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CLIMATE, CLIMATE CHANGE VARIABILITY AND PREDICTABILITY

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The views expressed in this paper are those of the author and are not necessarily those of the Institute.

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CLIMATE, CLIMATE CHANGE, VARIABILITY AND PREDICTABILITY

1. Introduction

It is indeed an honour and a privilege to be invited to deliver this Rajiv Gandhi lecture on “Climate, Climate Change, Variability and Predictability” to a distinguished audience. On behalf of the World Meteorological Organization and my own, I wish to thank the Foundation and, in particular, Mrs Sonia Gandhi, President of the Rajiv Gandhi Foundation for this invitation. I wish to express my appreciation to the Foundation for its support to science and technology as an instrument of sustainable development. Indeed, Rajiv Gandhi had recognized the importance of having a “very broad base of people who have scientific learning from which we can draw and reach out to the best people available”. In this regard, I hope that the lecture, which addresses a subject of major concern to humanity for the preservation of planet Earth, would be a further contribution to the objective of the Rajiv Gandhi Institute for Contemporary Studies — namely acting as an intelligent bridge between science and the world at large.

The Earth’s climate is one of mankind’s greatest natural resources. The very existence of man on Earth depends fundamentally on a benign climate. We depend on the right climate to produce the crops that feed us and on the right amount of rainfall occurring at the right times to provide the water resources which are fundamental to our very existence. Too little rainfall — or failure of expected seasonal rains — can lead to devastating droughts, crop failure and famine. Too much rainfall in a very short time, or even over a season, can result in catastrophic flooding causing direct loss of human life, as well as destruction of the infrastructure which we take for granted in our daily lives. We are all familiar with damaging effects of tropical cyclones, floods and droughts, and the extreme cold spells, or extreme heat waves. In fact, in some countries, extreme cold or heat occasionally account for a greater number of deaths in a year than other weather phenomena. We expect and depend on factors such as the right seasonal changes in temperature and rainfall for sustaining the biosphere, including plants and animals. We know that climate in general also plays an important role in our culture, habitat and health. Like humankind’s other precious natural resources, we should be “conserving” climate, or at least making use of it in a sustainable manner. But — as in so many other areas — we are not; and human activities today have reached the stage where they are producing a discernible effect on climate.

In light of these considerations, this lecture will cover the fundamental work that is going on for: (a) improving our understanding of the Earth’s climate system and its evolution; (b) studying the impact of climate, as well as the implications of its variability and change on human activities; (c) predicting climate variations; and (d) providing scientifically founded quantitative estimates of how climate may change taking human influence into consideration. The lecture will also consider the role of the World Meteorological Organization (WMO) as the driving force in the international arena in climate monitoring, the scientific study of climate and climate change, its impact and prediction, and in the international efforts towards protection of the Earth’s climate.

2. The climate system

The climate system, shown in Figure 1, consists of the atmosphere, the hydrosphere (comprising the liquid water distributed on the surface of the Earth), the cryosphere (comprising the snow and ice on the surface of the Earth), the surface lithosphere (comprising the rock, sand, soil and sediment of the Earth's surface) and the biosphere (comprising the Earth's plant and animal life, as well as the activities of people). Principally under the influence of the solar radiation received by the Earth and its atmosphere, the climate system determines the climate of the Earth. Although climate relates essentially to the varying states of the atmosphere, the other parts of the climate system as described above have a significant role in the formation and development of climate through their interaction with the atmosphere.

This definition of the climate system leads into the question of climate variability and climate change. The term "climate variability" denotes deviations or anomalies of climate parameters over a given period of time, e.g. a specific month, season or year from the long-term climate averages. In the most general sense, however, climate variability can be described by the differences between long-term statistics of meteorological elements calculated for different periods.

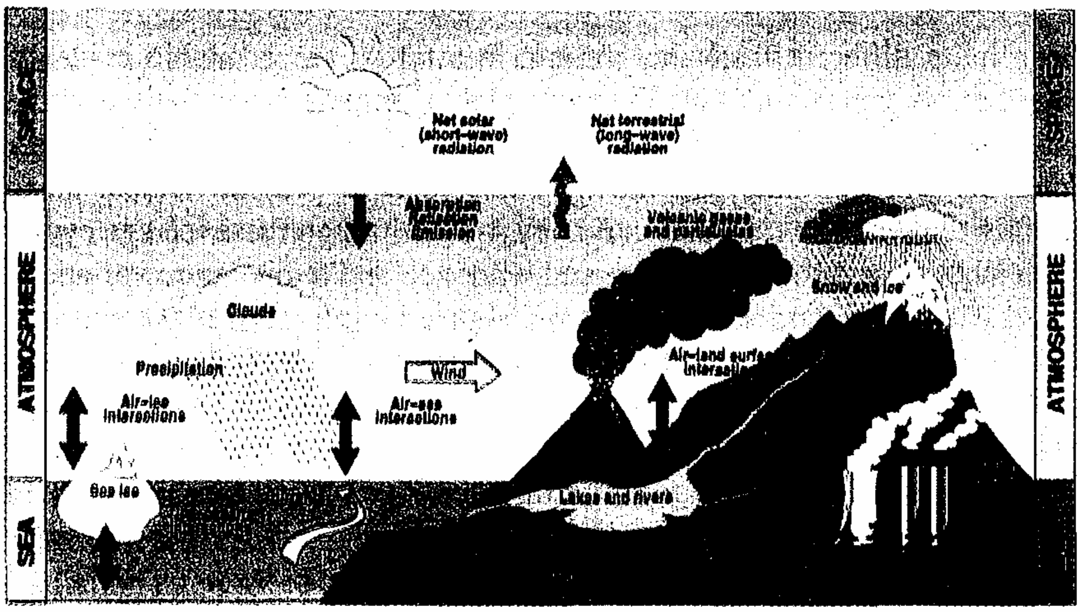


FIGURE 1. *The climate system. The complex interaction of all of these components contributes to the state of the atmosphere*

3. Climate variations — historical perspective

We are all aware of how a given month, or season, or year, can differ from what we would normally expect — how we may appear to have a long series of unusually dry or wet, or unusually hot or cold months, or seasons, or years. Climate, as we know it, is made of extreme events, or spells of abnormal weather, possibly having destructive consequences, as well as periods of more normal conditions. To a large extent, human societies have become attuned to the current climatic conditions: that is, the conditions over the last 30 to 50 years. Crops flourish within an expected range of climatic variations, and our dams and dykes are often built on assumptions based upon the climatological record over that short 30- to 50-year period.

Longer time-scale climate variability

Considering the much longer period, one sees that the Earth's climate has never been static. Climate is a dynamic regime subject to changes on all time- scales ranging from decades to millennia to millions of years. Many scientific clues can be found in glacial records which indicate that past climates have been quit from the present. Putting all the available evidence together, we can deduce (see Figure 2) global temperature variations in the pas. Prominent are the glacial-interglacial cycles at about 100 000 year intervals when climate was mostly cooler than at present. Global mean surface temperature typically varied by 4-5C through these ice age cycles with large changes in ice volume and sea level, and temperature variations as great as 10-15C In some middle and high latitude regions of the northern hemisphere. Since the beginning of the current interglacial epoch, about 10 000 years before present (Figure 2b), global temperatures have fluctuated within a much smaller range. Some fluctuation have nevertheless lasted several centuries, including the "Little Ice Age" from the sixteenth to nineteenth centuries which was global in extent.

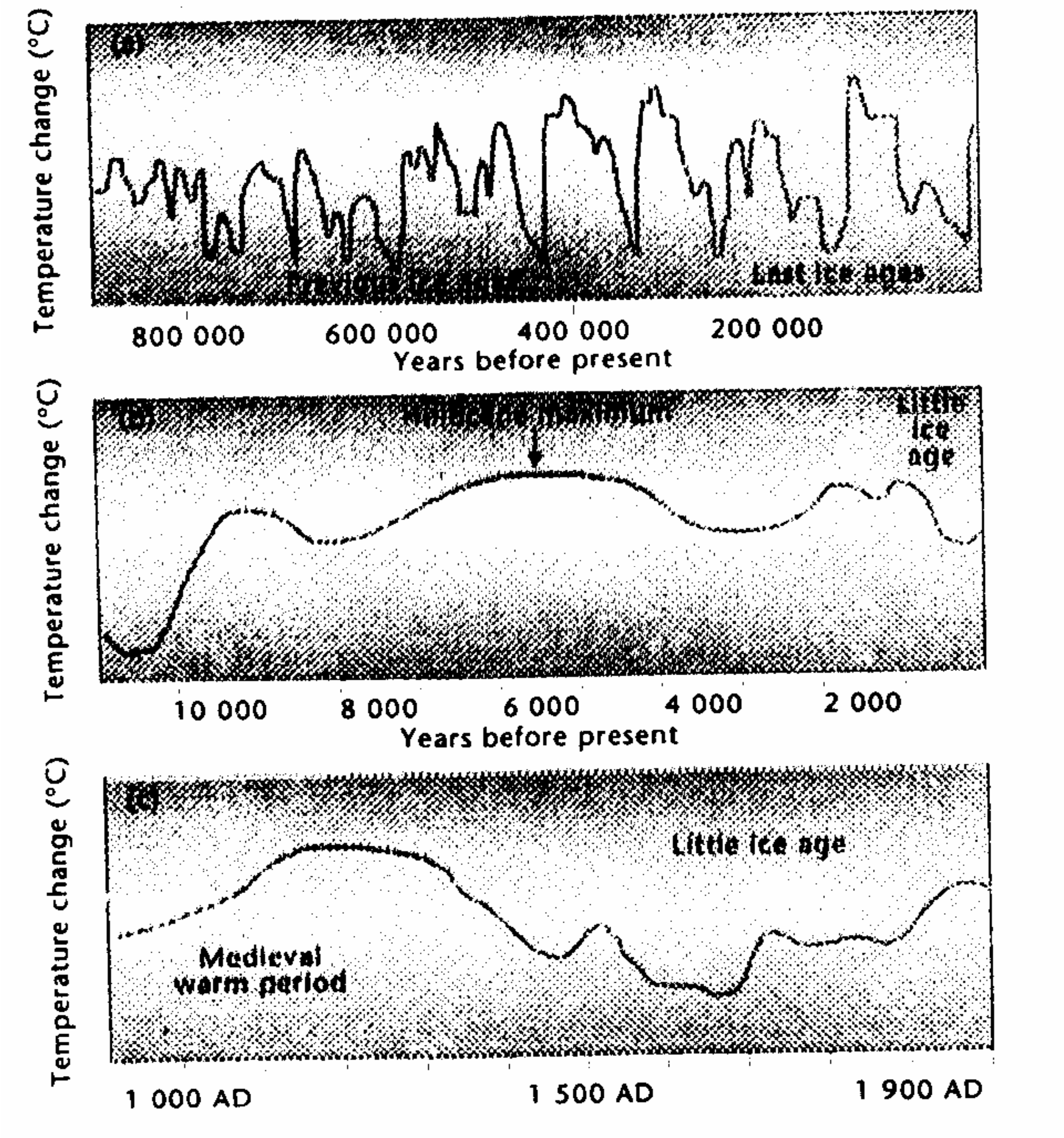


FIGURE 2. ***Schematic diagrams of global temperature variations since the Pleistocene on three time-scales(a) the last million years; (b) the last ten thousand years; and (c) the last thousand years. The dotted line nominally represents condition near the beginning of the twentieth century***

Causes of significant longer-term climate variability

Orbit-induced changes

One important factor in the repeated glaciations on earth related to alterations of the Earth's orbital parameters – the "Milankovitchhypothesis". These alterations take the form of a recurrent variation of the eccentricity of Earth's elliptical orbit around the sun with a period of about 100 000 years (resulting in small changes in the distance of the Earth from the sun in given seasons) and slow changes in the angle of the Earth's axis which affects the amplitude of the seasonal insolation. However, this phenomenon causes a variation of only about 0.2% in the amount of solar radiation intercepted by the Earth. Such a small change in the solar radiation flux must in some manner be considerably amplified by the Earth's climate system to induce the profound changes climatic conditions, such as those which occurred in the transition to an ice sheets of Antarctica and Greenland preserve the climatological history of the last ice age. The composition of deep ice cores provides a basis for estimating the air temperature over many millennia. Small air bubbles are also trapped in the ice sheet as it was formed – and the composition of these air bubbles can be analysed to give an estimate of variation of the atmospheric composition paralleling the temperature record (see Figure 3). This shows that variations in carbon dioxide during ice age cycle are also very important factors, serving to modify and perhaps amplify other forcing effects.

Ocean-induced changes

There are also rapid changes in climate on time-scales of about a country which cannot be directly related to orbital effects or to changes in atmospheric composition. A notable example is the Younger-Dryas cold episode which was manifested by an abrupt reversal of the general warming trend in progress about 10 500 years before the present as the last episode of continental glaciation came to an end. There is as yet no consensus on the reasons for this reversal which lasted about 500 years and ended very suddenly. However, since the change was strongest around the North Atlantic Ocean, it has been suggested that this climatic reversal had its physical origins

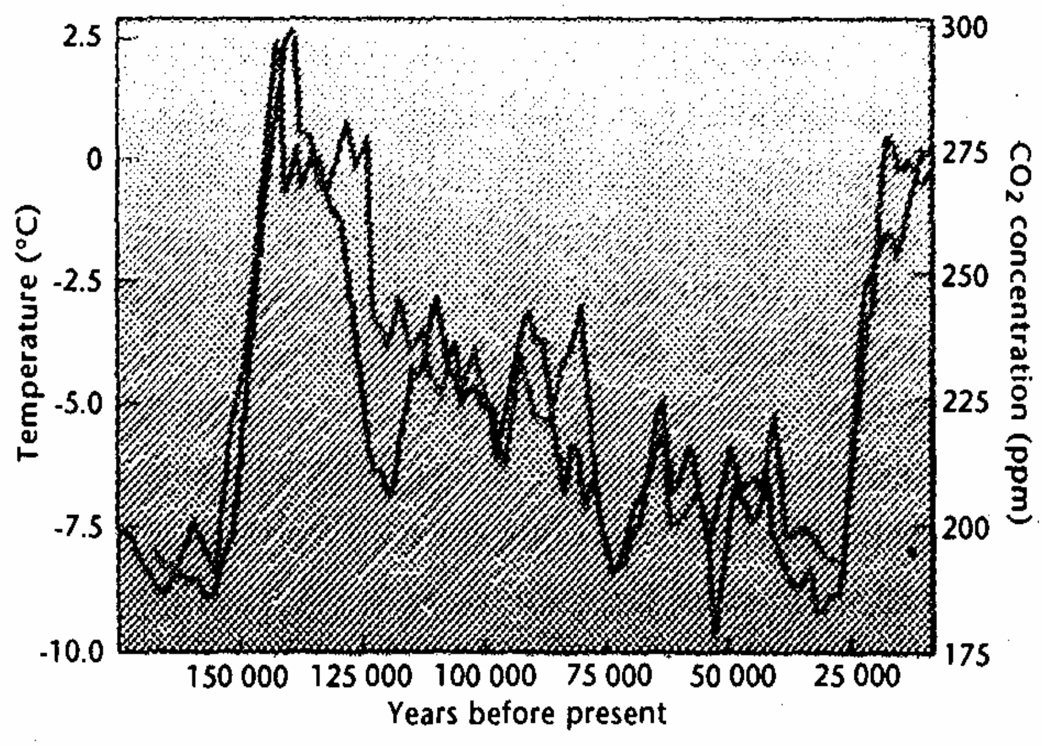


FIGURE 3. Paleoclimatological record of temperature change with respect to modern climate (grey line) and atmospheric CO_2 concentration (red line) over Antarctica during the last glacial cycle (adapted from Barnola et at., 1987)

in a marked decrease in the surface temperature of this ocean, following large-scale melting of the Laurentide ice-sheet and consequential changes in the oceanic circulation.

These changes hold a warning for us today in that alterations of the ocean circulation could result from modification of climate, induced by the increasing atmospheric concentrations of greenhouse gases — though the alterations are likely to be considerably smaller than in the Younger-Dryas event. This is brought out to illustrate that nothing is straightforward in the climate system — changes may sometimes he very unexpected. Great care is needed in studying the climate system and to take into account all the possible degrees of freedom and interactions between the different components of the climate system.

Climate changes since the last glaciation

The period since the end of the last glaciation (about 10 500 years ago) has been characterized by smaller changes in the global average temperature with a range of probably about 2°C — although it is not clear whether all the fluctuations were truly global. However, large regional changes in hydrological conditions have occurred, particularly in the tropics. Wetter conditions in the Sahara from 12 000 to 4000 years before present enabled man to survive by hunting and fishing on what is today among the most arid regions on Earth. Pollen sequences from lake beds of northwest India suggest that periods with subdued monsoon activity existed during the last glacial maximum, but in the epoch 8000 to 2500 before present, there was a humid climate with frequent floods. The late tenth to early thirteenth centuries (AD 950-1250) appear to have been exceptionally warm in western Europe, Iceland and Greenland — a period that is known in Europe as the "Medieval Climatic Optimum". On the other hand, it seems that China may have been cold in this period (mainly in the winter), although the southern part of Japan was warm. This episode of generally widespread warmth is notable in that there was no evidence of any increase in greenhouse gases, a subject which will he discussed later.

A striking indicator of climate changes is the advances and retreats of glaciers in mountainous regions of the world. In the most recent cooler period, the "Little Ice Age", glaciers advanced markedly in almost all alpine regions, and glaciers were much more extensive 100-200 years ago than now. Since 1850, most glaciers have been retreating rapidly.

4. Present day climate change concerns — the human element

The climate variations of the past, as described in the previous section, have been essentially natural, without any human influence. However, a major concern now is that for the first time in history, human activities have reached the stage where they are having a discernible effect on climate on regional and global scales. Few scientific issues in recent years have attracted as much public interest and political attention as the looming threat of climate change that now faces us; and the study of climate change has become an area of intense activity in both scientific and political terms. Essentially, climate .change is viewed as any significant change (one climate mode to another climate mode) which is outside the range of climate variability, whatever the cause. These changes usually have important economic, environmental and social effects. I shall say more later how anthropogenic activities influence climate, in particular the effects of increasing concentrations of carbon dioxide and other greenhouse gases in the atmosphere. Suffice to comment now that, given the present rate of increase of greenhouse gases in the atmosphere, the general scientific consensus is that global mean temperature could increase by anywhere in the range of 1 to 3.5° Celsius from today's values by the end of the next century. We can expect this change to be superimposed on the natural variations of climate which we already see. The alarming aspect of this is that the expected rate of increase of the global mean temperature over the next century would be the highest known in the past 10 000 years. Such changes will have implications for socio-economic activities in all parts of the world.

Observations over the past century

At any one location year-to-year variations in weather can be large, but analyses of meteorological and other data over large areas and over periods of decades or more have provided evidence for some important systematic changes:

- The global mean surface temperature has increased by between about 0.3 and 0.6°C since the late 19th Century; the additional data available since 1990 and the re-analyses since then have not significantly changed this range of estimated increase.
- Recent years have been among the warmest since 1860, i.e. in the period of instrumental record, despite the cooling effect of the 1991 Mt Pinatubo volcanic eruption.
- Night-time temperatures over land have generally increased more than daytime temperatures.
- Regional changes are also evident. For example, the recent warming has been greatest over the mid-latitude continents in winter and spring, with a few areas of cooling, such as the North Atlantic Ocean. Precipitation has increased over land in high latitudes of the Northern Hemisphere, especially during the cold season.
- The global sea level has risen by between 10 and 25 cm over the past 100 years and much of the rise may be related to the increase in the global mean temperature.
- There are inadequate data to determine whether consistent global changes in climate variability or weather extremes have occurred over the 20th Century. On regional scales there is clear evidence of changes in some extremes and climate variability indicators (e.g. fewer frosts in several widespread areas; an increase in the proportion of rainfall from extreme events over the contiguous states of the USA).
- The 1990 to mid-1995 persistent warm-phase of the El Nitro/ Southern Oscillation (which causes droughts and floods in many areas) was unusual in the context of the last 120 years.
- Figure 4 is an example of the major global climate anomalies and events during 1995. WMO issues annually the state of the global climate.

5. Implications of climate change

In view of the observed and the predicted changes in climate and the probability that climate change will be characterized by more extreme weather events than in the past, it is useful to review the dependence of various aspects of human well-being on climate and indicate some of the impacts which it is believed that a climate change of the magnitude expected could have. Many regions are likely to experience adverse effects, some of which are potentially irreversible. On the other hand, some effects of climate change could be beneficial. However, the vulnerability of human health and socio-economic systems and, to a considerable degree, ecological systems,

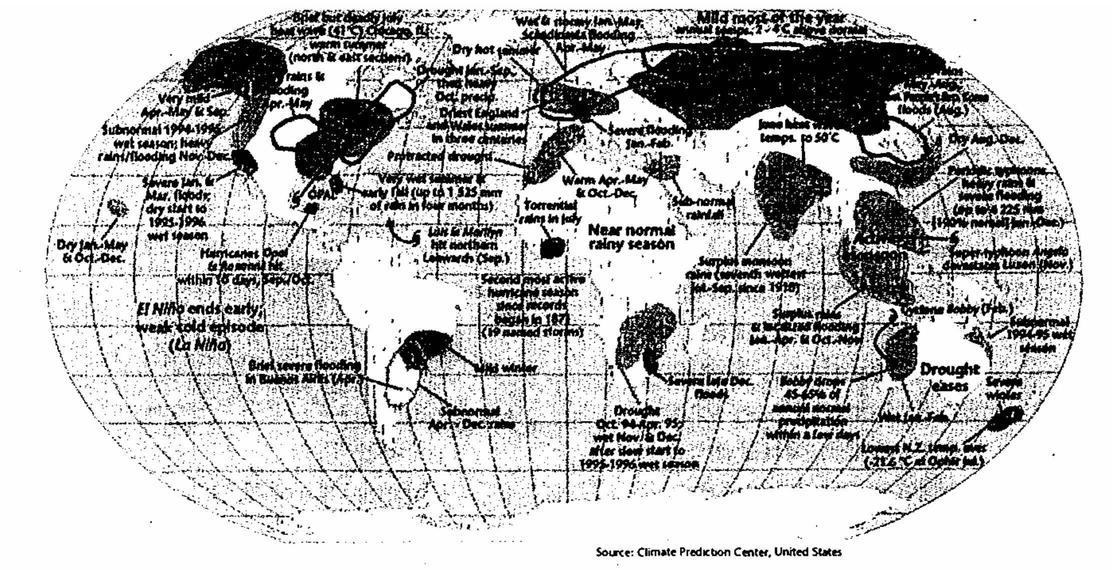


FIGURE 4. *Major global climate anomalies and events in 1995*

depends upon economic circumstances and institutional infrastructure. Unfortunately, this means that developing countries, where economic circumstances are less favourable, will be more vulnerable to climate change.

Extreme weather events

Among the dramatic occurrences of extreme weather phenomena and their direct impact on human life, the most significant are tropical cyclones, floods and droughts (see Figure 5). In an average year, about 80 tropical cyclones form over warm ocean waters in various parts of the tropics and affect 50 different countries. On average, about 20 000 people lose their lives each year and the damage caused by the associated violent winds, floods and tidal surges can reach many thousands of millions of US dollars. In some years, individual cyclones can have even more tragic consequences. In 1970 and 1991, for example, severe cyclones in the Bay of Bengal resulted in the loss of some 300000 and 138 000 lives, respectively. Many countries of the world, including South Asia and the Indian subcontinent, are all too familiar with the large losses in human and economic terms, as a result of flooding of major rivers. Similarly, drought is a recurrent phenomenon which causes great human suffering. In addition, there are other types of life-threatening weather phenomena, such as tornadoes, lightning, hail and heavy snowfall, all of which cause extensive damage and loss of life every year in many countries. The need to provide accurate and timely warnings of these disaster-causing weather events becomes more important every year. However, there are hopeful signs that this is being achieved in many parts of the world.

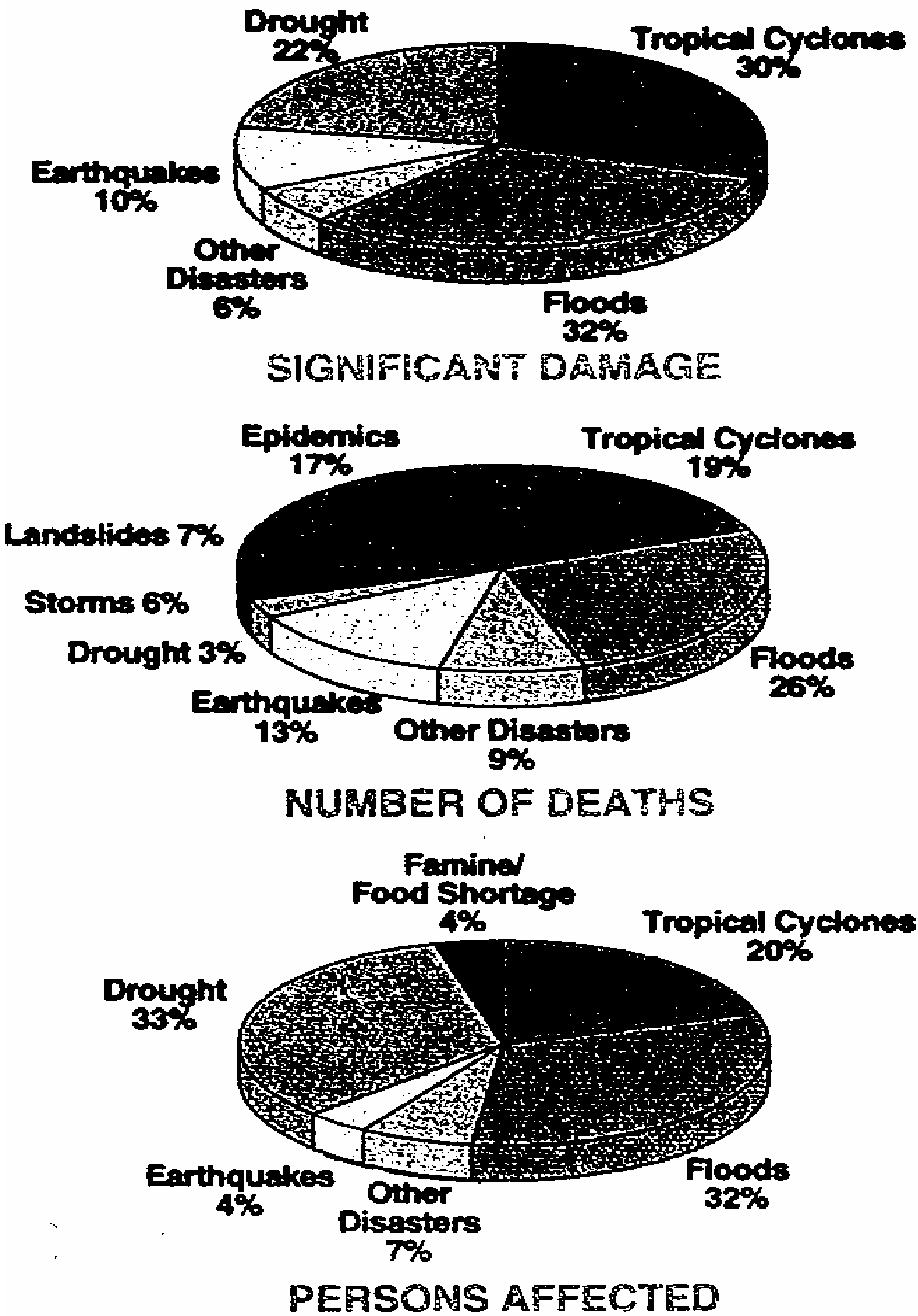


FIGURE 5. *Extreme weather and other events and their impacts*

The predicted warmer temperatures are likely to result in a more vigorous hydrological cycle, bringing the prospect, on one hand, of local increases in precipitation intensity and the probability of extreme rainfall events and the risk of severe floods in some regions. On the other hand, intensified droughts are probable in other areas. Furthermore, although current knowledge is insufficient to say whether climate change will bring about any changes in the occurrence, intensity or geographical distribution of severe storms, such as tropical cyclones, recent monitoring has shown records in the frequencies (e.g. in 1993, Philippines) and increased intensity (e.g. Hurricane Andrew in 1992, USA) of these storms, and previously unknown tracks (e.g. tropical cyclone across Southern Africa in January 1996 from the Indian Ocean to the Atlantic Ocean).

Socio-economic activities

Agriculture and forests

Agriculture is a basic area of human activity that is particularly sensitive to climate. The production, collection, transportation, storage, processing and distribution of agricultural produce are all greatly influenced by climatic factors. It frequently happens that if a %particular area experiences unfavourable seasons climatically, major or even virtually total losses of crops can occur. In many tropical countries dependent on specific annual rainfall events, such as, of course, the monsoon, losses on average may be 30 per cent or more of the annual agricultural production if the rains are exceedingly delayed, or fall short of the normal value. A significant proportion of the agricultural production losses that result could be avoided by the better use of appropriate information on climate that is already available with the national Meteorological and Hydrological Services. The benefit from the application of this information far surpasses its cost. Furthermore, climate information and weather forecasts can be used to reduce crop and livestock losses, anticipate when and where irrigation would be needed, when pesticides should be applied, the choice of the best harvest time and so on. Prevalence of particularly dry or particularly wet conditions can affect the incidence of pests. An example of this is the major problem of devastation caused by locust swarms in some parts of the world. Locusts can begin to breed a few days after the onset of rain in an otherwise dry environment. If we can predict this rainfall, action can be taken to prevent swarms from developing and thus avert significant crop losses.

All the studies indicate that climate change will certainly have important consequences for agriculture. Crop yields and changes in productivity will vary considerably from place to place, with marked alterations in patterns of production. Productivity would be expected to decrease in regions of high present-day vulnerability that are least able to adjust, especially in the tropics and subtropics, including parts of South East Asia, the Sahel region of Africa and parts of South America. On the other hand, potential productivity in some high- and mid-latitude regions may increase because of a longer growing season, and limited new areas for production could open up — but this would be confined to the northern hemisphere. Increasing dryness and summer heat in certain present temperate mid-latitude areas could reduce grain and horticultural production.

A substantial fraction of the Earth's existing forested area could be expected to undergo major changes. The rate of climate change will be rapid compared to that of the growth of forest species, and forest zones could decline in a climate to which they are increasingly ill-acclimatized. Generally, flora and fauna will not be able to adapt rapidly to climatic zones which could be expected to move up to several hundred kilometers pole ward over the next fifty years. Some species will be lost as a result of the increased climatic stress, leading to a reduction in global biospheric diversity. On the other hand, there could be improved efficiency of plant growth in a higher carbon dioxide ($C0_2$) environment. Unfortunately, there is already a major problem of deforestation existing in many developed and developing countries of the world. This is not only having a negative impact on plant and animal life, on soil conservation and watershed protection, but is a contributor to global warming by reducing the number of trees that can retain CO_2, a greenhouse gas.

Water resources

Another basic concern to humankind, and increasingly as we near the end of this century, is the availability of freshwater resources. Meeting the water demands in quality and quantity of increasing populations and in support of agriculture is currently a vital problem in many parts of the world. Projections indicate a significant decrease of per capita freshwater availability by the end of this century and well into the next (see Figure 6). In order to develop and improve the administration of water resources, detailed knowledge of rainfall that can be normally expected and the variations that can occur both in space and time are essential in all countries. This knowledge also underpins the need for planning national responses to droughts and floods. Again, predictions of anomalously wet and dry periods, a season or more in advance, would be of enormous benefit in managing freshwater resources.

Desertification

The anticipated changes in the global hydrological cycle as a result of global warming would have major impacts on regional water resources. While some parts of the globe would have increased rainfall, droughts would likely intensify in others. Even relatively small increases in temperature or

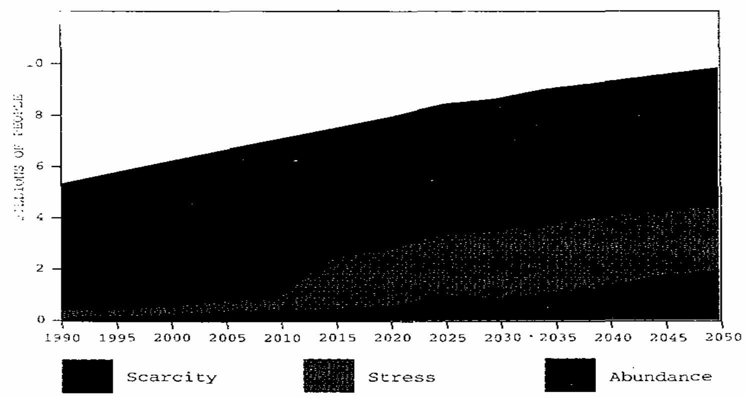


FIGURE 6. *Population experiencing freshwater scarcity, 1990-2050*

reduction in precipitation may aggravate the already serious problems of quantity and quality of water supplies in many parts of the world. Existing deserts would likely become hotter but not significantly wetter, limiting still further any productive use of the marginal land. The risk of desertification will be increased as the environment becomes drier, and the soil becomes further degraded through erosion and compaction as well as human activities. In this connection, the world community has already taken appropriate action, through the negotiation of an International Convention to Combat Desertification.

Sea-level rise

Another serious consequence of global warming is a rise in sea level, mainly through the thermal expansion of sea-water, with considerable potential socio-economic impacts. Current estimates range from 15 to 95 cm, with a "best estimate" of 50 cm. A 50 cm sea-level rise (that could occur by later next century) would threaten low islands and coastal zones. A 95 cm rise would render some island countries uninhabitable, displace tens of millions of people, menace many low-lying urban areas, flood productive lands, contaminate freshwater supplies and change coastlines. The major low-lying deltas in the Bay of Bengal and many small flat islands in the Indian Ocean could be threatened (see Figure 7). These impacts would be exacerbated if floods and storms became more severe. The additional coastal protection required will involve major extra costs.

Impacts on other activities

In case of significant warming, the global areal extent and volume of the terrestrial cryosphere (comprising seasonal snow cover, near-surface layers of permafrost and ice masses such as the ice caps and glaciers) will be substantially reduced. In particular, between one-third and one-half of the existing mountain glacier mass could disappear over the next century. Glacial recession and loss of ice from ice sheets will add to sea-level rise.

Many other activities are fundamentally dependent on climate. For instance, major economic benefits can be derived from the ability to foresee and plan energy consumption, such as the high levels of energy used in unusually cold spells, or nowadays in hot spells as the use of air conditioning increases. In the area of marine activities, some nations rely to a considerable extent on food from the sea. Marine climate information is needed in supporting the management and exploitation of expanded coastal and deep- sea fisheries. The safety of all types of craft at sea and air requires accurate weather forecasts and warnings. In the building industry, good architectural design, taking advantage of information on the likely range of temperature humidity and wind speed, can contribute significantly to energy conservation.

Climate change will also impact human health, leisure and tourism industries. Certain climate conditions very much influence the human body. Cardio-vascular diseases are known to be more likely in people subject to severe climatic stress, whether extreme heat or extreme cold. Many tropical areas are prone to diseases which depend to a varying extent on heat and humidity. In other regions, respiratory illnesses are aggravated by cold, damp weather, or by pollution. Finally, it should be noted that tourism and leisure industries are now a major source of income in many countries and most of these, activities depend on climate. Clearly, any changes in climate which upset current weather patterns, or produce greater extreme conditions, would impact adversely in these activities.

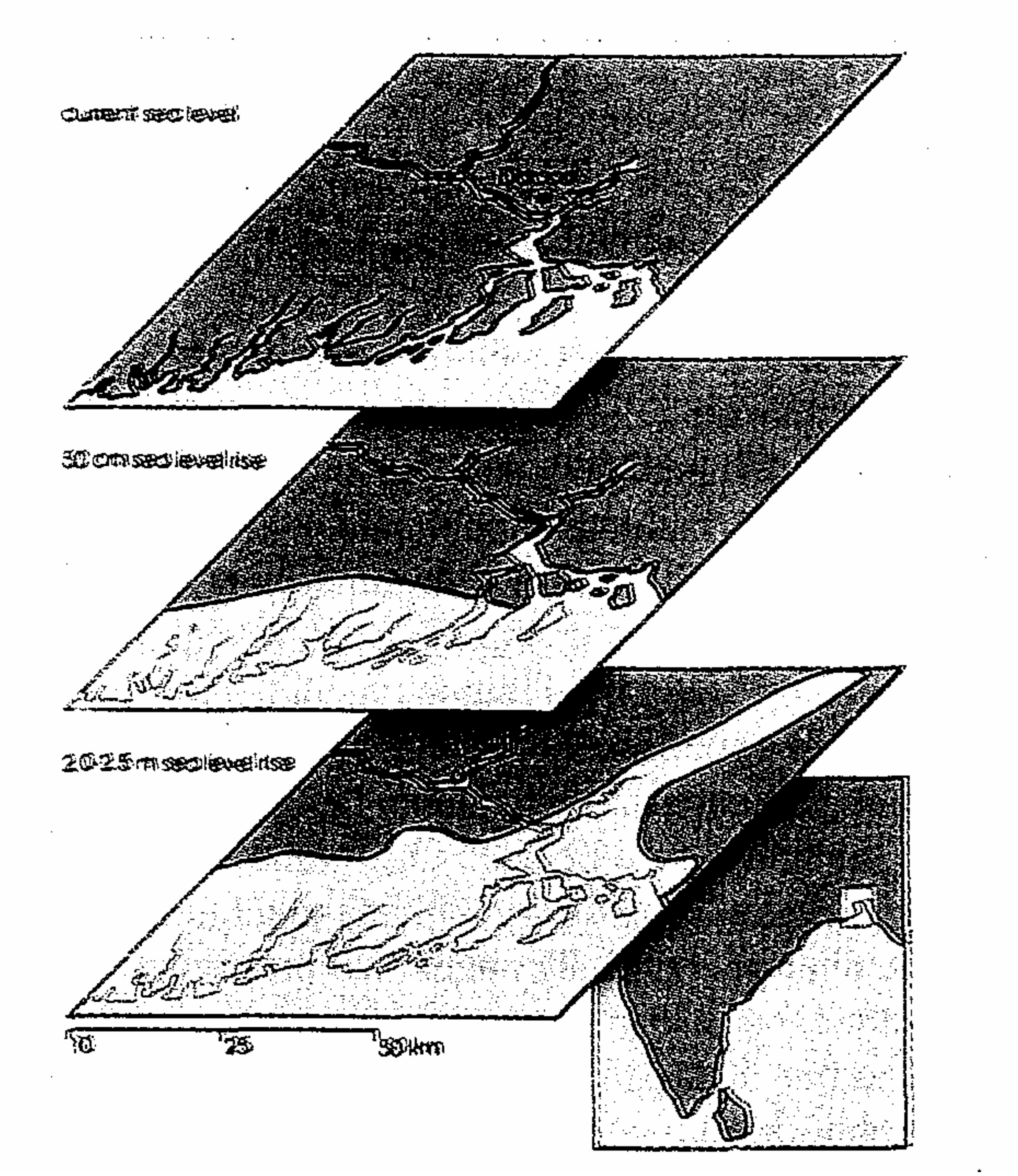


FIGURE 7. Coastal areas of Bangladesh that may be inundated by different rises in sea-level

6. The challenge of climate change and climate prediction — international efforts

Data needs for detecting changes

In the context of the potential socio-economic impacts of climate change that could be induced by human activities, we also need, as a matter of high priority, confident answers, explanations and clarification to the issues being raised on climate change. Crucial therefore to the issue of understanding climate and thus detecting climate change are data collection and the need for long, accurate and consistent data records. The longer the data record, the more is the likelihood of detecting changes. The greater the accuracy of the data set, the less liable it is to conflicting interpretations, which goes to the heart of the question of uncertainties that are so commonly associated with evaluation of the scientific assessment of climate change. Consistency is vital so that we are sure that we can distinguish the detail in various elements in the data.

Monitoring, assessment, research and prediction programmes

The history of internationally coordinated research efforts goes back to the latter part of the last century and involved the predecessor of WMO, the International Meteorological Organization (IMO). Among more recent and larger-scale programmes were the International Geophysical Year (IGY1957-58) and the Global Atmospheric Research Programme (GARP), spanning the fifteen years of 1967 to 1982 with the close cooperation of WMO and the International Council of Scientific Unions (ICSU). The focal points of GARP were the major field experiments, such as the First GARP Global Experiment (FGGE) which was carried out between December 1978 and November 1979. Following the first World Climate Conference in 1979, the WMO established the World Climate Programme (WCP) to address the full range of climate and climate change issues. These earlier programmes, which involved both data collection and research, and which accumulated a vast amount of experience, led to our understanding of the climate system and lay the foundation for the present-day atmospheric research programmes.

The enormous potential benefits of having the ability to actually predict climate anomalies on various time-scales in different parts of the world have been stressed several times. These include the prediction of how hot and dry or how cool and wet the summer may be, the intensity of the coming monsoon season, whether the next five years will be dry compared to the last five, and soon. Consider also the value to society of precise information on long-term trends in mean sea level, changes in precipitation and river flow, or changes in frequency of tropical cyclones or other extreme events. In the face of the challenge of climate predictions, therefore, the World Meteorological Organization has naturally been very active. The operational networks of WMO include the World Weather Watch (WWW), the Global Atmosphere Watch (GAW) and the networks of hydrological stations, all of which support the development of the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS), which are being implemented together by WMO and other partner organizations and agencies. These networks are designed to collect data on the components of the global climate system which require long-term monitoring to determine the present and future state of the atmosphere and climate. These networks encompass almost every nation on earth. The understanding of climate and prediction of climate variations or changes requires input from many scientific disciplines, and therefore, WMO has joined with ICSU, and the UNESCO Intergovernmental Oceanographic Commission (IOC) in sponsoring the World Climate Research Programme (WCRP).

The objective of the WCRP is to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of man’s influence on climate. The programme encompasses wide-ranging studies of the global atmosphere, oceans, sea and land ice, and the land surface which together make up the Earth’s climate system. Significant strides towards predicting climate anomalies on seasonal and interannual time-scales, and anthropogenic effects on climate have already been made.

I would like to mention here one other very important activity which is jointly sponsored by WMO and the United Nations Environment Programme (UNEP). It is the activity of the Intergovernmental Panel on Climate Change (IPCC), which carries out periodic assessments of the science, impacts and the economics of climate change, and of the response options available to manage climate change. Through the IPCC assessments, gaps in data and knowledge are identified. The technical and scientific findings of IPCC played a major role in the negotiation of the United Nations Framework Convention on Climate Change, which came into effect in March 1994 and will be described later. There is a close linkage between IPCC, WCRP and the data-related WMO activities.

7. Climate predictability

Prediction methodology

The basic tool we use to predict climate or climate change is a model of the general circulation of the atmosphere which is broadly represented in Figure 8. Models of this type are based on the laws of physics and use descriptions in simplified physical terms of, for instance, the effects of clouds and their influence on the incoming solar radiation and radiation from the Earth's surface, or mixing in the oceans. The most advanced general circulation models now cover the entire Earth, and include representations of the atmosphere, ocean, cryosphere and land surfaces. There is no need to go into details concerning the construction of these

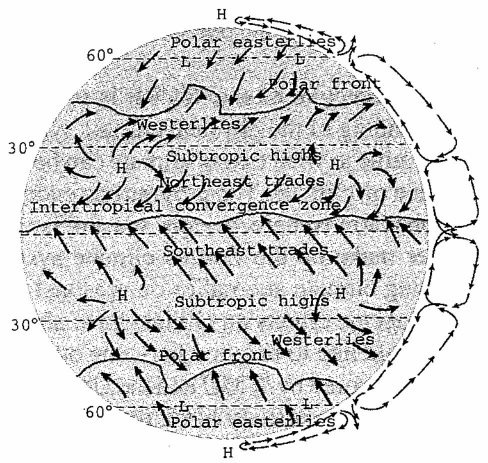


FIGURE 8. *General circulation of the atmosphere*

models — suffice to say they are extremely complex, particularly as a result of the need to reproduce routinely and as accurately as possible, the important processes in climate, and the interactions between different components of the climate system, such as ocean, atmosphere, land surface and the cryosphere, that is, all the elements of Figure 1. A state-of- the-art model of the Earth's climate system, coupling both the atmosphere and the oceans, stretches to the very limit even the most powerful of modern computers — and the development of these models is constrained by limitations in computing resources. The concept of such models has been known for many years, but it is only comparatively recently that their use for climate studies has become practical. Scientific organizations which possess super computers, such as the Indian Meteorological Department, have a special role to play in this regard.

It should be recognized here that the Earth's climate system is in essence a vast and complex generator of random natural variations; it is, in fact, a classical example of a chaotic system. Chaotic or random variability occurs on all time-scales and can obscure predictable climate signals and climate change patterns. Nevertheless, some variations in the natural climate system do recur with recognizable patterns, and may be associated with specific mechanisms which can be definitely predicted for a finite period of time, before being overwhelmed by chaotic dynamics. On the other hand, in the prediction of long-term climate change as a result of, for example, increasing quantities of atmospheric carbon dioxide, we have to compare the statistics of the model's representation of the existing climate with the statistics of the model's representation of the changed climate. If the model is good and includes all the important climate processes, it will be very much like those of the real atmosphere of today. The differences between these statistics provide an estimate of the climate change we can expect (for example, differences in mean temperature or interannual variability). It is worth repeating that, because of the basic chaotic nature of the climate system, there is no possibility of predicting in detail the climate for years ahead, such as forecasting the character of individual months in the year 2005. The best we can hope for on these time-scales is a quantitative estimate of how long-term climate statistics may change.

8. The breakthrough to climate prediction

The El Niño/Southern Oscillation phenomenon

Up to periods of a few seasons, perhaps up to a few years, there are several possibilities of exploiting the inherent predictability in certain variations of the climate system associated with specific mechanisms. The identification of these variations and the development of the capability of their prediction over their lifetime opens for the very first time the possibility of genuine forecasts of the likely characteristics of seasons up to a year or two ahead, at least in some regions of the world. One such global-scale feature, the El Nino/Southern Oscillation (ENSO) phenomenon (see Figure 9), is the first predictable variation that has been clearly identified, and represents the first major breakthrough to climate prediction; it is an achievement of the greatest

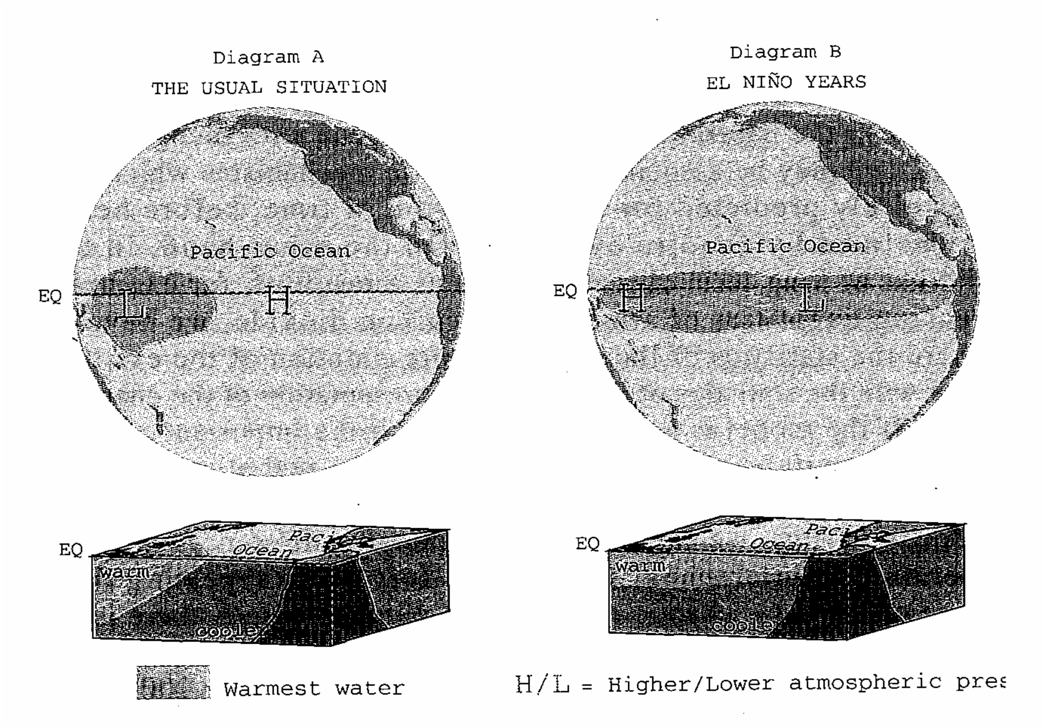


FIGURE 9. *El Niño and the Southern Oscillation*

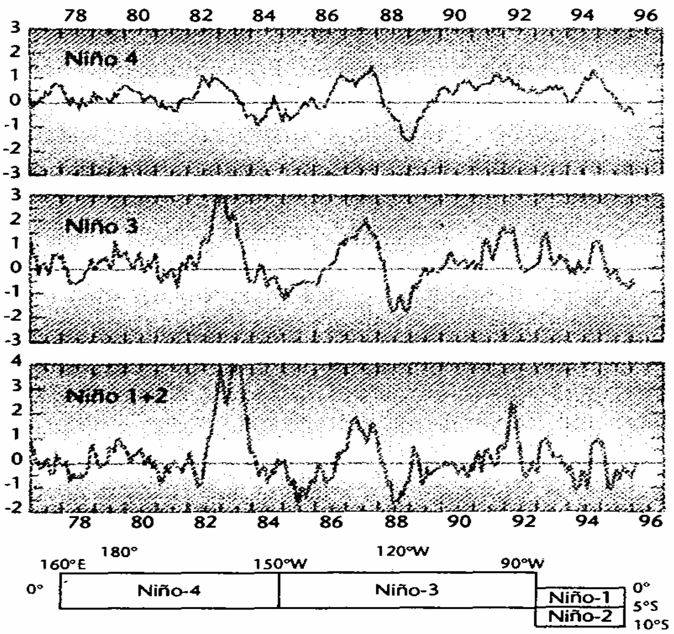
importance for the climate science research community, - with exciting potential benefits. Previously, seasonal or longer forecasts were not really feasible. Several attempts had been made using statistical or analogue techniques but these had only met with comparatively limited success, and there was only a restricted understanding of the real physical processes involved.

In fact, the periodic occurrence of El Niño has been known for many years. The term El Niño (Spanish for “Christ child”) was originally used by fishermen along the coasts of Ecuador and Peru to refer to unusually warm offshore ocean conditions that typically appeared near Christmas and lasted for several months. Fish were less abundant during these warm intervals. During the past 40 years, nine El Niflos have affected the South American coast. Most of them raised water temperatures along the coast as well as in a belt stretching 8 000 km, or 5 000 miles, across the equatorial Pacific. The weaker of these events raised sea temperatures by only about 1°C and had only minor impacts on South American fisheries. However, strong events, such as that of 1982-83 (see Figure 10), left an imprint not only on local weather and marine life, but on climatic conditions around the Earth.

Reacting to the changes in wind speed and direction associated with El Nino, the sea level at Christmas Island in the mid-Pacific rose several centimeters, and by October 1982, sea-level rises up to 30 cm had spread 10 000 km, or 6 000 miles, east to Ecuador. The sea-level rises in the east were accompanied by simultaneous drops in the western Pacific, exposing and destroying the upper layers of fragile coral reefs, thereby seriously affecting marine life. By the time conditions returned to normal in mid-1983, 25 per cent of the year’s fur seal and sea lion adults and all of the pups had died. Fisheries in Ecuador and Peru suffered heavily when the anchovy harvest failed and sardines unexpectedly moved south.

On land there were equally dramatic effects (see table on page 23). In Ecuador and northern Peru, up to 250 cm (100 inches) of rain fell during a six-month period. The abnormal wind patterns steered tropical cyclones away from their usual tracks to islands such as Hawaii and Tahiti, unaccustomed to such severe weather. Heavy rain fell over the central instead of over the western Pacific, resulting in severe droughts and disastrous forest fires in Indonesia and Australia. Winter storms battered southern California and caused widespread flooding across the southern United States. Overall the

FIGURE 10. *Equatorial Pacific sea-surface temperature anomaly (°C) for the areas indicated in the figure. Niño 1 + 2 is the average over the Niño 1 and Niño 2 regions. Anomalies are departures from the adjusted climatology* (Reynolds and Smith 1995, J. Climate 8, 1571-1583)



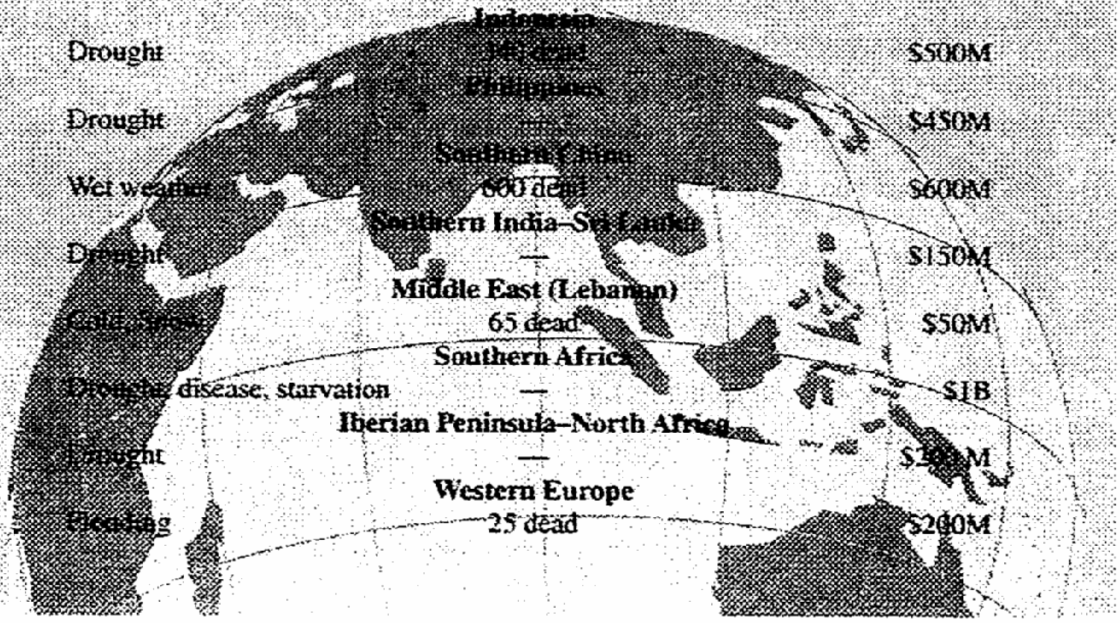
loss to the world economy as a result of this El Niño is estimated to have amounted to over US$ 8 billion.

The Tropical Ocean and Global Atmosphere programme

This 1982-83 event was a tremendous spur to studying ocean atmosphere interactions in the tropical Pacific and the climatic impacts around the world. The study, called the Tropical Ocean and Global Atmosphere (TOGA) programme, was conducted as part of the World Climate Research Programme. As a result, a large natural climate variation occurring on time- scales of a few years has now been thoroughly documented and understood. The process is as follows. The normal distribution of atmospheric mass along the equator results in a pattern of high and low pressure such that the low pressure is over the western ocean and the high pressure over the eastern ocean (see Figure 9). In certain years, the pattern reverses itself and then gradually reverts back to normal.

Effects Related to the 1982-1983 El Niño

Phenomenon	Victims	Damage
	U.S. Mountain and Pacific States	
Storms	45 dead	$1.1B
	U.S. Gulf States	
Flooding	50 dead	$1.1B
	Hawaii	
Hurricane	1 dead	$230 M
	Northeastern U.S.	
Storms	66 dead	—
	Cuba	
Flooding	15 dead	$170M
	Mexico–Central America	
Drought	—	$600M
	Ecuador–Northern Peru	
Flooding	600 dead	$650M
	Southern Peru–Western Bolivia	
Drought	—	$240M
	Southern Brazil–Northern Argentina–Eastern Paraguay	
Flooding	170 dead, 600 000 evacuated	$3B
	Bolivia	
Flooding	50 dead, 26 000 homeless	$300M
	Tahiti	
Hurricane	1 dead	$50M
	Australia	
Drought, fires	71 dead, 8 000 homeless	$2.5B
	[illegible]	
Drought	[illegible]	$500M
	[illegible]	
Drought	—	$450M
	[illegible]	
Wet weather	600 dead	$600M
	Southern India–Sri Lanka	
Drought	—	$150M
	Middle East (Lebanon)	
[illegible]	65 dead	$50M
	Southern Africa	
Drought, disease, starvation	—	$1B
	Iberian Peninsula–North Africa	
Drought	—	$2[illegible]M
	Western Europe	
Flooding	25 dead	$200M



These shifts back and forth of atmospheric mass and changes of pressure patterns along the equator are known as the Southern Oscillation. The Oscillation is irregular, but normally occurs once every 2-7 years. The changes in atmospheric pressure patterns are linked to changes in the tropical oceans. Under normal atmospheric conditions, the sea surface in the eastern Pacific is relatively cool. In El Niño years, atmospheric pressure is unusually high in the western Pacific and dry weather conditions prevail (see Figure 11). The sea surface in the central and eastern Pacific tends to be unusually warm with lower atmospheric pressure. Moreover, these changes in the Pacific are now known to be associated with other unusual and sometimes catastrophic changes around the world often like those that occurred in 1982-83 that I have just described.

The understanding achieved of the behaviour of the coupled ocean/atmosphere system in the tropical Pacific has now been built into versions of climate models. TOGA also includes a major observational component. Providing measurements particularly of the tropical Pacific Ocean sea-surface temperature and the subsurface state of the Ocean. Using these measurements in models, we are now able to predict El Niño events in the tropical Pacific and the consequent changes expected round the world in terms of rainfall, droughts and regions of heat or cold up to a year in advance. The models of El Niño have progressed to the point where they can reproduce the characteristics of a typical event and their effects on weather

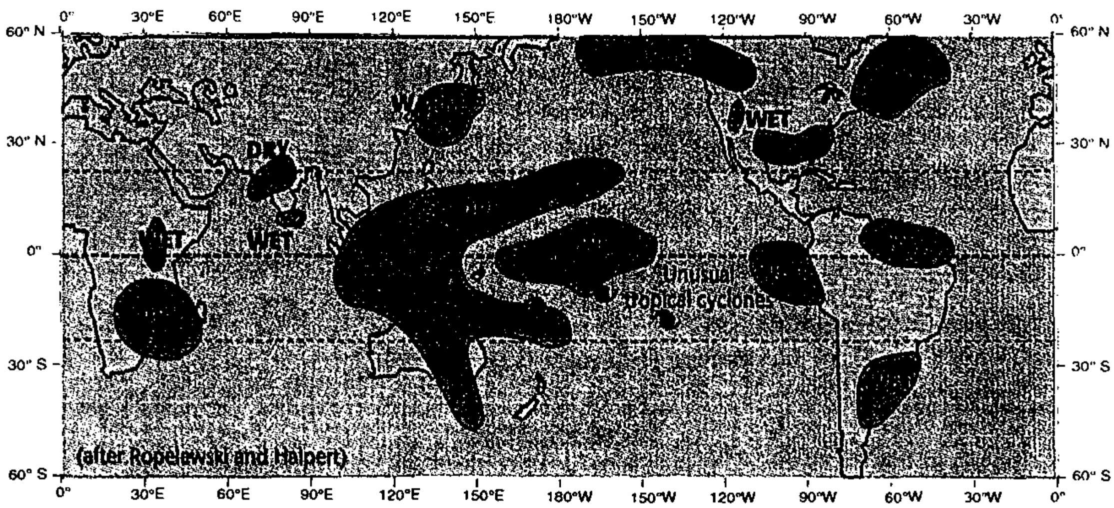


FIGURE 11. *Climate changes during El Niño*

patterns throughout the world. The results, though by no means perfect, give a much better indication of the climatic conditions that will prevail during the next few seasons than simply assuming that rainfall and temperature will be "normal". It is important to point out that, while these major strides have been made, the relationship between the El Nino, the Southern Oscillation and the monsoons have not yet been clearly defined. Progress in this area would be the key to major advances in the prediction of monsoons. The scientific community is thus working hard to improve the understanding and to explain more fully the nature of interannual variability of monsoons.

Immediate benefits of EI **Nino predictions**

Peru, among other countries, provides an excellent example of how valuable El Niño predictions can be, for as soon as the prediction for the coming season is made, farmers' representatives and government officials meet to decide on the appropriate combination of crops to sow in order to maximize the overall yield. Other countries are taking similar steps, including Australia, Brazil, Ethiopia, India and Indonesia. It is the tropical regions where the impacts of El Niño are most marked and where the accuracy of the predictions is greatest. But for many countries outside the tropics, such as Japan and the United States, more accurate prediction of El Nino will greatly benefit strategic planning in areas such as agriculture and the management of water resources. The phase of ENSO has also been used to predict, with significant success, the number of tropical cyclones in the North Atlantic well in advance. For instance, the number of tropical cyclones for 1995 was predicted to jump suddenly from below average, as it had been for over a decade, to well above normal. In fact, the actual number was well in excess of the prediction. One can visualize the enormous socio-economic benefits as officials were able to gear-up for an intense hurricane season.

There have been tantalizing indications of other predictable variations in the climate system like that of the El Nino/Southern Oscillation, but further research and study are necessary. Particularly promising lines that are being explored are the linkages between rainfall in the Sahel and anomalies in north and south Atlantic sea-surface temperatures. For some years now, predictions of Sahel rainfall in the forthcoming summer, based on the sea-surface temperature conditions in March or April, have been prepared.

The breakthrough in the prediction of climate has encouraged WMO to develop a new project — Climate Information and Prediction Services (CLIPS). Through CLIPS, countries will benefit from:

- the use of sector-specific climate information and prediction services;
- the development of networks of regional and national climate centers and their capabilities to deliver effective climate information and prediction services;
- support for interdisciplinary and user-oriented research and development to generate new applications of climate information and prediction products.

To summarize this part of the lecture, the Tropical Ocean and Global Atmosphere (TOGA) programme and the resulting accomplishment of being able to predict El Niño events in advance is a major and very exciting first breakthrough in the area of climate prediction — it is the first time that predictions have been achieved at such a time range, in which enough confidence is felt for the predictions to be used as a basis for economic decisions even if only for certain areas of the world. However, this is only the first step — scientific research is now being actively pursued to build on this foundation — particularly by trying to develop the capability of predicting the strength and duration of the monsoonal circulations that are so important in many parts of the world, particularly in India, south Asia and west Africa — and by beginning to extend the predictions to mid-latitudes.

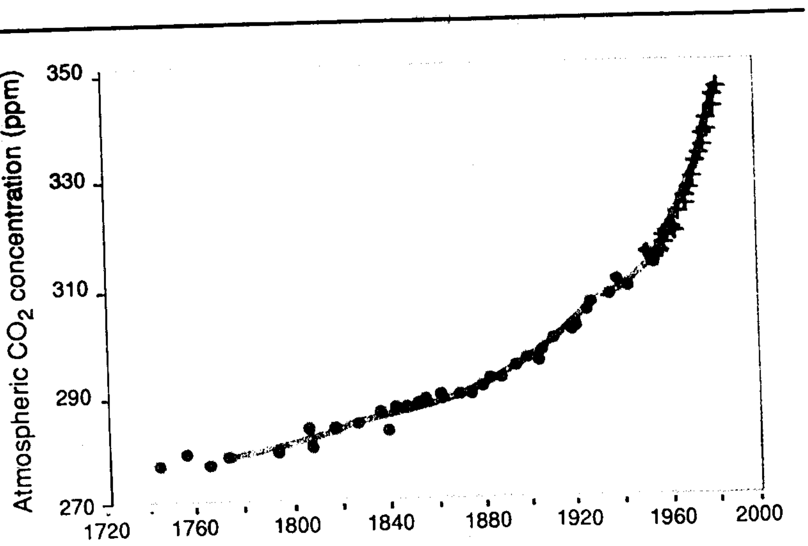
9. Longer-term prediction

The descriptions of the type and magnitude of variations that can occur, in the Earth's climate illustrate what can happen even without the effect of man's activities. If we are to be able to predict the effects of man's activity on climate, we must clearly understand the reason why climate has changed in the past. We know some of the basic factors and processes in the climate system that are likely to play a part. There is a wide variety of feedback processes involved, some of which will act to amplify a change in one direction, others which will damp that change. For instance, as climate warms, the extent of snow and ice over the Earth will tend to decrease. However, snow and ice are good reflectors of incoming radiation, therefore a decrease in snow and ice will increase radiation absorption and enhance the warming process. Also, as climate warms, the atmosphere can hold more water vapour; but water vapour, like carbon dioxide, is a strong greenhouse gas, and so this effect also automatically tends to reinforce a warming trend. Variations in solar input, the shielding effect from dust emitted into the atmosphere as a result of major volcanic eruptions, changes in atmospheric composition and changes in land use also have an important effect on climate. A range of fundamental scientific studies is needed to fully understand and predict the variability of climate. As described earlier, we have made a modest start in understanding one fairly short-term natural variation of climate, namely, ENSO events — but much more is needed. Again, the World Meteorological Organization, in the context of the Climate Variability and Predictability (CLIVAR) programme, is taking the lead, in conjunction with IOC and ICSU, in a comprehensive study of climate variability and predictability at interannual, decadal and centennial time-scales, with the objective of making the scientific breakthroughs required. I would point out that the study of monsoons and the improved predictability in this area is a particular focus of CLIVAR.

10. Anthropogenic climate change

The effects of human activities

This concluding section is certainly the most important section of the lecture, namely the assessment of man's effect on the climate system, and what has to be done about it. There is now very little question that man is already having, and will have, an increasing effect on climate as a result of emissions of greenhouse gases and other pollutants into the atmosphere from his activities, and which have now modified the atmospheric concentrations of particular trace gases quite significantly compared to pre-industrial levels. These include specifically gases such as carbon dioxide, methane, oxides of nitrogen and halocarbon compounds. Man also puts into the atmosphere suspensions of particles, known as aerosols, which result from the release of sulphur dioxide from fossil fuel combustion and from the burning of biomass. Since the pre-industrial era, carbon dioxide has increased from 280 to 360 parts per million by volume (see Figure 12), methane from 0.7 to 1.7 ppmv and nitrous oxide from 275 to 310 parts per billion by volume. These



Year

FIGURE 12. Record of the atmospheric concentration of carbon dioxide (adapted from siegenthater and Oeschger,1987). Circles refer to the composition of air bubbles trapped in Ataractic ice. Crosses are annual values measured at the Mauna Loa Observatory

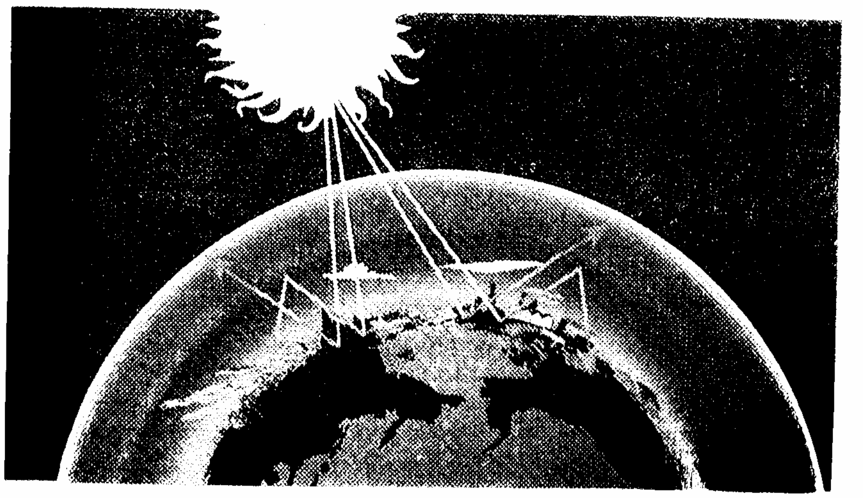
changes are important since these gases have a greenhouse effect: they are transparent to income solar radiation but absorb a proportion of the outward radiation from the Earth (i.e. like the horticulturist's greenhouse which lets in the sun's rays but retains the heat inside the glass). Thus an increase of carbon dioxide leads to a reduction in radiation able to escape from the Earth'surface-likewise for the other Gases like methane and nitrous oxide (see Figure 13).

Atmospheric reaction to emissions

Since the beginning of industrialization, the increases of greenhouse gases have resulted in an extra heating of the climate system – but it is hard to separate the change in climate as result of man's activates from the natural variations of the climate system described above. Moreover, the aerosols put into the atmosphere by man's activities have a cooling effect on climate. However, whereas the heating from greenhouse gases is more or less the same around the world, the cooling from aerosols occurs over or close to regions of industrial activity – the eastern United States, central Europe and eastern China, and is much more variable in space and time. By putting this heating from greenhouse gases, on one hand, and cooling from aerosols, on the other, into a climate model, the most recent results are giving global patterns of warming in some areas of the world, but with small or negligible warming in other, similar to the changes that have actually been observed over the past two three decades.

These results, together with other evidence, provide the foundation for suggesting that we are now actually seeing a discernible human influence on climate. An outstanding question has been to distinguish the human induced effects from the climate variability or volcanic eruptions. However, progress has recently been made in resolving this issue. Firstly, let me point out that the twentieth century global mean surface temperature is at lest as as warm as any century since at least 1400 AD.

Global mean surface temperature shows an increase 0.3 and 0.6 Celsius since the late nineteenth century and recent year have been among the



FIFURE 13. ***Greenhouse effect***

Warmest recorded (see Figure 14). Most statistical studies show that this observed warming trend is unlikely to be entirely natural in origin. Moreover, strong evidence for attributing the recent changes to human effects is emerging from detailed pattern-based studies. In these, the response of climate to the combined increases in greenhouse gases and changes in aerosol loadings, as indicated in models, is compared to the observed geographical, seasonal and vertical distributions of atmospheric temperature change. These studies are showing that the pattern correspondence is increasing with time as the anthropogenic signal grows in strength. The probability that these correspondences could occur by chance as a result of natural internal variability is very low — in particular the vertical patterns of temperature change which are not consistent with those that would be expected from any other cause.

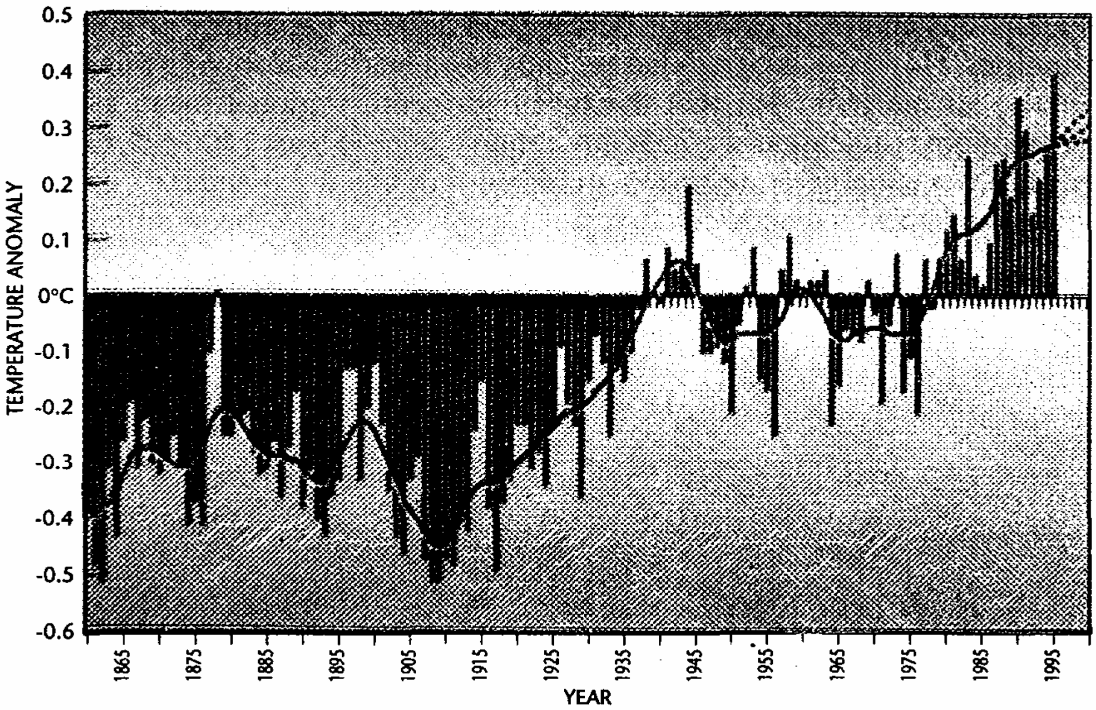


FIGURE 14. *Global land, air and sea-surface temperature anomalies (°C) are computed departures from the 1961-1990 base-period means. The fitted curve is a 21-point binomial filter. Dashed lines hint at possible future scenarios*
(adapted from Hadley Centre, Meteorological Office, and Climatic Research Unit, University of East Anglia, UK)

11. What can be done? The global response

There is thus every reason for nations to think very seriously about taking steps to mitigate possible climate change which has the potentially serious social and economic impacts mentioned earlier — the threats to agricultural production, especially in the developing world, to the world's forests, the dramatic consequences of a rise in sea level. The need to take precautions was perhaps recognized clearly for the first time in the Ministerial Declaration adopted by representatives from 137 participating countries in the Second World Climate Conference in October 1990, organized and hosted by the World Meteorological Organization. The Conference agreed that climate change was a global problem of unique character, and whilst taking into account the uncertainties in climate science, the economics and response options, considered that a global response should be implemented as soon as possible on the basis of the best available knowledge, while ensuring the sustainable development of all countries.

The persistence of the scientific community eventually led to the United Nations Framework Convention on Climate Change (UNFCCC), which entered into force in 1994. The convention sets out the blueprint for the reduction, by both developed and developing countries, of the greenhouse gas emissions well into the next century and the method of financing its implementation. It was recognized that developed countries, which are responsible for the larger part of emissions of greenhouse gases and aerosols, should take the lead in this global response. They should commit themselves to actions to reduce their contribution to global net emissions, and enter into and strengthen cooperation with developing countries to enable them to address adequately climate change without hindering the national development goals and objectives of developing countries. Additionally, it was suggested that adequate and additional financial resources would have to be mobilized and the best available environmentally-sound technologies should be transferred on a fair, favourable and affordable basis.

I would point out that the need to take precautions to try and mitigate climate change was agreed to be vital. Climate change, which is now discernible, may well accelerate in the future. The uncertainties in the actual change in climate that we may be faced with will mean that it will be far from viable to rely only on an adaptation strategy. This is particularly true with regional changes, which could well be much more dramatic locally than the expected mean global climate change, as well as possible changes in the frequency and intensity of extreme events. It is not possible to conceive of an adaptation strategy including all the wide-ranging, far-reaching measures that will undoubtedly be required for different regions of the globe. As suggested by the IPCC, the only way to proceed may be through a portfolio of actions, which would differ from country to country, aimed at mitigation of, or adaptation to, climate change, as well as improving estimates of the magnitude of changes expected.

The Conference of the Parties (COP) to the UNFCCC, the first of which was held in Berlin from 28 March to 7 April 1995, has now taken over responsibility for the lengthy process of implementing the Convention. The Berlin Conference agreed on the following:

-the establishment of a process for the adoption of a protocol on the reduction levels of greenhouse gas emissions, back to 1990 levels by the early part of next century, and for further reductions beyond;

-the methodology of calculation of sources and sinks of greenhouse gases, and to quantify agreed present and future emission levels in all countries;

-pilot projects on the joint implementation of the Convention between developed and developing countries. It is hoped that this could promote the development of low-emission technologies;

-methods of financing the implementation of the Convention. As an interim measure, the Global Environment Facility (GEF) would be the prime source for a period of up to four years.

This is a major start, and WMO has contributed positively through every stage of the process.

12. Conclusions

Over the last three decades, considerable progress has been made in the understanding of the Earth's climate system as well as in the prediction of climate change and its impacts on sustainable development. The progress achieved thus far is the result of many years of painstaking effort in the collection and analysis of climate and climate-related data from all over the world. These data confirm the increasing trend in global warming over the past century and suggest a discernible human influence on global climate. Furthermore, projections on the basis of population and economic growth, land use, technological changes, energy availability and fuel mix during the period 1990 to 2100 indicate that global warming will continue in the future and will continue to change climate.

The global concern over the impact of climate change has led to unprecedented cooperation and coordination among the nations of the world, as well as scientific organizations, academia, industry and international organizations in scientific research and policy formulation for an appropriate response strategy. A landmark instrument resulting from such collaboration is the United Nations Framework Convention on Climate Change, which is meant to counter the effects of human-induced change on the global climate. In this respect, governments should ensure that the Convention responds to the aspirations of all nations. Nations should also enhance their commitment to implement the Convention and provide the necessary support for scientific activities, including climate monitoring and research, in order to reduce the existing uncertainties in climate change prediction.

In this global undertaking, the civil society, including non-governmental organizations, has a crucial role to play in enhancing awareness at the grassroot and decision-making levels of the ongoing change in our environment. In this regard, the initiative of the Rajiv Gandhi Institute marks an important contribution to this effort. The World Meteorological Organization, as the leading authoritative scientific voice on the subject of climate and climate change, is a major driving force in the international arena in developing climate monitoring, application, research and prediction, as well as in leading the translation of today's scientific knowhow and warnings of impending climate change into action to protect the Earth's climate. WMO is therefore honoured to be associated with this undertaking of the Rajiv Gandhi Institute for Contemporary Studies.

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