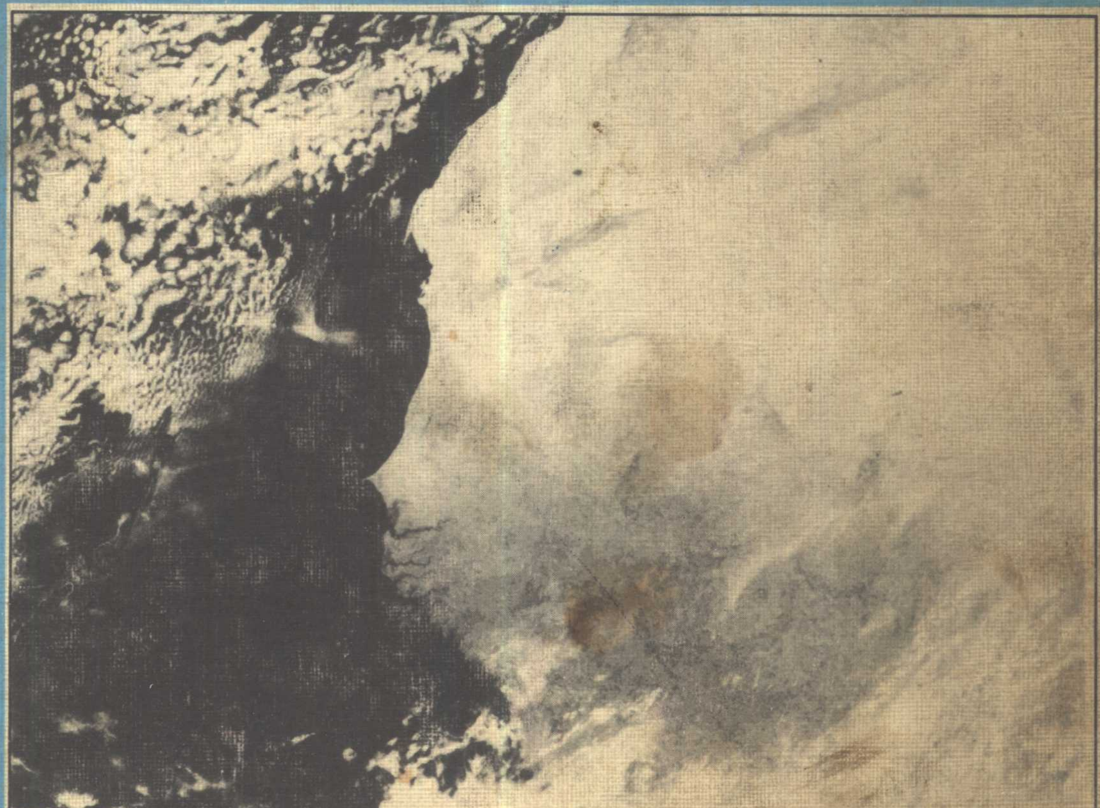
THE GLOBAL CLIMATE

EDITED BY JOHN T. HOUGHTON



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EDITED BY JOHN T. HOUGHTON
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Preface

The World Climate Research Programme (WCRP), which is the research component of the World Climate Programme, is one of the largest coordinated scientific enterprises man has tackled this century. This book has arisen from the desire of scientists involved with the World Climate Research Programme (WCRP) to explain to a wider scientific community the background, aims and main lines of research being pursued under the Programme. It is concerned with a very complex system. The Global Atmospheric Research Programme from which the WCRP developed was largely concerned with the atmosphere alone. Climate research is of necessity concerned with all components of the climate system, namely the atmosphere, oceans, ice and land surfaces and with the exchanges of heat, momentum and material (especially water) which occur between these different components.

Study of the climate system requires, on the one hand, observations with global coverage and, on the other hand, the development of sophisticated numerical models. Observations can be acquired through both remote sounding instruments mounted on satellites and through *in situ* measurements from ships, buoys, balloons, aircraft and land-based stations. Many of the techniques are at an early stage of development; for many of the observations, better coverage and higher accuracy need to be achieved. Regarding numerical models, progress is being made with the description of the physical and dynamical behaviour of various parts of the system, although in some cases serious work has only recently begun, particularly insofar as models with a global emphasis are concerned.

As will be clear from the first chapter, the emphasis of the World Climate Research Programme is on those climate changes which occur over periods of a few weeks to decades of years and on those changes which could be introduced by man's activities. Paramount among the latter is the change which could occur due to the increasing carbon dioxide content arising from the burning of fossil fuels.

The first two chapters in the volume introduce the World Climate Research Programme with its particular problems and major thrusts; after that, status reports are given of research, first in numerical modelling of the atmosphere, then in some of the major physical and dynamical processes which occur in the overall climate system or its different components. Experts from different scientific disciplines and various nations have contributed the articles.

I wish to thank members of the Joint Scientific Committee of the World Climate Research Programme for suggesting the different topics. I also wish to thank the contributors for the trouble they have taken to present their research areas in the general context of the global climate problem. Thanks are also due to the staff of the Cambridge University Press for the care they have taken and the courtesy they have shown in the preparation of the volume.

The scientific challenge of climate research is very large. By its very nature it is international in its scope; all countries of the world would be affected by the impact of major climate change. It is therefore appropriate that climate research should call for international effort. If through these articles which follow, the nature of the scientific problem and the degree of international challenge are more widely understood, the volume will have achieved its aim.

J T Houghton
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1 The World Climate Research Programme

Abstract

The objectives of the World Climate Research Programme (WRCP) are to determine (a) to what extent climate can be predicted and (b) the extent of man's influence on climate. The programme is primarily concerned with changes which occur on timescales from several weeks to several decades. WCRP has developed from the Global Atmospheric Research Programme (GARP) and like GARP is jointly sponsored by the International Council of Scientific Unions (ICSU) and the World Meteorological Organisation (WMO). The WCRP is concerned with the whole climate system, the main components of which are the atmosphere, the oceans, the cryosphere and the land, and with interactions and feedbacks which occur between these components.

Three objectives or streams of research in the WCRP have been identified, namely (1) long-range weather predictions over periods of several weeks, (2) interannual variability of the global atmosphere and the tropical oceans over periods of several years, (3) longer-term variations. Two major experiments, the TOGA (Tropical Oceans and Global Atmosphere) and the WOCE (World Ocean Circulation Experiment) have been identified as the foci of the second and third streams. For these, new modelling efforts (especially coupled atmosphere ocean models) and global observations, especially from satellites of all components (in particular the ocean) of the climate system are required.

1.1 The possibility of climate change

That climate changes on a wide range of timescales is well known from the record of the past. Over the past half million years (Fig. 1.1(*a*)), glacial and interglacial periods have alternated at intervals of about 100000 years. At the time of the last glacial maximum, 20000 years ago, ice sheets covered Canada and large areas of northern Europe and Asia. Sea ice was greatly extended (Untersteiner, 1983, this volume) and sea level was nearly 80 m lower than at present. During the last 1000 years (Fig. 1.1(*b*)) the most pronounced climatic feature has been the 'little ice age' between about 1300 AD and 1800 AD. Since that time, so far as we are able to ascertain, there has been a small general warming, at least in the northern hemisphere (Fig. 1.1(*c*), and Angell & Gruza, 1983, this volume).

Climate variation has a large impact on man's activities and on the economy of human populations. Occurrences of extreme variations in precipitation leading to droughts and floods have always been a cause of concern, increasingly so in recent years as the greater world demand for food resources, especially in developing countries, has created a greater vulnerability.

Even quite small, average hemispheric temperature changes can be reflected in large regional variatons. In the 'little ice age', for instance, winters in Europe were, on average, much more severe than now, glaciers and the cover of sea ice advanced considerably although the hemispheric average temperature only changed by a little over 1 K.

That climate changes can be induced by man's activities is an important current concern. Examples are the possibilities of man's activity influencing the growth of deserts (Rasool, 1983, this volume) and the likely change due to increasing carbon dioxide as a result of burning of fossil fuels. The concentration of atmospheric carbon dioxide will almost certainly nearly double its present value before the year 2100. One model estimate of the increase of atmospheric temperature resulting from such a doubling is shown in Fig. 1.2. About 2 °C rise in surface temperature may be expected in the tropics and mid-latitudes with a rather greater increase in polar regions. Changes in the distribution of precipitation would also be likely to occur with serious consequences in some parts of the world (Mitchell, 1983). There would also be changes in polar ice with consequent effects on the sea level. Changes in the concentrations of other minor atmospheric constituents, for instance the oxides of nitrogen or aerosol, can also have climatic consequences of a similar amplitude (Kondratyev & Moskalenko, 1983, this volume).

Estimates with current models of possible climatic changes from various causes, both so far as global average effects and the regional variations are concerned, need to be treated with great caution, however, because the models do not yet include many of the important feedback processes. It is because of the importance of understanding the extent to which man's activities can cause climate change, together with our lack of understanding of the mechanisms behind the natural variations of climate that concentrated international effort on the climate problem is being directed.

1.2 The World Climate Research Programme (WCRP)

The WCRP is a component of the World Climate Programme; its objectives are to determine:

(1) to what extent climate can be predicted;

(2) the extent of man's influence on climate.

The programme is not primarily concerned with timescales of millenia or the even longer timescales of the major ice ages, although any understanding of climate must in the end account for the major changes which have occurred in the prehistorical past. The programme's principal aim is the understanding of changes which occur on timescales from several weeks to several decades, a timescale consistent with the feasibility of obtaining comprehensive data sets, the practicalities of numerical modelling, and the major concerns of planners and decision makers.

Although climate is determined by complex interactions on the planetary scale, the WCRP is certainly not limited to the consideration of global average climate; regional climatic anomalies

Fig. 1.1. (*a*) Climate of last half million years deduced from measurements of oxygen isotope ratio in plankton shells which relate to global ice volume. (After Hays, Imbrie & Shackleton, 1976.) (*b*) Climate of last 1000 years estimated from evidence relating to east European winters. (After Lamb, 1966.) (*c*) Climate of last 100 years as evidenced by changes in average annual temperature of northern hemisphere. (After Mitchell, 1977.)

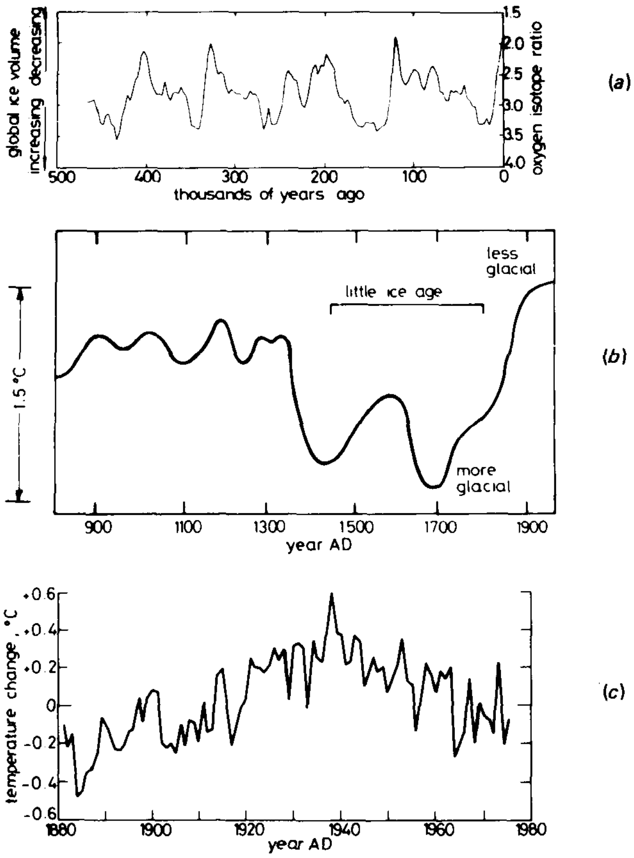
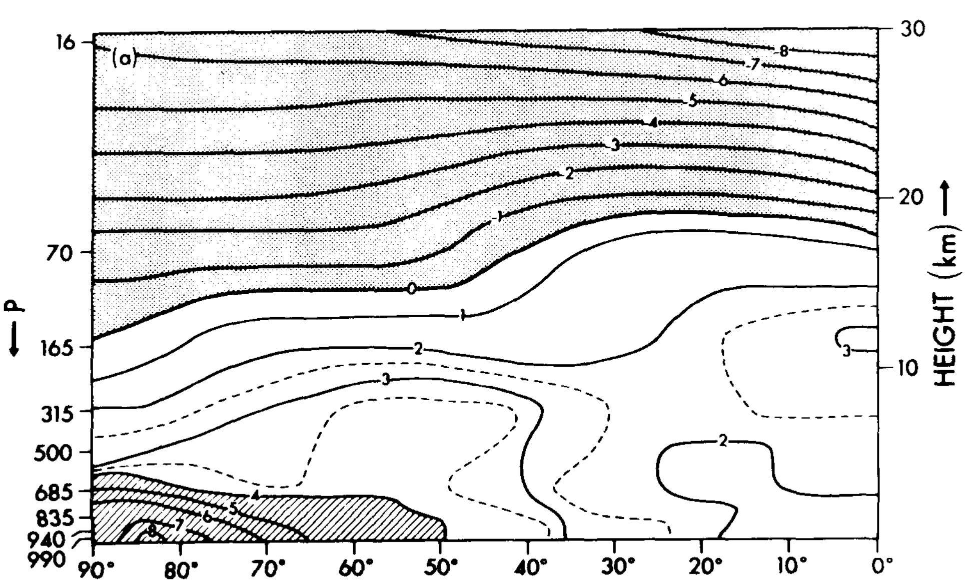


Fig. 1.2. Changes in atmospheric temperature (K) which would be expected to occur if the atmospheric CO_2 content were doubled as predicted from a model. (After Manabe & Wetherald, 1980.)



which may develop over periods of months or years are more significant and clearer manifestations of climatic variations. The WCRP is thus concerned with space scales ranging from about 1000 km to global, the lower limit of 1000 km being roughly consistent with the lower limit of timescales of several weeks.

The WCRP is organised internationally by the Joint Scientific Committee (JSC) and the Joint Planning Staff (JPS), both jointly sponsored by the World Meteorological Organisation (WMO) and the International Council of Scientific Unions (ICSU). The JPS is based at the WMO Headquarters in Geneva.

1.3

The Global Atmospheric Research Programme (GARP)

The World Climate Research Programme has developed from the Global Atmospheric Research Programme (GARP) of the 1970s – a programme which has its beginnings in the early 1960s. In an address to the United Nations in 1961, President Kennedy appealed for 'future cooperation efforts between all nations in weather prediction and eventually a weather control'. Stimulated by Kennedy's remarks, following several years of discussion (Ashford, 1982) the GARP was formulated and, in 1967, a joint organising committee (JOC, the predecessor to the JSC) and a joint planning staff (JPS), both jointly sponsored by WMO and ICSU, were set up. The main aim of the programme was to observe the global atmosphere in sufficient detail so as to investigate the way in which different scales of atmospheric motion are organised and how they interact, hence to determine the extent to which the larger-scale motions (1000 km in size and above) can be predicted by numerical models.

After an experiment called the GARP Atlantic Tropical Experiment (GATE) in 1974, whose purpose was to make detailed observations over a period of several months of the particular features of the atmospheric circulation in the tropical Atlantic, the programme culminated in the Global Weather Experiment mounted in 1979. For this experiment, the global system of weather observations was enhanced to cover the globe in a sufficiently comprehensive way (Figs. 1.3 and 1.4) and in a number of institutions around the world a capability in global circulation modelling of the atmosphere was developed based on the largest computers available. First results from the experiments have shown that, with data from the Global Experiments, prediction of the detailed structure of the global circulation can be made up to about five days ahead, and that each improvement either in the data, in its method of assimilation, or in the description of the dynamical or physical processes in the models, leads to a lengthening of the period of prediction.

1.4

The climate system

The GARP was concerned with the atmosphere contained between its upper and lower boundaries. At the upper boundary, solar radiation enters the atmospheric system; some solar radiation is reflected out again, infra-red emitted radiation also leaves the top of the atmosphere. The lower boundary is land, ocean or ice, the state of which, for the purpose of GARP models, was considered as defined and fixed. When dealing with the longer periods addressed by the WCRP, dealing with the atmosphere alone is not sufficient; all components of the climate system are involved and have to be considered. We can list them as follows (Fig. 1.5):

(1) the atmosphere, which comprises the earth's gaseous envelope and which is the most variable component of the system. The lower atmosphere possesses a characteristic thermal response time to imposed changes of about one month;

(2) the oceans, which absorb most of the solar radiation incident on their surface and which, because of their high heat capacity, represent a large energy reservoir. The oceans transport about as much heat as does the atmosphere from the equatorial regions to the polar regions (Woods, 1983, this volume). The upper layers of the oceans interact with the overlying atmosphere or ice on timescales of months to years while the deeper ocean waters have thermal adjustment times of the order of centuries;

(3) the cryosphere, which comprises the continental ice, mountain glaciers, surface snow cover and sea ice (Untersteiner, 1983, this volume). Snow cover and the extent of sea ice show large seasonal variations. The glaciers and ice sheets change much more slowly; variations in their volume are closely linked to variations in sea level;

(4) the land surface including the biomass within or above

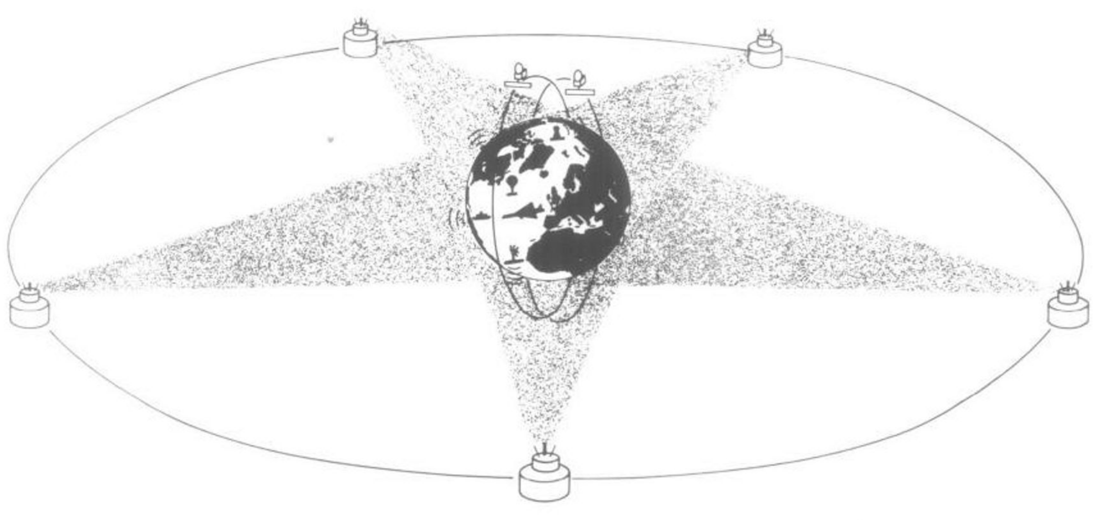
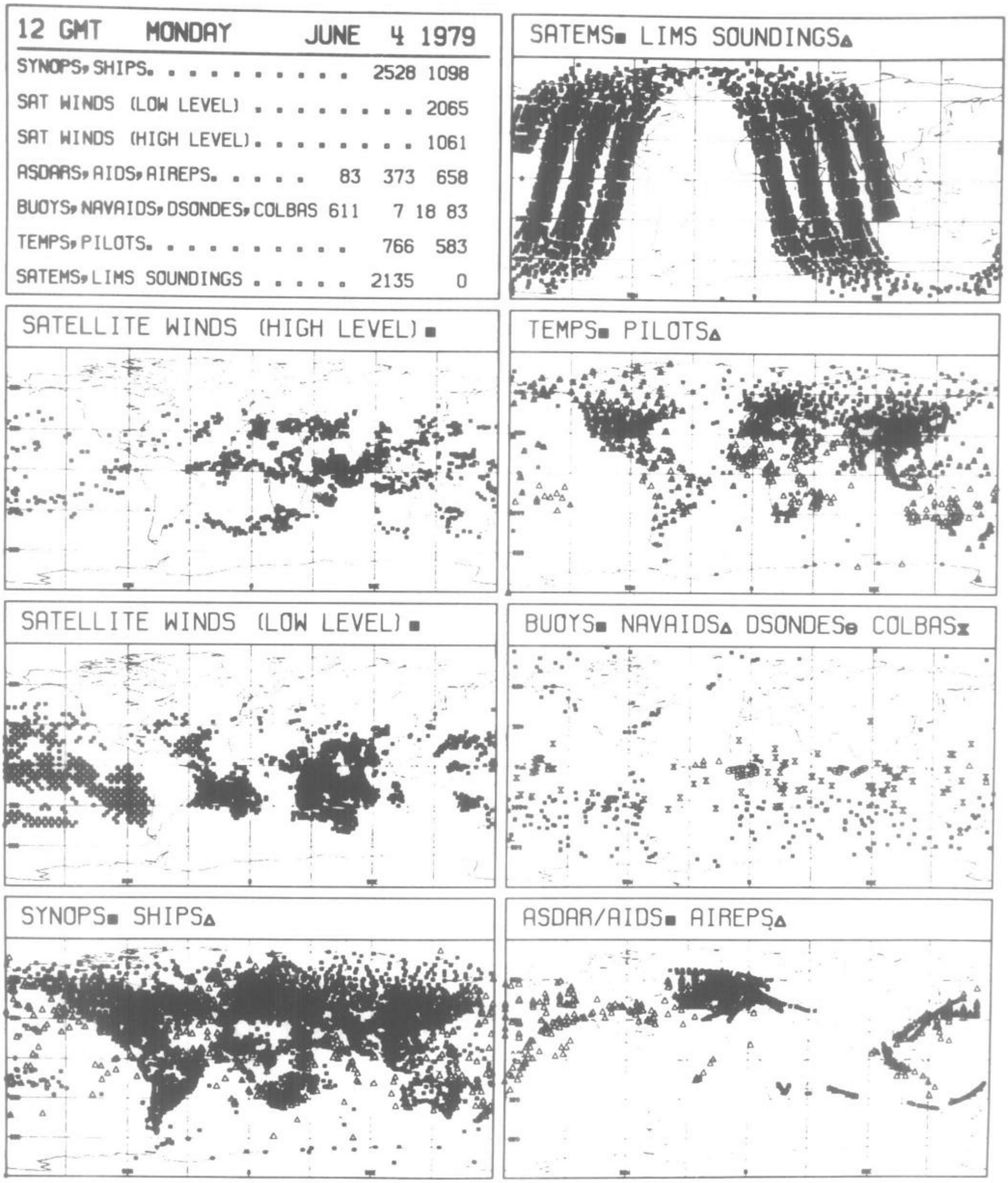


Fig. 1.3. System of five geostationary and at least two polar orbiting satellites in place for the Global Weather Experiment in 1979.

Fig. 1.4. Data distribution at the European Centre for Medium Range Weather Forecasting for 4 June 1979, 12 GMT ± 3 h. The diagrams show, respectively, the coverage of satellite winds from tracking cloud images from geostationary satellites (top two on left-hand side); surface observations from land stations and ships (bottom left-hand side); satellite temperature soundings (top right-hand side); radiosonde and pilot balloon ascents (upper middle right-hand side); buoys, drop-sondes and automatic stations (lower middle right-hand side); and aircraft observations (bottom right-hand side). (After Bengtsson *et al.* 1982.)



it, and also including those parts such as lakes, rivers and ground water which are important components of the hydrological cycle. Characteristic times for changes in the land surface vary from weeks for agricultural land to decades or centuries for some major forest areas.

Interactions between different components of the climate system occur in many ways. Exchanges of heat (through absorption and emission of radiation, air movement, evaporation of water and precipitation), water and minor chemical constituents (for example, CO_2, Bolin, 1983, this volume) between the land, ice or ocean surface occur on all timescales. The surface is also an important source of airborne particulates, through, for example, volcanoes, dust from deserts or salt particles from sea spray. These in turn, through radiative processes within the atmosphere, can have a significant climatic impact (Kondratyev & Moskalenko, 1983, this volume).

1.5

Climate feedbacks

A large number of feedback processes may be identified within the interactions which occur within the climate system. Some may act to amplify variations within the system (positive feedback) while others act to dampen them (negative feedback). Important examples of simple feedbacks are:

(1) ice–albedo feedback. An ice or snow covered surface reflects away nearly all the solar radiation incident on it, thus leading to further cooling of the surface. If melting of a part of the cover should occur, absorption of solar radiation warming the underlying land or water will lead to further melting – an example of positive feedback;

(2) water vapour–radiation feedback. An increase in temperature at the surface will lead to increased water vapour which, because of its opacity in the infra-red, acts as a radiation blanket over the surface thus further increasing the surface temperature – another example of positive feedback;

(3) cloud–radiation feedback. An increase of temperature at the surface will lead to increased water-vapour content, hence increased cloud cover will be expected. Increased cloud will reduce the amount of solar radiation reaching the surface, which will tend to reduce the surface temperature – an example of negative feedback. Some positive feedback also occurs through the blanketing effect of the cloud.

An illustration of the effect of including the first two of these feedbacks in a numerical model is shown in Fig. 1.6 where the results are shown of experiments on the effect of doubling the carbon dioxide content of the atmosphere with a model similar to that employed in obtaining Fig. 1.2. The effect of ignoring either feedback (1) or (2) above is to reduce the sensitivity of atmospheric temperature to increased carbon dioxide content by about a half.

Fig. 1.6. Model calculations of the sensitivity of the surface temperature to a doubling of the CO_2 content for the cases of full calculation including feedbacks (*a*) fixed ice snow cover (*b*) fixed meridional transport of latent heat (*c*) fixed absolute humidity (*d*) (After Chou *et al.*, 1982.)

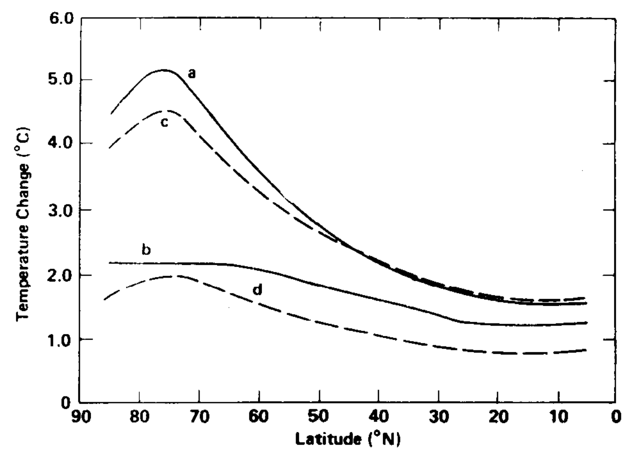
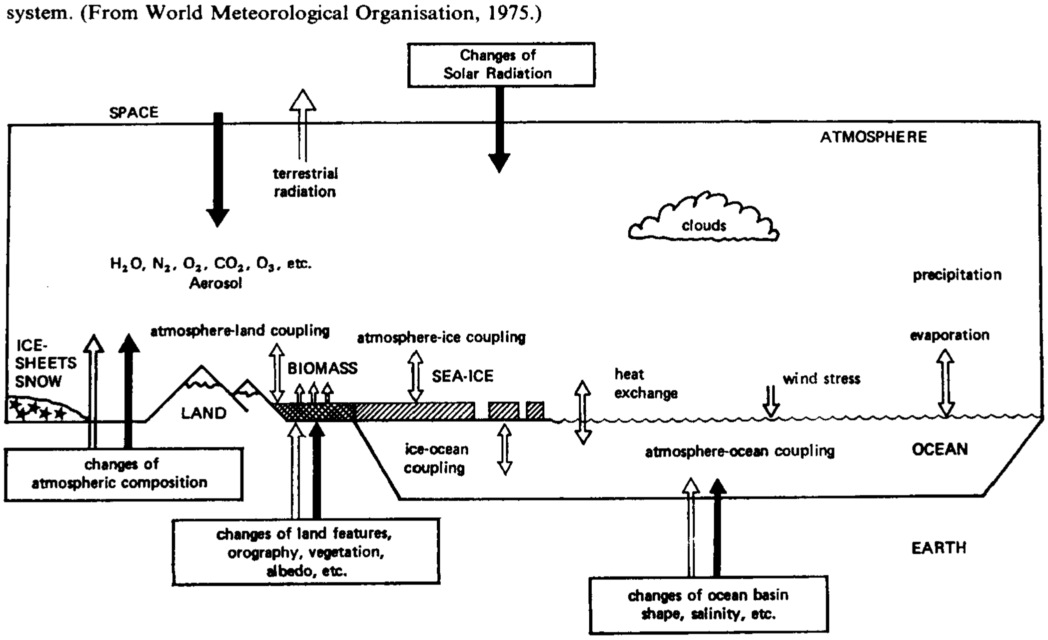


Fig. 1.5. Schematic illustration of the components of the climate system. (From World Meteorological Organisation, 1975.)



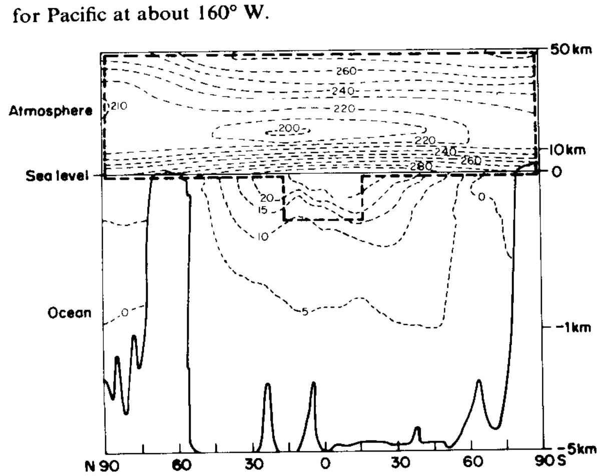
These examples and others are discussed in more detail in the chapters which follow (see especially Webster & Stephens, 1983, and Kondratyev & Moskalenko, 1983, this volume). It must be understood, of course, that the interactions and feedbacks in the whole climate system are very complex; no one process can be considered in isolation. The overall stability of the climate system as we know it must result from a whole variety of internal adjustment processes which as yet we only very partially understand.

1.6
Three research objectives or 'streams'

The knowledge acquired on the space and time structure of climate variations, and the scientific insight gained during recent years of climate research, have led to the formulation of the goals of the WCRP in terms of three objectives or 'streams' of climate research, each corresponding to a different kind of climate predictability and also to a different timescale. The first stream aims at establishing the physical basis for the long-range prediction of weather anomalies over periods of several weeks. The second stream is concerned with the interannual variability of the global atmospheric climate and the tropical oceans over periods of one to several years. Finally, the third stream addresses the problem of long-term variations and the response of the planetary climate to natural or man-made forcing factors over periods of several decades. This third stream of climate research is therefore particularly relevant in the establishment of the physical basis for the sensitivity of climate to external influences such as the increase of the atmospheric carbon dioxide concentration.

The first stream takes into account and aims to predict variability in the atmosphere, variability over short timescales of the land surface, but takes the ocean surface and sea ice to be a fixed defined boundary. The second stream takes into account and aims to predict, in addition, variability over longer timescales in the tropical oceans, and the third stream considers all components of the climate system which vary over timescales of weeks to several decades. Fig. 1.7 illustrates the parts of the system addressed by the three streams.

Fig. 1.7. Illustrating the regimes relevant to the three streams of climate research namely: stream 1: atmosphere alone with fixed lower boundary; stream 2: as stream 1 plus tropical ocean (approximately denoted by heavy dashed line); stream 3: complete system. Atmospheric cross-section shows isotherms for northern hemisphere winter. Ocean cross-section shows isotherms for Pacific at about 160° W.



The major tools of the research programme are observations on the one hand and theoretical models on the other. We have seen that a global observing system for the atmosphere was developed during the GARP. For the WCRP, observations of all components of the climate system will be required; indications of the extent of these requirements will be mentioned in Section 1.10; further details will be found in the following chapters of this volume.

Regarding modelling, global circulation models of the atmosphere were developed for the GARP. These need further refinements for the WCRP in ways that are outlined below. Further, for the WCRP, appropriate models for the other components of the climate system and of the processes at the interfaces between these components (for example, processes at the land surface) need to be developed and means of coupling the models together devised. Further discussion of the modelling problems are given in later chapters of this volume, especially those by Leith, and by Simmons & Bengtsson.

1.7
The first stream of climate research: the physical basis for long-range weather forecasting

It is well recognised that there exists a theoretical limit of about two weeks to the predictability of individual weather events; beyond this limit, the relatively fast, non-linear fluid dynamical interactions within the atmospheric flow itself produce unpredictable meteorological variations which may appropriately be called weather noise. Studies based on the observation of the actual behaviour of the atmosphere have indicated, however, that slower variations exist above the level of the weather noise. These variations are generally associated with the larger scales of atmospheric motions and timescales of the order of one month. Thus the persistence of weather patterns observed in the real atmosphere appears to be longer than usually demonstrated by numerical models of the atmospheric circulation, possibly because of the existence of quasi-stable circulation regimes such as the blocking situations which are intermittently observed at mid-latitudes. Longer persistence may also be caused by the slower evolution of land or sea surface boundary conditions, forcing, in turn, a corresponding evolution of the atmospheric flow. For instance, because variations in the fluxes of heat and water vapour at the interface with the oceans influence the atmospheric circulation on timescales of a few weeks, sea surface temperature anomalies which generally show substantial persistence constitute an important predictor for long-range weather forecasts. The first stream of climate research thus aims at understanding those aspects of atmospheric dynamics and thermodynamics which could account for the longer predictability of large-scale atmospheric circulation regimes, and at establishing the physical basis for improved long-range weather predictions on timescales of one to two months.

To achieve this requires the following improvements:

(1) a substantial reduction of systematic errors in numerical weather forecasting models, which cause long-range weather predictions to drift toward unrealistic mean atmospheric flow conditions and away from the actual behaviour of the real atmosphere. This, in turn, requires other improvements namely (2)–(4) below;

(2) a better representation of the effect of terrain roughness and mountains on model atmospheric flows;

(3) better simulation of clouds and the associated radiation fluxes in numerical models (Webster & Stephens, 1983, this volume);

(4) refined estimates of the fluxes of momentum, heat and water vapour from the land surface, taking into account the interplay between soil moisture, vegetation, sea ice and the atmospheric boundary layer (see Mintz, 1983, this volume).

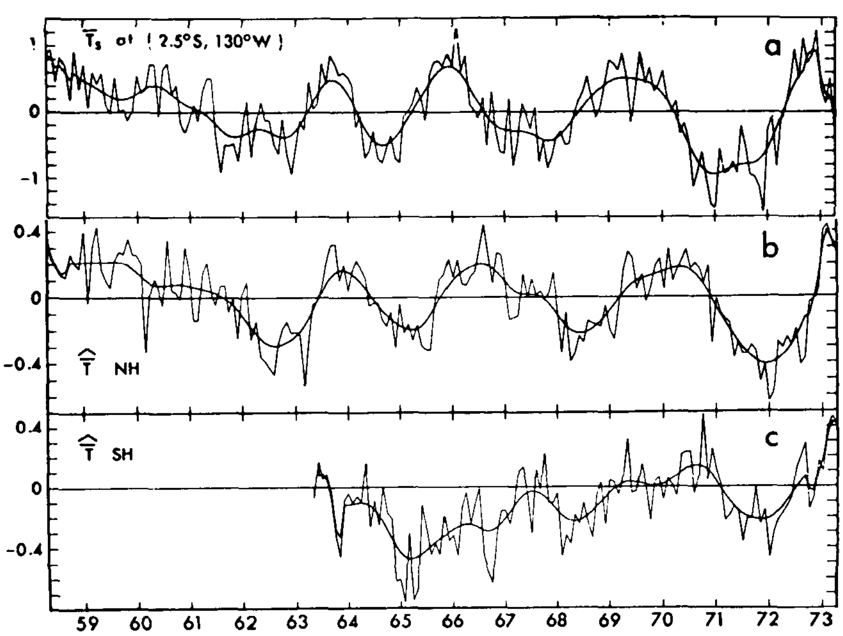
1.8 The second stream of climate research: interannual variability

A growing body of evidence is emerging from observations, indicating that worldwide climatic changes in middle and high latitudes, as well as climatic events on land within the equatorial zone, are related to year-to-year variations in the tropical ocean and the overlying atmosphere. It was in the 1920s that Sir Gilbert Walker first established remote influences in the tropical atmosphere, which were shown to be associated with a large shift of air mass. This phenomenon, which became known as the Southern Oscillation, is manifested by high atmospheric pressure in northern Australia and low pressure on the central South Pacific in one phase, while opposite pressure anomalies develop during the alternate phase. The cause for the persistence of each phase for periods of several months to years was unknown until later work established that the atmospheric pressure differences were related to changes of the sea surface temperature and mean sea level in the islands of the equatorial Pacific Ocean. Thus, the ocean dynamics driven by the atmospheric winds provide the memory which allows the anomalous atmospheric regime to persist.

The effect of this coupled atmospheric and oceanic behaviour is now believed to extend throughout the whole of the tropics. Analysis of 100 years' climatological record has shown that deficient monsoonal rains over India are associated with positive sea surface temperature anomalies in the eastern tropical Pacific Ocean, known as El Nino events (Angell & Gruza, 1983, this volume). Similar connections exist in the tropical Atlantic as far as the Gulf of Guinea where it has been established that warm sea surface temperature in the western tropical Atlantic is associated with droughts in north eastern Brazil. Similarly, warm western Pacific waters are related to droughts in China. These relationships are especially significant because the tropical zone accounts for a large part of the total energy release in the atmosphere. Further, there is also evidence of long-range correlations or teleconnections between the tropical oceans' temperature anomalies and the climate in mid-latitudes, particularly in the winter hemisphere (Fig. 1.8, and Angell & Gruza, 1983, this volume).

In addition to this empirical evidence, theoretical arguments support the idea that the atmosphere and oceans interact more effectively in the tropics. The vanishing of the Coriolis force allows the existence of basin-wide longitudinal oscillation modes trapped in the vicinity of the equator. The tropical oceans therefore exhibit relatively fast dynamic and thermal responses with time constants commensurate with the seasonal variations of the atmospheric circulation regime, thus allowing a strong coupling between the two media. The strongest oceanic signal of this nature has been found in the equatorial Pacific: its most striking manifestation, the El Nino event already mentioned, consists of the appearance of a strong positive sea surface temperature anomaly which develops off the coast of South America over a period of several months. A strong positive anomaly also develops in the central Pacific and persists for periods as long as 18 months. The faster response of tropical oceans has another important scientific implication: it makes it possible to design a first-order model of the tropical oceans interacting with the atmospheric circulation but essentially uncoupled from the mid-latitude ocean circulation.

Fig. 1.8. (*a*) Time series of monthly mean sea surface temperatures (K) in the region near 2.5.° S, 130° W in the eastern Pacific Ocean. (*b*) and (*c*) Time series of atmospheric temperature averaged vertically and horizontally over the entire mass of the northern hemisphere (b) and southern hemisphere (*c*). (After Oort, 1982.) The 1963–73 mean annual cycle has been removed.



To simulate what occurs in an El Nino event, an efficient and relatively simple model based on the free surface equations, but with active thermodynamics, has been developed by Anderson (1983 and private communication). In the model, wind stress is applied simulating the change of the Walker circulation superimposed on the normal flow in the region of the equatorial Pacific. A decrease in the zonal stress arising from the Walker circulation produces an oceanic response in the form of a Kelvin wave propagating from west to east. Fig. 1.9 shows the sea surface temperature anomaly predicted by the model 100 days after the decreased stress compared with the observed sea surface temperature anomaly at the peak of an El Nino event. Other major features of El Nino events, such as the occurrence of cold anomalies, show up in the model, demonstrating that considerable progress has been made in understanding the basic physics and dynamics underlying the oceanic response to atmospheric forcing in the equatorial regions.

So far as the tropical atmosphere is concerned, its special character makes it particularly sensitive to even modest variations of the ocean surface temperature through a strong modulation of the availability of moisture for the release of latent heat into the atmosphere. Simple models (for instance, Gill, 1980) illustrate the dynamic response of the tropical atmosphere to tropical sea surface temperature anomalies. When such anomalies are introduced into more-elaborate general circulation models (Simmons & Bengtsson, 1983, this volume), features of the circulation are generated which are similar to those shown in observational studies of the connections between sea surface temperature anomalies and atmospheric circulation. It appears that the interaction of the global atmosphere with the tropical oceans alone accounts for the larger part of the predictable variability of the earth's climate over time periods of one season to several years.

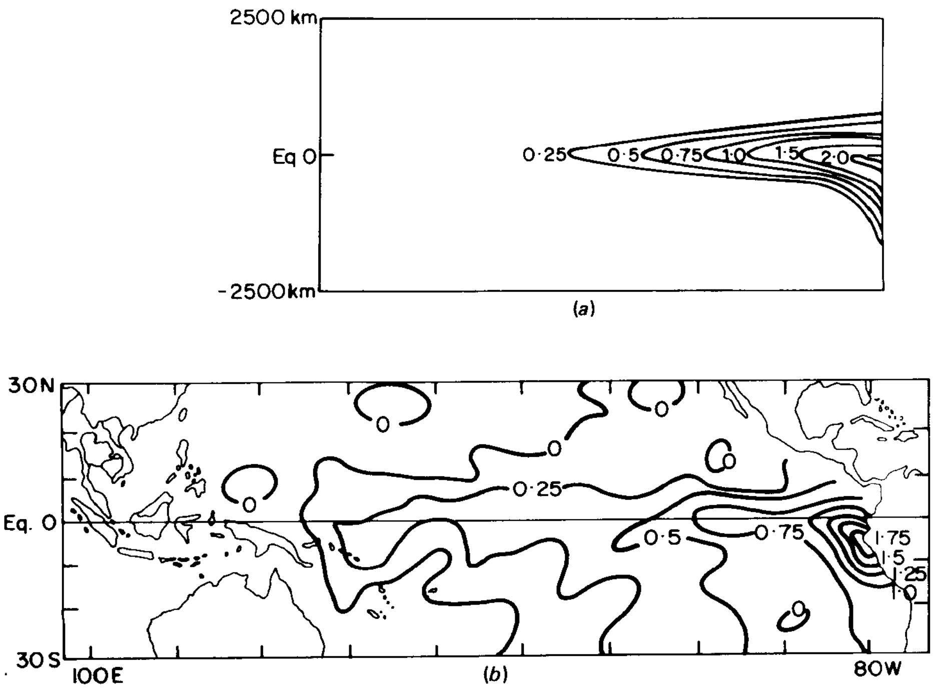
The objective of the second stream of climate research is therefore to understand and model the coupled variations of the global atmosphere circulation with the basin-wide transient modes of the tropical Atlantic, Pacific and Indian Oceans, and a programme with the acronym TOGA (Tropical Ocean and Global Atmosphere) has been constituted as the main focus of the second stream of the WCRP.

Because the responses of the three major tropical ocean basins are linked only through their interaction with the global atmosphere, an observation and ocean modelling strategy for each individual basin may be planned independently of the others. This is the path being followed by the international oceanographic community, represented by the Committee on Climatic Changes and the Oceans (a joint committee between the International Oceanographic Commission (IOC) of UNESCO and the Scientific Committee on Ocean Research (SCOR) of the International Council of Scientific Unions), which has joined the JSC in the TOGA programme. The representations of the general atmospheric circulation needed for modelling interannual climate variations do not differ in a major way from the level of refinement required for the long-range weather forecasts as described above for stream one.

1.9 The third stream of climate research: long-term climatic trends and climate sensitivity

The climate of the earth is unique in the solar system in that it involves not only an atmosphere and a land surface, but also a global ocean which absorbs a large fraction of the incoming solar energy, transports this energy in the form of heat on a global scale, supplies a global hydrological cycle with the formation of clouds, precipitation and sea ice and also intervenes strongly in the distribution of radiatively active minor constituents such as CO_2.

Fig. 1.9. (*a*) Sea surface temperature anomaly (K) as predicted for a simulated El Nino event by an ocean model due to Anderson (private communication). (*b*) Sea surface temperature anomaly (K) for the peak phase of the El Nino averaged over six events. (From Rasmusson and Carpenter, 1982.)



The currents that flow around the world oceans transport heat at a rate which is comparable to the transport by atmospheric winds, so that the seasonal and annual energy and water budgets of the earth can only be balanced globally if account is taken of both atmosphere and oceans. Not only does the thermal inertia of oceans regulate the seasonal temperature excursion of neighbouring land areas, but the meridional transport of excess heat absorbed in the tropical zone by the ocean currents controls the mean meridional temperature profile and thereby regulates the regime of atmospheric winds. The variations of the atmospheric climate over periods of several years to several decades or longer can only be fully understood on the basis of a description of the coupled dynamics of the global atmosphere and the global ocean. Also the oceans will strongly control the response of climate to external stimuli such as the man-induced increase of carbon dioxide concentration in the atmosphere. Because it is a very large heat reservoir, the global ocean could slow down the warming trend induced by excess CO_2 and delay the effect by as much as several decades. In addition, the oceans provide a large storage capacity which now contains about half the total excess CO_2 released recently in the atmosphere: reliable oceanic circulation models are required in order to estimate the rate of penetration of this chemical anomaly from the upper mixed layer of the ocean into the deep water. Consequently, the strategy for understanding the variations of climate over periods of 10 – 100 years and, especially, climate trends which may result from various forcing factors such as the increase of atmospheric CO_2, must include, in addition to the scientific advances already required in the first and second stream of climate research, a substantial improvement of our understanding of the global ocean circulation (Wunsch, 1983, this volume).

Dynamic and thermodynamic processes occurring inside the ocean determine the detailed character of its circulation, including the permanent large-scale currents and gyres, and the transient eddies which may be the oceanic equivalent of 'weather'. A model designed to compute the large-scale ocean heat transport from the surface boundary conditions must accurately describe the surface fluxes of energy, water and momentum which drive the ocean circulation and adequately simulate the circulation regime of the ocean, including both mean and eddy fluxes.

The development of global circulation models of the oceans, which include a good description of the exchanges with the atmosphere at the surface and which also can be coupled to general circulation models of the atmosphere, is one of the main aims of the World Ocean Circulation Experiment (WOCE) which is a primary focus of this third stream of climate research. Resulting from the data acquired during WOCE, estimates will be made of the heat transports by the ocean circulation at different locations and the variability of these transports from year to year.

Plant and animal life on earth depend on the cycling of chemical elements such as nitrogen, oxygen, carbon and sulphur through the soil, air, water and the biomass itself, as well as purely climatic factors such as solar radiation, temperature and precipitation. On the other hand, the extension, height, albedo and water-transfer properties of vegetation influence very significantly the processes at the land–air interface, which determine the fluxes of momentum, heat and water vapour into the atmosphere. Since the variable geographical extension and the nature of vegetation will respond to climatic variations over periods of years to decades, natural or man-made terrestrial ecosystems must be considered as interactive components of the climate system for the study of the long-term sensitivity of climate.

Because of the similarity of the various long-term climate sensitivity problems presented by the changing environment, the third stream of climate research may well be focused on one typical sensitivity problem, for example the quantitative assessment of the time-dependent response of the planetary climate to an increase in atmospheric CO_2. This strategy will not, however, detract from giving attention to the study of other significant factors such as the effect of tropospheric and stratospheric aerosols, the effect of radiatively active minor molecular constituents, the consequence of variations of solar activity and solar radiation, and the secular variation of the earth's orbit. With this in mind, in addition to what has already been included in the first and second streams, the two main components in the third stream of climate research will be the study of the coupled dynamics of the global atmosphere and the global ocean, including the role of sea ice and possibly the continental ice sheets, and the study of the processes involving the interaction of climate with terrestrial ecosystems.

1.10 Observational requirements

In the last sections we have explained the aims of the three 'streams' of the WCRP and detailed some of the major areas of theoretical work which need to be tackled. In this section, we address the observational requirements. Detailed specifications of these in connection with the three streams are being worked out by a number of international working groups. Here we can only describe the requirements in rather general terms, mentioning in particular the satellite observations that are relevant (Houghton, 1981).

For the first stream, that is, for long-range forecasting, the following will be needed:

(1) the existing global network of meteorological observations (see Figs. 1.3 and 1.4), including complete coverage around the equator by geostationary satellites and continuous observations from polar orbiting satellites. The satellite monitoring of the surface temperature of the global oceans is an important requirement for describing the surface forcing anomalies which may account for a good part of the predictable variability of weather on timescales of several weeks. Very high accuracy (better than 0.5 K) is needed for this particular measurement. Current satellite techniques approach this accuracy; new methods under development should enable it to be exceeded (Harries *et al.*, 1983);

(2) more-refined interpretation of observations of clouds from meteorological satellite images. The WCRP has defined the International Satellite–Cloud Climatology Project ISCCP whose purpose is to acquire a 5-year cloud climatology so as to establish the statistics of cloud variability over the period and to enable better descriptions of cloudiness and the associated radiation field to be incorporated into numerical models;

(3) more-refined interpretation of satellite observations of the land surface in terms of quantities which can be employed to describe the surface fluxes of heat and water vapour.

For the second stream, the major requirements additional to those listed above are for observations over tropical regions of the heat content of the upper layer of the ocean, sea surface stress, and sea surface topography (from which surface currents can be derived). Such observations can be made with limited coverage from ships, buoys and island stations, but for adequate coverage over the three tropical ocean basins, satellite observations will be required. The Seasat satellite, in 1978, demonstrated the feasibility of utilising radar scatterometer observations to measure surface stress (Fig. 1.10) and radar altimeter observations to determine the surface topography (Fig. 1.11). All these measurements need to be made not only with good coverage but with high accuracy. Observations of sea ice coverage are also required for stream two; these can be provided by imagery from satellites with passive microwave radiometers.

For the third stream of climate research, global observations of the ocean surface are, of course, required, of the same kind as are necessary for the tropical oceans for stream two. Measurements are also needed of the thermohaline structure and motion within the oceans. In addition to observations from ships, promising new techniques such as acoustic tomography are being developed; further details are given by Wunsch (1983, this volume) and by Munk & Wunsch (1982). A further requirement for stream three is that of accurate measurement of the radiation fluxes from satellites to determine the net energy input and its distribution at the top of the atmosphere, and to provide information required for the estimation of energy fluxes at the ocean surface and of heat transport within the oceans.

For experiments such as TOGA and WOCE, highly co-ordinated sets of observations will be required. For this reason, the JSC is proposing that a five-year period in the late 1980s and early 1990s be denoted an intensive period of ocean observation, during

Fig. 1.10. SASS wind vector comparisons with buoy reports during study in Gulf of Alaska. (After Linwood Jones *et al.*, 1979.)

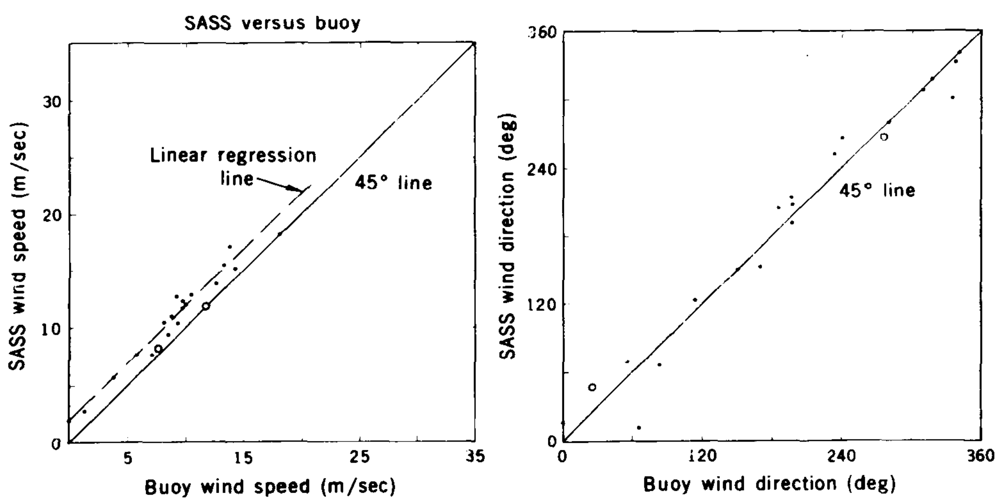


Fig. 1.11. Global circulation of the oceans as observed from radar altimetry from the satellites Seasat and Geos-3 by Cheney & Marsh (1982). Contours show ocean surface topography in cm relative to GEM-L2 Geoid.