characterize its strength. Although data from many sea-level gauges are available to warning systems (Figure 9), most are designed to measure tides and are located in protected harbours or bays. Consequently, the data from these gauges is less than ideal for determining what is propagating out in deep water and for forecasting what the impacts may be in other locations. For these reasons, a new generation of deep sea pressure sensors has been developed to measure tsunamis offshore and send their data back to warning centres via undersea cables or through buoys and satellites. Such gauges can also be placed strategically off dangerous source areas or vulnerable coasts. Although this type of instrumentation can be significantly more costly than a tide gauge, the extra cost must be weighed against the cost of unnecessary warnings and evacuations, or of missing a warning for an anomalously large tsunami.

Warning centres are now beginning to use numerical model data to assist with tsunami forecasts (Figure 10). The tsunami models are pre-run, and results for the appropriate epicenter location and magnitude recalled from storage during an event. Forecasts based on these model data are adjusted appropriately, as readings from sea-level sensors become available. The model data provide a way to better estimate which coastlines are likely to be affected, and what the likely range of run-up heights will be. Their use should lead to a reduction in the number of unnecessary warnings, and provide local emergency managers with better guidance about what to expect along their shores when warnings are necessary.

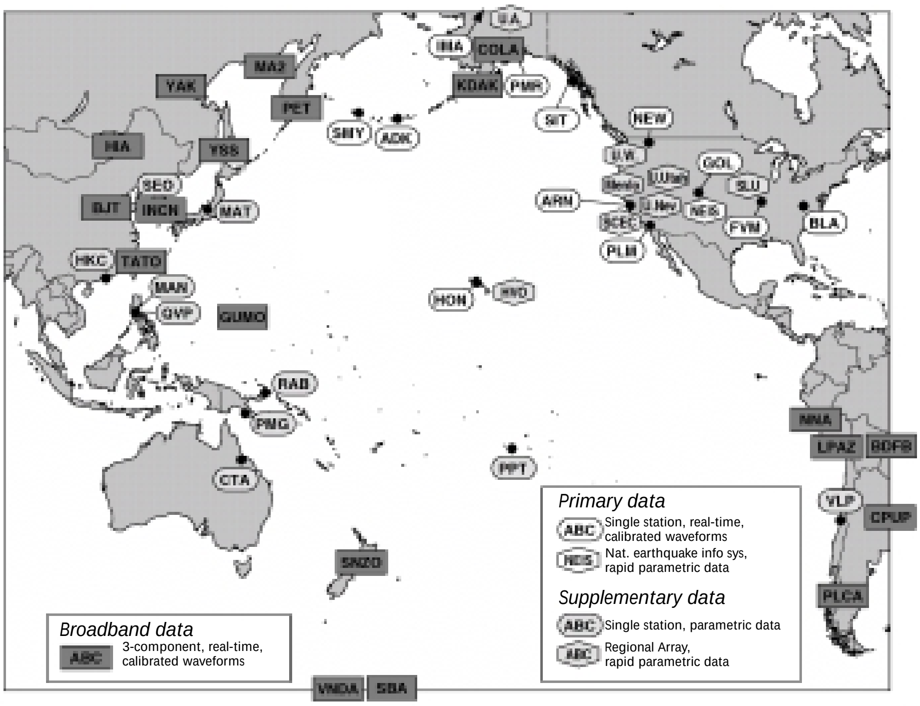


Figure 8. Seismic stations and networks that provide data in real-time to PTWC for rapid evaluation of the tsunamigenic potential of earthquakes in the Pacific region. The broadband stations are of the highest quality and their data is the most useful for estimating the tsunamigenic potential of an earthquake. Modern communications methods are increasingly being used to make available in real-time these worldwide data to the warning centers.

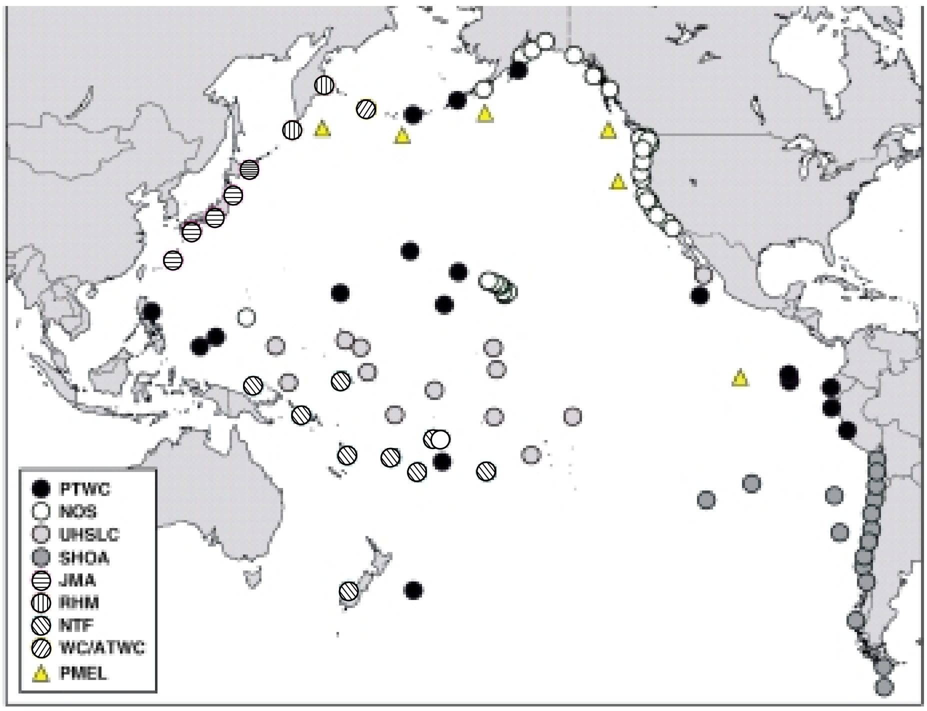


Figure 9. Sea-level gauges that provide, or will soon provide, real-time data in support of the Tsunami Warning System in the Pacific. The gauges are operated by a variety of national organizations, and most of them serve several purposes including measurement of tides, El Niño, and long-term sea-level change. The two Russian ROSHYDROMET (RHM) gauges shown in the Kuril-Kamchatka region are planned for installation in late 1999. Several gauges of the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) were recently acquired and are now in the process of being installed along the coast of Chile. The six US Pacific Marine Environmental Laboratory (PMEL) gauges are deep sea pressure gauges that transmit from a buoy and are scheduled to be deployed over the next few years. They represent a new generation of instruments designed for measuring tsunamis in strategic deep-water locations to provide better data for forecasting.

The success of a warning system strongly depends on how timely and effectively the warning gets disseminated to potentially affected coastal communities. Advances in satellite and other communications technologies are making it increasingly possible to quickly reach even the most remote communities with both text and graphical information. These techniques are now beginning to be applied for dissemination of tsunami warnings.

Warning systems are classified by the type of tsunami they are prepared to warn against – local, regional, or teletsunami; and by their area of responsibility – sub-national, national, regional, or international. There are more than a dozen warning centres operating in the Pacific, including ones in Japan, Russia, the United States, French Polynesia, and Chile. Most of these are sub-national or national systems for warning against local or regional tsunamis. A regional tsunami warning system is being developed by Japan and its neighbouring countries for the Sea of Japan, and a regional system is also under development in

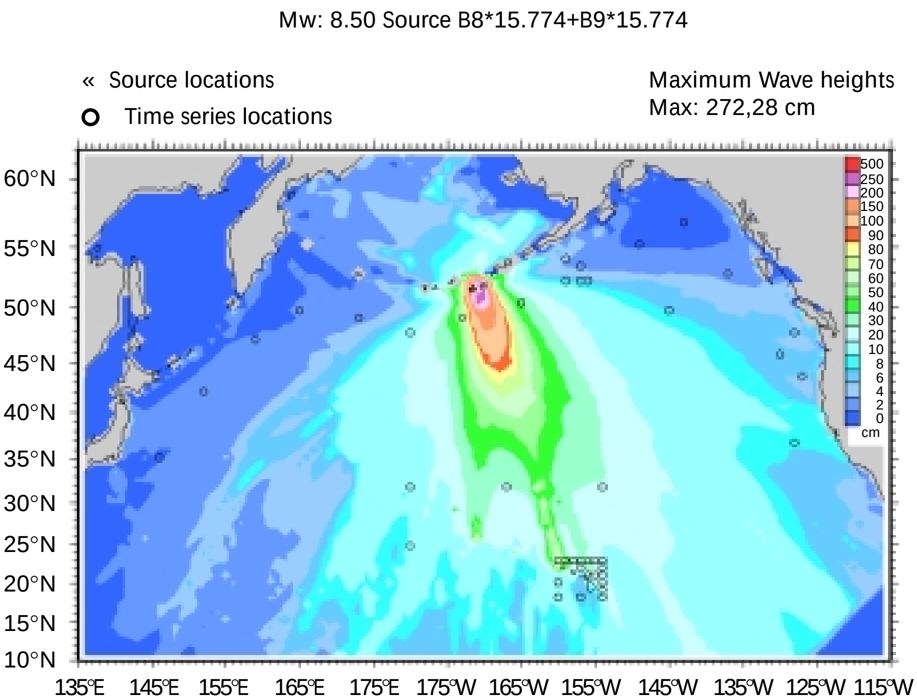


Figure 10. Techniques for numerical modeling of tsunamis have significantly improved during the past decade, as they have been repeatedly tested against a wide variety of sea-level and run-up data from recent events. This technology has now been transferred to many countries at risk through the IOC/ITSU Tsunami Inundation Modeling Exchange (TIME) program for the production of potential run-up maps in high-risk coastal zones. Numerical models are also increasingly being used to help warning centers improve tsunami forecasts. In the example shown here, the tsunami produced by a moment magnitude 8.5 earthquake in the Aleutian Islands has been modeled and the maximum wave height at each location in the north Pacific indicated. The model predicts that most of the tsunami energy from this type of event is directed towards the Hawaiian Islands, while coasts in the western Pacific are not affected. (Model output and figure courtesy of the NOAA Pacific Marine Environmental Laboratory).

Costa Rica for Central America. The Pacific Tsunami Warning Center has international responsibility to the entire Pacific for teletsunamis. Nevertheless, many high-risk coastal areas remain without access to a warning system, and only a few coastlines are protected by a system for local tsunamis. Shaking from the earthquake is the only warning that most coastal residents can expect to have for a local tsunami. That is one reason why public education is so important.

PREPAREDNESS

The most effective preparedness efforts are education and awareness programs for the public, emergency managers, and decision makers. The public needs to know enough about the tsunami hazard to take the appropriate life-saving actions quickly whenever an official tsunami warning is issued, or whenever they observe one of nature's tsunami warnings such as strong shaking from a nearby earthquake or an unusual withdrawal of the sea. Emergency managers and decision makers also need adequate knowledge of the tsunami hazard so they can give it appropriate consideration in their planning and so they know how to respond when necessary. Educational programs must be institutionalized in school curricula, and for example through monuments to past tsunamis or with annual events such as a tsunami awareness month. Without institutionalization, the level of awareness can be lost in the interval between destructive tsunamis, which typically ranges from decades to centuries. ITSU and its Member States have developed and published in small quantities a wide variety of educational materials, some of it in several languages (Fig. 11). Most of these materials are available at no cost for further translation, modification and reproduction. There is a need for better education and awareness about tsunamis in most coastal communities, and it is clear that this factor alone would have saved many lives in the tsunamis that have occurred in this decade.

Figure 11. One of the most important keys to effective tsunami mitigation is adequate awareness and knowledge of the tsunami hazard by the public, emergency managers, and decision makers. For this purpose, IOC/ITSU and its Member States have produced a wide variety of educational materials for both children and adults, some of it published in several languages.

Some of the most important safety facts about tsunamis are simple:

- If you feel a very strong earthquake near the sea, evacuate immediately;
- If the sea recedes unusually, evacuate immediately;
- If the sea has abnormally strong or unusual currents, evacuate immediately;
- A tsunami is not a single wave but a series of waves;
- The first wave of a tsunami may not be the largest;
- The tsunami hazard can continue for many hours.

Tsunami preparedness also includes the development of evacuation plans for both local and teletsunamis. Evacuation maps should be based upon inundation levels predicted by the historical data and numerical models. For local tsunamis they should take into consideration damages that may have occurred from the generating earthquake that could block access routes. Land-use planning is also important. Critical facilities such as fire stations, police stations, and hospitals can be sited outside the inundation zones and have access routes that do not cross inundation zones. Vulnerable populations should not be put at risk, so schools and retirement homes can be located outside inundation zones. Building codes for inundation zones can include measures to minimize the effects of tsunamis such as barriers to prevent the scouring of foundations by repeated flooding and draining at the coast. When there are substantial assets at risk and the risk is high, large engineering works such as protective seawalls and dikes may be justified.

RESEARCH

Tsunami research is carried out primarily by academic and government research institutions. Research efforts are coordinated, with a considerable exchange of data and ideas, through bodies such as the IUGG Tsunami Commission and the Tsunami Society. Areas for research include numerical modelling, paleotsunamis, remote sensing of tsunamis, tsunami source parameters from seismic data, tsunamis generated by non-seismic sources, and even the response of the public to tsunami warnings. Continued research is needed to improve all methods of tsunami mitigation.

CONCLUSIONS

Although significant progress has been made in recent years to mitigate the adverse effects of tsunamis, with numerous advancements in hazard assessment, warnings, and preparedness, much remains to be done. Potential run-up maps based on historical and numerical model data need to be produced for all vulnerable coastal communities. More local and regional warning systems are needed for high-risk areas without access to warnings. Instrumentation to measure tsunamis in the deep ocean as well as appropriate numerical model data are needed for more accurate tsunami forecasts. Educational programs need to be more widely established and institutionalized to give the public, emergency managers, and decision makers the crucial information they need to minimize the loss of life and property damage from the tsunami hazard. Only with these kinds of improvements can the impact of future tsunamis be reduced.

STORM SURGES IN THE MARGINAL SEAS OF THE NORTH INDIAN OCEAN

By T.S. Murty; Senior Scientist

ABSTRACT

One of the major natural marine hazards on the globe is the storm surge phenomenon. Large storm surges with amplitudes of up to several meters generated by tropical cyclones occur in many areas of the world, including the Gulf of Mexico and the Northern Indian Ocean. The storm surges in the marginal seas of the North Indian Ocean are discussed here. These marginal seas include the Bay of Bengal, the Arabian Sea, the Persian (Arabian) Gulf and the Red Sea. Since storm surge prediction also involves tides, some tidal regimes are also discussed. Finally, some comments are made on the possible influence of the greenhouse warming and the El Niño phenomenon on storm surges.

1. INTRODUCTION

Storm surges are oscillations of the water level in a coastal water body due to the tangential wind stresses and atmospheric pressure gradients mainly associated with the meteorological forcing fields of travelling synoptic scale weather systems such as tropical cyclones (TC's) and Extra-Tropical Cyclones (ETC's). On occasion, meso-scale weather systems embedded in the larger scale synoptic systems can also provide the required forcing mechanisms to generate surges. These meso-scale systems include mostly squall lines, also referred to as pressure-jump lines.

Most of the surge is generated by the wind field, with the pressure field accounting for about 10 to 15 per cent. In the higher latitudes of the globe, surges are generated by ETC's which generally travel from west to east, with some north-south component. In the lower latitudes, TC's mostly travel from east to west with a south to north (in the Northern Hemisphere) component, usually referred to as recurvature.

In this study, our focus is on surges generated by TC's only and Gray (1978) discussed their genesis mechanisms. We confine our discussion to the marginal seas of the North Indian Ocean. These include the Bay of Bengal, the Arabian Sea, the Persian (Arabian) Gulf and the Red Sea (Figure 1).

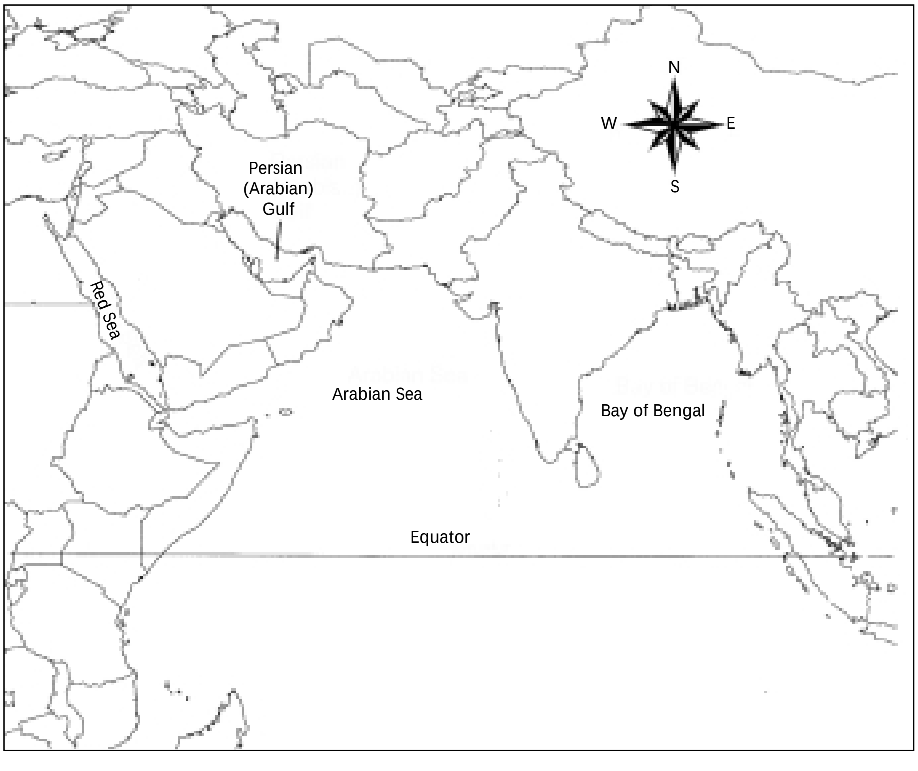


Figure 1. Northern Indian Ocean.

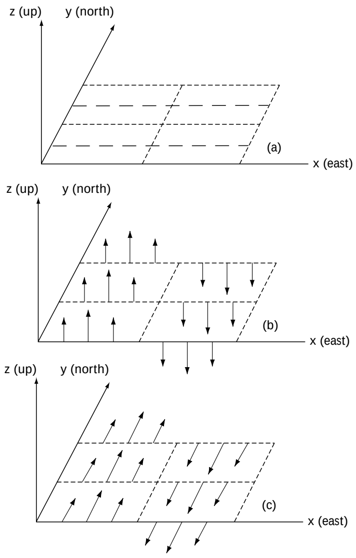


Figure 2. Schematic distribution of velocity perturbations associated with (a) eastward moving compression waves; (b) eastward moving vertical transverse waves and (c) eastward moving horizontal transverse waves (after: Thompson 1961).

There are three types of pure wave motions in the atmosphere and the ocean (Figure 2). The first type is the acoustic (sound) wave or the longitudinal wave. As these waves propagate in the horizontal direction, the particles move back and forth in the direction of propagation (compression and rarefaction).

The second type of waves are gravity waves, which are vertically transverse waves. As the waves propagate in a horizontal direction, the particles move up and down in the direction of gravity. Since these waves have a vertical component, these are relevant from a hazard point (i.e. land inundation).

The third type is the horizontally transverse wave or the Rossby Wave. As the wave propagates in a horizontal direction, the particles move north and south, due to the so-called beta parameter associated with the Earth's rotation. Rossby waves are extremely relevant for circulation in the atmosphere as well as in the oceans.

Figure 3 shows the short wave part of the ocean wave spectrum. In the ocean, electro-magnetic waves cannot penetrate to great depths, and acoustic waves provide a mechanism somewhat like radar in the atmosphere.

Under wind waves, there are capillaries, sea waves and swell, and their periods are of the order of a few seconds. These are the waves that one observes while standing on a beach.

These waves could be quite hazardous over water because they can attain amplitudes up to several meters. However, because of their short wave lengths (at most a few tens of meters) they break at the coastline and cannot cause any significant land inundation. However, they cause a set-up at the coastline, which should be added to the storm surge.

Figure 4 shows the long wave part of the spectrum, by long wave we mean that the wave length is much greater than the water depth over which it travels. Generally, under long waves, one includes tides, storm surges and tsunamis. Here we will confine our discussion to storm surges and tides only.

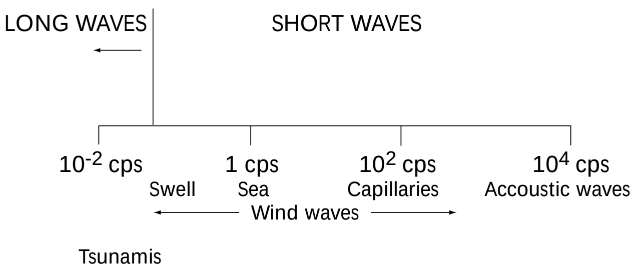


Figure 3. Ocean wave spectrum for short waves (cps = cycles per second) (Modified from Platzman, 1971).

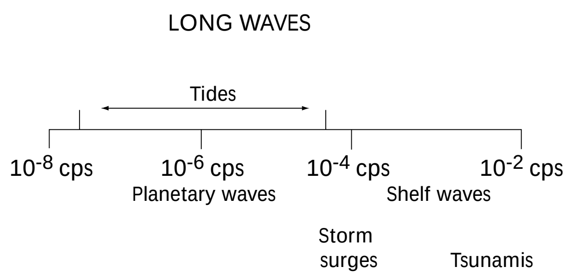


Figure 4. Ocean wave spectrum for long waves (cps = cycles per second) (Modified from Platzman, 1971).

3. STORM SURGE

Figure 5 shows the area of Genesis (hatched regions) and the tracks of tropical cyclones.

Rao (1968) classified the Bay of Bengal and Arabian Sea coasts (mainly for India) from a storm surge point of view (Figure 6).

Figure 7 (Dube *et al*, 1994) shows the maximum probable surge amplitudes for the Bay of Bengal coast.

Table 1 lists the peak surge amplitudes for various return periods on the Indian coastlines (Jayanthi and Sen Sarma, 1986).

Figure 8 shows how the storm surge builds up as the water depth decreases. In the deep water, the surge (which is a long gravity wave as explained in Section 2) travels much faster (with a speed which is approximately proportional to the square root of the water depth) than the weather system travelling over the water body. As the water depth decreases, there is a match between the speeds of movement of the surge and the cyclone and efficient resonance transfer of energy takes place from the cyclone to the surge.

Figure 5. Area of genesis and tracks of tropical cyclones.

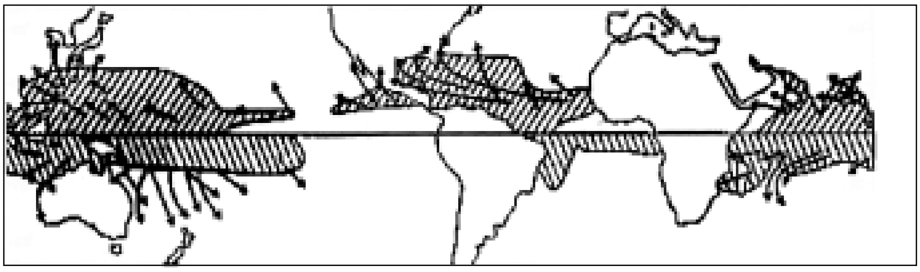


Figure 6. Storm surge amplitudes on the coasts of the Arabian Sea and the Bay of Bengal (Rao, 1968).

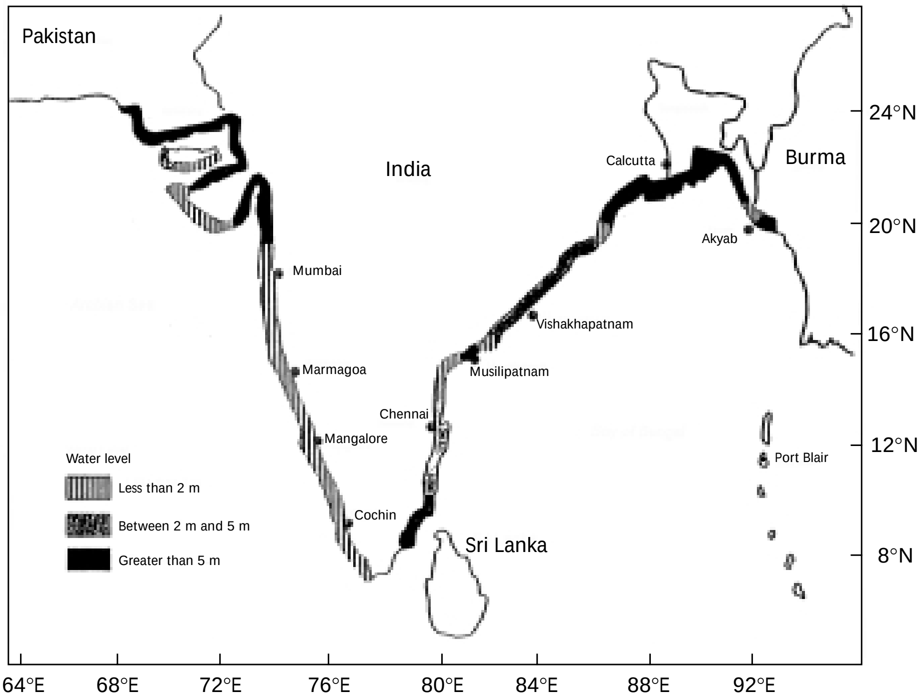


Figure 7. Maximum probable storm surge amplitudes (m) on the Bay of Bengal coast (Dube *et al*, 1994).

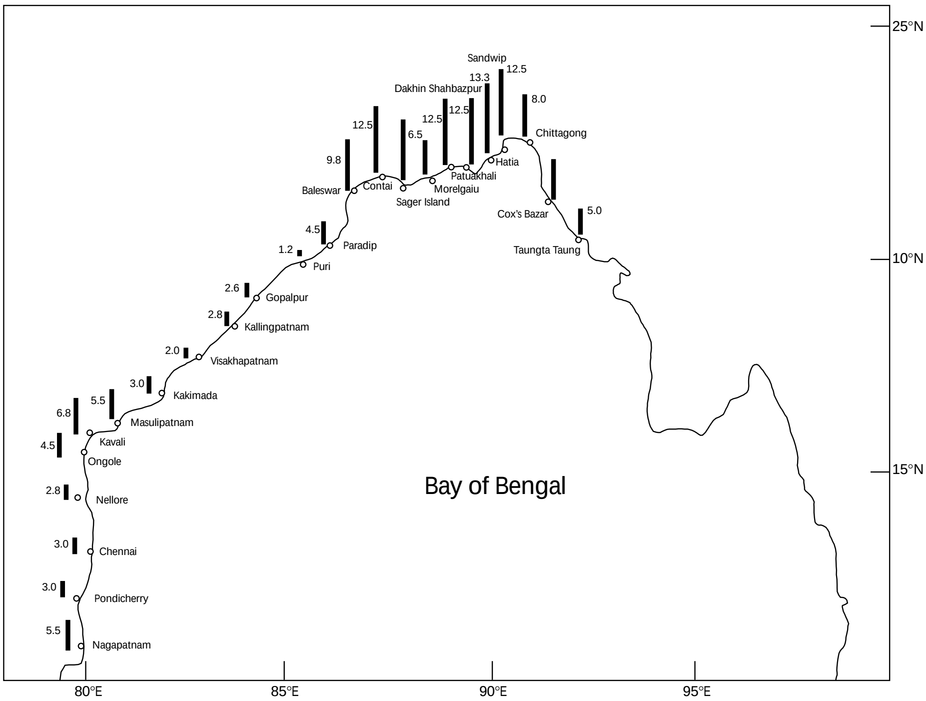


Table 1. Peak surge amplitudes (m) for various return periods, on the coastlines of India, based on data for 1890 to 1984 (from Jayanthi and Sen Sarma, 1986).

State	*Peak Surge (m) for Return Periods (Years of 1890–1984)*				
	10	25	50	100	200
Tamil Nadu South of 10°N	4.8	5.9	6.6	7.5	8.1
Tamil Nadu North of 10°N	2.2	2.7	3.0	3.4	3.7
Andhra Pradesh	3.8	4.2	4.8	5.2	5.6
Orissa-S. of 20.5°N	2.0	2.7	3.2	3.8	4.4
Orissa-N. of 20.5°N	5.1	6.4	6.9	8.8	10.4
West Bengal	4.5	6.3	7.8	9.2	10.9
Maharashtra	1.1	1.4	1.6	1.8	2.0
Gujarat	1.9	2.2	2.4	2.6	2.9

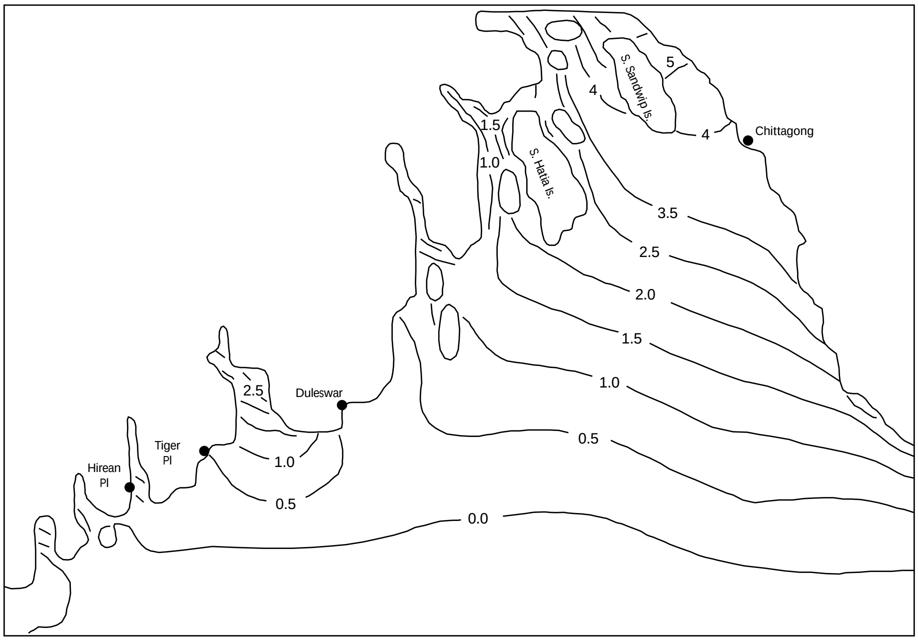


Figure 8. Storm surge heights in the northern part of the Bay of Bengal from a hypothetical storm modeled after the November 1970 storm.

Another qualitative way of explaining the build-up of the surge is in terms of the wind field associated with the weather system. The tangential wind stress pushes the water towards the coast. In deep water, the water could escape laterally or sideways, whereas in shallow water, it cannot go anywhere but up. This is a very simple explanation of how the surge is generated.

The peak surge usually only occurs on a relatively small stretch of the coastline (a hundred km at most, usually a few dozen of km), as can be seen from Figure 9. The fact that the peak surge occurs on only a small stretch of the coastline can also be seen from Figures 10, 11 and 12 (Rao, 1968). It should be noted that in the Northern Hemisphere, the peak surge occurs to the right of the storm track (and to the left in the Southern Hemisphere).

In Figure 12, the fact that the surge did not occur continuously everywhere on the coast needs some explanation. The orientation of the coastline with reference to the storm track as well as the local bathymetry also plays an important role.

Computation and prediction of the land inundation in river deltas is a complex problem involving interaction of the surge with tide, river flow and precipitation. Figure 13 and 14 show inundation limits for two major river deltas on the east coast of India. Such inundation computations can be done more accurately through the use of finite element (f-e) models employing irregular triangular grids rather than the traditional finite-difference (f-d) models with regular grids. Figure 15 shows an irregular triangular grid for the northern part of the Bay of Bengal and Figure 16 shows a zoom-in for the northern extremity of the grid.

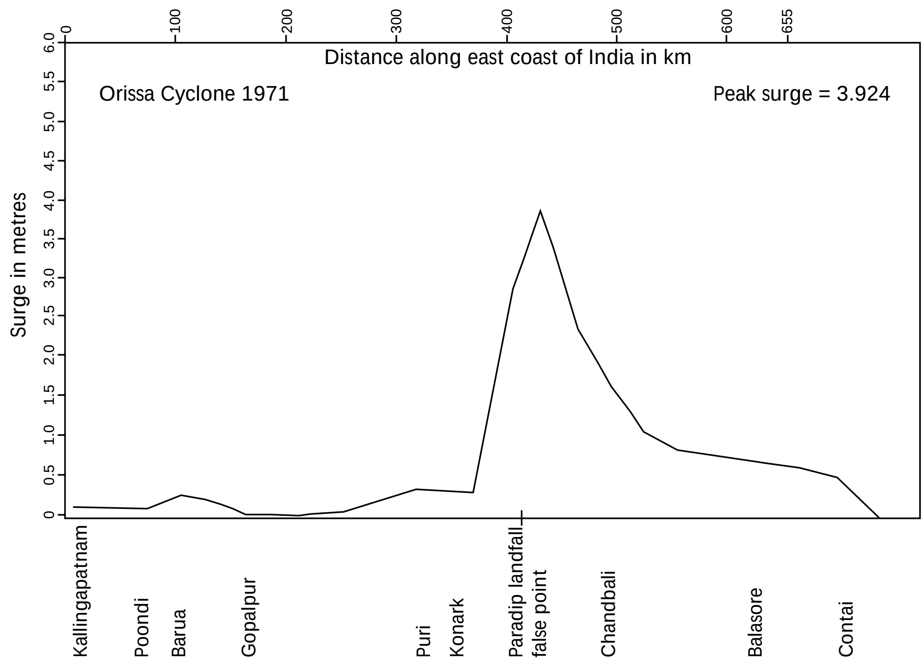


Figure 9. Peak surge (m) along the east coast of India for the Orissa Cyclone of 1971 (Dube et al., 1997).

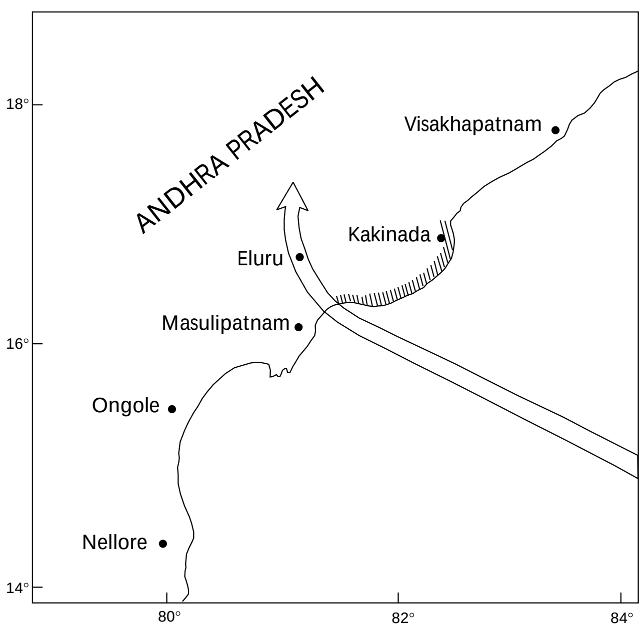


Figure 10. Track of the storm of October 1949 on the southeast coast of India. Hatched area shows the coastline affected by the storm surge (Rao 1968).

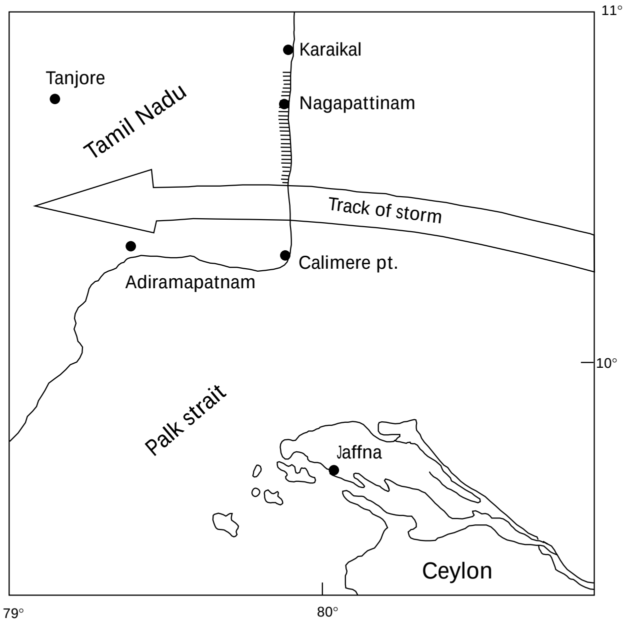


Figure 11. Track of the storm of November 1952 on the southeast coast of India. Hatched area shows the coastline affected by the storm surge (Rao 1968).

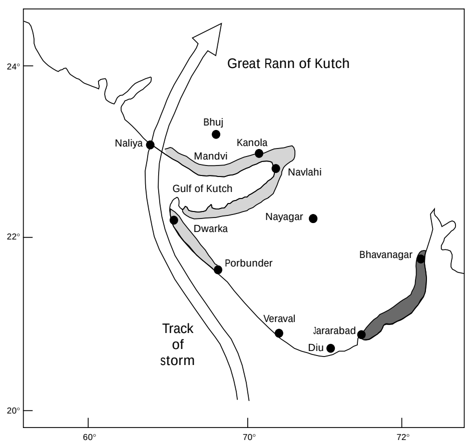


Figure 12. Track of the Kutch cyclone of June 1964 on the west coast of India. Dark grey area is affected by minor surges; light grey areas are affected by major surges (Rao 1968).

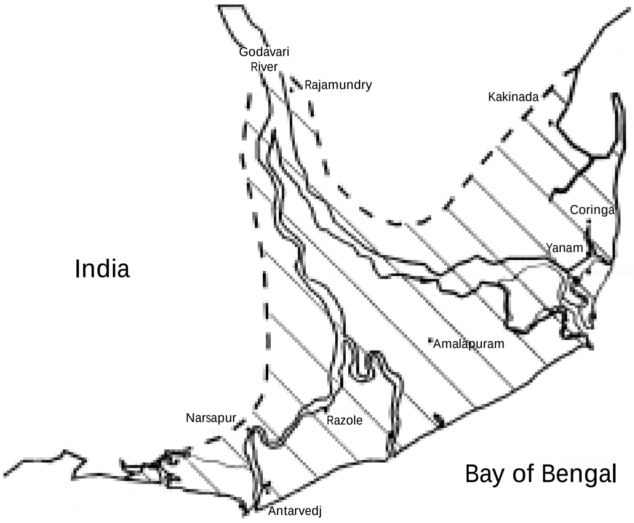


Figure 13. Composite cyclone flood map for the Godavari river.

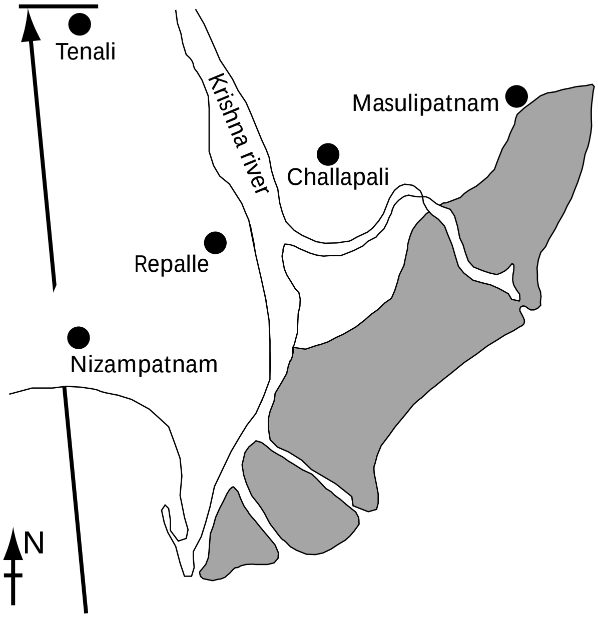


Figure 14. Cyclone map for the Krishna River.

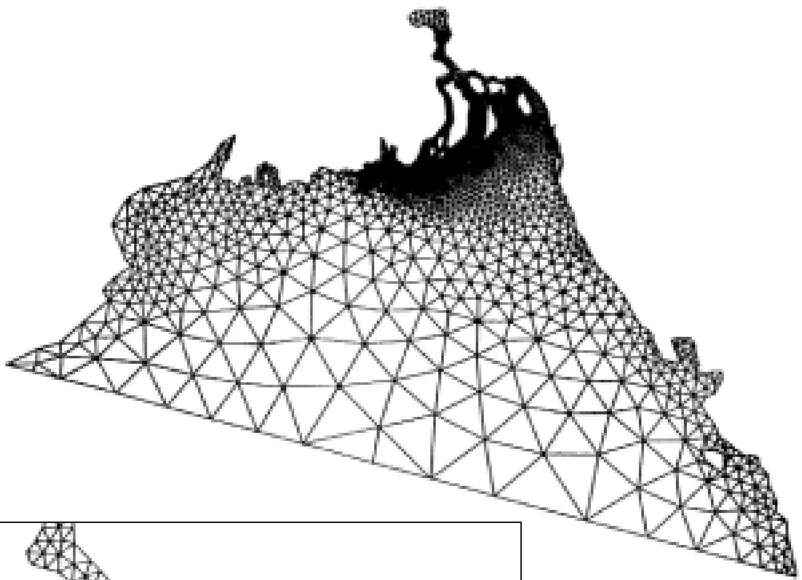


Figure 15. Irregular triangular grid for the northern part of the Bay of Bengal (Henry et al., 1997).

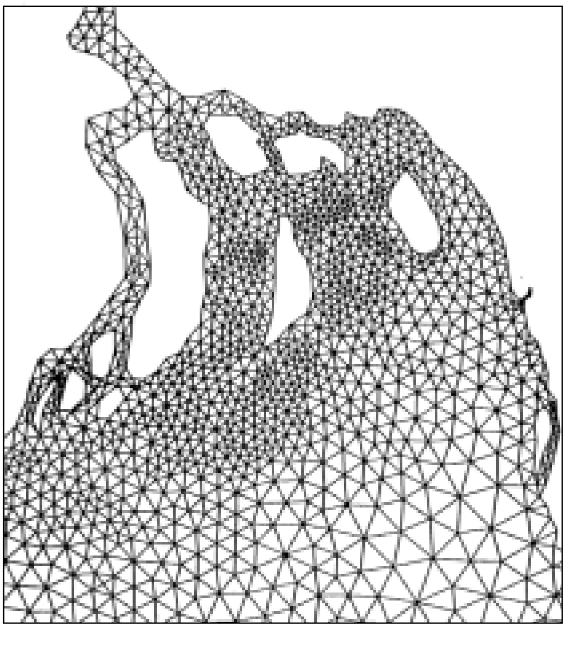


Figure 16. Zoom-in for the northern extremity of the grid.

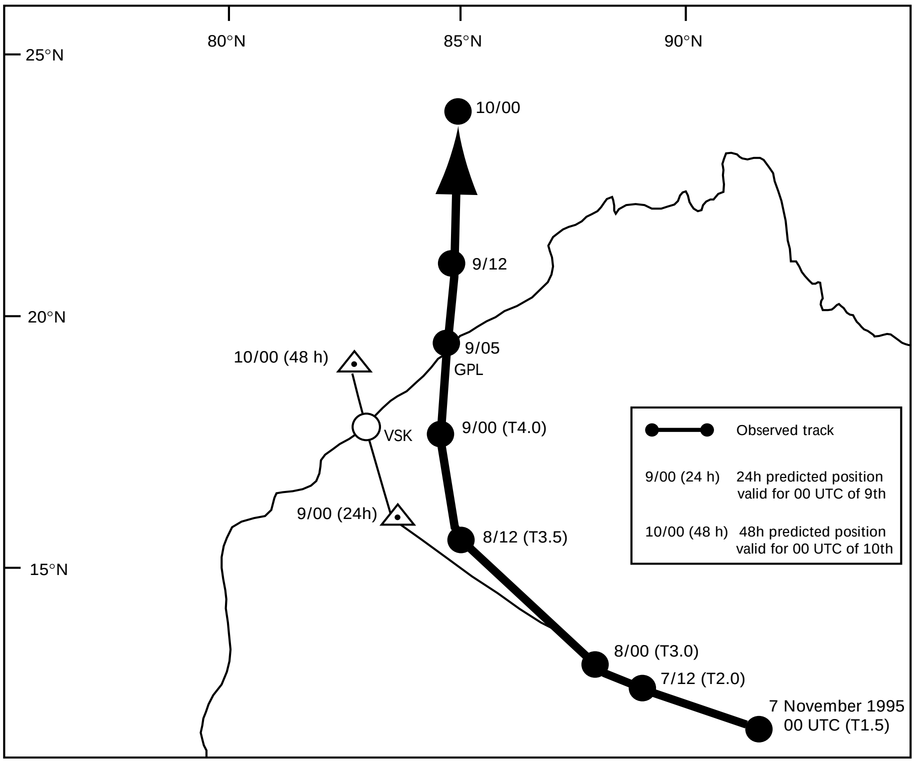


Figure 17. Comparison of predicted track with observed track for a cyclone on the east coast of India (Prasad, 1997).

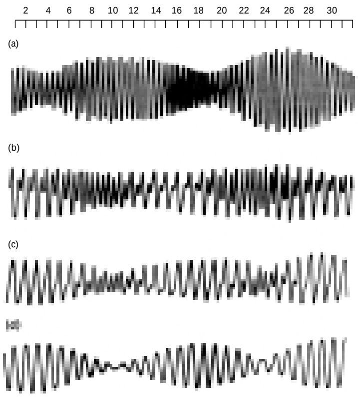


Figure 18. Schematic representation of a 1- mo-long tidal record. (a) Semi-diurnal; (b) mixed, mainly semi-diurnal; (c) mixed, mainly diurnal; (d) diurnal.

Figure 17 compares a predicted track with an observed track for a cyclone on the east coast of India. Even though the agreement may be termed satisfactory under the present state-of-the-art of tropical cyclone track prediction, from a practical point of view, the prediction is not satisfactory. For a densely populated coast such as this one, even an error of a few km in the track prediction means evacuating a large number of people in the wrong place.

4. TIDES

For storm surge prediction one uses the concept of the total water level envelope (TWLE) which is made up of the surge, the tide and the wind wave set-up. Hence, tidal prediction is needed to understand the surge-tide interaction. Figure 18 shows the classification of the tides into four different regimes. A semi-diurnal tide has two high waters (HW) and two low waters (LW) everyday. A mixed mainly semi-diurnal tide has two HW's and two LW's everyday, but the two HW's (and the two LW's) do not have roughly equal amplitudes. A diurnal tide has one HW and one LW everyday. Upon these is superimposed the spring-neap tidal regime. Table 2 lists the principal semi-diurnal and diurnal tidal constituents.

Because of the earth's rotation, amphidromic points as shown in Figure 19 occur. At these points, the vertical motion associated with a given tidal constituent is zero and the horizontal component of the motion is a maximum.

Figure 20 shows the amphidromic point for the K1 tide in the Arabian Sea.

Figure 21 shows the half range of tide for the Bay of Bengal.

Figure 22 shows the amphidromic point in the Red Sea for the M2 tide.

Figure 23 shows the amphidromic points in the Persian (Arabian) Gulf.

Table 2
Principal Tidal Constituents

Symbol	*Name of Partial Tides*	*Argument (deg./hr) (hr. min)*	*Period in Solar Hours*	*Coefficient Ration M2:100*
M_2	Principal lunar	28.98	12.25	100.0
N_2	Larger lunar elliptic	28.44	12.39	19.2
S_2	Principal solar	30.00	12.00	46.6
K_2	Luni-solar semi-diurnal	30.08	11.58	12.7
O_1	Principal lunar diurnal	13.94	25.49	41.5
P_1	Principal solar diurnal	14.96	24.04	19.4
K_1	Luni-solar diurnal	15.04	23.56	58.4

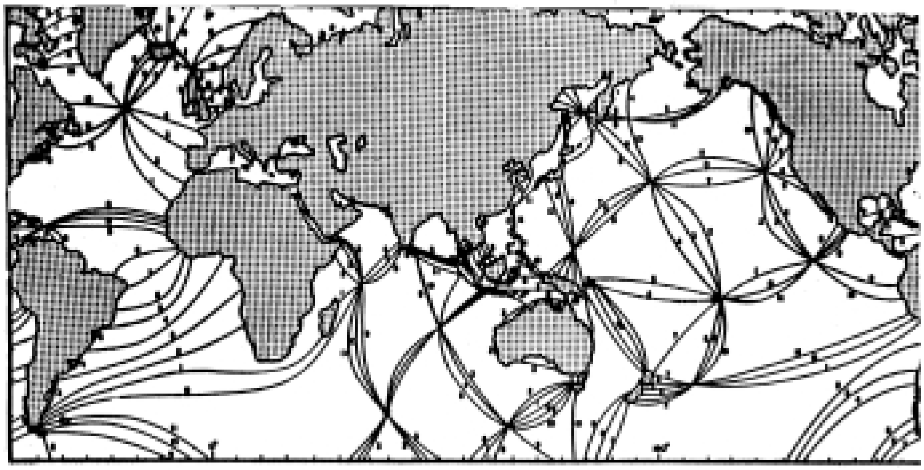


Figure 19. Co-tidal lines of the semi-diurnal tide in the Oceans (Srerneck, 1920).

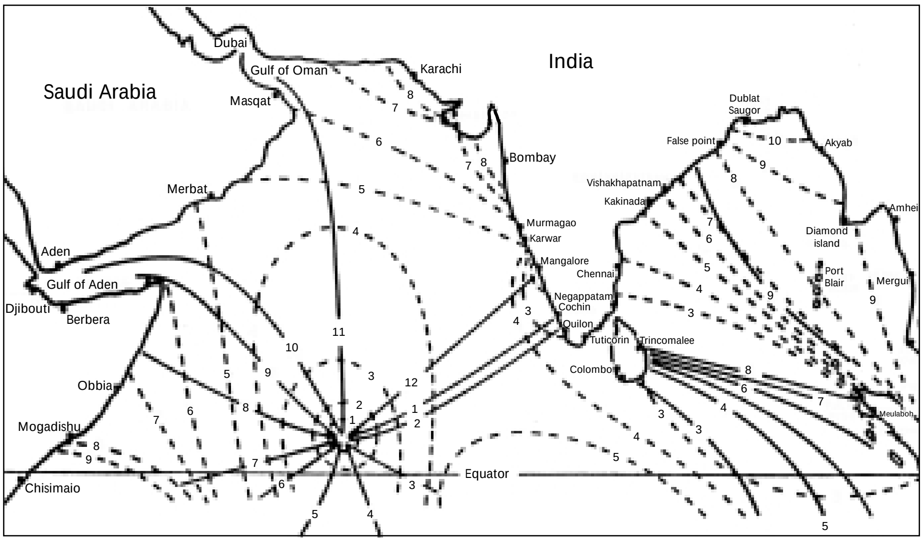


Figure 20. Co-tidal and co-range lines for the constituent K1. Numbers on solid lines are the time (hours) of high water that are half of the period, the time origin the standard meridian. Numbers on broken lines are the amplitudes (centimetres) (Fairbairn, 1954).

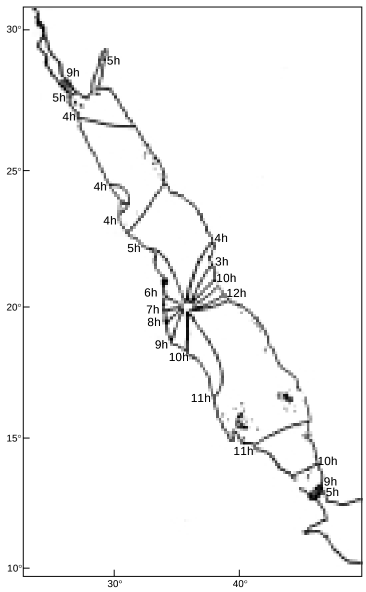


Figure 22. Amphidromic print in the Red Sea for the M2 tide (Rady *et al.*, 1994).

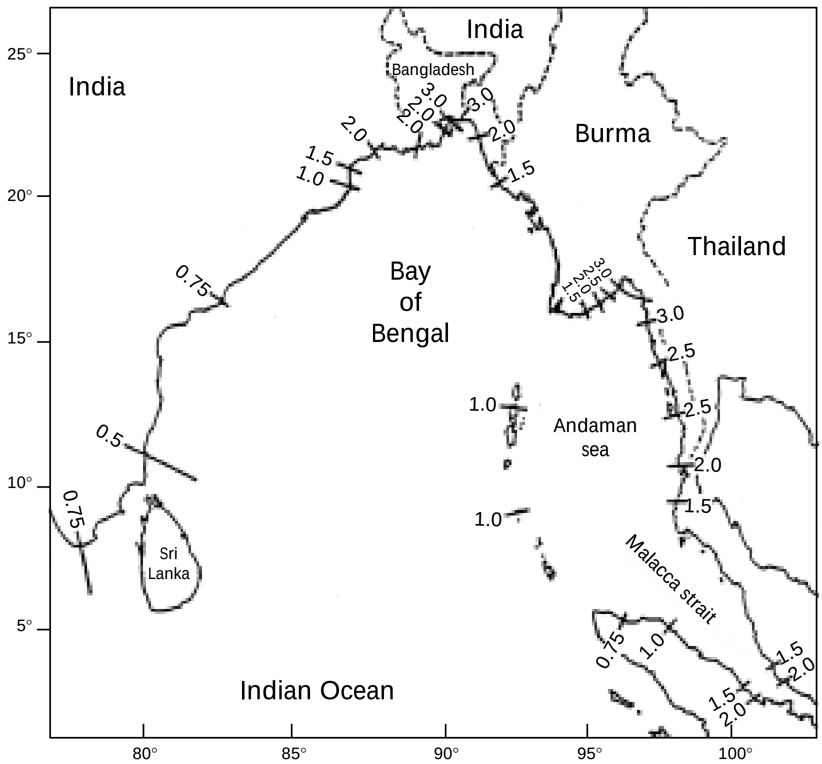


Figure 21. Half range of tide (m) in the Bay of Bengal (Murty *et al.*, 1986).

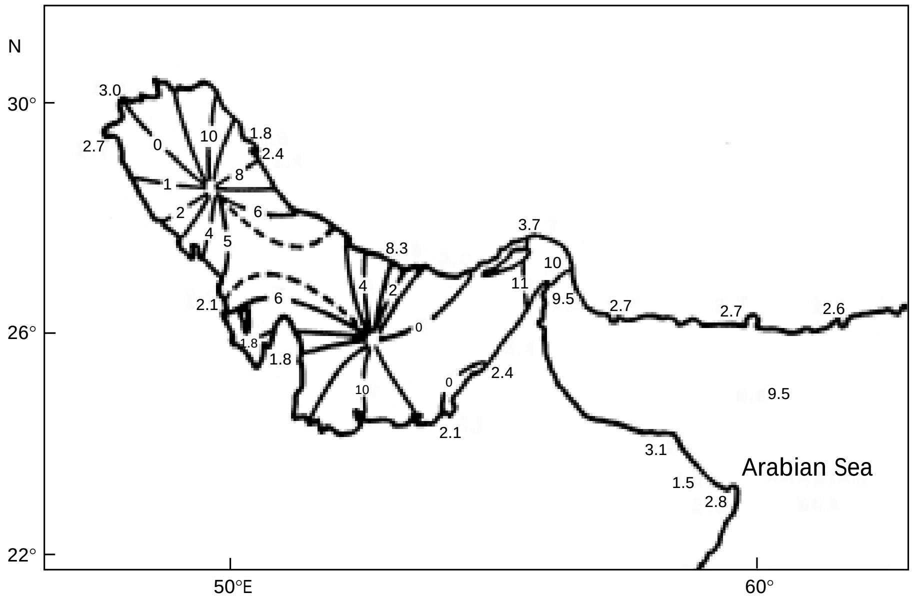


Figure 23. Phase (lunar hours and amplitude (cm) of the springtides in the Persian (Arabian) Gulf derived from observations (Defant 1961).

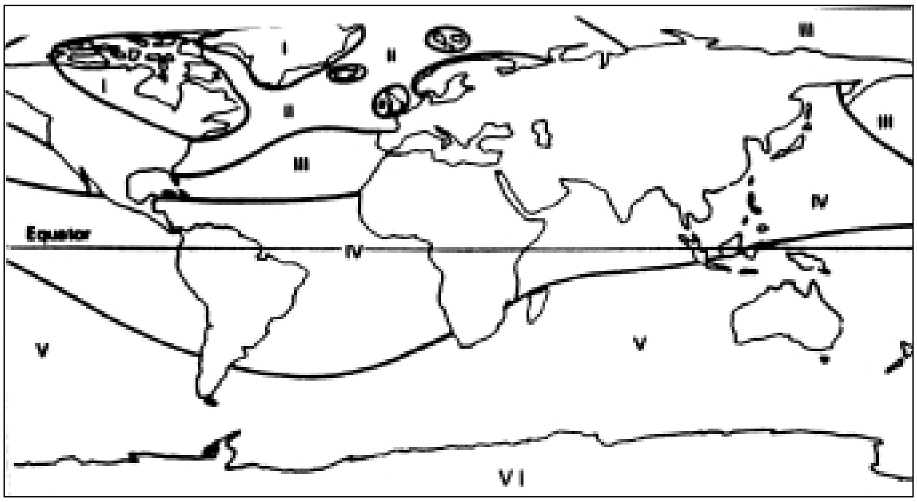


Figure 24. Six predicted zones of relative sea-level change: emberged beaches are dictated for zones I, III, V and VI and submergence in zones II and IV (S. Jelgersma and M.J. Tooley, 1993).

5. INFLUENCE OF GREENHOUSE EFFECT AND EL- NIÑO EVENTS

There is a lot of literature on the possible influence of greenhouse warming on tropical cyclones and all of it is inconclusive. Before worrying about how the greenhouse warming may or may not influence future storm surges, it is more appropriate to recognize the seriousness of the existing problem and try to mitigate it.

Due to global warming, if there is any sea-level rise in the Northern Indian Ocean, it will have some effect on future surge amplitudes. Sinha *et al* (1997) studied the effect of sea-level rise on tides in the Hoogly estuary of the Bay of Bengal.

When one thinks of sea-level rise, one should also consider possible land subsidence. Figure 24 shows that land subsidence is expected for the coastlines of the North Indian Ocean. If this comes true, the storm surge amplitudes could become greater.

Regarding the influence of ENSO events, again there is a lot of literature (Dong, 1988; Gray and Sheaffer, 1991; Evans and Allan, 1992 and Wu and Lau, 1992). Gupta and Muthuchami (1991) and Murty and Neralla (1996) studied this problem with respect to the north Indian Ocean. Although, there are some indications that ENSO events may have some influence on the location of the storm tracks, this problem needs further study.

6. SUMMARY

There is a storm surge problem in the marginal seas of the North Indian Ocean, the severest being in the Bay of Bengal. It is not clear at this time how much influence greenhouse warming and ENSO events would have on future surge amplitudes. However, if sea-level rises and also if the land subsides, the surges will be somewhat greater than at present.

REFERENCES

Defant, A., (1961): *Physical Oceanography*, Vol. 2, Pergamon Press Inc., New York, 598p.

Dong, K., (1988): El Niño and tropical cyclone frequency in the Australian region and Northwest Pacific. *Australian Meteorological Magazine*. Vol. 36. No. 4, pp. 219-225.

Dube S.K., A.D. Rao, P.C. Sinha and P. Chittibabu, (1994): *A real-time storm surge prediction system: An application to east coast of India*, Proc. Indian National Sci. Academy, Vol. 60, pp. 157-170.

Dube S.K., A.D. Rao, P.C. Sinha, T.S. Murty and N. Bahulayan, (1997): *Storm surge in the Bay of Bengal and Arabian Sea*. The problem and its prediction, Mausam, Vol. 48, No. 283-304.

Evans, J.L. and R.J. Allan, (1992): El Niño/Southern Oscillation: Modification to the structure of the monsoon and tropical cyclone activity in the Australasian Region. *International Journal of Climatology*. Vol. 12, pp. 611-623.

Fairbairn, L.A., (1954): *The semi-diurnal tides along the equator in the Indian Ocean*, Phil. Trans. Proy. Soc. London, Ser. A., Vol. 247, No. 927, pp. 191-212.

Gray, M. and J.D. Shaeffer, (1991): El-Niño and QBO influences on tropical cyclone activity, in *Teleconnections linking worldwide climate anomalies: scientific basis and social impact*. Edited by M.H. Glantz, R.W. Katz and N. Nicholls. Cambridge University Press. New York pp. 258-284.

Gray, W.M., (1978): *Hurricanes: their formation, structure and likely role in the tropical circulation*, p. 155-218, in D.B. Shaw (Edited), Meteorology Over the Tropical Oceans, Royal Meteorological Society, Bracknell, U.K.

Gupta A. and A. Muthuchami, (1991): *El Niño and tropical storm tracks over Bay of Bengal during post-monsoon season*. Mausam. Vol. 42, No. 3, pp. 257-260.

Henry, R.F., D.S. Duncalf, R.A. Walters, M.J. Osborne, and T.S. Murty, (1997): *A study of tides and storm surges in offshore waters of the Meghna estuary using a finite element model*, Mausam, Vol. 48, No. 4, pp. 519-530.

Jayanthi, N. and A.K. Sen Sarma, (1986): *A catalogue of storm surges in India*, Report 86-1, Regional Meteorological Center, Madras, India, 25p.

Jelgersma, S. and M.J. Tooley, (1993): *Sea-level changes during the recent geological past, state-of-the-art report, sea-level changes and their consequences for hydrology and water management*, International Workshop, 19-23 April 1993, Noordwijkerhout, Netherlands, pp. 9-41.

Murty, T.S., (1984): Storm surges-meteorological ocean tides, *Canadian Bulletin of Fisheries and Aquatic Sciences*, No. 212, 897p.

Murty, T.S. and V .R. Neralla, (1996): El-Niño and storm surges in the Bay of Bengal, in *Land-based and marine hazards: scientific and management issues, advances in natural and technological hazards research*, edited by M.I. El-Sabh, S. Venkatesh, H. Denis and T.S. Murty, Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 97-111.

Murty, T.S., R.A. Flather and R.F. Henry, (1986): *The storm surge problem in the Bay of Bengal*, Progress in Oceanography, Vol. 16, pp. 195-233.

Platzman, G.W., (1971): *Ocean tides and related waves, lectures for the American mathematical society*, 1970, Summer Seminar on Mathematical Problems in the Geophysical Sciences, Held at the Rensselaer Polytechnique Institute, Troy, N.Y., 94p. (also in W.H. Reid (Ed). Mathematical Problems in the Geophysical Sciences, Vol. 14, Part 2, pp. 239-291.

Prasad, K., (1997): Prediction of tropical cyclones by numerical models, A Review, Mausam, Vol. 48, No. 2, pp. 225-238.

Rady, M.A., M.I. El-Sabh, T.S. Murty and J. O. Backaus, (1994): *Numerical modelling of tides in the Gulf of Suez*, Egypt, Marine Geodesy, Vol. 17, No. 1, pp. 11-36.

Rao, N.S.B., (1968): *On some aspects of local and tropical storms in the Indian area*, Ph.D. Thesis, University of Jadavapur, Jadavapur, West Bengal, India, 262 p.

Sinha P.C., Y.R. Rao, S.K. Dube and T.S. Murty, (1997): *Effect of sea-level rise on the tidal circulation in the Hooghly estuary, Bay of Bengal,* Marine Geodesy, Vol. 20, No. 4, pp. 341-366.

Sterneck, R.V., (1920): *Die Gezeiten Der Ozeane*, Stiz.Ber.Akad.Wiss.Wien, Vol. 129, pp. 131-150.

Thompson, P.D., (1961): *Numerical weather analysis and prediction*, the MacMillan Company, New York, 170 p.

Wu, G. and N.C. Lau, (1992): A.G.C.M. Simulation of the relationship between tropical storm formation and ENSO. *Monthly Weather Review*. Vol. 13, pp. 958-977.

EARLY WARNING FOR THE 1991 ERUPTIONS OF PINATUBO VOLCANO — A SUCCESS STORY —

by Raymundo S. Punongbayan and Christopher G. Newhall

ABSTRACT

The success or failure of a warning system can be gauged in terms of the number of lives (and value of assets) lost to or saved from a disaster causing event. In these terms, the early warning system used at Pinatubo Volcano in 1991 can be considered a success story — the death toll of 250-300 out of the 20 000 immediately at risk was small despite the magnitude and violence of the eruption which was one of the world's biggest eruptions this century. This success can be attributed to a number of factors: early detection of the unrest, timely identification of hazards and delineation of vulnerable areas to them, successful application of state-of-the-art monitoring and surveillance techniques, accurate prediction of the most destructive phase of the eruption, timely issuance and dissemination of easily understood warnings, prompt action of key civil defence officials and disaster response workers, and timely evacuation of majority of the inhabitants at risk.

What made the Pinatubo story a classic are not only its success factors but also its near-misses — the things that could easily have gone wrong but luckily did not, which provide valuable lessons for developing warning systems in particular and volcanic risk mitigation plans in general. The positive aspects of the experience highlighted the value of the following: state-of-the-art monitoring equipment and techniques, international cooperation based on mutual respect, sustained intensive public education on volcanic hazards; active involvement of selected scientists as the designated spokespersons in awareness promotion and warning dissemination; open and speedy communication lines between the science people on one hand and the civil defence officials on the other; and good relations between scientists and the media. The near-misses or potentially negative aspects of the experience underscored the need to conduct geologic data base studies and hazard zonation on all active volcanoes long before the onset of unrest. We were lucky because Pinatubo gave us sufficient lead time to conduct reconnaissance geological studies and mapping of deposits of its past eruptions, thus enabling us to forecast the life-threatening hazards when it decided to erupt and to warn/educate concerned sectors into taking appropriate protective actions. We know that we will not always be as lucky. Hence, efforts will now be focussed on detailed studies and mapping of the unmonitored active volcanoes and on conducting in communities-at-risk an Pinatubo education campaign that would erode their indifference, scepticism and hostility to long-term action plan for volcanic disaster mitigation.

1. INTRODUCTION

Ideally, for a nation to effectively minimize or prevent disasters from volcanic phenomena, it must be able and willing to: 1) identify its high-risk volcanoes; 2) assess the hazards posed by these volcanoes, and delineate the areas likely to be affected by these hazards in hazard zonation maps; 3) monitor and forecast/predict the eruptions of these volcanoes; and, based on the outputs of these three activities; and 4) adopt measures or take actions that would reduce potential losses to volcanic hazards, such as: a) the formulation and strict implementation of land use and development plans as constrained by major volcanic hazards; b) relocation of communities at risk; c) emplacement of structural protection measures; and d) putting in place contingency plans and volcano emergency response. These four volcanic disaster mitigation components require two major sets of people and activities: the scientists on one hand to do the first three, and on the other the concerned policy makers, disaster management officials/organizations and endangered communities to do the fourth. The scientific findings of the former must be communicated effectively to the latter who, in their turn, plan and implement appropriate mitigation measures and actions. The chain linking these two sets of people and activities, ensuring that scientific findings are translated into concrete loss reduction/prevention actions is — the warning system. Each link in the chain — monitoring and forecasting, warning message formulation, transmission and response to warning — is important; any weakness or failure in one component could render the whole system ineffective in preventing or averting volcanic disaster.

The 1991 Pinatubo Volcano eruption experience can be considered a warning system success story. The unrest was diagnosed early enough, the hazards were identified and the areas vulnerable to them were delineated based on interpretation of geologic record of the volcano's past eruptions, the most destructive phase of the eruption was predicted, timely warnings were issued, the disaster response machinery was mobilized, and endangered populations were evacuated on time. Thus, all except about 250-300 of the more than 20 000 dwellers in the areas overrun by the destructive agents unleashed by Pinatubo's climactic 12-15 June eruption, escaped certain death. This death toll is small considering that the magnitude and violence of the eruption made it one of the world's largest this century.

What makes the Pinatubo story a classic are not only its success factors but also its near-misses — the things that could easily have gone wrong, but luckily did not. These provide valuable lessons for developing warning systems in particular and volcanic risk mitigation plans in general. We keep discovering more and more of these "lessons" each time we recall and retell the Pinatubo story. So we shall keep recalling and retelling the story until we exhaust its treasure of lessons.

The Pinatubo story recounted in this paper shows how the warning system evolved as scientists, disaster response officials and workers, and the endangered inhabitants responded or acted in each scene of the unfolding Pinatubo Volcano drama. For additional information on the story, see Punongbayan *et al* (1996) and Newhall and Punongbayan (1996).

2. VOLCANIC RISK MITIGATION EFFORTS BEFORE THE 1990S

Before the 1980s, the Commission on Volcanology or COMVOL, the government agency responsible for monitoring active volcanoes and forecasting their eruptions, had a reactive orientation: waiting for a volcano to erupt, monitoring the activities of an erupting volcano and pulling out of the scene when the volcano stopped erupting. Volcanology, as pursued then by COMVOL, had been mainly done by identifying volcanoes with short repose periods and constructing one or two monitoring stations on their slopes. No attention was given to conduct volcanogeological mapping of the monitored active volcanoes and generate volcanic hazards zonation maps, nor were there attempts to map areas impacted by volcanic hazards from a volcano that just erupted. Hence when COMVOL was re-organized into the Philippine Institute of Volcanology and Seismology (PHIVOLCS) in 1984 and transformed into a research and monitoring body, the latter only inherited volcano monitoring stations on five active volcanoes with short repose periods and growing populations (and therefore high-risk), namely Mayon, Bulusan, Taal, Canlaon and Hibok-Hibok.

During the 1980s, PHIVOLCS started upgrading and expanding the monitoring network with the addition of a sixth permanent station at Mt. Banahaw. Also initiated was a long-term program of basic studies on these six monitored volcanoes and Iriga Volcano, another known active volcano. These studies were aimed at generating information for deciphering past eruptive behaviour, understanding current behaviour and making long-term forecasts of the volcanoes' activities. Hazard assessments and zonation were also conducted on these volcanoes and the hazard zone maps produced have been disseminated to concerned land use and development planners, policy makers and local leaders of endangered communities. However, the results of these hazards assessments and our long-term (looking years to decades ahead) forecasts and warnings have been largely ignored or met with scepticism and/or outright hostility. Long-term mitigation measures such as restricting land uses and development activities for a mere "probable" event in the not-too-distant to distant future are often unpalatable to both policy makers and citizens.

During this same decade, three of the monitored volcanoes erupted — Mayon, Bulusan and Canlaon. In these volcanic crises, our medium- to short-term forecasts and warnings were often received with scepticism. Luckily, with the exception of Mayon's eruption in 1984, the other events were mild and of short duration thus not necessitating evacuation. During the Mayon Volcano 1984 eruption, the respondents to a post-eruption survey claimed that they evacuated more on the basis of their own perception of the volcano's activity than on warnings from government and media sources (Tayag *et al.*, 1985).

Of the 220 or so Quaternary volcanoes in the Philippine Archipelago, we have classified as active the 22 that have erupted during historic time (or within the past 500 years) and those with no reported eruption during historical time but which showed evidence of having erupted during the last 10 000 years. Pinatubo Volcano is one of the active volcanoes with no historical eruption but was classified as such (Punongbayan 1987) on the basis of the youngest age yielded by radiocarbon dating of charcoal fragments from one of its pyroclastic flow deposits: 650 + 80 radiocarbon years (Ebasco Services Inc, 1977). Parker Volcano in southern Mindanao was added to the list in 1995 as collected charcoal fragments from its deposits yielded a carbon-14 date of 250 years.

In view of the limitations of PHIVOLCS monitoring capability and the priority given to volcanoes with short repose periods, Pinatubo Volcano which has a long repose period was not covered by the PHIVOLCS monitoring network and because of this, the onset of its unrest was not properly documented. Pre-eruption Pinatubo Volcano used to be the home of Aeta or Negrito tribes which were scattered on the slopes of the volcano straddling the three provinces of Zambales, Tarlac and Pampanga. Traditionally semi-nomadic, these tribes thrived on kaingin, or slash and burn farming, producing mostly coffee, root crops and bananas. The Aetas consider Pinatubo as their god whom they call as Apo Namalyari. When they have a good harvest, they make offerings to Apo Namalyari in the steaming ground located on the northern slopes of Pinatubo.

3. CHRONOLOGY OF PINATUBO'S ACTIVITIES AND SCIENTIFIC RESPONSES

3.1 JULY-AUGUST 1990

On 16 July 1990, a Magnitude-7.8 earthquake was generated by the Digdig Fault segment of the Philippine Fault Zone and whose epicenter was located about 100 km northeast of Pinatubo Volcano (Figure 1). A few hours after the main shock, a small magnitude earthquake occurred about 10 km southeast of the volcano. Quakes continued to be felt around the volcano area during the following weeks. We do not know, and will probably never know, whether these earthquakes were locally generated volcanic quakes or distant aftershocks of the 16 July northern Luzon earthquake.

In early August, indigenous Aetas living on the slopes of Pinatubo accompanied by nuns of the Franciscan Missionaries of Mary, reported to PHIVOLCS audible rumbling sounds, ground cracking and increased steaming from a pre-existing thermal area. A quick response team was dispatched by PHIVOLCS to investigate the reported phenomena. After conducting a cursory investigation around the thermal area, the team reported that: "Preliminary findings indicate that the phenomenon is not related with any volcanic activity...The parameters necessary for deducing an approaching... volcanic eruption were not observed in the locality" (Ramos and Isada, 1991). The team thus concluded that the reported observations of the volcano dwellers were possibly related to a landslide that was triggered by the continuing aftershocks of the regional earthquake and the recent heavy rains in the area.

3.2 APRIL 1991

On 2 April 1991, an unusually large explosion at the volcano's northern slope, accompanied by rumbling sounds and intense new steaming from several vents, prompted the same nuns and Aetas to again call on PHIVOLCS on 3 April.

PHIVOLCS again reacted by immediately dispatched another Quick Response Team which conducted ocular and aerial observations with the assistance of the Office of Civil defence and the Philippine Air Force. The team found all the reported manifestations, as well as a fissure and new craters at the northeast end of an east-west line of steaming vents. The initial assessment of the team was that the explosion was of hydrothermal origin and from one of the steaming vents on the northern slopes of Pinatubo Volcano. The team was ordered to deploy a seismograph on Pinatubo when it failed to give a satisfactory answer to the question: "Why were the Aetas bothered

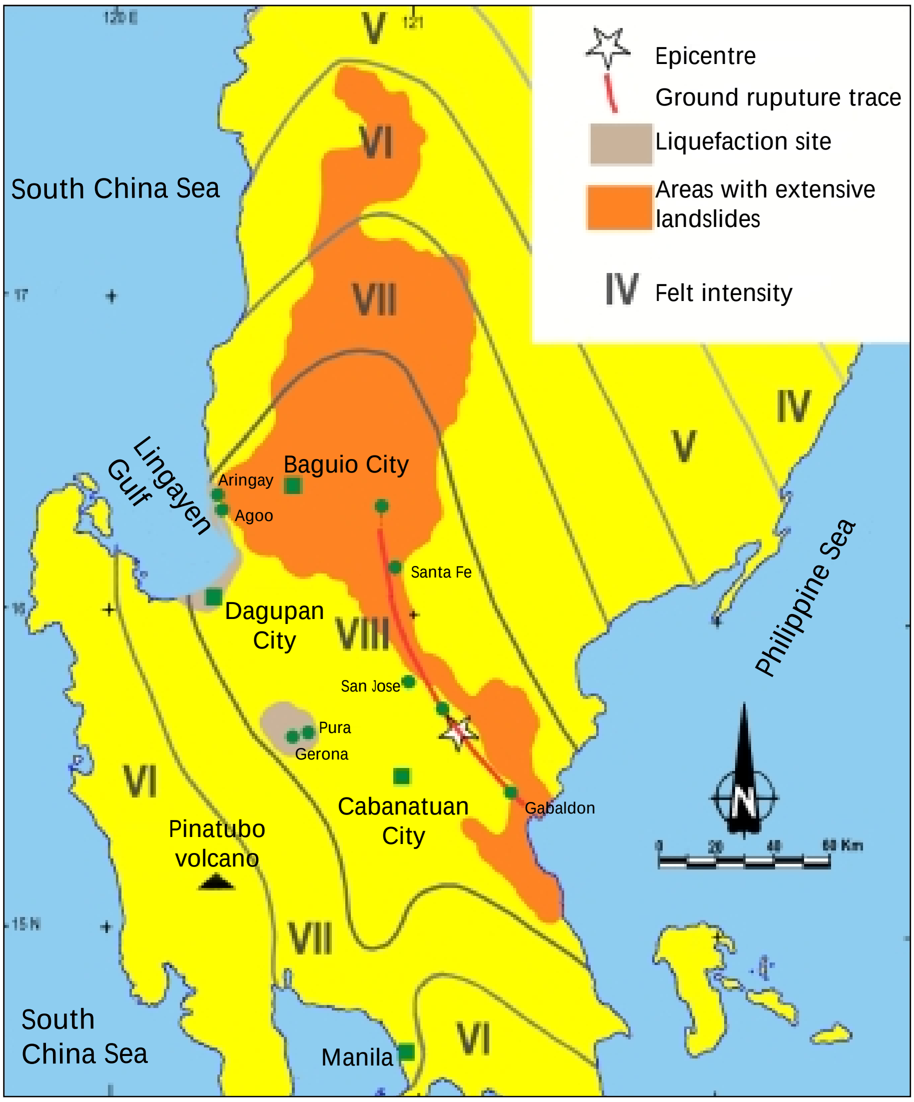


Figure 1. Map showing the location of epicentre of the 16 July 1990 M7.8 earthquake, intensity distribution and the areas affected by liquefaction and landslides.

enough to report to us the presence of new steaming vents and the unusually large explosion that occurred on 2 April ?"

A temporary seismic station was installed on 4 April at Sitio Yamut, about 12 km WNW of Pinatubo. This recorded about 500 high frequency volcanic earthquakes, some large enough to be felt at varying intensities. Convinced that Pinatubo was showing definite signs of unrest, we declared on 7 April a 10 km-radius permanent danger zone, and advised evacuation of the residents therein.

Warnings issued by PHIVOLCS at this stage took the form of volcano bulletins which contained daily earthquake counts, visual observations and assessments of the volcano's condition. Uncertain of the applicability of the alert levels previously used for the monitored Philippine volcanoes, the term "unstable" was used for describing the volcano's conditions.

The updates were prepared in the field then radioed to the PHIVOLCS central office for review and release. From the PHIVOLCS Central Office in Quezon City, these volcano bulletins were transmitted to the National Disaster Coordinating Council (NDCC) through the Office of Civil defence (OCD), the Office of the President and the Department of Science and Technology (DOST). The updates were also radioed back to volcano monitoring field stations, for local dissemination.

Additional seismograph units were later installed to augment the monitoring network. Electronic Distance Meter (EDM) stations were also set up at Sitio Yamut.

With Taal Volcano also restive at that time, we called up the United States Geological Survey (USGS) and asked for the assistance of the Volcano Crisis Assistance Team (VCAT). A three-man USGS team led by Dr. Christopher Newhall arrived on 23 April.

A PHIVOLCS-USGS team was formed and with logistical support from the US Air Force based at Clark Air Base, set up a telemetered seismic network around Pinatubo and started measurements of sulfur dioxide emissions. A central station was installed at Clark Air Base on 26 April. Thus the Pinatubo Volcano Observatory (PVO) was created.

The state-of-the-art monitoring system installed at Pinatubo enabled us to track the location, size, type, magnitude and frequency of occurrence of volcanic quakes underneath the volcano on a near real-time basis. The monitoring of sulfur dioxide gave us very good clues about possible magma involvement with increasing fluxes as eruption nears.

3.3
MAY 1991

We realized that the Volcano Bulletins were inadequate media for disseminating information on the volcano's condition and activities and for transmitting advisories on appropriate precautionary actions and safety measures to concerned civil defence officials, disaster response organizations and the public. With no baseline monitoring data for the volcano, no information on precursors of its previous eruptions and practically no information about precursors of large explosive eruptions anywhere, we felt that we could not promise a specific prediction. But we thought that we could offer a simple, multi-level description of unrest. So, we designed a 5-level scheme of Alert Levels (Table 1) patterned after schemes used at Rabaul (Papua New Guinea), Redoubt (Alaska) and Long Valley (California), and in the generic model described in UNDRO-UNESCO (1985). This scheme did not technically make predictions, but simply pointed out increasing levels of unrest and corresponding decreasing assurances that an eruption would not occur within a specified period of time. The scheme was formally adopted on 13 May and Alert Level 2 was declared on the same day.

By this time, we had enough data to conclude that an eruption was entirely plausible. Our next questions were: "How large and violent would the eruption be? What areas are likely to be affected"?

Together with the USGS geoscientists, we conducted topographic map and airphoto analyses and field verification to identify hazards that could be unleashed in the event of a Pinatubo eruption. We identified three major hazards: pyroclastic flows, ashfalls and lahars. Areas likely to be affected by these hazards were delineated by analysing airphotos, topographic maps and particularly for ashfall, prevailing wind patterns. The resulting hazard zonation maps showed

Table 1

Alert level	Criteria	Interpretation
No alert	Background; quiet	No eruption in the foreseeable future
1	Low level seismicity, other unrest	Magmatic, tectonic or hydrothermal disturbance; no eruption imminent
2	Moderate level of seismicity,other unrest, with positive evidence for involvement of magma	Probable magmatic intrusion, could eventually lead to an eruption
3	Relatively high and increasing unrest including numerous b-type earthquake; accelerating ground deformation; increased vigour of fumaroles, gas emissions.	If trend of increasing unrest continues, eruption possible within 2 weeks
4	Intense unrest, including harmonic tremor and/or many "long period" (=low frequency) earthquakes	Eruption possible within 24 hours
5	Eruption in progress	Eruption in progress

STAND-DOWN PROCEDURES:
In order to protect against "lull before the storm" phenomena, alert levels will be maintained for the following periods AFTER activity decreases to the next lower level:
From Alert Level 4 to 3: Wait 1 week
From Alert Level 3 to 2: Wait 72 hours

what we thought was a composite worst case scenario, based on the geologic record. These were completed on 23 May 1991 and immediately disseminated to local government officials of the provinces at risk, namely: Zambales, Pampanga and Tarlac. Events were soon to mimic the hazard zone maps for pyroclastic flows and lahars (Figure 2). However, the aggravating effect of typhoon Yunya was not anticipated and reflected in the hazard zone map for ashfalls. We also later found out that worse eruptions had occurred at Pinatubo more than 35 000 years ago. Had the 1991 eruption been as large as that of more than 35 000 years ago, our hastily prepared hazard zone maps would not have held and tens of thousands of people would have died. We were just lucky. We shall have to do better in future by doing the baseline geologic and hazard mapping of all active volcanoes long before they become restive.

Zones for evacuation based on the hazard maps were designated as danger zones and were delineated as circular zones of increasing radius centred on the volcano. As mentioned earlier, as early as 7 April, a ten-km radius danger zone was declared, centred on the volcano's active vent. This danger zone was to be expanded later as the danger escalated.

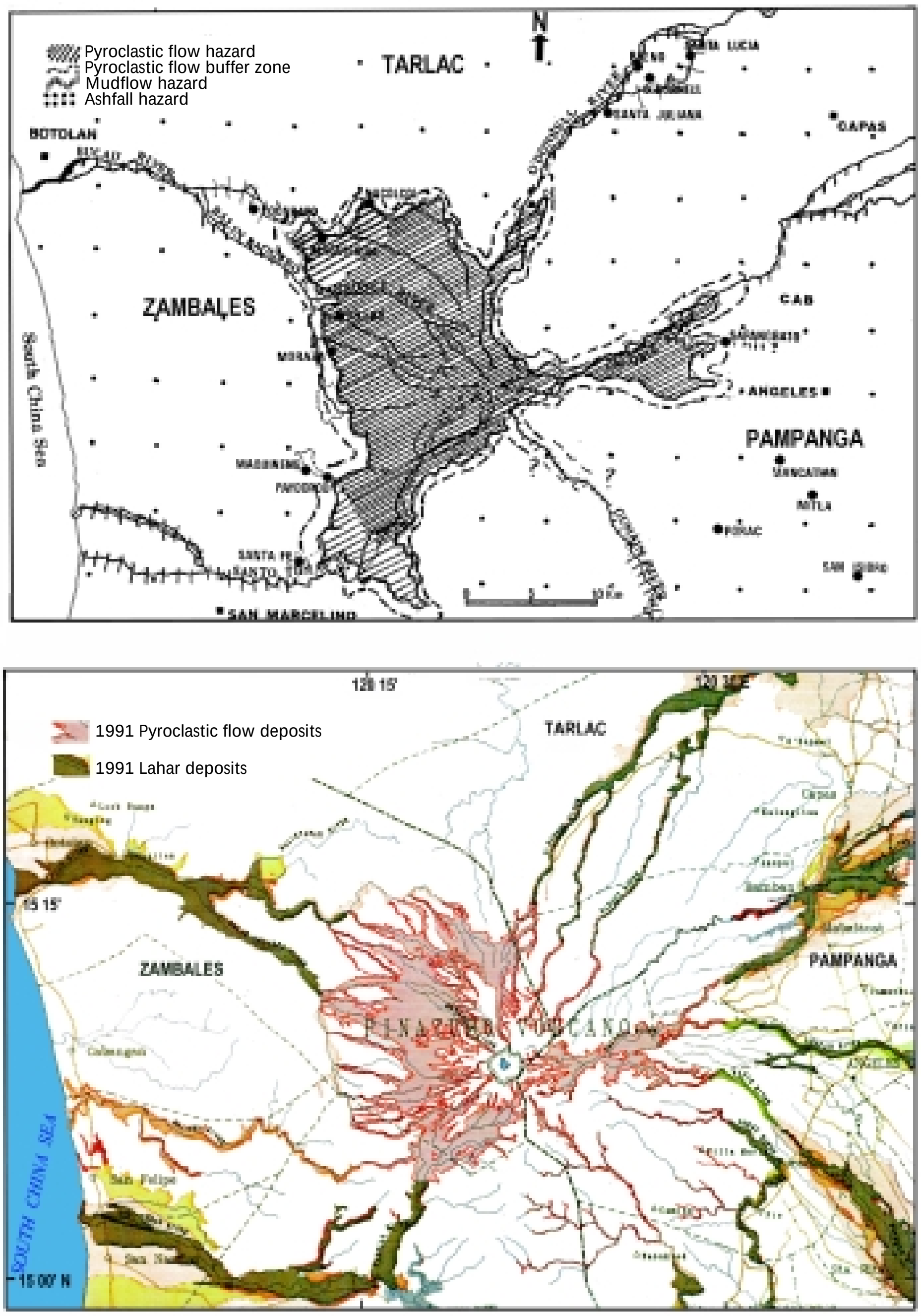


Figure 2. Above: Pinatubo volcano preliminary hazard map issued on 23 May 1991 and showing areas that may be affected by pyroclastic flows, lahars and ashfall. Below: Map showing areas covered with pyroclastic flow and lahar deposits after the major eruptions of Pinatubo Volcano in June 1991.

Having devised several ways of expressing the warning messages, our next problem was how to make the concerned officials, community leaders and endangered inhabitants appreciate the dangers they faced — at least to the extent that they could take appropriate defence or protective actions. How could we explain to them the hazards, the need for action as well as the uncertainties in our warnings with possibilities for both false alarms and unpredicted eruptions?

Nagging at us was the tragedy of Nevado del Ruiz in 1985 where 22 000 people died as a result of the failure of key officials to heed and act on the hazard assessments and warnings of the scientists (Hall, 1990; Voight, 1990). We were determined that such a tragedy would not be repeated but we were faced with a similar problem. The people at risk and their leaders were understandably sceptical as most of them had never heard or witnessed an eruption, Pinatubo had been dormant throughout their and their grandfathers' lifetime, and such terms as pyroclastic flows, ashfalls and lahars were new to them. So we launched an aggressive and intensive education campaign, first among the concerned civil defence officials, then among the endangered inhabitants.

We took advantage of briefing sessions for government officials. We found that we could catch audience attention most effectively by showing the video entitled *Understanding Volcanic Hazards* produced by the late Maurice and Katia Krafft for the International Association on Volcanology and Chemistry of the Earth's Interior (IAVCEI). The video shows dramatic examples of hot ash flows, ashfalls, lahars, large volcanic landslides, volcanogenic tsunami, lava flows and volcanic gases. It illustrates the nature of each hazard, how fast and far it travels and what it does to people and objects on its path. For maximum impact, we showed only the segments on ash flows, ashfall and lahars during each briefing session to retain the attention of government officials and because these were the major hazards that Pinatubo may unleash when it erupts.

We showed the video to as many audiences as we could reach — the then President of the Republic, Corazon C. Aquino, the then Secretary of defence and Chairman of the National Disaster Coordinating Council (NDCC) Fidel V. Ramos, Department Secretaries, Governors and other provincial officials, base commanders, municipal/city officials, students, religious leaders and barangay residents. We made about 50 copies of the tape and left a copy with each group that we briefed; an untold number of second generation copies were made. Initial response was, typically, shock and disbelief or denial, but somehow, the tape must have jolted many viewers into preparing for a possible eruption.

We also had to see to it that the information and warnings we were disseminating to higher government and military officials were being transmitted to the inhabitants on the volcano. PHIVOLC usually channeled warnings through the concerned Disaster Coordinating Council which upon receipt of the warning, sets in motion its machinery for warning transmission and response. In the case of Pinatubo, we reached out to the villages, whenever we could. We conducted intensive information drives among the inhabitants in the barangays just outside the Clark Air Base. A similar grassroots educational campaign was also conducted in the villages at the western flank of Pinatubo, by PHIVOLCS staff with the assistance of the Franciscan Missionaries of Mary and the LAKAS, an organization of Aytas in Zambales. Our monitoring personnel staying in the villages at risk entertained and answered the queries of the villagers.

To expand the coverage of the campaign, we involved the national and local media. Press, radio and TV people practically camped at the PHIVOLCS main office and at the field station in Zambales, grabbing every information which they felt would make the headlines. The quality and actual contributions of media coverage to the pre-eruption education campaign remain to be assessed but there is no doubt that media involvement was a key factor in rapid and widespread dissemination of information.

3.4 1-11 JUNE

During the first few days of June, shallow seismicity and the amount of ash in the steam plume gradually increased. The clusters of earthquake epicentres also started to shift from the NW to the active vent area and were located at shallower depths. More high frequency or rock fracturing earthquakes were being recorded but some of these had a lower frequency component. On 05 June, SO_2 values suddenly decreased, suggesting that some new material from below was plugging the path of these gases. Some of the steaming vents had also stopped steaming and ash emission increased. These developments prompted us to raise the alert level to 3, indicating that eruption was "possible within 2 weeks". On 7 June , we raised the alert level to 4 (meaning eruption possible within 24 hours) due to further increase in seismicity, and the noticeable shift in the earthquake type —from a dominant high frequency to a low frequency type, suggesting shallow earthquake source and/or magmatic origin. A telemetered tiltmeter installed at the steaming vent area also showed progressive tilting from 6 to 7 June. A lava dome, measuring about 150 m long, 100 m wide and 50 m high was sighted near the most active steam vent the next day. This dome was the first visible manifestation that magma had risen to the surface. At this point, we began to question the appropriateness of alert level 4 because technically, dome growth is an eruption in progress.

On 9 June, when the monitoring team in Zambales reported the sighting of a pyroclastic flow (this was actually a pyroclastic flow-like ash cloud) rolling down the northwest flank of the volcano, we declared Alert Level 5 (meaning "eruption in progress") and recommended a 20 km radius danger zone on all sides of the volcano. The declaration of Alert Level 5 convinced more people to evacuate before the large eruptions actually began. By 10 June, about 25 000 inhabitants, mostly Aytas, were evacuated from the barangays closest to the volcano. Some 14 500 US personnel and their dependents were also evacuated from Clark Air Base to Subic Naval Base, leaving behind skeleton security and the Clark Air Base Command (CABCOM) personnel.

The evacuation of the endangered inhabitants should have made us feel relaxed, but at that time, it made us feel uncomfortable. Evacuation of large numbers of people is costly, and the "eruption in progress" on 9-11 June did not appear to warrant such massive evacuation. We were under considerable pressure to prove that our forecasts were correct and that our recommendations were necessary.

3.5 12-15 JUNE

When the large explosive eruptions began on 12 June, the volcano spoke mainly for itself. At the height of the climactic eruption on 15 June, we expanded the danger zone radius to 40 km, fearing that a large sector of the volcano edifice might collapse as a result of a large caldera eruption. However, during this time, our monitoring operation was temporarily disabled and radio link was disrupted while our personnel were fleeing from the volcano. We re-established our monitoring station some 25 km northwest of Pinatubo. The enlarged evacuation zone had been immediately transmitted to the concerned communities with the assistance of major radio stations. On 16 June, we were able to tell the country that the caldera-forming eruption had already created a 2 km-diameter summit caldera and that the worst had probably passed.

A typhoon happened to pass by on the same day, its winds carrying Pinatubo's ash to distant lands. Pinatubo's ash reached Metro Manila, giving the nations' policy makers and leaders a direct experience of the eruption and possibly inspiring their meaningful responses to the ongoing disaster. Classes in the city were suspended and the Ninoy Aquino International Airport was closed. The typhoon brought rains, wetting the ash that accumulated on roofs, causing roof collapse. About 200 persons died under roofs that collapsed. The typhoon-triggered lahars claimed more lives in addition to the several dozens who were buried by pyroclastic flows and the 200 victims of collapsed roofs, increasing the casualty number to 250-300.

3.6 16 JUNE - 4 DECEMBER 1991

After 16 June, Pinatubo's activities gradually abated. The danger zone was officially reduced to a 20 km radius on 18 June. Most of our warnings and concern since then until the volcano's renewed activity in 1992 were about lahars and secondary explosions. The last eruption of 1991, a small puff, occurred on 4 September, the same day on which the alert level was lowered from 5 to 3 and the 20 km radius danger zone was reduced from to 10 km radius.

On 4 December 1991, the eruption alert level was lowered to 2, but the 10 km radius danger zone was retained.

4. PUBLIC RESPONSE TO THE PINATUBO WARNINGS

Not all the civil defence and public officials and community leaders whom we reached were responsive to our warnings and advisories. Some provincial and municipal groups and military commanders remained sceptical until the volcano proved us right. The most vocal sceptic was the then mayor of Angeles City who refused to meet with national civil defence officials and USGS-PHIVOLCS scientists, and accused us of speaking in ignorance and berating the Americans at Clark Air Base of overreacting to a non-existent threat !

However, most of the key officials and groups who mattered were responsive and supportive. First and foremost, the then Chairman of the National Disaster Coordinating Council (Secretary Fidel V. Ramos) who later became President of the Philippines, actively participated in promoting mitigation and preparedness among the local and national officials, nongovernmental organizations and endangered communities. He personally visited the vulnerable communities, held briefings and dialogues with concerned officials and saw to it that the President and her Cabinet were informed about the volcano's activities and potential hazards. Without being asked, he also gave substantial additional operating funds to PHIVOLCS for carrying-out monitoring activities with the USGS.

Second, the Administrator of the Office of Civil defence, an engineer, appreciated both the value and the uncertainties of scientific investigations, and provided us considerable support in our monitoring activities as well as in our education and information dissemination campaign.

The Regional Disaster Coordinating Council officials of Region 3 and a number of NGOs, including the Franciscan Missionaries of Mary, were equally supportive. Several individuals in the commands and ranks at Clark Air Base and Subic Bay Naval Station, supported us and volcano emergency planning in the face of scepticism among their colleagues.

Many media reporters established and maintained strong "friendly" links with us and helped us promote public awareness of the impending hazards. They were ever present around the volcano during the unrest and crisis and shared and cross-checked with us whatever news or information they gathered in the field. In this manner it was possible to avoid causing undue panic among the people at risk. These reporters also heeded our plea to refrain from venturing into the declared danger zone and helped us convince others to comply.

How about the affected inhabitants, how did they respond to the warnings ? To assess this, a post-eruption survey was conducted by a PHIVOLCS team. Results show that a majority (58 per cent) took defensive/adaptive action and evacuated immediately as and when advised. Communities covered by the LAKAS, an organization of Aytas or natives, showed the most exemplary operation of the system, namely transmission was total and response was consistently appropriate. These communities were reached by information drives which featured the showing of the tapes on volcanic hazards produced by the Kraffts. Results of the study indicated some weakness in the transmission system and the failure of some endangered inhabitants to fully appreciate the risks and take protective action. Those who did not evacuate immediately when, and as advised, gave various reasons, such as: they thought the eruption would not be strong enough to affect their place; they were reluctant to leave behind their properties, livestock and crops — especially as it was harvest time; they had no ready means of transport and some community members could not walk long distances; and, they believed that their god, Apo Namalyari which is Pinatubo Volcano, would not let them come to harm (Tayag *et al.*, 1996).

5. INSIGHTS AND LESSONS FROM THE EXPERIENCE

From the positive aspects of the experience, the following insights were highlighted: the value of state-of-the-art monitoring equipment and techniques, international cooperation, intensive public education on volcanic hazards; the active involvement of scientists in awareness promotion and warning dissemination; the open and speedy communication lines between the science people on one hand and civil defence officials on the other; and the good relations between scientists and the media.

Without the state-of-the-art monitoring equipment loaned (and later donated) to us by the USGS and the assistance of our American geoscientist friends who spent sleepless nights and hectic days with us to the end, we doubt if we could have been able to forecast Pinatubo's activities as accurately as we did.

We also believe that if we had simply confined ourselves to the responsibility of studying, forecasting and releasing warnings and did not take the pains of educating the concerned officials, the media and the endangered inhabitants, making them understand/appreciate the hazards, and ensuring that they took appropriate protective actions — more lives would have been lost and the Pinatubo crisis would have created another Nevado del Ruiz tragedy.

From the near-misses or potentially negative aspects, the experience underscored the need to conduct geologic database studies and hazard zonation on all active volcanoes long before the onset of unrest. Had we done these before Pinatubo, we would not have had to cram and prepare hazard zonation maps hastily. The hazard zone maps would have reflected the worst worst-case scenario which we later discovered, and perhaps the ashfall hazard map would have been more accurate. Many of our conclusions were tentative, based on the sketchiest of data and review. Our warnings and emergency preparations by civil defence and other officials, were only one step ahead of Pinatubo. We were only lucky that Pinatubo gave us this short lead time, and then followed a remarkably straight and rapid course toward eruption once we declared its eruption deadline in our hastily prepared Alert Level scheme.

It is our goal at PHIVOLCS to identify all our active and potentially active volcanoes, study them in sufficient detail to determine which of them are the most dangerous and likely to erupt within our lifetime, conduct hazards assessments, produce hazards zonation maps and see to it that these are reflected in land use and development plans, establish adequate monitoring networks that would enable us to make medium-term, as well as short-term forecasts of these volcanoes' activities and accordingly issue timely warnings and appropriate advice to reduce if not prevent volcanic disasters. It is also our objective to pursue a sustained education and information dissemination program to promote and sustain awareness of volcanic hazards and appreciation of the need for mitigation or prevention.

REFERENCES

Ebasco Services Inc, 1977: *A report on geochronological investigation of materials relating to studies for the Philippine Nuclear Power Plant Unit I.*

Hall M.L., 1990: *The 1985 Nevado del Ruiz eruption: scientific, social and governmental response and interaction prior to eruption*. In: McCall G.J.H, Laming D.J.C. and Scott S. (eds) Geohazards. Chapman and Hall, London , pp 43-52.

Newhall C.G, Punongbayan R.S., 1996: *The narrow margin of successful volcanic-risk mitigation*. In: Scarpa and Tilling (eds) Monitoring and mitigation of volcano hazards. Springer-Verlag Berlin Heidelberg, pp. 808-838.

Punongbayan R.S., 1987: *Disaster preparedness systems for natural hazards in the Philippines: an assessment*. In: PHIVOLCS, Geologic hazards and preparedness systems. PHIVOLCS Press, Quezon City, pp 77-109.

Punongbayan R.S., Newhall C.G., Bautista M.L,P., Garcia D., Harlow R.P., Sabit J., Solidum R.U., 1996: *Eruptive hazard assessment and warnings*. In: Newhall C.G., Punongbayan R.S. (eds) Fire and mud: eruptions and lahars from Mount Pinatubo, Philippines. PHIVOLCS, Quezon City and University of Washington Press, London and Seattle, pp 67-86

Ramos A.F., Isada M.G., 1990: *Emergency investigation of the alleged volcanic activity of Mount Pinatubo in Zambales Province*. PHIVOLCS Memorandum Report,1-2.

Tayag J.C., Cola R., Natividad R., 1985: *Socio-economic impacts of the Mayon Volcano 1984 eruption*. PHIVOLCS Press, Quezon City

Tayag J.C., Insauriga S., Ringor A., Belo M., 1996: *People's response to eruption warning: the Pinatubo experience, 1991-1992, Philippines*. In: Newhall C.G., Punongbayan R.S. (eds) Fire and mud: eruptions and lahars from Mount Pinatubo, Philippines. PHIVOLCS, Quezon City and University of Washington Press, London and Seattle, pp 87-106.

UNDRO/UNESCO, 1985: Volcanic Emergency Management.UNDRO/UNESCO, pp 1-86.

Voight B., 1990: *The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retrospection*. J Volcanol Geotherm Res 44:349-386.

REDUCING THE IMPACTS OF TROPICAL CYCLONES DURING THE IDNDR

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ABSTRACT

An overview is provided of the impacts of tropical cyclones and of the activities that have occurred during the IDNDR to help ameliorate these impacts. The focus is on WMO and ICSU activities and their major international activities and achievements. A discussion is provided on tropical cyclone impacts, the WMO and ICSU programs during the decade, major related research programs and efforts to reduce the impacts of tropical cyclones. An outlook for the next decade completes the essay.

1. INTRODUCTION

Tropical cyclones are rightly feared as being amongst the most destructive weather systems on earth and potentially the most destructive for coastal communities in tropical and subtropical countries. The historical toll in human life has been huge. Although the death toll has been reduced dramatically during this century, more than 125 000 people were killed in Bangladesh as recently as 1991. The increasing development and population density in coastal regions affected by tropical cyclones has further resulted in an exponentially increasing scale of disruptions and long-term effects to communities, small states and even the global economy. A landfall by a severe tropical cyclone on a small island nation can cause damage that exceeds the GNP of the country and can severely disrupt the economy for several years afterward. The combination of Hurricanes Andrew, Iniki and Omah in 1992 shook the global insurance industry and brought major companies to the brink of collapse.

> "Insurers had at least one 'billion dollar' storm event every year from 1987 to 1993. With such an unexpectedly high frequency, some local insurance companies collapsed, and the international reinsurance market went into shock." (Watson *et al.* 1996, p547)

Here, I provide an overview of the impacts of tropical cyclones and of the activities that have occurred during the IDNDR to help ameliorate these impacts. My overview focuses on WMO and ICSU activities as these have been the major international components and are the ones with which I am most familiar. I start with a brief discussion of cyclone impacts, then describe the WMO and ICSU programs during the decade. Some major related research programs and efforts to reduce the impacts of tropical cyclones are next described. Finally, I look forward to where we might be going in the next decade.

2. TROPICAL CYCLONE IMPACTS

Tropical cyclones are characterized by a relatively small core of intense winds and very low surface pressure surrounded by a decreasing wind field with radius. The surrounding winds can extend destruction and disruption over very large distances of over 1 000 km in extreme cases. The core of an intense system contains a clear eye surrounded by a wall of clouds with heavy rainfall and the high winds. Farther out are often found major spiral bands of clouds that can also produce heavy rainfall, strong winds and occasionally tornadoes.

Tropical cyclones impact oceanic regions, particularly international shipping and offshore structures, but the major impact occurs when they move over islands or come ashore and move inland over major land masses. As summarized in Figure 1, the coastal and inland impacts are quite varied.

The intensity of tropical cyclones is universally related to the maximum winds and the highest observed gusts approach 300 km/h*. These strong winds impact on structures and the natural environment with a static force that varies with the square of wind speed. Thus, doubling the wind speed quadruples the static forces on structures. Added to this are dynamic forces in which shedded vortices from overhanging eaves, local wind channeling around obstacles, etc, further increase the loading on structures. A cascade effect of damage due to

* All extreme values quoted here have been referenced in Holland et al., 1993, p9.28

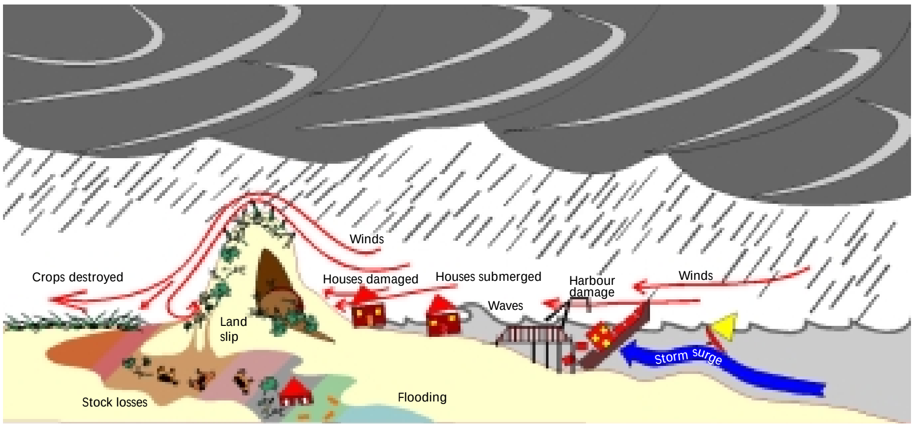


Figure 1. Schematic of the wide range of impacts of tropical cyclones on coastal regions (R. Falls personal communication 1995).

debris often also occurs, with debris from one damaged building smashing into others and creating more debris, and etc.

The strong winds acting on the ocean surface produce high waves over the ocean, which cause substantial disruption to shipping. An extreme wave of 34 m in height was observed in a typhoon in the Western North Pacific. In vulnerable coastal regions, the winds also can drive a substantial body of ocean ashore in a devastating storm surge that can exceed 10 m in extreme cases. Added to this surge will be breaking waves, which directly impact coastal structures and also enhance the landward ingress of seawater by wave run-up and set-up.

The cyclone loses wind intensity as it moves inland, although some re-intensification can occur and tornadoes and locally intense microbursts have been recorded. When interacting with local orography, or in the process of a mid-latitude transformation, intense and sustained rain can develop. Such rain has led to flash flooding, local landslides and devastating mudflows that can tear through communities with little or no warning. Widespread flooding can also leave communities isolated without proper housing for extended periods and destroy food crops and farming infrastructure.

The post-landfall impacts can be much larger and more devastating than those which occur at the original landfall. At the recent WMO/CAS-ICSU International Workshop on Tropical Cyclones, precipitation was ranked with wind fields at landfall as the primary issues to be addressed by the research community.

3. THE WMO/CAS-ICSU COLLABORATION ON TROPICAL CYCLONES AS A PRIORITY MISSION UNDER THE IDNDR

The Tropical Meteorology Research Program, within the WMO Commission for Atmospheric Sciences (CAS), has supported a strong tropical cyclone program since the 1960s. The goals of this program are to help reduce the impacts of tropical cyclones by supporting and promoting appropriate research, development and technology transfer. In 1994, CAS established a program to enhance tropical cyclone activities as a priority mission under the IDNDR. Under this program, CAS worked with ICSU on several high-profile projects that have ranged from major international research projects through forums promoting interaction between forecasters, researchers and impacts specialists, to compilation of text books and forecast guides. Three of these are described in this section.

3.1. THE INTERNATIONAL WORKSHOP ON TROPICAL CYCLONE SERIES

The IWTC is a quadrennial series of workshops that commenced in 1985, as a response to a growing awareness of the benefits that could arise from a strong international linkage between forecasters and researchers. The goals are to provide a forum for discussion between forecasters and researchers and particularly:

- To update forecasters with the latest research findings and forecasting technology;
- To update researchers on tropical cyclone forecast and warning developments;
- To identify basic and applied research priorities and opportunities; and,
- To identify opportunities and priorities for acquiring observations.

A feature of the IWTC series has been the extensive preparation of material before the workshop. This has involved appointing rapporteurs and working groups to investigate the state of the science in each of a defined set of topic areas and to submit recommendations on impediments and opportunities.

During the IDNDR, WMO and ICSU collaborated on two workshops: IWTC-III held in Huatulco, Mexico and IWTC-IV held in Haikou, China. Further, the IWTC-II, held in Manila in the Philippines, had a marked impact on IDNDR activities. Each of these workshops produced a large number of recommendations and resulted in collaborations extending across forecast and research activities. Only a brief summary of a few major outcomes is provided here.

IWTC-II produced two major outcomes: the international research program on tropical cyclone motion, described in Section 3, and the Global Guide to Tropical Cyclones (Holland *et al.*, 1993).

The Global Guide utilized the extensive material produced during the first two IWTCs, together with an extensive review of the state of the science, to summarize available information on tropical cyclone forecasting. The contents covered all aspects of the forecast requirement, including a global climatology and summary of warning zones, specific forecast techniques, an extensive bibliography, and a list of useful facts and figures. The initial book was printed in a loose-leaf format, with the support of the WWW Tropical Cyclone Program, and distributed free of charge to all forecast offices. Following a recommendation at IWTC-IV the Global Guide has been transferred to a web page <http:www.bom.gov.au/bmrc/meso/New/wmocas_pubs/global_guide/globa_guide_intro.htm> that will be substantially updated over the next few years.

IWTC-III came at the maturation of the intensive international research effort on tropical cyclone motion and the discussion and recommendations reflected the substantial progress in knowledge that had been gained from this program. The major outcome was the compilation of the publication "*A Global Perspective on Tropical Cyclones*" (Elsberry *et al.*, 1997), an update of "*The Global View of Tropical Cyclones*" (Elsberry *et al.*, 1987) produced following the first IWTC. The Global Perspective provided an extensive review of the state of knowledge of tropical cyclones. It was printed by WMO and distributed free of charge to all forecast offices with tropical cyclone responsibilities. The collaboration between WMO and ICSU in this meeting also led to development of an initial scientific consensus on the potential impacts of climate change on tropical cyclones (Lighthill *et al.*, 1994).

IWTC-IV saw the changing emphasis on forecasting towards addressing the societal impacts of tropical cyclones directly and on ameliorating the effects of tropical cyclone landfall. The emphasis on societal impacts arose directly from the focus on such issues arising out of the IDNDR and particularly the Beijing Symposium described in the next section. The major outcomes of IWTC-IV have been the continued development of the "*Global Guide to Tropical Cyclone Forecasting*", together with initiation of international efforts to directly address tropical cyclone landfall issues.

3.2 THE BEIJING SYMPOSIUM ON TROPICAL CYCLONES AS NATURAL DISASTERS

ICSU and WMO collaborated in convening a major symposium covering both the scientific and societal aspects of tropical cyclones in Beijing in 1992. This was part of the Joint ICSU/WMO Program on Tropical Cyclone Disasters, which recognized the vital role that the world scientific community could play in helping to alleviate the impacts of tropical cyclones. As with the IWTC series, this symposium provided an opportunity for the research, operational and impacts communities to meet.

The major outcomes of the meeting were a book, together with several recommendations on research and data collection. The book "*Tropical Cyclone Disasters*" (Lighthill *et al.*, 1993) contained 59 papers presented at the meeting. This provides a valuable snapshot of the state of the science at the time and covered almost all related fields, from observations, to understanding and predicting cyclone processes, and to methods of mitigating the cyclone impacts.

The meeting recognized the major uncertainties in both observations and knowledge of the processes operating in the surface spray layer of intense wind regimes. Of particular concern were the complex ocean-atmosphere feedback cycle and its impact on cyclone intensity and structure. This recognition has led to a substantial international effort addressing the cyclone-ocean interface.

The meeting also helped increase research interactions by recommending visits from scientists in small countries to major research institutes.

A major outcome of the meeting was the recognition of the need for improved data to enable better specification of the detailed structure of tropical cyclones and their near environment. In particular, a strong recommendation was made to pursue development of small autonomous aircraft, such as the Aerosonde, for use in tropical cyclone reconnaissance. The development of this aircraft has been one of the more innovative programs under the IDNDR.

3.3 TROPICAL CYCLONES AND CLIMATE CHANGE

The potential impacts of climate change on tropical cyclones have been the subject of considerable debate both within and outside the scientific community. The IPCC report on the effects of climate change noted the considerable uncertainty in our knowledge and concluded that:

> "It is not possible to say whether the frequency, area of occurrence, time of occurrence, mean intensity or maximum intensity of tropical cyclones will change" (Houghton *et al.*,1996, p. 334).

At the same time, Watson *et al.*, (1996) stated that:

> "Reinsurers have noted a fourfold increase in disasters since the 1960s. Much of the rise is due to socioeconomic factors, but many insurers feel that the frequency of extreme events also has increased." (p. 547)

and that:

> "Lack of information about extreme events…makes insurers wary of committing their capital." (p. 548)

In recognition of the importance of the issue and the fact that the understanding of tropical cyclone processes had moved rapidly in the period since the IPCC deliberations, the WMO/CAS Working Group on Tropical Meteorology Research and ICSU established a steering committee to report on the state of the science. This committee, consisting of eminent tropical cyclone experts and a representative of the Insurance Industry, under the leadership of Professor Henderson-Sellers, produced a report to CAS (Henderson-Sellers *et al.*, 1997*a*) and published an article in the Bulletin of the American Meteorological Society (Henderson-Sellers, 1997*b*). Their main conclusions were as follows:

> "Recent studies indicate the MPI of cyclones will remain the same or undergo a modest increase of up to 10-20%. These predicted changes are small compared with the observed natural variations and fall within the uncertainty range in current studies. Furthermore, the known omissions (ocean spray, momentum restriction and possibly also surface to 300 hPa lapse rate changes) could all operate to mitigate the predicted intensification."

> "Little … can be said about the potential changes of the distribution of intensities as opposed to maximum achievable intensity. Current knowledge and available techniques are too rudimentary for quantitative indications of potential changes in tropical cyclone frequency."

> "The broad geographic regions of cyclogenesis and therefore also the regions affected by tropical cyclones are not expected to change significantly. It is emphasized that the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy. The very modest available evidence points to an expectation of little or no change in global frequency. Regional and local frequencies could change substantially in either direction, because of the dependence of cyclone genesis and track on other phenomena (e.g. ENSO) that are not yet predictable. Greatly improved skills from coupled global ocean-atmosphere models are required before improved predictions are possible."

The research on tropical cyclones has continued to move rapidly since 1997 and further information is being provided to the new round of IPCC deliberations.

4. MAJOR IDNDR-RELATED RESEARCH INITIATIVES

4.1 TROPICAL CYCLONE MOTION

The commencement of the IDNDR occurred in conjunction with the establishment of a major international program aimed at improved track forecasting through a better understanding of the processes responsible for tropical cyclone motion. This program was carried out under the WMO/CAS Tropical Meteorology Research Program, with major funding support from the US Office of Naval Research.

The program started with specialist meetings that both defined the scope of the research effort that was required and the level of current understanding. Three main themes evolved:

- Basic research aimed at understanding the mechanisms of tropical cyclone motion;
- Conduct of a series of field experiments in the western North Pacific Region, to both test a set of hypotheses and to gather data to support the research effort; and,
- Transfer of the improved understanding to the forecast community and the development of forecast techniques.

The major early effort was directed towards international collaboration on a field program in the western North Pacific (Elsberry, 1990). This program, organized under the auspices of the WMO/CAS Tropical Meteorology Research Program and the ESCAP/WMO Typhoon Committee, consisted of four coordinated programs:

- Tropical Cyclone Motion 1990 (TCM-90), conducted by the USA and Australia;
- Special Experiment Concerning Typhoon Recurvature and Unusual Motion (SPECTRUM) conducted by the Typhoon Committee countries;
- TYPHOON 90, conducted by the former USSR; and,
- The Taiwan Area Typhoon Experiment (TATEX).

The result of these experiments was a data set of unprecedented value for examining the environmental influences on tropical cyclone motion, together with a surge of research investigations and collaborations. The data were available both in raw form and analyzed into gridded form using specially developed 4D assimilation processes. The grid analysis of one typhoon has been used as the basis for an intercomparison of regional models, conducted by the JMA under the WMO/CAS-ICSU Working Group on Numerical Model Experimentation.

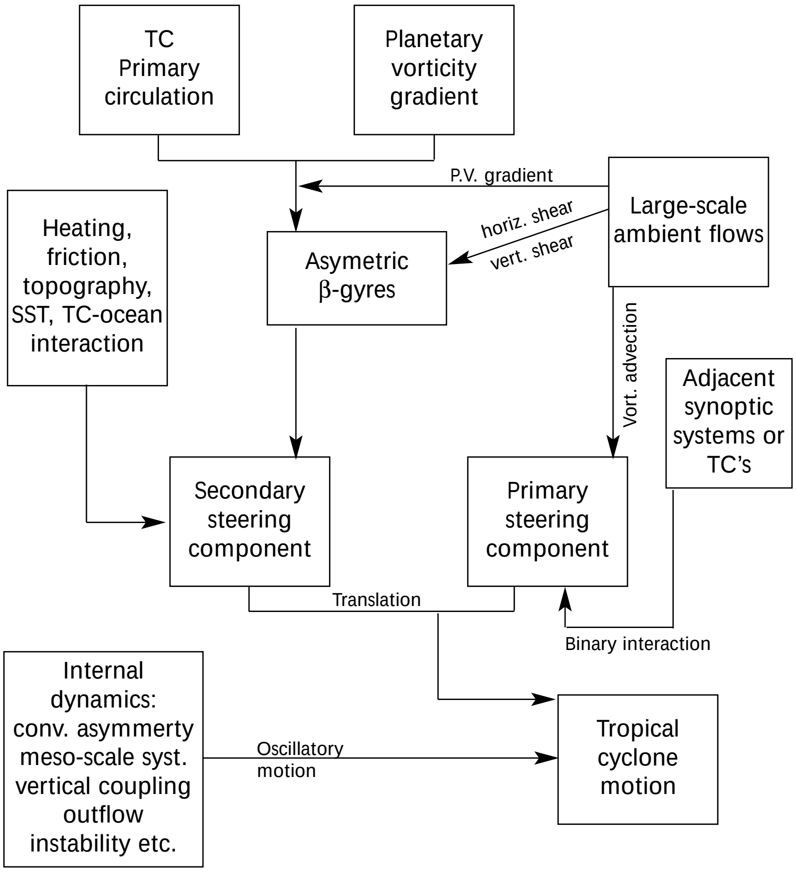
This research identified and examined a range of motion mechanisms, which have been reviewed in Wang *et al.* (1998).

The effects of the interactions between the cyclone and its environment were extensively investigated in this research phase. These interactions are essentially non-linear and cannot, in general, be clearly separated. However, a conceptual picture similar to that shown in Figure 2 has emerged. In this picture, cyclone motion consists of a stable translation, associated with the mean atmospheric flow, with a superimposed secondary translation and oscillations or transient motion arising from complex interactions between the cyclone and its environment.

The major process is the steering of the vortex by the environment in which it is embedded. This is a relatively straightforward process for a uniform environment, being simply the advection of the cyclone vorticity by the general flow. The dominant environmental interaction (though not necessarily the major one in individual storms) is the effect of a cyclone rotating across a gradient of earth rotation (the Beta effect). In essence, the cyclone generates a set of gyres that introduce an additional flow component across the cyclone centre, with a resulting deviation from the movement that would result from large-scale steering alone. A number of methods have been derived to attempt to separate out these two processes, but with only marginal success due, largely, to the highly non-linear nature of the process.

Environmental interactions take on a range of guises. If there is a horizontal shear of the wind, then the resulting vorticity gradients can act in a similar sense to the Beta effect. However, in this case, the cyclone also modifies the wind shear, leading to a complex, non-linear interaction that can evolve substantially in time. Vertical wind shear tends to tilt the cyclone initially in the direction of the shear. The tilted vortex then begins to act on itself, with the upper part advecting the lower part and vice versa. In some cases, a large distorted upper cyclone can develop, which affects the cyclone over a long period. In other cases, the cyclone goes through a series of small oscillations or loops.

Figure 2. An illustration of some of the processes that effect tropical cyclone motion (Adapted from Wang *et al*., 1998).



It is difficult to precisely define the mean environmental flow, as this is made up of a wide range of scales. At the very large scale are seasonal winds, such as the trade winds, monsoons and mid-latitude westerlies. Their effect on cyclone motion is evident in the manner in which cyclones typically track westward in low latitudes and recurve to move eastward in high latitudes. The presence of nearby weather systems produces large variations from this climatological track. Whether recurvature will occur is very dependant on development and breakdown of the subtropical ridge, together with transient anticyclone cells that can capture the cyclone in their large circulation for a period of time. Interactions with local weather systems, including monsoon gyres and other tropical cyclones have been observed to produce major track oscillations, and even demise of one system as it is subsumed by the other.

As a general rule, the convection occurring in the cyclone acts as an effective integrator, removing part of the vertical shearing effect. However, nearby convective systems, such as cloud bands or mesoscale convective systems, have been shown to induce oscillations in the cyclone path. The essential physical process is that the convection generates local vorticity anomalies and convergence fields, which change the flow over scales much larger than the actual convection. The convective system and the cyclone thus couple and move toward each other in a dance of intricate detail. The resulting track oscillations can vary in amplitude from almost unobservable to several hundreds of kilometres. Likewise, they can be seen as true oscillations extending over several cycles or a transient loop or deviation in the mean track.

Whilst many of the interactions are inherently complex, they often have well-defined life cycles. This information has been used to great effect by forecasters in understanding the tracks that are being analyzed and the potential consequences for future motion. Such knowledge has been encapsulated in a number of forecast procedures, the most comprehensive of which has been described by Carr and Elsberry (1997).

The research has also shown, quite clearly, the need for an accurate depiction of tropical cyclone structure in numerical models. Poorly-defined structure leads to highly inaccurate forecasts, due to the incorrect interactions that occur with the environment. Such knowledge has led to substantially improved specification of the cyclone and its immediate environment in numerical models. In some cases, this has been achieved by special observing methods. In other cases, various forms of bogussing have been used.

Evidence for the impact of such research lies in the improved forecast accuracy that has been achieved by both numerical models and official forecasts over the decade (Elsberry, 1999). The prospects are good for further major improvements in tropical cyclone track forecasting by numerical models. Particularly important to this improvement are the introduction of more sophisticated initialization methods, improved data collection in the vicinity of tropical cyclones and the use of ensemble forecasts and targeted observing strategies.

4.2 THE AEROSONDE ROBOTIC AIRCRAFT

The Aerosonde Robotic Aircraft was conceived as a means of providing an economical method for undertaking observations with considerable flexibility of operation (Holland *et al.*, 1992). A particular aim of the program has been meteorological observations in remote and otherwise inaccessible regions, such as tropical cyclones.

The international community recognition of the importance of the Aerosonde concept has been a crucial component in its development. The Aerosonde was strongly endorsed by the IDNDR/WMO Beijing Symposium on Tropical Cyclone Disasters (Lighthill *et al.*, 1993) and subsequently endorsed by the full IDNDR committee.

Following an initial prototyping period, largely sponsored by the US Office of Naval Research (ONR), a major development program was initiated in Australia in 1995. With sponsorship from an Australian Research and Development syndicate and support from ONR, Environmental Systems and Services Pty Ltd (ES&S) developed the current aircraft, between 1995 and 1998, in collaboration with the Australian Bureau of Meteorology and the US-based Insitu Group.

The development program was completed in 1998 when the Aerosonde passed a comprehensive trial conducted by the Bureau of Meteorology. In August 1998, The Insitu Group and the University of Washington further demonstrated the long-range feasibility of the Aerosonde by conducting the first transatlantic flight by a robotic aircraft. This is commemorated by the Aerosonde being placed on display in the Seattle Museum of Flight.

The aircraft resulting from the development program has undergone extensive improvement to increase reliability and robustness and to expand its operational capacity. The Mark 1 Aerosonde entered operations with Aerosonde Robotic Aircraft Pty Ltd in 1999 and the lessons learnt from these programs have been incorporated into the Mark 2 Aerosonde shown in Figure 3, which will be operational from October 1999.

Continued development is aimed at introducing further significant improvements over the next 3 years. The main thrust is to improve the operational

Figure 3. The Aerosonde Robotic Aircraft at launch from a car roof rack (K. McGuffie, personal communication 1998).

capacity of the aircraft, for example by development of the power plants, more flexible payload capacity, longer range and endurance, higher altitude operation, the addition of satellite communications and incorporation of a range of improved ground and airside operational systems.

A crucial component for tropical cyclone observations is the addition of a Low Earth Orbiting (LOE) satellite communications system. Delays in availability of the LOE satellite have frustrated attempts to undertake the first cyclone reconnaissance, as the range requirements are too far for the current UHF radio system. As a result, only one mission into the periphery of Severe Tropical Cyclone Tiffany (Western Australia) was accomplished in 1998. It is expected that this system will become available in late 1999, leading to the first full tropical cyclone missions soon after.

Aerosondes are particularly seen as providing an excellent support for targeted observations both within tropical cyclones and in the surrounding environment. They will be used to satisfy the requirements of numerical models and to both complement and extend other observing systems such as satellite remote sensing.

5. ANALYSIS AND FORECASTING OF TROPICAL CYCLONES DURING THE IDNDR

Please refer to Elsberry (1999) for a more detailed assessment of these trends described above.

The decade has been one of contrasts for observing tropical cyclones and related parameters. We have seen a sustained threat to essential observing systems, such as radiosondes, together with remarkable progress in others, such as satellites. The reality remains that, over much of the globe, crucial details of the core region of tropical cyclones are only obtainable by inference and assessment from external parameters. Only the USA retains direct observing capacity for cyclone core region dynamics and recent observations have shown that there is considerable variability and transient changes especially in the low-level wind fields.

The Dvorak satellite assessment technique for estimating tropical cyclone intensity is now the international standard. Indeed, much of the cyclone database has been derived largely from Dvorak analysis. Whilst this has introduced a welcome degree of consistency in tropical cyclone analysis, the lack of ground-truth validation in many regions is of major concern.

Substantial improvements in track forecasting have been achieved through the decade, largely due to a combination of improved observing systems, numerical model capacity and the understanding of relevant processes that has enabled improved forecaster assessment and proper targeting of forecast improvements. These are analyzed by Elsberry (1999). An indicative figure for the western North Pacific is provided in Figure 4.

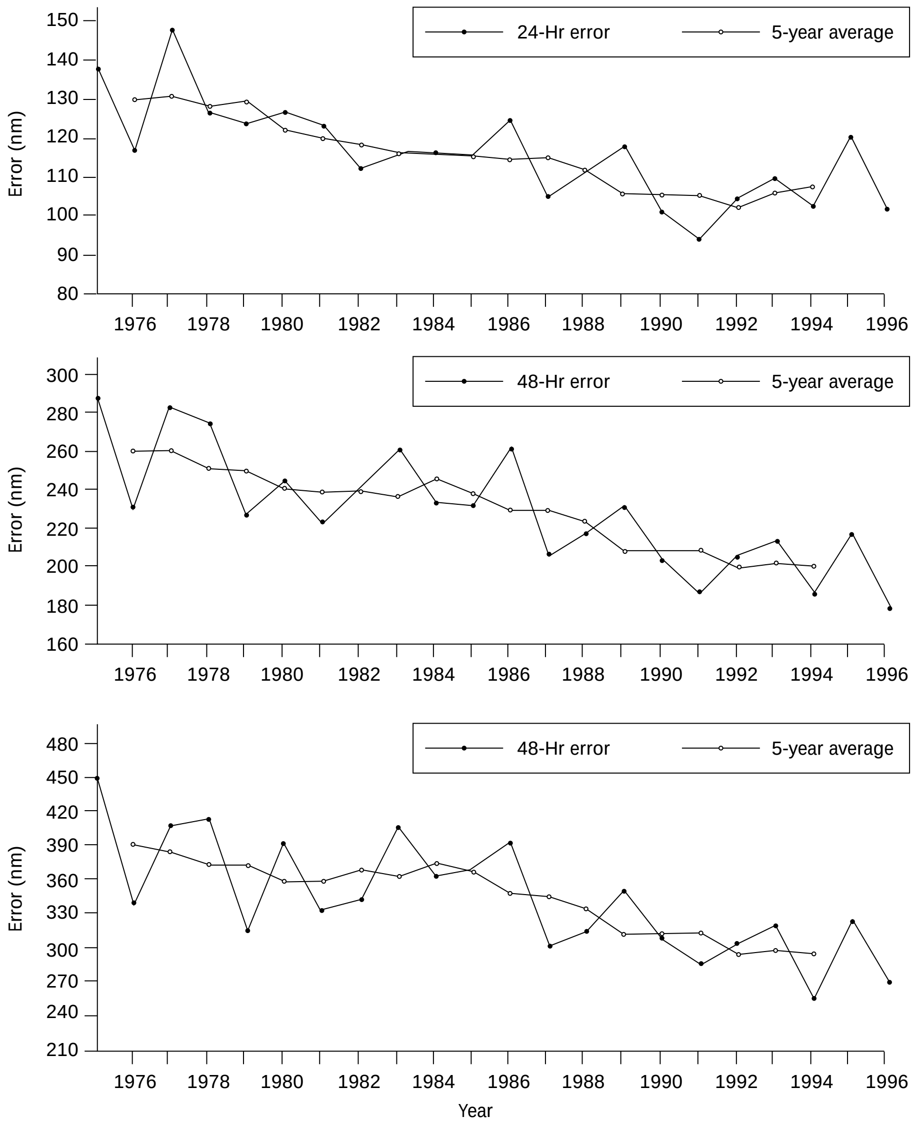
There has not been the same level of improvement in forecasting cyclone structure and intensity for which forecasts are barely better than simple climatology can provide. However, numerical models have shown considerable potential for forecasting tropical cyclone formation in recent years.

6. REDUCING SOCIETAL IMPACTS DUE TO TROPICAL CYCLONE LANDFALL

WMO members have organized five Regional Specialized Meteorological Centres (RSMC) in a number of strategic locations to promote local sharing of tropical cyclone analyses and forecasts (Figure 4). Each centre, which is hosted by a national weather service, monitors tropical disturbances and provides analyses and forecasts of tropical cyclones in their area of responsibility. The responsibility for issuing warnings resides with individual countries and the RSMCs provide analysis and forecast support for these activities, as required. Crucial to the successful analysis and prediction of tropical cyclones is the free distribution of satellite and other data to and from RSMCs and cyclone warning centres.

In addition to the forecast function, the real amelioration of cyclone impacts requires careful attention to the cultural, social and economic conditions of affected communities. Whilst there has been substantial work on such aspects in individual countries in the past, the IDNDR has seen the growth of a major international effort in this area. The IWTC-IV in 1998 contained a full session on reducing tropical cyclone impacts, and several local programs have been

Figure 4. Annual mean track forecast error (n mi) and 5-year running mean for (a) 24-Hr, (b) 48-Hr, and (c) 72-Hr made by the Joint Typhoon Warning Center, Guam for western North Pacific tropical cyclones between 1976-1996 (Elsberry, 1999).



combined into a major program aimed at reducing the impacts of landfalling cyclones under both the WMO World Weather Research Program and the WMO Tropical Meteorology Research Program.

6.1 THE AUSTRALIAN TROPICAL CYCLONE COASTAL IMPACTS PROJECT (TCCIP)

The TCCIP was initiated in 1993 as a collaboration between researchers, forecasters, emergency services personnel and local community groups. The collaboration was based on three interdependent objectives:

1. Quantification of the impact of tropical cyclones on Australian coastal communities under current climatic conditions, including:
   - Development of techniques applicable to impact studies;
   - Assessment of the level of risk and its variability, with emphasis on vulnerability of communities to high winds, flood rains, ocean waves and storm surges;
   - Assessment of changing levels of risk associated with demographic growth.
2. Scientific assessment of the potential trends in tropical cyclone impact on Australian coastal communities arising from anthropogenic climate change (the Greenhouse Effect), including:
   - Critical review of current tropical cyclone models and methods applied to climate change;
   - Critical review of available climate models and their applicability to tropical cyclones;
     - Estimation of potential climate change trends in tropical cyclones, together with the reliability of this estimate.

3. Development of improved methods to counter disasters, including social and economic adaptation through infrastructure planning and education, which are based on the findings from 1 and 2.

Starting in Queensland and then joining with the AGSO cities program as part of a major assessment of threat by severe weather and geological activity to major population centres in Australia, the program has been a major success. TCCIP experience was also applied to the establishment of the USWRP Hurricanes at Landfall Program and the WWRP Landfalling Tropical Cyclones Program.

A feature of TCCIP was a series of interdisciplinary workshops that brought together participants in a medium designed to provide good exchange of views and requirements. The major progress within the program occurred in damage, impact and vulnerability assessment, particularly in the development of appropriate techniques and databases; research into the changes that occur when a tropical cyclone makes landfall; and potential changes due to enhanced greenhouse conditions, together with the relationship between long-term and short-term variability of cyclone activity.

A technique for assessing the potential for storm surge to occur during tropical cyclone landfall was developed and successfully tested at locations along the Australian East Coast. This technique, known as the Maximum Envelope of Waters (MEOW), utilized a state of the science numerical storm surge model and parametric wind field model to build up a database of potential surges occurring across the known range of cyclone activity. This database can then be accessed to provide rapid information on the potential threat to communities during impending cyclone landfall, whilst accounting for the degree of uncertainty in the landfall forecast. The technique is now established in the Bureau of Meteorology, and can be applied to any required site, by means of a menu approach.

Assessments of vulnerability have been made by comprehensive survey of all housing in the Townsville region and by community surveys in Cairns, undertaken by James Cook University. The vulnerability surveys have been extended to community education programs, including a Cyclone Game on CD-ROM for schools.

The TCCIP participants identified storm characteristics at landfall and the nature of the interaction of storms with topography as a priority area. Of particular concern were the structure of the storm wind field and the nature of transient wind structure changes within the cyclone as it comes ashore. Boundary layer study programs are now fully in place, including instrumented towers at North West Cape in Western Australia and modelling studies of the cyclone boundary layer. An international workshop was organized, for the insurance and reinsurance industry, on the dynamics of landfalling wind fields with emphasis on appropriate parametric models.

Potential changes to tropical cyclones associated with enhanced greenhouse conditions have been addressed. The research focussed on the development of a technique to enable assessment of cyclone intensity and genesis changes from environmental information that is readily available from both direct atmospheric soundings and climate models (Holland, 1997). This technique provided a direct benefit to several community groups and insurance companies by defining the worst-case scenario for tropical cyclones in defined regions. It was used as the basis for the CAS statement on climate change described in Section 3.3.

6.2 THE US WEATHER RESEARCH PROGRAM - HURRICANES AT LANDFALL PROGRAM (HAL)

The USWRP has initiated a program aimed at improving hurricane landfall predictions. The goal is to improve forecasts of actual landfall (intensity and location) and the onset of strong winds and to lengthen the time available for evacuation. Coupled with this will be action on both estimating and directly measuring the degree of wind damage, storm surge and related wave activity, and the location, timing and magnitude of heavy rainfall and tornadoes.

A major goal is to determine the full cost of hurricanes to society and how to communicate warnings to produce a maximum community response and related reduction in hurricane impacts. Its specific goals are to:

- Double the lead time for hurricane watches to two days and increase warning lead time for gale-force winds;
- Reduce the length of coastline warned from nearly 400 miles to as little as 200 miles;
- Provide more exact estimates of hurricane intensity, cutting errors by half, and;

- Improve forecasts of inland flooding by 50%.

Following an extensive program of discussion and development of priorities and needs, USWRP's HAL program identified the following priority research topics:

- Pre-landfall track: Crucial for the provision of maximum lead time and accuracy of landfall.
- Pre-landfall wind structure: Important for the warning requirements of onset of gale-force and higher winds, together with the intensity at landfall.
- Landfall wind structure: Provides input to storm surge and damage models.
- Landfall precipitation: Local flash flooding and especially combination with storm surge.
- Socioeconomic impact: Especially defining the benefits and costs of the analysis and warning system, and providing improved warning content.

Further information is available at <http://uswrp.mmm.ucar.edu/uswrp.html>.

6.3 THE WORLD WEATHER RESEARCH PROGRAM - TROPICAL CYCLONE LANDFALL INITIATIVE

There is considerable overlap between the objectives of USWRP's HAL and TCCIPs, and also with those determined from discussions at the IWTC-IV. This common theme across many warning systems and cultural requirements means that there is a large element of transferability of techniques and research findings. The major advantage that the USWRP has is access to a remarkable array of observation systems and a highly developed research infrastructure. The goals of the WWRP Tropical Cyclone Landfall program are to take advantage of this research and coordinate national activities by developing a set of forecast demonstration projects aimed at illustrating the potential improvements in landfall warnings in other regions.

The WWRP was established by the WMO Commission for Atmospheric Sciences in 1998, following extensive deliberation and discussion on both the need for, and the roles of, such a program. The mission and objectives are:

WWRP Mission

To develop improved and cost-effective forecasting techniques, with emphasis on high-impact weather, and to promote their application among Member States.

WWRP Objectives

- To improve public safety and economic productivity by accelerating research on the prediction of high-impact weather;
- To facilitate the integration of weather prediction research advances achieved via relevant national and international programmes;
- To demonstrate improvements in the prediction of weather, with emphasis on high impact-events, through the exploitation of advances in scientific understanding, observational network design, data assimilation and modelling techniques, and information systems;
- To encourage the utilization of relevant advances in weather prediction systems for the benefit of all WMO Programmes and all Members;
- To improve understanding of atmospheric processes of importance to weather forecasting, through the organization of focussed research programmes.

WWRP Strategies

- Identify the types of weather events where multinational research collaboration is likely to lead to improved prediction and associated benefits to participants;
- Develop and apply methods for assessing the cost-benefits of improved forecasts of high-impact weather events, in conjunction with other WMO Programmes;
- Promote, organize and/or endorse research programmes including, where necessary, field experiments to develop understanding of weather processes and improve forecasting techniques;
- Organize and lead projects, in conjunction with other WMO Programmes, to demonstrate and objectively verify improvements in weather forecasting accuracy;
- Sponsor technical workshops and conferences to further understanding of the science and technology involved in improved weather prediction;
- Organize training programmes to ensure that all Members can benefit from WWRP advances.

A key component of the WWRP activities will be to sponsor forecast demonstration projects, which can both illustrate the application of research findings to operations and provide an objective verification of new forecast methodologies.

Further information can be obtained from:
<http://uswrp.mmm.ucar.edu/uswrp/wwrp/reports/Bulletin_WWRP.html>.

The WMO/CAS WWRP and TMRP have proposed an international Tropical Cyclone Landfall initiative with the goal of improving specification of the rainfall and wind field occurring both at the coast and inland as a cyclone makes landfall. This will implicitly require improved track forecasts and will lead to improvements in secondary parameters, such as storm surge estimation. This will require a program of research and development into cyclone intensity and structure changes that accompany landfall, including the potential for rapid intensification. Since the actual impact is crucially dependent on the landfall location, a continued program of research and development into track is required, but with an emphasis on track processes near landfall.

This program will have several components but will develop from existing programs on tropical cyclone research, including the long-standing international initiative on tropical cyclone track forecasting coordinated by the US Office of Naval Research, the USWRP Hurricanes at Landfall Program and the Australian Tropical Cyclone Coastal Impacts Project. The aim of the project is to:

- Develop an international research program aimed at improved understanding of the associated processes;
- Conduct associated field programs, especially in association with USWRP's HAL program and the ONR Tropical Cyclone Motion Initiative, both as a basis for the research and to provide indications of the likely data requirements for forecasting;
- Specify two or three Forecast Demonstration Projects, covering a range of forecast capacities, to assess the potential improvements in forecasting resulting from application of the research and development findings and the improved observing systems.

This program is expected to be one of the major initiatives to be taken from the IDNDR into the twenty-first century.

7. THE NEXT DECADE

It is always dangerous to peer into a crystal ball and even more dangerous to put in print what is seen there ! However, the IDNDR decade of the 1990s has seen steady and sustained improvements in the manner in which we forecast, prepare for and mitigate the impact of tropical cyclones. As we move into the next decade, a number of trends that will potentially lead to remarkable improvements are apparent in many aspects of cyclone mitigation.

The first trend is the major research and socioeconomic emphasis that is being placed on tropical cyclones. This has occurred through national programs, such as the Australian Tropical Cyclone Impacts Project and the US Weather Research Program. Interactions between these programs and the newly-established World Weather Research Program will strongly focus research and impacts studies on landfalling tropical cyclones and will support transition of the findings to operations through Forecast Demonstration Projects.

The second trend is the enormous increases in computer power and the associated improvements in the capacity of numerical models to forecast many components of the tropical cyclone more accurately and to undertake ensemble forecasts aimed at defining the overall uncertainty in individual forecasts. Associated with this is the potential for improved weather system observations, by use of satellite and other remote sensing and by direct reconnaissance using robotic systems, such as the Aerosonde. Provided that we can hold against the considerable economic pressures being exerted on the current observation system, we shall move into a new era — one in which we will have an unprecedented opportunity to properly combine observations and modelling in an optimal mix that can target the regions and observations crucial to the forecast process.

The last, but by no means the least, important trend lies in the combined approach to all aspects of the cyclone mitigation problem. Attention to public education and community preparedness and a full understanding of the true economic and social benefits of the cyclone warning system will produce reductions in cyclone impacts far beyond what could be achieved by forecast improvements alone.

It is likely that improvements in the combined modelling and observation system will lead to quite accurate forecasts of cyclone genesis. This is a subtle process, but one that often seems to be associated with a well-defined, large-scale signature (e.g. Holland, 1995). Current model forecasts are already showing considerable skill in this regard. Cyclone track also has substantial potential improvement before the predictability limit is reached. A combination of carefully defined observations and numerical models, supported by statistical combinations of various models or ensembles, can potentially halve current forecast errors, especially over long-time periods.

Current research trends will lead to much better understanding of the transient, and potentially dangerous, processes occurring in the boundary layer of tropical cyclones, especially those that are making landfall. Making use of this knowledge will present a major challenge to warning and communications systems and to the way in which society reacts to the warnings.

Perhaps the major continuing difficulty will lie in both fully understanding and predicting cyclone intensity change. Substantial research into the related mechanisms remains a major requirement. It may well be that, for the next decade, intensity forecasts will continue to be best undertaken by statistical techniques and prudently conservative forecast strategies.

REFERENCES

Carr, L. and R.L. Elsberry, 1997: Systematic and integrated approach to tropical cyclone track forecasting. Part I: Overview and environmental structure characteristics. *Weather Forecasting*.

Elsberry, R. L., 1990: International experiments to study tropical cyclones in the western North Pacific. *Bull. Amer. Meteor. Soc.*, 71, pp. 1305-1316.

Elsberry, R. L., 1995: *Tropical cyclone motion*. Chap. 4, Global Perspectives on Tropical Cyclones, (R. L. Elsberry, Ed.), WMO/TD-No. 693, WMO, Geneva, Switzerland, pp. 106-197.

Elsberry, R.L., 1999: *Track forecast guidance improvements for early warnings of tropical cyclones*. Potsdam INDNDR Symposium (in press).

Elsberry, R.L. (Ed) 1987: *A global view of tropical cyclones*. Marine Meteorology Program, Office of Naval Research, 185pp.

Elsberry, R. L., and R. F. Abbey, Jr., 1991: *Recent advances in the understanding of tropical cyclone motion*. Tech. Rep. NPS-MR-91-003, Naval Postgraduate School, Monterey, CA 93943, 92 pp.

Henderson-Sellers A., G. Berz, R. Elsberry, K. Emanuel, W.M. Gray, C. Landsea, G. Holland, J. Lighthill, S-L. Shieh, P. Webster and H. Zhang, 1997a: *Tropical cyclones and global climate change*: Report from the WMO/CAS/TMRP Committee on Climate Change Assessment (Project TC-2)

Henderson-Sellers A., G. Berz, K. Emanuel, W.M. Gray, C. Landsea, G. Holland, J. Lighthill, S-L. Shieh and H. Zhang, 1997b: Tropical Cyclones and Global Climate Change. *Bull. Amer. Meteor. Soc.*, 79, 9-38.

Holland, G.J., T. McGeer and H. Youngren, 1992: Autonomous Aerosondes for economical atmospheric soundings anywhere on the globe. *Bull. Amer. Met. Soc.*, 73, 1987-1998.

Holland, G.J., 1995: Scale interaction in the western Pacific monsoon. *Met. Atmos. Phys.*, 56, 57-79.

Holland, G.J., 1997: The maximum potential intensity of tropical cyclones. *Journal of Atmospheric Sciences*, 54, pp. 2519-2541.

Holland, G.J., ed, 1993: *The global guide to tropical cyclone forecasting*, WMO/TD-560. World Meteorological Organization, Geneva, 342 pp.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, 1996: *Climate change 1995: The science of climate change*, Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change, Cambridge University Press, 572pp.

Lighthill, J., Zheng, Z., G.J. Holland, and K. Emanuel, ed., 1993: *Tropical cyclone disasters*. Peking University Press, Beijing, 588pp.

Lighthill, J., G.J. Holland, W.M. Gray, C. Landsea, G. Craig, J. Evans, Y. Kurihara and C.P. Guard, 1994: Global climate change and tropical cyclones. *Bulletin of the American Meteorological Society*, pp. 2147-2157.

Wang, B., R. Elsberry, Y. Wang, and L. Wu, 1998: Dynamics in tropical cyclone motion: A review. *Chinese Journal of Atmospheric Sciences*, 22, pp. 535-547.

Watson, R.T., M.C. Zinyoweya, and R.H. Moss (eds.), 1996: *Climate change 1995: Impacts, adaptations and mitigation of climate change: scientific-technical analyses*. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 879pp.

REVIEW OF SCIENCE, TECHNOLOGY AND POLICY FOR RIVER AND COASTAL FLOODING

By Tauhidul Anwar Khan and Stephen Brichieri-Colombi

ABSTRACT

This paper looks at the causes and impacts of two natural disasters, river and coastal flooding, through reviews of papers written by people living worldwide and from our own experience of living and working in Bangladesh. We offer no apology for referring frequently to Bangladesh as, more than any other country in the world, it has learned to endure the consequences of these twin events which occur with dreadful regularity. The less well-known fact is that Bangladesh also suffers from water shortage and droughts in its seven month dry season.

The paper considers the concepts of vulnerability and hazard, and the changes in our perceptions of them in the light of global climate change. Experiences with physical protection measures, assessing risks and improving warning capacities in the major flood events of recent years are discussed, and strategies for basin wide water resource policies reviewed.

The paper concludes by pointing out the benefits which have accrued in richer countries from investments made long ago over many decades in flood control infrastructure, and the advantages of investment in prevention rather than cure for the people still at risk, many of them living in the poorer countries of the world.

1. FLOODING AS A NATURAL HAZARD

Flooding from rivers is a natural phenomenon that can occur in great and small rivers, and in wet and dry climates and affects great numbers of people around the world. Four main types of flooding are recognized these ones:

- Local drainage congestion: This occurs when run-off from local intense rainfall exceeds the capacity of natural or artificial drainage canals, causing them to back up or overflow. The rainfall can be due to an intense storm, cyclone or hurricane.
- Flash flooding: Flooding which occurs in smaller rivers in response to rainfall on an upstream catchment, with a very sudden rise in water level. Frequent in plains areas close to hilly areas, or in desert wadis.
- Major river floods: Flooding as a result of prolonged rainfall in the river catchment, causing a large but relatively slow-moving wave to descend the river, overtopping its banks as it moves downstream
- Surge-induced flooding: Sudden and violent flooding when strong winds cause the sea-level to rise locally due to low pressure and shear forces on the surface, and drive it into a confined area where a steep fronted wave develops, often moving as a tidal bore many kilometres up estuaries.

The first three types of flooding can occur anywhere where there is rainfall or a major river. Surge, the other topic of this paper, is much more localized, affecting only those who live in coastal areas, where the rather specialized conditions behind this phenomenon are created and in the lower reaches of rivers draining to these coasts. However, as a natural disaster, surge is the killer. River floods can cause huge economic losses, but do not kill people on the scale of the 300 000 people who died in 1970 on the shores of Bangladesh. In the decade up to 1996, 245 000 people died from floods throughout the world, but 140 000 of these deaths occurred in a single surge event, again in Bangladesh, in 1991.

The impact of flooding tends to be described in numbers of events, in flood damage and in numbers of deaths. The following table clearly shows that in Asia, we do pay not in dollars, but with our lives. A better measure might be damage expressed as a proportion of GNP but even this does not reflect the real impact. When a family is warned to evacuate in the face of an impending flood in a rich country, it drives off in the car and files an insurance claim for US $3 000 for carpets and repainting. A family in a poor country clings to a tree as the family pair of bullocks are drowned and the few possessions worth US $300 are washed away, and retreats to the nearest urban slum, never to return. What value is placed on a livelihood lost ?

Continent	Number of floods	Damage in million US $	Deaths	Damage ($M) per flood	No of deaths
per flood					
Africa	124	1 576	6 200	13	50
Americas	270	24 656	7 249	91	27
Asia	432	135 509	227 612	314	527
Europe	100	88 568	3 878	886	39
Oceania	56	349	416	6	7

Source: Miller, 1997

As we distinguish surges from tides, so we distinguish flooding from seasonal inundation. The regular pattern of astronomical tides lead to a rhythm of life for coastal people to which they are well adjusted and the terms high or spring tide hold no fears for them. Contrast this with the terror they experience as winds of over 200 km/hr accompany the gradual build-up of the sea's energy, which suddenly releases itself in the fury of a tidal bore, 7 m high, sweeping over the flat coastal wetlands and destroying life and property in a few hours. Similarly, the seasonal rise and fall of even the largest rivers can be watched with equanimity by people who have built their houses on platforms or protected areas, laid in stocks of food and planted crops which are adapted to the event. It is only when the rivers rise to an exceptionally high level, or exceptionally quickly, that the life-giving flow become a destructive force. Our people have two words, *bonnya* and *plabon*, for these two events.

Tales of floods and the fury of the sea are deeply embedded in the history of many regions of the world and we must accept that the hazards of floods and surges have been with us as natural phenomena since the dawn of civilisation. However, the development process gives us the potential to minimize their damaging consequences, either by reducing the hazard itself or our vulnerability to its effects. There are, however, many feedback paths, so development itself often increases the hazard and those who reduce their vulnerability by protecting themselves may, in the process, increase the vulnerability of others. As with so many other activities, the richer have the opportunities and choices, while the poorer have to make do with that they can afford. In a world that claims to recognize the rights of all to basic freedoms, we much seek win-win solutions, both within and among nations.

2. VULNERABILITY

In general, riverbanks and shorelines are good places to live and civilisations have tended to grow and develop in their proximity. Even now, relatively few major towns develop far from either (Johannesburg may be the biggest exception). Flood plains are fertile areas and good crops can be grown there. Crops damaged by flood tend to be followed by bumper yields the next season and low-input agriculture is clearly a good use of flood plains. However, as investment in seeds and crops increases, vulnerability to flood hazard increases.

Urban areas also develop near rivers and coasts, often for historical reasons related to transport. This trend continues as people with the available means enjoy living near water. Whereas the original site may be in a naturally well protected area, expansion leads to urbanization of more exposed areas, and increases the population at risk. High value commercial and industrial developments increase the vulnerability of the settlement.

The general trend in societies with increasing populations or increasing standards of living is increasing vulnerability of life and property to the hazards of flood or surge.

3. HAZARD

Primary flood-inducing events are well-known and are addressed under the topics of tropical cyclones and severe local storms. Translating these events into estimates is the domain of hydrology and hydraulics, using the tools that have been developed in the last 100 years, based on the original hydrodynamic equations of St Vennant. Using either the characteristics of the catchment, or more recently the capability for pixel analysis provided though the data management capability of Geographic Information

Systems (GIS) combined with kinematic wave theory, estimates can be made of the effects of the passage of a flood of a event of given probability.

These analysis have to be kept continuously up-to-date as land use and floo plain configurations change and the channels change both in plan geometry and in cross-section, due to the continuous processes of erosion, accretion and sedimentation. Suites of programmes, now widely available both in the public domain and in more sophisticated form within specialist institutes, allow modellers to calibrate the models to observed conditions at the boundaries and gauging stations, and then extrapolate with new boundaries or river configurations. The transport of sediments, pollutants and salinity can be modelled by post-processing of the output files, thereby facilitating the study of the impacts of changes in conditions due, for example, to climate change.

4. TRENDS AND CLIMATE CHANGE

Despite the worldwide concern over global climatic change, there is little evidence of a change in the frequency and severity of primary flood-inducing events such as rainfall and cyclones. However, general circulation models do predict that there will be changes in patterns such as monsoon intensity and duration, as well as increased frequency of days with heavy precipitation (Huq *et al*., 1999). Such predictions tend to be revised fairly frequently as more parameters are introduced, such as the effect of sulphate aerosols, and it is necessary to view them as potential scenarios rather than forecasts. Under these scenarios, we can expect both flash floods and seasonal floods to increase, but not necessarily in a uniform fashion. Scenarios for northern India, for example, indicate more intense annual floods but little change in lower frequency flooding (e.g. 1:20 years flood), for which much non-critical flood protection infrastructure is designed.

What effect this will have on flood design infrastructure depends on how rigidly economic principles are followed. Engineers design embankments to minimize the sum of capital cost, operation and maintenance costs and expected annual damage, all capitalized at a certain discount rate which is intended to reflect the opportunity cost of investment capital. In developed countries with low interest rates in the 2-3 per cent range, the long-term benefits of protecting against future conditions will figure significantly in the equation. In poorer countries, development agencies typically require public infrastructure investment to show a return of 12 per cent, and potential benefits accruing gradually over 25 years and beyond are heavily discounted. Unless the poorer countries depart from currently accepted advice and abandon these high discount rates for investment in flood alleviation infrastructure, they will be left with only the “poor man’s solution” of flood-proofing. This is particularly ironic given that the causes of climate change arise within the richer developed world.

Although there is little evidence that the incidence of cyclones that give rise to surges will increase, many cyclones die before reaching landfall. One effect of a rise in sea surface temperatures will be that a proportion of those that die under present conditions will retain enough energy to reach land, and one recent estimate was that the incidence of surge-inducing cyclones could increase by 30 per cent (Ali, 1999) as a result. Areas affected by storm surges include India, Bangladesh and Myanmar around the Bay of Bengal; Germany, Netherlands and England around the North Sea; and China.

Sea-level rise will increase flooding in estuarial areas of rivers and could have effects further inland due to a regrading of river beds. The effect of a sea-level rise of 0.5 m in the Bay of Bengal would be to raise the bed of the Brahmaputra by 15 cm for a distance of at least 200 km from the coast (Halcrow, 1995).

Countries with extensive areas of land close to sea-level have tended to build coastal polders to protect farmland and this complicates the assessment of the impacts of sea-level rise on flooding and waterlogging. These polders are drained by tidal sluices and pumps such as the famous Dutch windmills. Where drainage is by pumps, sea-level rise will increase drainage pumping costs, but only gradually and not by very much. Where drainage is by tidal sluices, the sluices will gradually go out of operation as the tide-locked period increases, requiring more or larger sluices. Re-investment is unlikely as the economics of farming have changed since many of polders were built. Governments around the North Sea are rethinking policies in view of high maintenance costs and, indeed, the last polder of the Zuyder Zee in the Netherlands was never drained. In areas around Chesapeake Bay, polders are already being demolished as environmental costs are weighed against the limited benefits they now bring (Stevenson, 1999).

In Bangladesh, most of the area less than 1m above sea-level is already empoldered, but very few polders have pumped drainage as very large capacities would be required to drain monsoon rainfall. The result has been extensive water-logging, a situation which will be aggravated but not necessarily extended. The response has been a change from rice farming to shrimp cultivation in many areas, a change that has brought about economic gains to a minority and losses to a majority, leading to severe social impacts.

Sea-level rise will, for many decades, be small in relation to surge and wave run-up, so the direct effect on the design height of embankments and structures such as the tidal barriers on the Thames will be small. However, there are situations where indirect effects are significant. Wave run-up is affected by the depth of water on the foreshore and greater depths mean that waves reach embankments without having dissipated energy in the approach, thus releasing more energy against the structure. In other situations, the dominant direction of the incoming waves may change due to changes in diffraction caused by the change in wave velocity associated with increased water depth and a corresponding change in the direction of waves reflected by marine structures. Studies using numerical and physical models will be needed to assess these effects in individual cases and may well lead to design modifications other than raising structure heights.

5. PROTECTIVE MEASURES

The two major structural measures used to control floods are reservoirs and dykes. Reservoirs (and detention ponds) formed behind dams and embankments hold water back at the peak of the flood for later controlled release. Dykes confine floodwaters into the river and parts of its flood plain reserved for that purpose.

A 1:100 year flood may be typically 2 to 6 times the magnitude of the mean annual flood (MAF), a 1:1000 year flood 3-15 times MAF. To be effective, flood control dams have to be large, and and are in consequence, expensive. To cover the cost, they are frequently designed for multi-purpose use, for irrigation and hydropower, and often during project life the structure is operated to raise revenue. As one South African writer observed:

> "Due to the trauma of water managers in seeing crucially important dams reaching levels of less than 20 per cent during drought situations, their inclination is to operate dams as full as possible" (Sweigers, 1997).

For efficient hydropower, reservoir levels are kept high and flood control benefits accrue only at the start of the wet season. Larger reservoirs can be very effective in controlling flash floods, which tend to have a small volume but a high peak that can be attenuated with little rise in reservoir level. Very large reservoirs can regulate for hydropower and flood control simultaneously by smoothing seasonal flows over several years and have the added advantage that they take centuries rather than decades to silt up, even in areas of high sedimentation such as the Himalayas.

The High Aswan Dam in Egypt provided a good example of flood control in 1988. After eight dry years, the reservoir level was close to minimum operating level when the Blue Nile flooded. Although the flood caused major problems when it swept through the suburbs of Khartoum, on arrival at Aswan a few days later it merely replenished vital storage instead of sweeping through the streets of Cairo as in former times. Nevertheless, the reservoir is operated entirely for irrigation benefits, even hydropower being generated as a secondary benefit.

Embanking has been practiced on river like the Po and the Yangtze for centuries, and the tradition has been continued on rivers like the Mississippi in conjunction with flood storage reservoirs.

The 70 800 km^2 basin of the Po lies largely in Italy, but also drains parts of France and Switzerland. Over 1 000 km of levees have been constructed over the last 500 years but, despite continuous improvement, they still do not provide complete protection from floods. Failures of flood control dykes and levees may occur through mechanisms such as:

- simple overtopping, when the cumulative level of the flood and wave run-up cause water to spill over the crest;
- erosion, when the velocity of water at the toe of the embankment removes material from the embankment or the bank on which it is founded;
- seepage, when water seeping from the river through the embankment emerges above ground level on the landward side, causing the back face to start collapsing, and;
- piping, when water flows through or under the embankment in pipes of weak sandy materials, animal burrows or holes left by old tree roots.

All are still common, the last two being particularly dangerous because of their relatively sudden development. Piping can cause failure within 45 minutes of fine sediment appearing at the toe of the embankment (Govi et al, 1996). In 1994, almost all the 86 km valley floor of the Tanaro tributary was flooded, and pulse flooding occurred in downstream reaches when logjams of trees and debris against bridges suddenly collapsed.

The “Great Flood” of 1993 on the Mississippi also led to the collapse of a large proportion of the levees constructed since the eighteenth century to contain floodwater failed, flooding some 6 Mha of farmland and 50 000 homes in hundreds of towns (Ingram, 1996), some of which may never be rebuilt. The levees nevertheless prevented damages of US $11.6 billion, against total losses estimated at US $ 15-20 billion (Miller, 1997).

In China, the Yangtze River has been bounded by levees for centuries but progressive siltation has caused the bed to rise 5 m above the surrounding plain. When these levees burst, as they did in 1996, they caused the worst flooding for decades, with 10 Mha of farmland flooded, 5 million homeless and losses of some US $20 billion.

The evidence suggests that structural protection can confer only partial safety for people inhabiting the flood plain and must be combined with other measures for flood management to be effective. When protection fails, damages can be increased because of the increased investment made by those living behind the embankments. Current opinion in Bangladesh is that that full flood control is neither practicable nor, indeed, desirable for rural areas on environmental grounds. However, the benefits of urban protection were obvious to many city dwellers in Dhaka when, in 1998, river flood levels rose to the same levels experienced a decade earlier, but large parts of the city were protected by embankments built since that time.

6. RISK ASSESSMENT

The components that the engineer has to consider when designing for flood risk include the water level with a given probability of occurrence, afflux due to changes in physical surroundings, wave run-up, and settlement of the construction and its foundations. Other events may also occur, such as tsunamis, low-frequency oscillations in large lakes or inland seas and collapse of ice or mud dams. Some are interdependent, others not, but in the assessment of risk all may need to be considered.

Methods for the statistical analysis of river floods were introduced into hydrology in the 1920s (Kite, 1963) and the distribution functions developed over the next 30 years are still used today, with variations in fitting methods. Other techniques, such as the unit hydrograph and non-linear catchment routing methods have also been developed to estimate floods. Combined with estimates of extreme rainfall, these techniques can be used to estimate “maximum” events. These are used in the design of critical structures intended to “never” fail (probability of events 1:100 000 years or greater). There are fundamental philosophical objections to the concept of a maximum event and economic design principles require costs to be justified through risk assessment.

The estimation of the risk of surge events is more complicated as there are several factors to be taken into account, such as atmospheric pressure, wind speed and direction and time of landfall in relation to the astronomic tide.

Independently maximising each of these may lead to over investing in structures, which may need to be long and contiguous to be effective. The 1800 km long coast of China is exposed to tropical cyclones in the south and extratropical cyclone in the north and different fitting parameters are required for fitting statistical models in each zone.

Computer-based deterministic models are also needed, especially for the prediction of specific events in real-time. Methods used in China are reviewed in a 1994 WMO paper (Guo Dayuan *et al.*, 1994), which points out the need for models to be tailored to the data and financial resources available. Complex models can certainly provide improved accuracy, but only if funds are available for installation, and operation and maintenance of the sensing equipment.

As noted earlier, computer models are also used to model hydraulic processes but, in many cases, physical models are required to confirm findings. Few major flood control structures are built these days without physical models to examine some aspect of their behaviour, whether it be the influence on currents, scour or wave regime. Both fixed and mobile bed models are used, often requiring large amounts of space in speciality laboratories in many parts of the world.

Hybrid models, which combine features of both physical models and computer simulations, are also being used to assess the interactions of complex events. The Hybrid Simulation Model (Barthel, 1991) developed at the Hydraulic Laboratory in Ottawa is one such example. Such models are particularly important in view of the work done in Australia (Neilson *et al.*, 1991) on wave set-up, which show large differences between the results of theoretical models and actual measurements.

7. WARNING CAPACITIES

For many people and many situations in throughout the world, the cost of controlling floods is simply too high to be affordable, or the side effects of the works required too damaging to the environment. The options are then to avoid habitation and development of flood prone areas or to devise means to warn people of impending floods.

The evidence worldwide is that people will not abandon flood prone areas, whether they are in the flood plains of the Mississippi, the mountains of Honduras, or the tidal mud flats of the Bay of Bengal. Consequently, the task of the water resources planner is to find ways to make life liveable in the flood plains, even if there is considerable risk to life and property. The greatest contribution the Government can make is to enable people to save their lives by warning them of impending floods, and facilitating their evacuation to temporary safe havens.

There are several components of this activity. Forecasters must be able to make reasonably accurate forecasts with an appropriate lead time; the information must be relayed in a reliable manner to the people likely to be affected; and the people must have a clear idea of what they should do to protect themselves when warned.

Flood plain maps, which show the area at risk of flooding with a given probability, provide the most advance warning. Typical maps in use in Canada and the USA are based on a flood with a return probability of 1 per cent (1:100 years), routed through the current configuration of the flood channel and plain. Variants include maps that show flooding at a given time of year, such as harvest time for a major crop, with a 20 per cent risk, appropriate to agriculture. Such maps allow people to improve their own decisions about their investments, whether in a factory or an earth mound on which to build their houses. Flood plain zoning goes one step further and imposes regulations on the types of activity which can be carried out in vulnerable areas. This can be unpopular, and can lead to legal action where it limits profitable developments.

Flood forecasting for rivers can use radar reflections from raindrops to estimate rainfall intensity a few hours ahead and routing models to generate real-time forecasts, which can be updated and recalibrated as the storm event develops. Such systems are in widespread use in countries that can afford them. The system on the Rhine (Wilke, 1996) includes no less than 19 flood forecasting centres distributed over 5 countries. Other systems use satellite information relayed to ground stations in near real-time. One such system, developed in Cairo for the Nile (Barrett, 1995), uses satellite observations of cloud temperature readings over the upper catchment. These are calibrated with data from a few synoptic stations in Ethiopia and Sudan and used to generate estimates of the flood volume in the Blue Nile and Abara. Such systems are much more affordable and appropriate for larger rivers with slower response times.

Political difficulties may surround the exchange of the data needed and this is an area of greatest need in integrated river basin management. Despite meetings over many years between experts from India and Bangladesh, the release of the data from the upper catchment of rivers like the Ganges and Brahmaputra, needed to make predictions 72 hours ahead on the major rivers, has still not been agreed, despite the major benefits this would bring.

An integral part of the system is the telemetry network needed to transmit the data reliably from the sensors to the modelling centres. Here again satellites play a major role, although other ingenious methods are also used, such as meteor burst telemetry, which uses the ionised particles in the trail of small meteorites as a reflector for radio signals.

The key issue is how much time is needed to prepare and disseminate a forecast, and for people to react. Floods on the lower reaches of large rivers and cyclone-induced surges can be predicted, but the accuracy diminishes rapidly with increases in lead time. The flood warning agency has to be careful not to issue false warnings, which not only cause unnecessary disruption but also reduces the credibility of the agency and could lead to later warnings being ignored.

In poorer countries, there are few options for people without motorized transport. They can go to cyclone shelters, stand in the wind and the rain on embankments, or stay and pray for deliverance. It is a sad reality that mothers with teenage daughters will sometimes chose the third option rather than risk harassment in the shelters.

Nevertheless, the programme of construction of shelters on the cyclone prone coast of Bangladesh is held to be the major reason why the death toll of 140 000 in 1991, horrifying as it is, was less than the 300 000 in 1970. Conditions of wind and tide were similar and there had been a 50 per cent growth in population. The reduction in the number of deaths was, in part, because of improved warning systems and the fact that people had somewhere safe to go.

8. BASIN-WIDE WATER RESOURCES AND LAND MANAGEMENT

Within the river basin, there is little to be done to reduce the intensity of rainfall or cyclone events. However, flooding is often exacerbated by human use and abuse of the land and it may be possible to do much to mitigate the intensity of flood hazard or the vulnerability of human activities.

It is now commonplace to advocate policies for integrated basin-wide measures to harness water resources and improve land management practices, particularly afforestation of the uplands and control of agriculture. These are seen as complementing structural measures such as dam and embankment construction. A typical flood plain management strategy is shown in Table 2.

Neat presentations of integrated strategies can all too easily conceal some very hard choices. What may be a satisfactory solution for some may be a much less satisfactory solution for others. Almost all structural measures require land to be acquired, and that can mean a dramatic change of life for those affected. The problem is made considerably worse if compensation is slow or important aspects of community social life are destroyed, such as the networking arrangements upon which many people in developing countries depend.

Structural measures also have environmental impacts. The protection of arable lands by ring dykes in Bangladesh has impacts upon fish stocks, which are the main source of protein for its people. Some rivers have silted up and waterlogging is widespread in heavily empoldered areas. Any new dam anywhere in the world is the immediate target for activist groups campaigning on social or environmental issues. Such concerns are legitimate but must be related to the actual needs of each country to reconcile conservation and development objectives.

Table 2. A typical flood plain strategy

STRATEGY 1: REDUCE FLOODING	Dams and reservoirs High flow diversions Dykes, levees, flood banks Land treatment measures Channel improvements On-site detention
STRATEGY II: REDUCE SUSCEPTIBILITY TO DAMAGE	Flood plain regulation Development and redevelopment policies Flood Plain Zoning Design and location of facilities Housing, sanitary and building codes Land rights, acquisition and open space Subdivision and other regulations Redevelopment or permanent evacuation Flood Proofing Flood forecasting and warning systems
STRATEGY III: REDUCE THE IMPACT OF FLOODING	Information and education Tax adjustment Disaster preparedness Flood emergency response Disaster assistance Post-flood recovery Flood Insurance
STRATEGY IV: Restore and preserve the natural and cultural resources of the flood plain (Source: Modified from Thomasm (1995))	Flood Plain and wetland regulations Tax adjustments Information and education Other administrative measures

Deforestation may not be the primary cause of flooding or sedimentation in mountain areas as orogenic processes have a major role to play. Deltas of the Nile, Irrawaddy and Ganges were built up from several kilometres of sediment millennia before deforestation was rife. Equally, reforestation may not be the panacea for those whose livelihood depends on what they can grow in a season, rather than tree crops that take 10 years to mature.

Dykes and levees can raise river bed levels, entraining a costly process of operation and maintenance. They can increase the cost of flooding by encouraging inappropriate structures to be built within areas which people mistakenly believe to be secure. Furthermore, the loss of storage within the protected area can only aggravate the problem for those living in unprotected areas; and in certain places retribution takes the form of deliberate breaching of embankments by those who feel they have been victims of development.

Thus, each of these strategies will require an evaluation of the winners and losers in the process. In principle, a process of negotiation is possible between landowners whose activities will tolerate a higher degree of flooding than those of others. French law, for example, now requires that flood management be dealt with at the catchment level and this has led to the possibility of a negotiated solution based on an objective evaluation of the level of flood hazard and of flood vulnerability for each parcel of land. Ways to treat the difference in value of these parcels as a tradeable commodity is currently under research (Gilard, 1996).

The problems are difficult to manage even at a national level. At an international level they become even more difficult and there are relatively few examples of works built in one country for the benefit of another. Indeed, around the Aral Sea countries, the break-up of the Soviet Union has led to increased difficulties as dam releases upstream on the Syrdarya have been increased for power generation despite the consequences in term of increased flooding downstream (Konovalov, 1996).

Increased regional cooperation and improvements in integrated river basin management go hand-in-hand, each acting as a catalyst for the other. Within Europe, the EurAqua network, founded in 1992, is examining the question on the

"*Prevention and management of crisis situations: Floods, droughts and the institutional aspects*" and, using the Rhine as the cornerstone of policy, has identified ten points to be followed in practical flood-related management (Lullwitz, 1996). Other forums such as the Mekong Secretariat and the Ganges-Brahmaputra-Meghna Track II initiative are pursuing similar basin-wide goals.

9. RESEARCH AND CAPACITY BUILDING

Investments in flood control works are huge and it is vital that they be made correctly. Worldwide, about 20 major dams collapse each decade. In a survey by the US Corps of Engineers, one-third of 9 000 US dams in high-hazard areas were tentatively classified as unsafe, but the cost of bringing them up to current safety standards is prohibitive. River embankments regularly fail in a variety of modes, sometimes with considerable loss of life. They then have to be reconstructed, often in a hurry, before the next flood season, leaving little time for thorough investigation. Maintenance costs are also high, particularly for embankments on major rivers.

Good design is essential, and elaborate test beds mounted on centrifuges are now being used by US Bureau of Reclamation to examine failure modes and assess solutions. Other problems can arise on rivers such as the Ganges and the Brahmaputra, where scour depths of up to 60 m are recorded. A recent failure was attributed to mass movement of sand fill with small amounts of silica, following very rapid scour hole development at the toe of the launching apron within a few weeks of construction.

Food forecasting and flood warning systems are expensive, but considerably less expensive, and costs are falling as remote sensing systems and telecommunications costs fall. This allows for improvements not only on the forecasting side, but also in the dissemination of information. As real incomes rise around the world, more and more people have access to radio and television, more roads are built, and more safe havens can be provided.

There are still major uncertainties about the combined effects of wind, surge and river flow. In 1998, we in Bangladesh experienced the most severe long duration flood in our history, a flood aggravated by a significant rise in sea-level (compared with the astronomical tide) in the Bay of Bengal for a 40-day period. The cause has yet to be identified.

The likelihood of a major pay-off from increased research is high, particularly if this is linked to field trials of promising solutions. Recent years have seen greatly increased use of complex geotextiles in river and marine embankment works. These expensive materials are fabricated to exact specifications according to the geotechnical properties of the soils and exposure to abrasion. Other materials, blending artificial fibres with natural ones such as jute, could reduce costs and offer environmental advantages. In Bangladesh, we have been building pilot projects with costs from $300 to $10 000 per metre and annual maintenance costs of 5 to 20 per cent but, even so, have no guarantees we can keep our major rivers stable. Research into new and cheaper solutions is desperately needed.

10. OPTIONS FOR FLOOD MANAGEMENT AND CONTROL

Options to reduce damage by flood may be summarized as:

- Keep the flood away from people — control or reduce the flood, through structural and catchment management;
- Keep people away from the flood — use flood zoning and judicious practices in the flood plains, and help them find shelter when floods occur

The costs of the first option are huge and, if some of the possible scenarios for global climate change materialize, will increase rather than decrease. As recent floods in Europe and the USA have shown, even the richest countries of the world are unable to construct works that provide full protection. But it is the failures that make the headlines, the exceptional circumstances when floods exceed design standards which are a compromise between a desire for complete safety and limitations on the budget available to pay for it. The successes go unrecorded when, year after year, all but the most extreme floods are contained. In these years, economic activity continues and expands, creating the wealth to repay the earlier investment.

The investment costs of the second option are rather less, although the toll in human misery is greater, and this tends to be the poor man's solution. However, one great turning point may be approaching, as the growth rate in the populations of LDCs slows to the point (as in Bangladesh) where rural growth rates are outstripped by urban migration. As a result, the pressure to live on the flood plains may reduce, or at least stop expanding, and judicious policies may finally be given a chance to work effectively. However, lower investment brings lower returns and the penalty is reduced economic activity at a time when expansion is needed.

However, in the developing countries today, we are being advised to adopt a third option "clean-up afterwards", — i.e., to use all means possible, including insurance and post-flood assistance and rehabilitation, to get people back on their feet. Countries hit by flooding depend on each other for post-flood recovery and one of the more encouraging sights of the twentieth century has been the willingness of governments to come to the assistance of those in need. Offers of help by countries with military personnel and equipment, NGO's and relief organizations and dispersal of food, medical supplies and shelter are greatly welcomed. These cement understanding and humanitarian concepts and will probably always be a necessary part of the solution. The post-flood rehabilitation in Bangladesh this year has been enormously aided because of the timely assistance which enabled people to replant immediately after the floodwaters receded and bring in a bumper spring rice crop.

The flood-affected nations, and the people directly affected, must be grateful for assistance in the clean-up option, but how much better it would be if money which seems to flow so freely after a disaster has hit could be made available before hand. Used wisely to invest in either of the first two options, it would show a far higher rate of return, improve standards of living and the quality of life for people now reduced to depending on others to survive the hazards of flooding.

These arguments point to the potential benefit from investment into improved designs and warning systems and to the need for strengthening the capacity of organizations to manage the entire flood mitigation and preparedness process. Such investment needs to be on a broad front, for people living in all countries, not just those in developed countries. Let us remember that "rich man's solutions" were being built 100-200 years ago in countries which were no richer then than poor countries are today. The difference is that, then, there were no rich countries telling them what they could or could not afford. They were simply building for a better future, and their children, and their children's grandchildren, are the beneficiaries. We, in this generation, are trying to improve our management of natural disasters, and we must create a comparable legacy for our own children.

REFERENCES

Ali. A., 1999: *Impacts of global warming on tropical cyclones and storm survey in Bangladesh*. International seminar on sea-level rise and sustainable coastal management, Dhaka, March 1999.

Barrett C.B., 1993: *The development of the Nile hydrometeorological forecast system*.

Barthel V., 1991: *Hybrid modelling techniques for the simulation of extreme events in tidal rivers*. Intl. workshop on storm surges, river flow and combined effects, Hamburg, 1991.

Gilard O., 1996: *Flood risk management: risk cartography for objective negotiations*. Proc. Sem. River Flood Disasters, Koblenz, 1996.

Govi M. and O. Turitto, 1996: *Recent floods and past experience in northern Italy*. Proc. Sem. River Flood Disasters, Koblenz, 1996.

Guo Dayuan and Wang Juemou, 1994: *Methods for estimating and forecasting floods in areas affected by tides and storm surges*. WMO Technical Reports in Hydrology and Water Resources, WMO/TD-644, 1994.

Halcrow Sir W.,1995: *Brahmaputra river training studies*. Gov. of Bangladesh, Water Development Board, 1995.

Huq S. *et al.*, 1999: *Vulnerability and adaptation to climate change in Bangladesh*. Bangladesh Centre for Advance Studies, Kluper, 1999.

Ingram J.J., 1996: *Lessons taught by floods in the USA*. Proc. sem. river flood disasters, Koblenz, 1996.

Kite J.W., 1963: *Frequency and risk analysis in hydrology*.

Konovalov V.G. *et al.*, 1996: *Natural and man-made floods in the river basins of Central Asia*. Proc. sem. river flood disasters, Koblenz, 1996.

Lüllwitz T., 1996: *Report on the results of the European workshop*. Proc. sem. river flood disasters, Koblenz, 1996.

Miller J.B., 1997: *FLOODS: People at risk, strategies for prevention*.

Neilson P. and P.G. Evans, 1991: *Wave set-up on beaches and river entrances*. Intl. Workshop on storm surges, river flow and combined effects, Hamburg, 1991.

Stevenson J. C.,1999: *Personal communication*. U. Maryland.

Sweigers C.G., 1996: *Flood management in South Africa*. Proc. sem. river flood disasters, Koblenz, 1996.

Thomas F.H., 1995: *Principles of flood plain management*. In J. Gardiner *et al.*, Defence from flood and flood plain management, Kluwer Academic Publishers, Dordrecht.

Wilke K., 1996: *Operational flood forecasting in the River Rhine basin*. Proc. sem. river flood disasters, Koblenz, 1996.