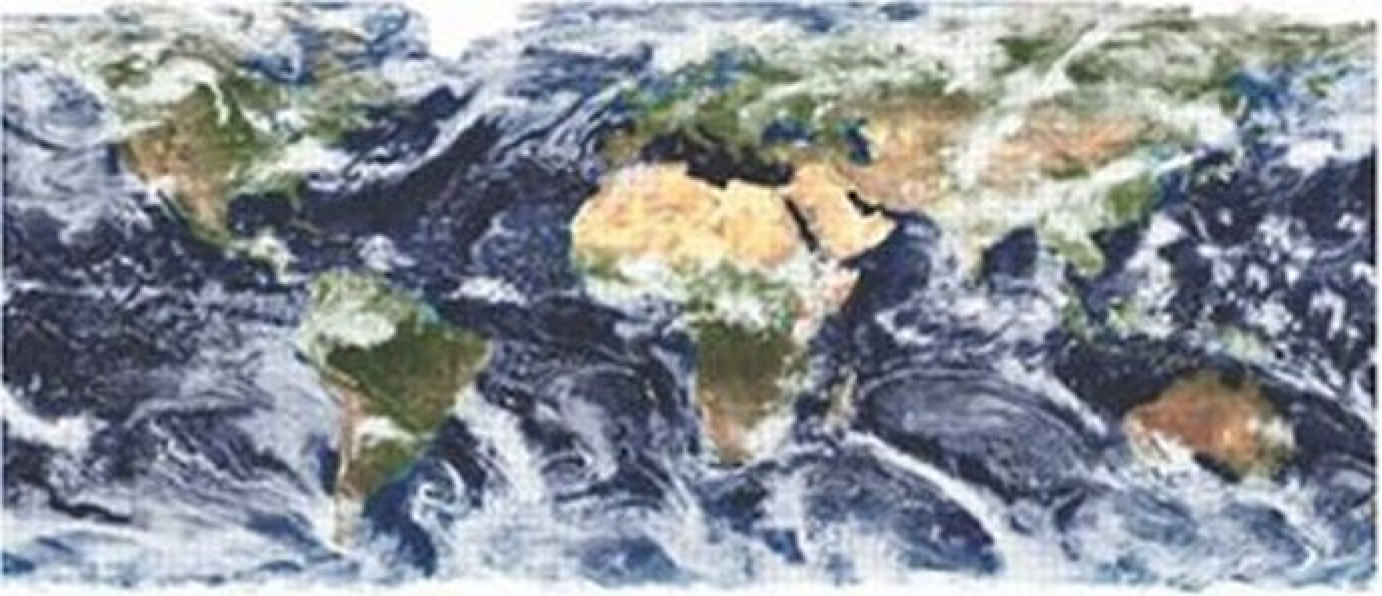
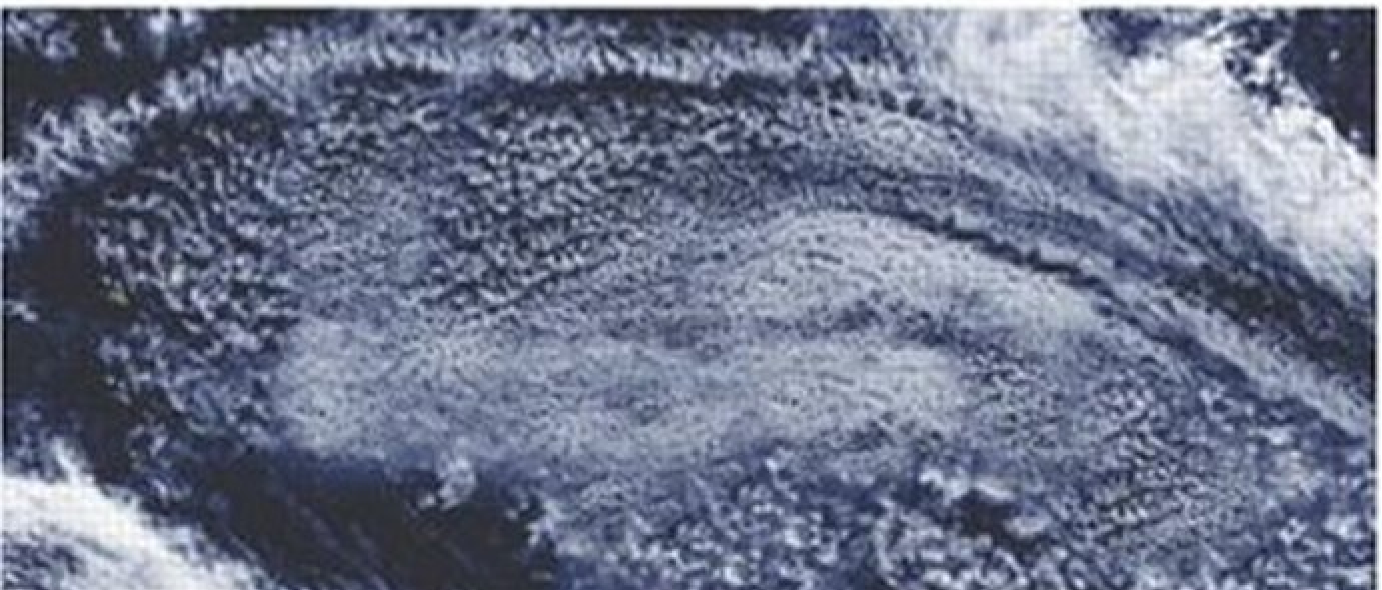


ATMOSPHERE, WEATHER AND CLIMATE

EIGHTH EDITION



ROGER G. BARRY AND RICHARD J. CHORLEY

Atmosphere, Weather and Climate

Atmosphere, Weather and Climate is the essential introduction to weather processes and climatic conditions around the world, their observed variability and changes, and projected future trends. Extensively revised and updated, this eighth edition retains its popular tried and tested structure while incorporating recent advances in the field. From clear explanations of the basic physical and chemical principles of the atmosphere, to descriptions of regional climates and their changes, *Atmosphere, Weather and Climate* presents a comprehensive coverage of global meteorology and climatology. In this new edition, the latest scientific ideas are expressed in a clear, non-mathematical manner.

New features include:

- new introductory chapter on the evolution and scope of meteorology and climatology
- new chapter on climatic models and climate system feedbacks
- updated analysis of atmospheric composition, weather and climate in middle latitudes, atmospheric and oceanic motion, tropical weather and climate, and small-scale climates
- chapter on climate variability and change has been completely updated to take account of the findings of the IPCC 2001 scientific assessment
- new more attractive and accessible text design
- new pedagogical features include: learning objectives at the beginning of each chapter and discussion points at their ending, and boxes on topical subjects and twentieth-century advances in the field.

Roger G. Barry is Professor of Geography, University of Colorado at Boulder, Director of the World Data Center for Glaciology and a Fellow of the Cooperative Institute for Research in Environmental Sciences.

The late **Richard J. Chorley** was Professor of Geography at the University of Cambridge.

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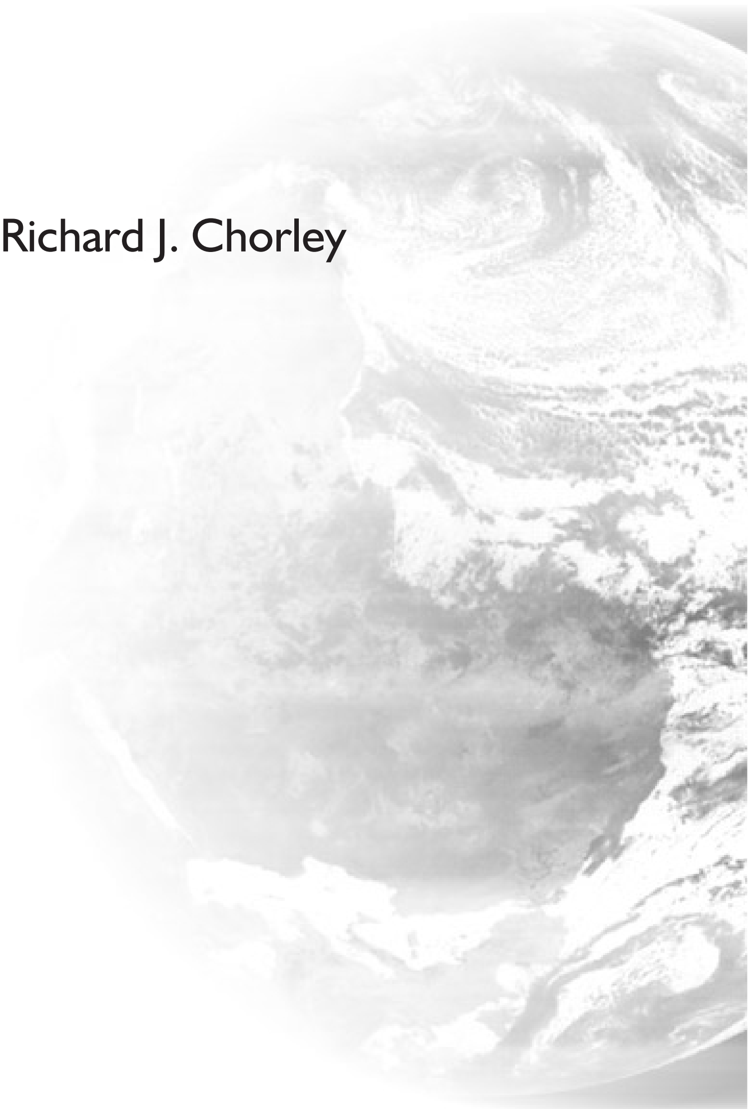

Roger G. Barry and Richard J. Chorley

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This edition is dedicated to my co-author Richard J. Chorley, with whom I first entered into collaboration on *Atmosphere, Weather and Climate* in 1966. He made numerous contributions, as always, to this eighth edition, notably Chapter 1 which he prepared as a new introduction. His many insights and ideas for the book and his enthusiasms over the years will be sadly missed.

Roger G. Barry
March 2003

Contents

Black and white plates 1–19 are located between pp. 88–9 and plates 20–29 between pp. 111–12.
Colour plates A–H are between pp. 176–7.

Preface to the eighth edition

When the first edition of this book appeared in 1968, it was greeted as being 'remarkably up to date' (*Meteorological Magazine*). Since that time, several new editions have extended and sharpened its description and analysis of atmospheric processes and global climates. Indeed, succeeding prefaces provide a virtual commentary on recent advances in meteorology and climatology of relevance to students in these fields and to scholars in related disciplines. This revised and expanded eighth edition of *Atmosphere, Weather and Climate* will prove invaluable to all those studying the earth's atmosphere and world climate, whether from environmental, atmospheric and earth sciences, geography, ecology, agriculture, hydrology or related disciplinary perspectives.

Atmosphere, Weather and Climate provides a comprehensive introduction to weather processes and climatic conditions. Since the last edition in 1998, we have added an introductory overview of the historical development of the field and its major components. Following this there is an extended treatment of atmospheric composition and energy, stressing the heat budget of the earth and the causes of the greenhouse effect. Then we turn to the manifestations and circulation of atmospheric moisture, including atmospheric stability and precipitation patterns in space and time. A consideration of atmospheric and oceanic motion on small to large scales leads on to a new chapter on modelling of the atmospheric circulation and climate, that also presents weather forecasting on different time scales. This was prepared by my colleague Dr Tom Chase of CIRES and Geography at the University of Colorado, Boulder. This is followed by a discussion of the structure of air masses, the development of frontal and non-frontal cyclones and of mesoscale convective systems in mid-latitudes. The treatment of weather and climate in temperate latitudes begins with studies of Europe and America, extending to the conditions of their subtropical and high-latitude margins and includes the Mediterranean, Australasia, North Africa, the southern westerlies, and the sub-arctic and polar regions. Tropical weather and climate are also described through an analysis of the climatic mechanisms of monsoon Asia, Africa, Australia and Amazonia, together with the tropical margins of Africa and Australia and the effects of ocean movement and the El Niño–Southern Oscillation and teleconnections. Small-scale climates – including urban climates – are considered from the perspective of energy budgets. The final chapter stresses the structure and operation of the atmosphere–earth–ocean system and the causes of its climate changes. Since the previous edition appeared in 1998, the pace of research on the climate system and attention to global climate change has accelerated. A discussion of the various modelling strategies adopted for the prediction of climate change is undertaken, relating in particular to the IPCC 1990 to 2000 models. A consideration of other environmental impacts of climate change is also included.

The new information age and wide use of the World Wide Web has led to significant changes in presentation. Apart from the two new chapters 1 and 8, new features include: learning points and discussion topics for each chapter, and boxes presenting a special topic or a summary of pivotal advances in twentieth-century meteorology and climatology. Throughout the book, some eighty new or redrawn figures, revised tables and new plates are presented. Wherever possible, the criticisms and suggestions of colleagues and reviewers have been taken into account in preparing this latest edition.

This new edition benefited greatly from the ideas and work of my long-time friend and co-author Professor Richard J. Chorley, who sadly did not live to see its completion; he passed away on 12 May 2002. He had planned to play a diminishing role in the eighth edition following his retirement several years earlier, but nevertheless he remained active and fully involved through March 2002 and prepared much of the new Chapter 1. His knowledge, enthusiasm and inspiration will be sorely missed.

R. G. BARRY
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Most of the figures were prepared by the cartographic and photographic staffs in the Geography Departments at Cambridge University (Mr I. Agnew, Mr R. Blackmore, Mr R. Coe, Mr I. Gulley, Mrs S. Gutteridge, Miss L. Judge, Miss R. King, Mr C. Lewis, Mrs P. Lucas, Miss G. Seymour, Mr A. Shelley and Miss J. Wyatt and, especially, Mr M. Young); at Southampton University (Mr A. C. Clarke, Miss B. Manning and Mr R. Smith); and at the University of Colorado, Boulder (Mr T. Wiselogel). Every edition of this book, through the seventh, has been graced by the illustrative imagination and cartographic expertise of Mr M. Young of the Department of Geography, Cambridge University, to whom we owe a considerable debt of gratitude.

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Our grateful thanks go to our families for their constant encouragement and forbearance.

The authors wish to thank the following learned societies, editors, publishers, scientific organizations and individuals for permission to reproduce figures, tables and plates. Every effort has been made to trace the current copyright holders, but in view of the many changes in publishing companies we invite these bodies and individuals to inform us of any omissions, oversights or errors in this list.

Learned societies

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1

Introduction and history of meteorology and climatology

Learning objectives
When you have read this chapter you will:

- Be familiar with key concepts in meteorology and climatology,
- Know how these fields of study evolved and the contributions of leading individuals.

A THE ATMOSPHERE

The atmosphere, vital to terrestrial life, envelops the earth to a thickness of only 1 per cent of the earth's radius. It had evolved to its present form and composition at least 400 million years ago by which time a considerable vegetation cover had developed on land. At its base, the atmosphere rests on the ocean surface which, at present, covers some 70 per cent of the surface of the globe. Although air and water share somewhat similar physical properties, they differ in one important respect – air is compressible, water incompressible. Study of the atmosphere has a long history involving both observations and theory. Scientific measurements became possible only with the invention of appropriate instruments; most had a long and complex evolution. A thermometer was invented by Galileo in the early 1600s, but accurate liquid-in-glass thermometers with calibrated scales were not available until the early 1700s (Fahrenheit), or the 1740s (Celsius). In 1643 Torricelli demonstrated that the weight of the atmosphere would support a 10 m column of water or a 760 mm column of liquid mercury. Pascal used a barometer of Torricelli to show that pressure decreases with altitude, by taking one up the Puy de Dôme in France. This paved the way for Boyle (1660) to demonstrate the compressibility of air by propounding his law that volume is inversely proportional to pressure. It was not until 1802 that Charles showed that air volume is directly proportional to its temperature. By the end of the nineteenth century the four major constituents of the dry atmosphere (nitrogen 78.08 per cent, oxygen 20.98 per cent, argon 0.93 per cent and carbon dioxide 0.035 per cent) had been identified. In the twentieth century it became apparent that CO_2, produced mainly by plant and animal respiration and since the Industrial Revolution by the breakdown of mineral carbon, had changed greatly in recent historic times, increasing by some 25 per cent since 1800 and by fully 7 per cent since 1950.

The hair hygrograph, designed to measure relative humidity, was only invented in 1780 by de Saussure. Rainfall records exist from the late seventeenth century in England, although early measurements are described from India in the fourth century BC, Palestine about AD 100 and Korea in the 1440s. A cloud classification scheme was devised by Luke Howard in 1803, but was not fully developed and implemented in observational practice until the 1920s. Equally vital was the establishment of networks of observing stations, following a standardized set of procedures for observing the weather and its elements, and a rapid means of exchanging the data (the telegraph). These two developments went hand-in-hand in Europe and North America in the 1850s to 1860s.

The greater density of water, compared with that of air, gives water a higher specific heat. In other words, much more heat is required to raise the temperature of a cubic metre of water by 1°C than to raise the temperature of a similar volume of air by the same amount. In terms of understanding the operations of the coupled earth–atmosphere–ocean system, it is interesting to note that the top 10–15 cm of ocean waters contain as much heat as does the total atmosphere. Another important feature of the behaviour of air and water appears during the process of evaporation or condensation. As Black showed in 1760, during evaporation, heat energy of water is translated into kinetic energy of water vapour molecules (i.e. latent heat), whereas subsequent condensation in a cloud or as fog releases kinetic energy which returns as heat energy. The amount of water which can be stored in water vapour depends on the temperature of the air. This is why the condensation of warm moist tropical air releases large amounts of latent heat, increasing the instability of tropical air masses. This may be considered as part of the process of convection in which heated air expands, decreases in density and rises, perhaps resulting in precipitation, whereas cooling air contracts, increases in density and subsides.

The combined use of the barometer and thermometer allowed the vertical structure of the atmosphere to be investigated. A low-level temperature inversion was discovered in 1856 at a height of about 1 km on a mountain in Tenerife where temperature ceased to decrease with height. This so-called Trade Wind Inversion is found over the eastern subtropical oceans where subsiding dry high-pressure air overlies cool moist maritime air close to the ocean surface. Such inversions inhibit vertical (convective) air movements, and consequently form a lid to some atmospheric activity. The Trade Wind Inversion was shown in the 1920s to differ in elevation between some 500 m and 2 km in different parts of the Atlantic Ocean in the belt 30°N to 30°S. Around 1900 a more important continuous and widespread temperature inversion was revealed by balloon flights to exist at about 10 km at the equator and 8 km at high latitudes. This inversion level (the tropopause) was recognized to mark the top of the so-called troposphere within which most weather systems form and decay. By 1930 balloons equipped with an array of instruments to measure pressure, temperature and humidity, and report them back to earth by radio (radiosonde), were routinely investigating the atmosphere.

B SOLAR ENERGY

The exchanges of potential (thermal) and kinetic energy also take place on a large scale in the atmosphere as potential energy gradients produce thermally forced motion. Indeed, the differential heating of low and high latitudes is the mechanism which drives both atmospheric and oceanic circulations. About half of the energy from the sun entering the atmosphere as short-wave radiation (or 'insolation') reaches the earth's surface. The land or oceanic parts are variously heated and subsequently re-radiate this heat as long-wave thermal radiation. Although the increased heating of the tropical regions compared with the higher latitudes had long been apparent, it was not until 1830 that Schmidt calculated heat gains and losses for each latitude by incoming solar radiation and by outgoing re-radiation from the earth. This showed that equatorward of about latitudes 35° there is an excess of incoming over outgoing energy, while poleward of those latitudes there is a deficit. The result of the equator–pole thermal gradients is a poleward flow (or flux) of energy, interchangeably thermal and kinetic, reaching a maximum between latitudes 30° and 40°. It is this flux which ultimately powers the global scale movements of the atmosphere and of oceanic waters. The amount of solar energy being received and re-radiated from the earth's surface can be computed theoretically by mathematicians and astronomers. Following Schmidt, many such calculations were made, notably by Meech (1857), Wiener (1877), and Angot (1883) who calculated the amount of extraterrestrial insolation received at the outer limits of the atmosphere at all latitudes. Theoretical calculations of insolation in the past by Milankovitch (1920, 1930), and Simpson's (1928 to 1929) calculated values of the insolation balance over the earth's surface, were important contributions to understanding astronomic controls of climate. Nevertheless, the solar radiation received by the earth was only accurately determined by satellites in the 1990s.

C GLOBAL CIRCULATION

The first attempt to explain the global atmospheric circulation was based on a simple convectional concept. In 1686 Halley associated the easterly trade winds with low-level convergence on the equatorial belt of greatest heating (i.e. the thermal equator). These flows are compensated at high levels by return flows aloft. Poleward of these convectional regions, the air cools and subsides to feed the northeasterly and southeasterly trades at the surface. This simple mechanism, however, presented two significant problems – what mechanism produced high-pressure in the subtropics and what was responsible for the belts of dominantly westerly winds poleward of this high pressure zone? It is interesting to note that not until 1883 did Teisserenc de Bort produce the first global mean sea-level map showing the main zones of anticyclones and cyclones (i.e. high and low pressure). The climatic significance of Halley's work rests also in his thermal convectional theory for the origin of the Asiatic monsoon which was based on the differential thermal behaviour of land and sea; i.e. the land reflects more and stores less of the incoming solar radiation and therefore heats and cools faster. This heating causes continental pressures to be generally lower than oceanic ones in summer and higher in winter, causing seasonal wind reversals. The role of seasonal movements of the thermal equator in monsoon systems was only recognized much later. Some of the difficulties faced by Halley's simplistic large-scale circulation theory began to be addressed by Hadley in 1735. He was particularly concerned with the deflection of winds on a rotating globe, to the right (left) in the northern (southern) hemisphere. Like Halley, he advocated a thermal circulatory mechanism, but was perplexed by the existence of the westerlies. Following the mathematical analysis of moving bodies on a rotating earth by Coriolis (1831), Ferrel (1856) developed the first three-cell model of hemispherical atmospheric circulation by suggesting a mechanism for the production of high pressure in the subtropics (i.e. 35°N and S latitude). The tendency for cold upper air to subside in the subtropics, together with the increase in the deflective force applied by terrestrial rotation to upper air moving poleward above the Trade Wind Belt, would cause a build-up of air (and therefore of pressure) in the subtropics. Equatorward of these subtropical highs the thermally direct Hadley cells dominate the Trade Wind Belt but poleward of them air tends to flow towards higher latitudes at the surface. This airflow, increasingly deflected with latitude, constitutes the westerly winds in both hemispheres. In the northern hemisphere, the highly variable northern margin of the westerlies is situated where the westerlies are undercut by polar air moving equatorward. This margin was compared with a battlefield front by Bergeron who, in 1922, termed it the Polar Front. Thus Ferrel's three cells consisted of two thermally direct Hadley cells (where warm air rises and cool air sinks), separated by a weak, indirect Ferrel cell in mid-latitudes. The relation between pressure distribution and wind speed and direction was demonstrated by Buys-Ballot in 1860.

D CLIMATOLOGY

During the nineteenth century it became possible to assemble a large body of global climatic data and to use it to make useful regional generalizations. In 1817 Alexander von Humboldt produced his valuable treatise on global temperatures containing a map of mean annual isotherms for the northern hemisphere but it was not until 1848 that Dove published the first world maps of monthly mean temperature. An early world map of precipitation was produced by Berghaus in 1845; in 1882 Loomis produced the first world map of precipitation employing mean annual isohyets; and in 1886 de Bort published the first world maps of annual and monthly cloudiness. These generalizations allowed, in the later decades of the century, attempts to be made to classify climates regionally. In the 1870s Wladimir Koeppen, a St Petersburg-trained biologist, began producing maps of climate based on plant geography, as did de Candolle (1875) and Drude (1887). In 1883 Hann's massive three-volume *Handbook of Climatology* appeared, which remained a standard until 1930–40 when the five-volume work of the same title by Koeppen and Geiger replaced it. At the end of the First World War Koeppen (1918) produced the first detailed classification of world climates based on terrestrial vegetation cover. This was followed by Thornthwaite's (1931–33) classification of climates employing evaporation and precipitation amounts, which he made more widely applicable in 1948 by the use of the theoretical concept of potential evapo-transpiration. The inter-war period was particularly notable for the appearance of a number of climatic ideas which were not brought to fruition until the 1950s. These included the use of frequencies of various weather types (Federov, 1921), the concepts of variability of temperature and rainfall (Gorczynski, 1942, 1945) and microclimatology (Geiger, 1927).

Despite the problems of obtaining detailed measurements over the large ocean areas, the later nineteenth century saw much climatic research which was concerned with pressure and wind distributions. In 1868 Buchan produced the first world maps of monthly mean pressure; eight years later Coffin composed the first world wind charts for land and sea areas, and in 1883 Teisserenc de Bort produced the first mean global pressure maps showing the cyclonic and anticyclonic 'centres of action' on which the general circulation is based. In 1887 de Bort began producing maps of upper-air pressure distributions and in 1889 his world map of January mean pressures in the lowest 4 km of the atmosphere was particularly effective in depicting the great belt of the westerlies between 30° and 50° north latitudes.

E MID-LATITUDE DISTURBANCES

Theoretical ideas about the atmosphere and its weather systems evolved in part through the needs of nineteenth-century mariners for information about winds and storms, especially predictions of future behaviour. At low levels in the westerly belt (approximately 40° to 70° latitude) there is a complex pattern of moving high and low pressure systems, while between 6000 m and 20,000 m there is a coherent westerly airflow. Dove (1827 and 1828) and Fitz Roy (1863) supported the 'opposing current' theory of cyclone (i.e. depression) formation, where the energy for the systems was produced by converging airflow. Espy (1841) set out more clearly a convection theory of energy production in cyclones with the release of latent heat as the main source. In 1861, Jinman held that storms develop where opposing air currents form lines of confluence (later termed 'fronts'). Ley (1878) gave a three-dimensial picture of a low-pressure system with a cold air wedge behind a sharp temperature discontinuity cutting into warmer air, and Abercromby (1883) described storm systems in terms of a pattern of closed isobars with typical associated weather types. By this time, although the energetics were far from clear, a picture was emerging of mid-latitude storms being generated by the mixing of warm tropical and cool polar air as a fundamental result of the latitudinal gradients created by the patterns of incoming solar radiation and of outgoing terrestrial radiation. Towards the end of the nineteenth century two important European research groups were dealing with storm formation: the Vienna group under Margules, including Exner and Schmidt; and the Swedish group led by Vilhelm Bjerknes. The former workers were concerned with the origins of cyclone kinetic energy which was thought to be due to differences in the potential energy of opposing air masses of different temperature. This was set forth in the work of Margules (1901), who showed that the potential energy of a typical depression is less than 10 per cent of the kinetic energy of its constituent winds. In Stockholm V. Bjerknes' group concentrated on frontal development (Bjerknes, 1897, 1902) but its researches were particularly important during the period 1917 to 1929 after J. Bjerknes moved to Bergen and worked with Bergeron. In 1918 the warm front was identified, the occlusion process was described in 1919, and the full Polar Front Theory of cyclone development was presented in 1922 (J. Bjerknes and Solberg). After about 1930, meteorological research concentrated increasingly on the importance of mid- and upper-tropospheric influences for global weather phenomena. This was led by Sir Napier Shaw in Britain and by Rossby, with Namias and others, in the USA. The airflow in the 3–10 km high layer of the polar vortex of the northern hemisphere westerlies was shown to form large-scale horizontal (Rossby) waves due to terrestrial rotation, the influence of which was simulated by rotation 'dish pan' experiments in the 1940s and 1950s. The number and amplitude of these waves appears to depend on the hemispheric energy gradient, or 'index'. At times of high index, especially in winter, there may be as few as three Rossby waves of small amplitude giving a strong zonal (i.e. west to east) flow. A weaker hemispheric energy gradient (i.e. low index) is characterized by four to six Rossby waves of larger amplitude. As with most broad fluid-like flows in nature, the upper westerlies were shown by observations in the 1920s and 1930s, and particularly by aircraft observations in the Second World War, to possess narrow high-velocity threads, termed 'jet streams' by Seilkopf in 1939. The higher and more important jet streams approximately lie along the Rossby waves. The most important jet stream, located at 10 km, clearly affects surface weather by guiding the low pressure systems which tend to form beneath it. In addition, air subsiding beneath the jet streams strengthens the subtropical high pressure cells.

F TROPICAL WEATHER

The success in modelling the life cycle of the mid-latitude frontal depression, and its value as a forecasting tool, naturally led to attempts in the immediate pre-Second World War period to apply it to the atmospheric conditions which dominate the tropics (i.e. 30°N – 30°S), comprising half the surface area of the globe. This attempt was doomed largely to failure, as observations made during the air war in the Pacific soon demonstrated. This failure was due to the lack of frontal temperature discontinuities between air masses and the absence of a strong Coriolis effect and thus of Rossby-like waves. Tropical airmass discontinuities are based on moisture differences, and tropical weather results mainly from strong convectional features such as heat lows, tropical cyclones and the intertropical convergence zone (ITCZ). The huge instability of tropical airmasses means that even mild convergence in the trade winds gives rise to atmospheric waves travelling westward with characteristic weather patterns.

Above the Pacific and Atlantic Oceans the intertropical convergence zone is quasi-stationary with a latitudinal displacement annually of 5° or less, but elsewhere it varies between latitudes 17°S and 8°N in January and between 2°N and 27°N in July – i.e. during the southern and northern summer monsoon seasons, respectively. The seasonal movement of the ITCZ and the existence of other convective influences make the south and east Asian monsoon the most significant seasonal global weather phenomenon.

Investigations of weather conditions over the broad expanses of the tropical oceans were assisted by satellite observations after about 1960. Observations of waves in the tropical easterlies began in the Caribbean during the mid-1940s, but the structure of mesoscale cloud clusters and associated storms was recognized only in the 1970s. Satellite observations also proved very valuable in detecting the generation of hurricanes over the great expanses of the tropical oceans.

In the late 1940s and subsequently, most important work was conducted on the relations between the south Asian monsoon mechanism in relation to the westerly subtropical jet stream, the Himalayan mountain barrier and the displacement of the ITCZ. The very significant failure of the Indian summer monsoon in 1877 had led Blanford (1860) in India, Todd (1888) in Australia, and others, to seek correlations between Indian monsoon rainfall and other climatic phenomena such as the amount of Himalayan snowfall and the strength of the southern Indian Ocean high pressure centre. Such correlations were studied intensively by Sir Gilbert Walker and his co-workers in India between about 1909 and the late 1930s. In 1924 a major advance was made when Walker identified the 'Southern Oscillation' – an east–west seesaw of atmospheric pressure and resulting rainfall (i.e. negative correlation) between Indonesia and the eastern Pacific. Other north–south climatic oscillations were identified in the North Atlantic (Azores vs. Iceland) and the North Pacific (Alaska vs. Hawaii). In the phase of the Southern Oscillation when there is high pressure over the eastern Pacific, westward-flowing central Pacific surface water, with a consequent upwelling of cold water, plankton-rich, off the coast of South America, are associated with ascending air, gives heavy summer rains over Indonesia. Periodically, weakening and breakup of the eastern Pacific high pressure cell leads to important consequences. The chief among these are subsiding air and drought over India and Indonesia and the removal of the mechanism of the cold coastal upwelling off the South American coast with the consequent failure of the fisheries there. The presence of warm coastal water is termed 'El Niño'. Although the central role played by lower latitude high pressure systems over the global circulations of atmosphere and oceans is well recognized, the cause of the east Pacific pressure change which gives rise to El Niño is not yet fully understood. There was a waning of interest in the Southern Oscillation and associated phenomena during the 1940s to mid-1960s, but the work of Berlage (1957), the increase in the number of Indian droughts during the period 1965 to 1990, and especially the strong El Niño which caused immense economic hardship in 1972, led to a revival of interest and research. One feature of this research has been the thorough study of the 'teleconnections' (correlations between climatic conditions in widely separated regions of the earth) pointed out by Walker.

G PALAEOCLIMATES

Prior to the mid-twentieth century thirty years of record was generally regarded as sufficient in order to define a given climate. By the 1960s the idea of a static climate was recognized as being untenable. New approaches to palaeoclimatology were developed in the 1960s to 1970s. The astronomical theory of climatic changes during the Pleistocene proposed by Croll (1867), and developed mathematically by Milankovitch, seemed to conflict with evidence for dated climate changes. However, in 1976, Hays, Imbrie and Shackleton recalculated Milankovitch's chronology using powerful new statistical techniques and showed that it correlated well with past temperature records, especially for ocean palaeotemperatures derived from isotopic ($^{18}0/^{16}0$) ratios in marine organisms.

H THE GLOBAL CLIMATE SYSTEM

Undoubtedly the most important outcome of work in the second half of the twentieth century was the recognition of the existence of the global climate system (see Box 1.1). The climate system involves not just the atmosphere elements, but the five major

GLOBAL ATMOSPHERIC RESEARCH PROGRAMME (GARP) AND THE WORLD CLIMATE RESEARCH PROGRAMME (WCRP)

box 1.1 topical issue

The idea of studying global climate through co-ordinated intensive programmes of observation emerged through the World Meteorological Organization (WMO: http://www.wmo.ch/) and the International Council on Science (ICSU: http://www.icsu.org) in the 1970s. Three 'streams' of activity were planned: a physical basis for long-range weather forecasting; interannual climate variability; and long-term climatic trends and climate sensitivity. Global meteorological observation became a major concern and this led to a series of observational programmes. The earliest was the Global Atmospheric Research Programme (GARP). This had a number of related but semi-independent components. One of the earliest was the GARP Atlantic Tropical Experiment (GATE) in the eastern North Atlantic, off West Africa, in 1974 to 1975. The objectives were to examine the structure of the trade wind inversion and to identify the conditions associated with the development of tropical disturbances. There was a series of monsoon experiments in West Africa and the Indian Ocean in the late 1970s to early 1980s and also an Alpine Experiment. The First GARP Global Experiment (FGGE), between November 1978 and March 1979, assembled global weather observations. Coupled with these observational programmes, there was also a co-ordinated effort to improve numerical modelling of global climate processes.

The World Climate Research Programme (WCRP: http://www.wmo.ch/web/wcrp/wcrp-home.html), established in 1980, is sponsored by the WMO, ICSU and the International Ocean Commission (IOC). The first major global effort was the World Ocean Circulation Experiment (WOCE) which provided detailed understanding of ocean currents and the global thermohaline circulation. This was followed in the 1980s by the Tropical Ocean Global Atmosphere (TOGA).

Current major WCRP projects are Climate Variability and Predictability (CLIVAR: http://www.clivar.org/), the Global Energy and Water Cycle Experiment (GEWEX), and Stratospheric Processes and their Role in Climate (SPARC). Under GEWEX are the International Satellite Cloud Climatology Project (ISCCP) and the International Land Surface Climatology Project (ISLSCP) which provide valuable datasets for analysis and model validation. A regional project on the Arctic Climate System (ACSYS) is nearing completion and a new related project on the Cryosphere and Climate (CliC: http://clic.npolar.no/) has been established.

Reference

Houghton, J. D. and Morel, P. (1984) The World Climate Research Programme. In J. D. Houghton (ed.) *The Global Climate*, Cambridge University Press, Cambridge, pp. 1–11.

subsystems: the atmosphere (the most unstable and rapidly changing); the ocean (very sluggish in terms of its thermal inertia and therefore important in regulating atmospheric variations); the snow and ice cover (the cryosphere); and the land surface with its vegetation cover (the lithosphere and biosphere). Physical, chemical and biological processes take place in and among these complex subsystems. The most important interaction takes place between the highly dynamic atmosphere, through which solar energy is input into the system, and the oceans which store and transport large amounts of energy (especially thermal), thereby acting as a regulator to more rapid atmospheric changes. A further complication is provided by the living matter of the biosphere. The terrestrial biosphere influences the incoming radiation and outgoing re-radiation and, through human transformation of the land cover, especially deforestation and agriculture, affects the atmospheric composition via greenhouse gases. In the oceans, marine biota play a major role in the dissolution and storage of CO_2. All subsystems are linked by fluxes of mass, heat and momentum into a very complex whole.

The driving mechanisms of climate change referred to as 'climate forcing' can be divided conveniently into external (astronomical effects on incoming short-wave solar radiation) and internal (e.g. alterations in the composition of the atmosphere which affect outgoing long-wave radiation). Direct solar radiation measurements have been made via satellites since about 1980, but the correlation between small changes in solar radiation and in the thermal economy of the global climate system is still unclear. However, observed increases in the greenhouse gas content of the atmosphere (0.1 per cent of which is composed of the trace gases carbon dioxide, methane, nitrous oxide and ozone), due to the recent intensification of a wide range of human activities, appear to have been very significant in increasing the proportion of terrestrial long-wave radiation trapped by the atmosphere, thereby raising its temperature. These changes, although small, appear to have had a significant thermal effect on the global climate system in the twentieth century. The imbalance between incoming solar radiation and outgoing terrestrial radiation is termed 'forcing'. Positive forcing implies a heating up of the system, and adjustments to such imbalance take place in a matter of months in the surface and tropospheric subsystems but are slower (centuries or longer) in the oceans. The major greenhouse gas is water vapour and the effect of changes in this, together with that of cloudiness, are as yet poorly understood.

The natural variability of the global climate system depends not only on the variations in external solar forcing but also on two features of the system itself – feedback and non-linear behaviour. Major feedbacks involve the role of snow and ice reflecting incoming solar radiation and atmospheric water vapour absorbing terrestrial re-radiation, and are positive in character. For example: the earth warms; atmospheric water vapour increases; this, in turn, increases the greenhouse effect; the result being that the earth warms further. Similar warming occurs as higher temperatures reduce snow and ice cover allowing the land or ocean to absorb more radiation. Clouds play a more complex role by reflecting solar (short-wave radiation) but also by trapping terrestrial outgoing radiation. Negative feedback, when the effect of change is damped down, is a much less important feature of the operation of the climate system, which partly explains the tendency to recent global warming. A further source of variability within the climate system stems from changes in atmospheric composition resulting from human action. These have to do with increases in the greenhouse gases, which lead to an increase in global temperatures, and increases in particulate matter (carbon and mineral dust, aerosols). Particulates, including volcanic aerosols, which enter the stratosphere, have a more complex influence on global climate. Some are responsible for heating the atmosphere and others for cooling it.

Recent attempts to understand the global climate system have been aided greatly by the development of numerical models of the atmosphere and of climate systems since the 1960s. These are essential to deal with non-linear processes (i.e. those which do not exhibit simple proportional relationships between cause and effect) and operate on many different timescales.

The first edition of this book appeared some thirty-five years ago, before many of the advances described in the latest editions were even conceived. However, our continuous aim in writing it is to provide a non-technical account of how the atmosphere works, thereby helping the understanding of both weather phenomena and global climates. As always, greater explanation inevitably results in an increase in the range of phenomena requiring explanation. That is our only excuse for the increased size of this eighth edition.