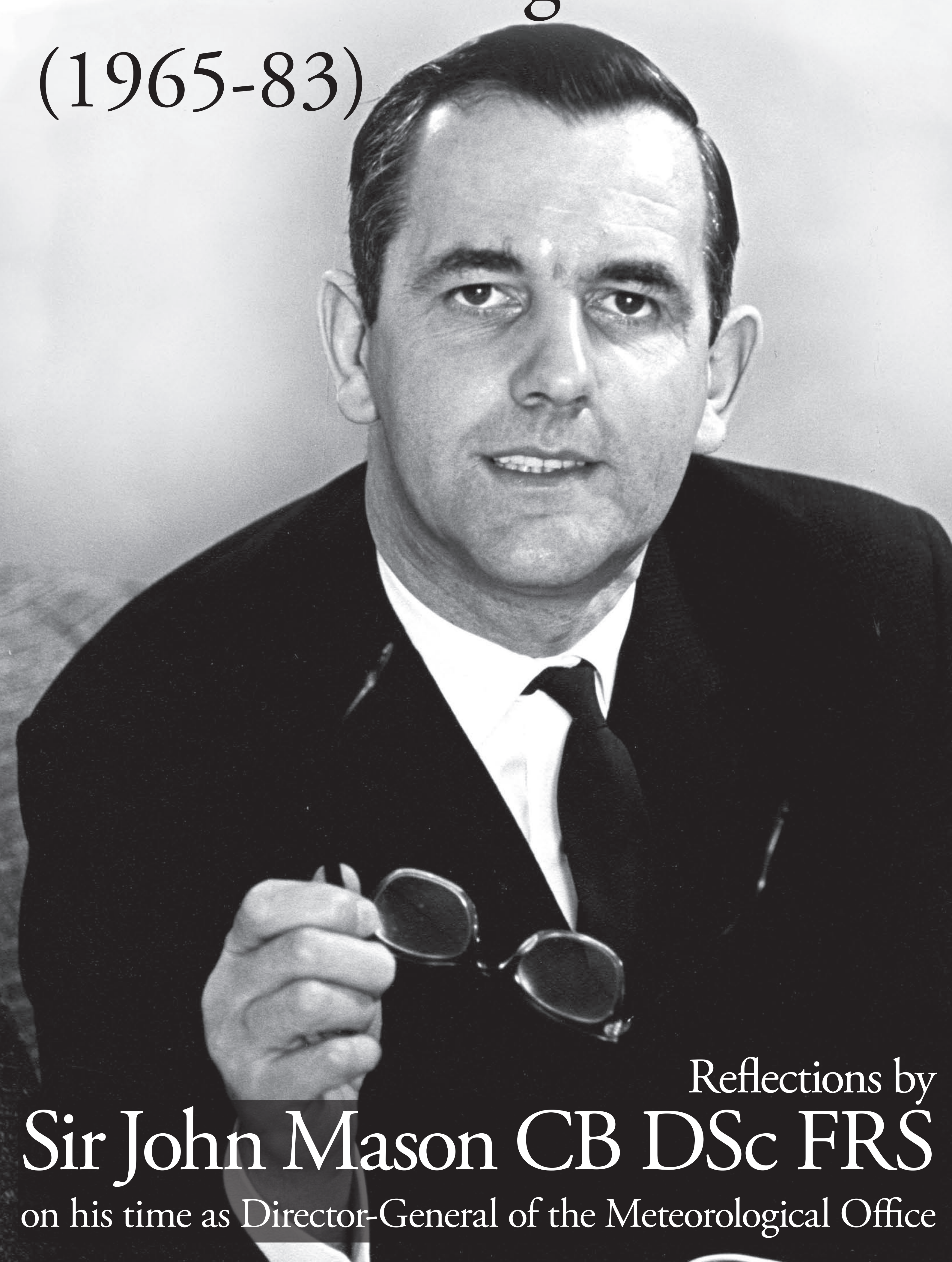
The Meteorological Office (1965-83)



Reflections by

Sir John Mason CB DSc FRS

on his time as Director-General of the Meteorological Office

Sir John and Prime Minister Heath at the opening of the Met Office's new Richardson Wing.

Biography

S**ir (Basil) John Mason, CB, DSc, FRS,** was born on 18 August 1923. After war service in the Radar Branch of the Royal Air Force and having been awarded a first-class honours degree in physics by the University of London, he was appointed lecturer in the post-graduate department of meteorology at Imperial College, London, in 1948. Here he formed an active research group to study physical processes involved in the formation of clouds, rain, hail and snow, and wrote his definitive book on 'The Physics of Clouds' published by the Clarendon Press in 1957. A second updated and enlarged edition of 670 pages, all personally written, was published in 1971. The Oxford University Press has recently (in 2010) published an attractive re-print of this unrivalled version as one if its "Oxford Classic Texts in the Physical Sciences".

In 1961, after returning from a one-year visit as a research professor in the University of California, Sir John was appointed the first professor of cloud physics in the physics department at Imperial College. In 1965 he was elected a Fellow of the Royal Society and appointed Director-General of the Meteorological Office which he modernized and equipped to be a world leader in the forefront of the computer and satellite age. He was appointed Companion of the Order of the Bath in 1973 and knighted for his outstanding services to meteorology in 1979.

On a broader canvas he served as Treasurer and Vice President of the Royal Society from 1976 to 1986, and gave its Bakerian Lecture in 1971 on his new quantitative theory of thunderstorm electrification for which he received the Rumford Medal. He delivered the Rutherford Memorial Lecture in Canada in 1990 and was awarded the Society's Royal Medal in 1991. He received many other academic honours including honorary degrees of Doctor of Science from twelve universities. He was Chancellor of the University of Manchester Institute of Science and Technology until 1996.

A Fellow of the Royal Meteorological Society since 1948, and now an Honorary Fellow, Sir John was its President from 1968 to 1970. In 2006 he endowed the Society's Mason Gold Medal for outstanding contributions to the understanding of meteorological processes. There are several portraits of Sir John. One of these hangs in the Society's headquarters. Another hangs in the National Portrait Gallery's collection of distinguished British scientists.

After his retirement from the Met Office in 1983 he became Director of the Acid Rain Research Project, involving some 300 scientists from 30 institutes affiliated to the Royal Society or the National Academies of Norway and Sweden. The results, conclusions, and recommendations for remedial action were discussed at a week-long conference at the Royal Society, attended by the three Prime Ministers, and published in a book edited by Sir John. The monitoring and reduction of acidic emissions continues.

Sir John with a Cumulonimbus cloud in the background, taken through his office window at the Met Office in Bracknell.

Foreword

The United Kingdom's National Meteorological Service is provided by the 'Meteorological Office', a Trading Fund and Executive Agency of the Ministry of Defence. The 'Met Office' traces its origin back to 1854 when, in response to proposals from Admiral Robert Fitzroy FRS, a hydrographer and meteorologist and former captain of HMS Beagle on Charles Darwin's celebrated voyage in the 1830s, the Board of Trade established a Meteorology Department with Fitzroy as its first Director, with the title of 'meteorological statist'. The Met Office's general functions include the production of weather forecasts – a term coined by Fitzroy – and other meteorological services and related scientific research in atmospheric science, where appropriate through international collaborative programmes.

When asked in 1900 to speculate about likely scientific progress in the twentieth century, prominent scientists missed many of the advances that were made and were over-optimistic about many that actually occurred. One leading physicist was bold enough to suggest that highly accurate weather forecasts would become available well before 1950. This was presumably because he shared the view of many of his contemporaries that further work on macroscopic systems satisfying the mathematical equations expressing the laws of classical mechanics and thermodynamics, already well established by 1900, would be a matter of mere routine. He was evidently unaware of a prescient warning against over-optimism about the practical applications of these equations issued three decades earlier by the great physicist James Clerk Maxwell. Maxwell complained that the traditional preoccupation of most theoretical physicists and applied mathematicians with phenomena that are simple, stable and insensitive to boundary conditions and initial conditions had created over-confidence in the "all encompassing influence of the laws of Nature".

Thanks to the development of powerful electronic super-computers, the past half-century has witnessed impressive progress in fluid dynamics. This has resulted from the application of numerical methods for dealing with the highly nonlinear governing mathematical equations, a development in which dynamical meteorologists at the Met Office and other centres of weather and climate forecasting have been at the forefront. A serious difficulty confronting meteorologists attempting to improve the accuracy and range of weather forecasts was exposed in the 1960s, when it was recognised that the equations of Newtonian dynamics, and even much simpler systems of nonlinear mathematical equations, do not necessarily exhibit the property of predictability beyond a definite 'predictability horizon'.

The international meteorological community confronted the problem of extending 'predictability horizons' in weather forecasting when it embarked on the ambitious 'Global Atmospheric Research Programme' (GARP), the initiation of which was announced in 1961 by the then President of the USA, John F. Kennedy (in the speech to the United Nations in which he also announced his country's decision to land an American on the Moon before the end of the decade). The planners of GARP hoped that the predictability horizon for useful numerical weather forecasts based on greatly improved data sets and advanced computational methods could eventually be extended from a day or so to more than a week.

It was against this background, soon after the initiation of GARP, that in 1965 the Met Office appointed a new Director-General. In B. J. Mason FRS, Professor of Cloud Physics at Imperial College London – a well-known physicist with a distinguished record in scientific research and an outstanding reputation as a lecturer and public speaker – an ideal candidate was found for the post. Forty-five years later, in this highly readable and informative personal memoir, 'The Meteorological Office (1965-83)' published by the Royal Meteorological Society, Sir John Mason gives a fascinating account of the modernization and strengthening of the Met Office under his strong leadership and of many impressive achievements by the organization during his eighteen years as Fitzroy's sixth successor as head of the UK's National Meteorological Service, which he describes as "the happiest and most productive period of (his) life".

Professor Raymond Hide, CBE, FRS
East Molesey, Surrey.

The Met Office in Bracknell before it moved to Exeter in 2003.

The Meteorological Office (1965-83)

by Sir John Mason, CB, DSc, FRS

Transition to the Computer and Satellite Age

Following my appointment as Director-General on 1st October 1965, I was convinced that meteorology as a science and a service was about to undergo major changes and that my main task would be to modernize, re-organize and equip the Office for the approaching computer and satellite age, and to ensure that it became a world leader in the new developments.

I was fortunate that in my first year the Office was inspected by the powerful Parliamentary Estimates Committee (later the Public Accounts Committee). This gave me the opportunity to describe the expanding horizons, challenges and opportunities for meteorology on a global scale in the context of the planned World Weather Watch (WWW), based on satellite observations and communications and rapid advances in computer technology. The Committee were impressed and recommended that I should prepare a detailed plan that would allow the UK to play a leading role and that the Ministry of Defence and HM Treasury should provide the resources to implement it.

The plan was designed to place the Met Office in the forefront of meteorological research and practice; to provide forecasts of greater reliability and range; to cope with increasing demands for services from defence, civil aviation, weather-sensitive industries, the media and the general public; and to fulfil our international obligations under the WWW. It called for, *inter alia*, a major building programme at Bracknell, modernization of infrastructure based on computer technology and a major expansion of basic and applied research.

The plan was strongly supported by the then Secretary of State for Defence, The Rt. Hon. Mr Denis Healey MP, who endorsed it during a press conference in Bracknell. But even so, its successful implementation would depend critically on recruiting a small number of proven scientific leaders and a steady influx of high-quality graduates in physics and mathematics against strong competition from the universities, government laboratories, the Atomic Energy Authority etc. This took a good deal of my time in lecturing at universities, especially in the early years. In my first year, 14 graduates and 5 Research Fellows joined the Office, most of them with first-class honours and/or PhDs. From there on graduate recruitment was not a problem; 50 joined in each of the years 1974 and 1979 and in my last year, 1983, 861 applications were received; 27 were successful. At a senior level, Raymond Hide, a full professor at MIT, returned to establish a new Geophysical Fluid Dynamics Laboratory, Keith Browning returned from NCAR to head the Radar Research Unit, and Philip Goldsmith came from Harwell to head the new Cloud Physics Branch. I also judged that several long-serving middle-ranking scientists had not received well-deserved promotion. In my first year I nominated six of them, in a civil-service wide competition, for 'special merit' promotions. All six were successful and this raised morale all round. During my tenure, three colleagues were elected to the Fellowship of the Royal Society and four more were elected later. The Met Office emerged from relative obscurity to become pre-eminent in the scientific civil service and a world leader in meteorology. In 1977 the Royal Society arranged a major exhibition to mark the Queen's Silver Jubilee. This demonstrated the advances made by the Met Office in numerical weather prediction as one of the twelve most important UK contributions to science during Her Majesty's reign.

In 1965 the large staff of 3,800 was largely employed in making routine observations, plotting and analyzing these by hand, and in preparing forecasts for dissemination to more than a hundred outstations at home and abroad and to the media. Many of these tasks were ripe for automation under computer control and soon released many staff for re-training in computing, data processing and in support of new and expanded research groups. These changes, together with the withdrawal of the Royal Air Force from the east of Suez and the decommissioning of our four Weather Ships, led to the reduction of 1,000 posts, mainly in the scientific assistant and junior technician grades.

Before describing the main changes in infrastructure, meteorological operations, services and research during my tenure, I should mention an important event in the first month that led to a revolution in the thinking and *modus operandi* of the Office.

The Introduction of Computer-Generated Numerical Weather Forecasts

Starting in the mid-1950s, a small group of scientists under J.S. Sawyer were developing its first numerical forecasting model using a Ferranti mercury computer. Based on simplified dynamical and thermodynamical equations governing the development of the pressure, temperature and wind fields for a dry atmosphere, these were integrated to forecast changes in these parameters at three levels; the surface, 500mb and 200mb, at 300km intervals on a grid covering Western Europe and the North Atlantic. Experimental forecasts were made for up to 48 hours ahead but the computer, capable of only 3,000 numerical operations/sec, was far too slow to produce forecasts ahead of the actual weather. This became possible only after an English Electric KDF9, about 100 times faster (0.3 million operations/sec), was commissioned in July 1965.

Soon after I arrived on 1st October, I became impressed that the experimental forecasts for aircraft crossing the Atlantic were systematically more accurate than traditional forecasts based on extrapolation of time sequences of hand-drawn charts. Accordingly I decided, against the advice of some senior colleagues, who favoured a longer trial period that the numerical forecasts would be issued routinely twice a day from Monday, 2nd November 1965. The Press and TV were invited to witness this landmark in the history of the Met Office and gave it wide coverage. Fortunately the first forecast was excellent and ushered in a new era in which weather forecasts were to become objective exercises in mathematical physics replacing the empirical methods that, for more than a century, had depended on the skill and experience of the individual human forecaster.

Within two years the forecasts were extended to 3 days ahead, covered much of Europe, North Atlantic, North America and the Polar Basin. They were also transmitted to the National Meteorological Services of Western Europe and to operational stations of the Royal Air Force. Special forecasts were prepared for both French and British Concorde's, at altitudes up to 60,000 feet, until their demise in 2003.

Meanwhile a research group under F.H. Bushby was developing a remarkably advanced 10-level 'primitive equation' model on a 100km grid, formulated by J.S. Sawyer in 1965 to predict the structure and development of cyclones and fronts and their associated precipitation. The model, described in detail by Bushby and Timpson in 1967, was so complicated that a 24-hour forecast took 8 hours on the fastest available computer (Ferranti Atlas) and the routine issue of forecasts had to await the arrival in 1971 of the IBM 360/195 supercomputer, some 20 times faster than the KDF9. By this time the 10-level model had been extended to cover the Northern Hemisphere poleward of 15°N on a 300km grid and this replaced the operational 3-level model in 1972. A year later, it was producing routine hemispheric forecasts of surface weather up to 3 days ahead and experimental forecasts up to 6 days ahead. This gave the Met Office a world lead in numerical weather prediction which it has maintained. Further developments during my tenure leading to global multi-level models for weather and climate simulation and prediction are described later.

Developments in NWP 1968-83

© Crown Copyright. Sir John examines the print out from the first numerical weather prediction model output, in the computer room at the Met Office.

Soon after I retired from the Met Office, I decided to investigate how the numerical forecasts, which I introduced in 1965, had changed in accuracy and range during my tenure. The results were published by the Royal Society in 1986. They showed that the correlation coefficients between the numerical model predictions of changes in height of isobaric surfaces over the UK and the corresponding values derived from the observations increased substantially over the 20-year period. For example, for changes on the 1000mb surface, the coefficient increased sharply from 0.3 in 1968 to 0.66 in 1972 following introduction to the 10-level model and thereafter, more slowly to 0.8 after introduction of the 15-level model in 1982. These improvements were a consequence of the halving of the root mean square error in the model-predicted heights of the 200, 500 and 1000mb surfaces. They were also reflected in the quality of the surface weather forecasts for the UK. Over the decade, 1972-1982, the proportion of poor 48-hour forecasts fell from 25% to only 5% and of poor 72-hour forecasts from 40% to 20%.

New Buildings and Facilities

When the Headquarters and central facilities were moved to Bracknell in 1963 an opportunity was lost to accommodate these on a single campus; instead they were scattered among several unsatisfactory sites around Bracknell and beyond. The main HQ building, opened in 1963, occupied a very restricted site on a large roundabout and was overcrowded and technically inadequate from the start. These deficiencies were largely remedied by new building and acquisitions there were an essential part of the modernisation plan. The most important changes were:

- Enlargement of the main building by a high-technology wing to house the central forecasting centre, a supercomputer, an advanced computerized telecommunications system to replace more than 100 teleprinters and facsimile machines. This was started in 1970, opened by Prime Minister Heath in 1972, and named after L.F. Richardson, the pioneer of numerical weather prediction.
- A residential Met Office College with 110 study bedrooms and excellent teaching accommodation, located in a pleasant site at Shinfield Park, near the University of Reading, to replace the old Training School housed in war-time huts at Stanmore.
- A 60-acre field-site at East Hampstead where laboratories were built for the development, calibration and trials of new instruments including a new radio-sonde.
- Buildings to house the archives and main stores.
- Provision of new accommodation at RAF Farnborough to service and equip aircraft of the Meteorological Research Flight. The three ageing aircraft were replaced in 1970 by a new 4-engined C130 (Hercules) aircraft, extensively modified and equipped with radar, a stable inertial platform, a data processing computer, and a wide variety of instruments to measure air and sea-surface temperatures, air motions, turbulent fluxes of heat, moisture and momentum, cloud liquid water and ice, cloud and precipitation particles, solar and terrestrial radiation and atmospheric chemistry. Operational in 1973, it was the most advanced flying laboratory for atmospheric research for the next 30 years.

Main Computers

After 1965 the Met Office commissioned a succession of the fastest available computers increasing from the English Electric KDF9 (0.3 million operations/sec) in 1966, to the CDC Cyber 205 (400 million operations/sec) in 1983. The latter was used to simulate the latest 15-level global model of the atmosphere coupled to a multi-level ocean containing sea-ice and interacting with ocean-floor topography. This produced global weather forecasts for 24 hours ahead in 3.7 minutes. The accuracy of these forecasts, especially of winds during the long refuelling flights from Ascension to the Falklands, was much appreciated by the RAF; no aircraft failed to reach its planned destination.

Satellite Observations

Although, in the 1960s, the Met Office contributed to experiments measuring ozone and oxygen on two British research satellites, ARIEL 2 and 3, and made good use of cloud images received from US polar-orbiting satellites in the preparation and verification of weather forecasts, it was only in the 1970s that it became seriously involved in developing algorithms for the retrieval of tropospheric and sea-surface temperatures from infra-red radiometers on US satellites, and in the development of new instruments for similar purposes.

The vertical distribution of temperature and water vapour in the atmosphere can be determined by measuring the thermal radiation emitted at well-defined wavelengths close to their absorption bands. The band pass can be chosen so that most of the measured radiation originates within a fairly narrow height interval and indicates the average temperature of that layer. A radiometer designed to receive radiation in several different narrow wavebands measures temperature over a range of heights. The wavelengths selected were mainly in the 15μm infra-red absorption band of carbon dioxide, and in the 5mm microwave band of oxygen which is much less attenuated by cloud than the infra-red.

In 1974 the Met Office agreed to provide a series of nine instruments over several years to measure stratospheric temperatures on TIROS-N satellites to complement US instruments measuring tropospheric temperatures. The Met Office Stratospheric Sounding Unit (SSU) was an infra-red radiometer which selected the narrow wavebands by a novel technique developed at Oxford and Heriot-Watt Universities. This used a pressure-modulated cell containing CO_2 to select the wavelength and chop the beam to produce an a.c. signal that could be readily amplified. The US instrument used interference filters to select the wavebands. The first SSU launched in October 1978, provided good profiles from 25km to 40km altitude; the second, launched in June 1979, performed excellently from 16km to 50km. Thereafter they were launched at about 2-yearly intervals until 1992, the temperature profiles being checked on occasion by Skua rocket sondes launched from South Uist to coincide with over-passes of the satellite. Complex computational schemes were devised to remove the obscuring effects of partial cloud cover in the radiometer's field of view but, even so, the reliability of the derived temperature profiles was often judged by comparisons with adjacent radiosonde soundings or with a 'first guess' provided by a weather forecasting model using all relevant data collected during the previous 12 hours. Their main value was in filling in gaps in data-sparse regions, particularly in the oceanic regions of the Tropics and the Southern Hemisphere.

In the early 1970s serious thought was given to the contribution that European countries should make, through the European Space Agency (ESA), to a global system of meteorological satellites that would form a permanent feature of the World Weather Watch. As the US undertook to maintain a continuous series of polar-orbiting spacecraft, it was decided that Europe should build and operate one geostationary satellite to complement two US and one Japanese satellite in providing near global coverage.

The first METEOSAT was launched in 1977 and operated for nearly two years; a second was launched in July 1981, and the last in 1990. Poised above the Equator at the intersection with the Greenwich meridian, they provided excellent cloud images covering about one-quarter of the Earth's surface every 30 minutes, with a horizontal resolution at the nadir of about 1km. Winds are derived from measurement of the cloud movements but assigning accurate heights to cloud features was more difficult than anticipated. Even so, about 1,000 wind vectors are assimilated in the Met Office global model every 24 hours.

In 1983 a conference of senior European government officials, which I chaired, signed an Agreement to fund an on-going programme of operational satellites, improved versions of METEOSAT I and II, the first of three to be launched in 1987. They were to be funded by National Meteorological Services, the Met Office paying 15% of the total cost. A new European Agency, EUMETSAT, was established to design, manage and operate the system. The first Director was J. Morgan from the Met Office.

In the same year, NASA and the Met Office agreed to collaborate with the US in flying Advanced

Microwave Sounding Units (AMSU) on future TIROS-N satellites in the expectation that they would not be obscured by cloud. The Office was to provide the unit to measure water vapour and cloud liquid water. The project was delayed but the first AMSU was launched in 1990.

One of the outstanding successes of the UK programme was provision of the Along Track Scanning Radiometer (ATSR) for the ESA Earth Resources Satellite (ERS-1). The Met Office designed the detectors and associated optics and the satellite was launched in 1990. It measured sea-surface temperatures with an accuracy of a few tenths of a degree Celsius.

The Met Office College

During my first visit to the Training School, housed in war-time huts at Stanmore, I was shocked by the sub-standard teaching accommodation and the total lack of residential, catering and recreational facilities. The students were required to find their own lodgings in an unattractive neighbourhood. I was worried about the impression that this would make on recently recruited high-quality graduates and post-doctoral scientists undergoing their initial training in meteorology.

I was therefore delighted to learn that the RAF was vacating the Headquarters of Flying Training Command located in a pleasant 20-acre park close to the University of Reading, and persuaded the Ministry of Defence to convert this into a residential College for the Met Office. A major conversion and refurbishment programme provided 110 study-bedrooms, a large dining room, common room, bar, billiards room and guest suites for important visitors. The College, opened in 1972, had a very beneficial effect on the morale of the staff, many of whom would attend courses, conferences and social events as part of their career development. There was now a meeting ground for our large, widely-dispersed family. This was especially appreciated by students from developing countries. In the 12-year period 1972-1983, 774 overseas students came from 76 countries.

The College provided a wide variety of courses ranging from academic courses of 25 weeks for graduates in physics or mathematics with no previous experience in meteorology, to short courses of 1-2 weeks for some observers and technicians. The graduates, having completed their lecture courses, and before joining their research groups, were attached for a few weeks to RAF operational stations, to civil airports, public weather centres, agricultural stations et alia to see meteorology practiced at the ‘sharp end’ and to become familiar with real problems at first hand. At this stage graduates could register with universities such as Oxford, Cambridge, Imperial College, Surrey and Belfast to study for a PhD under two supervisors, one each from the university and the Met Office. Several took advantage of this scheme and rose to senior positions in the Met Office.

In 1983 more than 600 students attended the College, 60 of these from overseas. In addition, 230 technicians were trained at the East Hampstead experimental site to install, calibrate and service observational systems and instruments.

Forecasters were trained on a progression of initial, intermediate and advanced courses at the College followed by long spells under supervision at outstations. Courses on similar lines were run on various aspects of applied meteorology such as agriculture, fisheries, shipping, off-shore industries (oil and gas), public utilities, the media, building and construction and many other weather-sensitive industries. A wide variety of 4-week courses catered for scientific assistants who provided support in many branches of the Met Office.

International Projects

On joining the Met Office in 1965 I was elected to the Executive Committee of the World Meteorological Organization (WMO) right away and so was able to play a prominent role in the planning of the World Weather Watch (WWW) and the associated Global Atmospheric Research Programme (GARP).

The World Weather Watch (WWW)

The basic plan of WWW was to establish a much improved global network of observations on land, at sea and in the upper air making good use of satellite data, and a dedicated global telecommunications system (GTS) to distribute the data and forecasts through a hierarchal system to national meteorological services. Three World Meteorological Centres were established to collect, process, exchange and archive global data, a number of Regional Meteorological Centres (RMCs) to undertake similar tasks on a regional basis, and a number of Regional Telecommunications Hubs (RTHs) connected to each other and the RMCs by a dedicated, high-speed communications system with low-speed links branching off to national centres.

Moscow was designated a World Centre for political reasons but it never had the computer capacity to compete with Washington and powerful Regional Centres such as Bracknell and, later, the European Centre for Medium Range Weather Forecasting at Reading. Melbourne was designated a World Centre for the Southern Hemisphere. Eventually the Main Trunk Circuit connected Washington, Bracknell, Paris, Offenbach, Moscow, Beijing, Tokyo, Melbourne, Cape Town and Brasilia. Specified data sets and forecasts were transmitted on regular time schedules between regional and national centres without charge.

Although observational networks improved in both coverage and quality in many developed countries in response to WWW, there were considerable losses in developing countries, particularly in Africa, South America and the Indian sub-continent, due to wars, natural disasters and increasing poverty. Systems often broke down because of a lack of spare parts and especially of skilled technicians. Moreover, observations from the oceans were reduced by the move to fewer but larger ships and the withdrawal of dedicated Weather Ships. The concentration of aircraft along certain routes and at restricted altitudes resulted in many fewer observations from lower levels. Although some of these deficiencies have been partly offset by satellite observations, automatically reporting buoys, and improved communications, serious gaps persist in the global networks, especially in the Tropics and Southern Hemisphere.

Sir John speaking at the Centenary Banquet of the US National Weather Service, at the Washington Hilton Hotel.

I was determined that the UK should play an important role in the planning and implementation of WWW and should help developing countries fulfil their obligations by providing equipment and training through a special Aid Programme. I was also keen that the European Satellite Research Organization (ESRO) should build meteorological satellites as part of its Applications Programme.

Accordingly I persuaded government to allow me to offer Bracknell as a RMC equipped with a powerful supercomputer, and as a RTH on the Main Trunk Circuit with computer controlled message switching and storage. Also to install radiosonde stations in Africa and on a number of Pacific Islands, and to train a substantial number of meteorologists and technicians from developing countries at the Met Office College.

The Global Atmospheric Research Programme (GARP) and the GARP Atlantic Tropical Experiment (GATE)

I thought that the Office should play an important part in the GARP, especially in its two major projects, the GARP Atlantic Tropical Experiment (GATE) implemented in 1974, and the First GARP Global Experiment (FGGE) planned for 1979.

The objectives of GATE were to study the structure and evolution of convective cloud systems in the tropical eastern Atlantic and to assess their role in transporting heat and moisture from the tropical oceans polewards and upwards to feed the global circulation of the atmosphere.

Satellite observations revealed that the clouds tend to form in large organised clusters, 100-1000km across, and to be associated with the Inter-Tropical Convergence Zone in the equatorial wind field and with the troughs of the easterly tropospheric waves that often originate over Africa and maintain their identity while crossing the Atlantic.

During three months in the summer of 1974 a field experiment of unprecedented scale and complexity was conducted off the West African coast involving an array of 40 dedicated ships and 13 large research aircraft from 10 countries using Dakar in Senegal as the operational base. The experiment was planned by an international team of scientists based in the Met Office during the previous three years, guided by an inter-Governmental Management Board under my chairmanship which committed resources on behalf of governments. The scientific planning group was also responsible for organizing the collection, validation, quality control, dissemination and archiving the huge quantities of data in five data centres which made them accessible to the scientific community.

The basic observations of the temperature and wind fields were provided by conventional surface and upper-air radiosonde networks over Africa and South America supplemented by ships in the Atlantic, by remotely-sensed temperature soundings from US polar-orbiting satellites and winds obtained from cloud movements as observed by a US geostationary satellite.

A finer network of observations required to resolve the internal structure of cloud clusters and their effect on their immediate environment was established by a mesoscale 1000km by 1000km array of observing ships. These were equipped with radiosondes and upper-air wind-finding systems. Some ships used radar to explore the internal structure of cloud clusters, to estimate the precipitation intensity and hence the release of latent heat. The larger research ships measured sea-surface temperatures, temperature and salinity profiles in the ocean boundary layer, and temperature, humidity and wind profiles by instruments suspended from tethered balloons to determine fluxes of heat, moisture and momentum in the atmospheric boundary layer.

Simultaneous aircraft flights at different levels, which measured turbulent fluctuations, vertical motions, temperatures, liquid-water concentrations and precipitation intensity within cloud clusters, provided valuable data on the transports by mesoscale (10-100km) convective cells within them. In addition, the Met Office C130 Hercules aircraft made extensive measurements of the microphysical structure of clouds and of solar and terrestrial radiation. It made 40 flights totalling 386 hours.

The Meteorological Research Flight

When I arrived in 1965 the MRF, established in 1942 with a Spitfire and a Boston, and which at its peak had four almost new aircraft, two Hastings and two Mosquitoes, was suffering from unserviceability of its ageing fleet now consisting of a Hastings, a Canberra and a Varsity. A planned expedition to Singapore to study severe turbulence around thunderstorms was largely nugatory because the Hastings was grounded for a structural failure, while the Canberra was able to make only half of the planned flights. It obtained some unique records of severe turbulence but the decision was made that in future the Canberra would operate only below 30,000ft.

Equipped with only an ageing Canberra and a Varsity, the MRF was now poorly able to perform many of the tasks required by the new research programme but, after much study and debate, the Air Staff was persuaded in 1968 to replace the Hastings by a new C130 (Hercules) for the exclusive use of the MRF. The Varsity was replaced by a newer Varsity equipped with Doppler radar for wind measurement and an infra-red thermometer to measure sea-surface temperature. Both aircraft were to be fitted with modern digital equipment for recording and processing the large quantities of data collected.

In order to equip the Hercules for its wide range of research tasks almost anywhere in the world required major changes to its structure, notably removing its radar from the nose and relocating it in a pod on top of the aircraft, and by fitting a 22ft long nose boom to carry wind, turbulence and temperature probes far from the disturbing influences of the aircraft. Both the Canberra and the Hercules were fitted with inertial stable platforms allowing highly accurate measurements of the components of the air motion relative to the stable baseline provided by the platform. Doppler radar was fitted to determine drift-angle and ground speed.

The conversion of the Hercules took 2½ years, so it was not delivered until late 1973 but was to become the best equipped meteorological flying laboratory in the world and remained so until the end of its service. The specialized instruments and sensors will be described together with their use under the various research projects in these reflections.

While the Hercules was being modified, the Canberra and Varsity supported Project Scillonia, the Varsity dropping the radar targets and the Canberra making general reconnaissance of cloud systems and precipitation cells, and accurate wind measurements at low levels.

In 1970 and 1971, the Varsity was detached to Malta to measure sea-surface temperatures in support of Professor John Woods's studies of the ocean thermocline. The Canberra investigated turbulence in the upper troposphere and lower stratosphere and obtained evidence for gravity waves in the stratosphere.

During the following two years the Canberra explored air motions in and above waves formed in the lee of hills and participated in a multi-aircraft project to measure the vertical flux of horizontal momentum in waves formed over the mountains of Colorado. An important series of measurements were made of water vapour in the stratosphere using an improved frost-point hygrometer. The Varsity was used to track and measure SO_2 concentrations downwind of industrial areas and power stations, especially over the North Sea.

In 1974 effort was concentrated on equipping the new Hercules aircraft for its important role in the huge international experiment to study the convective weather systems on the eastern tropical Atlantic and their importance in the energetics of the global atmospheric circulation. This flying laboratory, accommodating 5 flight crew and several scientists, was equipped with wind-vanes, pitot-static systems, a stable inertial platform and a Doppler navigation system enabling vertical and horizontal wind components to be measured with errors of less than 0.2ms^{-1} and 2ms^{-1} respectively. It also carried several types of thermometer and hygrometer, some with sufficiently rapid response to estimate eddy fluxes of heat and water vapour; an infra-red (8-12µm) radiometer, a 3cm weather radar, downward looking cameras and forward facing TV cameras; condensation and ice-nucleus counters, and facilities for taking air samples for chemical analysis, and for ejecting drop-sondes. During the 100-day GATE experiment it was based in Dakar, Senegal and was used exclusively for investigations in the lowest 2km of the atmosphere, especially to measure 3-dimensional fluxes of heat, momentum and water vapour. In 40 missions, totalling 336 flying hours, it acquired some 10^9 samples of meteorological data.

The Varsity was given up in 1975 but the Canberra was equipped with upward- and downward-looking multi-channel radiometers to measure atmospheric transmissivity to radiation in various spectral wavebands. Measurements were made over the sea near Dakar to ascertain the radiative properties of water vapour in the tropical atmosphere and their effect on the remote sensing of sea-surface temperatures from a satellite. Successful flights were made with a sub-millimetre interferometer designed by the National Physical Laboratory to measure long-wave infra-red emitted by trace ‘greenhouse’ gases such as water vapour, ozone, CFCs and oxides of nitrogen. Good spectra were obtained at levels up to 14km.

During the following 5 years, until it was given up as an economy measure in 1981, the Canberra continued to measure the water vapour content of the lower stratosphere and its variation with season and latitude. A series of flights were made above and below cloud sheets using a multi-channel radiometer, designed at the Clarendon Laboratory in Oxford, to measure the transmission and reflection of solar radiation in a number of narrow spectral intervals. On some occasions simultaneous measurements were made of ice crystals, cloud droplets and rain drops by the Hercules now equipped with a holographic instrument and a light-scattering spectrometer for this purpose. The object was to study the effect of ice crystal size and shape on radiative transfer in anticipation of the important role played by clouds in regulating the heat balance and hence the global climate. Measurements of the drag exerted by orographically induced waves revealed that this drag at high levels is communicated to the surface by a downward flux of momentum which, when measured at several lower levels was comparable with surface friction.

In 1980 the Hercules was equipped with instrumentation supplied by the Central Electricity Research Laboratory to investigate the fate of SO_2 carried downwind from an emitting source such as a power station. The instruments captured and analysed air samples, cloud and rainwater and particles. In order to ensure that the aircraft remained in the plume, the SO_2 emissions were labelled with SF_6 particles that were captured on glass slides and detected in UV-light under the microscope in the aircraft. At the same time pulses of fluorinated hydrocarbon were emitted at regular intervals to provide time markers and give the position of the aircraft downstream and in the plume. In this way the plume could be followed up to 300 miles and sampled for SO_2, O_3 and NO_X. The overall objective was to determine the travel and dispersal of the plume and follow the chemical reactions involved in the oxidation of SO_2 to H_2SO_4 (Sulphuric Acid) both in the air, and in cloud and rainwater, and also to estimate the deposition of SO_2 to the ground. This aircraft programme was to play a major role in the Acid Rain Research Project of the next decade to assess the contribution made by UK emissions of SO_2 to acid deposition.

In March 1983 an experiment was conducted in the triangle between Gander, Bermuda and Barbados with a spur down to 5°N to investigate the effects of high water vapour concentrations, cloud and rainfall on the accuracy of humidity profiles derived from microwave radiometers flown on US satellites. NASA provided an aircraft equipped with a microwave radiometer similar to the Advanced Microwave Sounding Unit (AMSU) being provided by the Met Office for the next generation of US satellites. At the same time the MRF Hercules released 29 drop-sondes and made 5 aircraft soundings to obtain accurate temperature and humidity profiles co-located with the radiometer data.

Otherwise, much of the MRF programme concentrated on cloud physics with additional new instruments to measure cloud droplet and ice-crystal size distributions, total cloud liquid water content, and in-cloud temperatures. These were used in obtaining the microphysical structure of the rainbands associated with an intense cold front over the North Atlantic while the temperature, wind and humidity structure was determined by sondes dropped from the aircraft.

The Hercules continued to give excellent service until 2003 when, after 30 years of continuous operations, it came to the end of its useful life. It was replaced in 2005 by a new, much smaller BAe 146-301 jet aircraft funded, and operated under contract, jointly by the Natural Environment Research Council (NERC) and the Met Office. The MRF, a unique facility for 60 years, ceased to exist.

Cloud Physics and Dynamics

Cloud physics is concerned with those processes which are responsible for the formulation of clouds and the release of precipitation as rain, snow or hail. They involve the micro-physical processes of nucleation, condensation, droplet growth, the initiation and growth of ice crystals and the formation of raindrops, snow crystals and hailstones. The basic physics of these micro-physical processes was extensively explored by my research group at Imperial College from 1950 to 1965 but it was evident, especially to my distinguished colleague, Professor F.H. Ludlam, that these are largely controlled by the atmospheric motions that determine the macro-physical features of cloud growth and development i.e. by the cloud dynamics. For example, the growth or freezing of cloud droplets is accomplished by the release of large quantities of latent heat, profoundly influencing the motion of cloudy air masses, while the motions which ultimately cause evaporation of the cloud determine its duration, and will set a limit to the size which its particles can attain.

The importance of the interactions between the microphysical processes of particle formation and growth and the air motions in and around clouds, although emphasized in the first edition of my book The Physics of Clouds (Clarendon Press, 1957) and more strongly in the second edition (1971), was not widely recognized or acted upon, so that our knowledge of cloud dynamics remained rudimentary for at least another decade. This was mainly because the air motions could not be simulated in the laboratory and could not be observed and defined by the observational network used for weather forecasting.

There was also a widespread but mistaken belief that the release of precipitation, its intensity and duration were largely determined by the microphysical processes rather than by the cloud dynamics, and this underlay the assumption that precipitation could be enhanced by seeding the clouds with dry ice or silver iodide to simulate the conversion of super-cooled water droplets to ice crystals.

The rapid spread of these ‘rain-making’ operations, involving some 75 countries at their peak, ensured that political support and research funding was concentrated on the microphysical processes during the 1950s and 1960s whilst the cloud dynamics was neglected. It was after the exaggerated claims of the rain-makers were largely discredited a decade later that attention was re-focussed on the need to study the microphysics in a dynamical context with due attention to the important interactions and feedbacks involved. Having realized early on that this would require new, sophisticated instrumentation and data-processing facilities in order to determine the air motions and the physical constitution of real clouds and that this could be achieved only by acquiring expensive flying laboratories, advanced radars and computers, was influential in my decision in 1965 to become head of the Met Office where such facilities existed or could be developed. As a consequence my group and its equipment at Imperial College were transferred to the Met Office to form a new Cloud Physics Branch under P. Goldsmith, recruited from AERE, Harwell. Laboratories were quickly set-up in a nearby modern building leased at an annual rental of 10 shillings (50 pence) per square foot!

At the same time the small Meteorological Radar Unit (MRU) operated jointly with, and based at, the Royal Radar Establishment at Malvern, was expanded to investigate the air movements and the development of precipitation in clouds using Doppler and conventional radars operating on several different wavelengths. The group was greatly strengthened in 1967 when I persuaded K.A. Browning, formerly a research student at Imperial College and by now one of the world's leading radar meteorologists, to return from the USA to head the MRU. He was elected a Fellow of the Royal Society in 1978 and later became Director of Research in the Met Office.

The new Cloud Physics Branch, the MRU and the Meteorological Research Flight (MRF), working in close collaboration, enabling the Met Office to make a major, sustained investigation of the structure, composition and dynamics of clouds over the following two decades.

Project Scillonia

Planning of the first major project to study the structure and evolution of frontal cloud systems started in 1967 and its core programme was carried out over several years. The main objective was to measure vertical air motions on the same scales as the structure and development of clouds and precipitation that were observed by radars and instrumented MRF aircraft and relate these to the larger-scale developments revealed by conventional observational networks, by satellite images and by the predictions of the 10-level numerical weather forecasting model.

The first measurements were made with a mobile Doppler radar installed on the Scilly Isles on cloud systems approaching from the Atlantic and before they were much modified by passing over land, and where the aircraft could operate free of Air Traffic Control restrictions. Of key importance was a unique experiment, started in 1968, to measure the convergence of the horizontal wind field and hence the vertical motion on a 100km scale and at heights between 1,500 feet and 3,000 feet by accurate tracking of free-falling radar reflectors ejected in a pre-determined pattern from the Varsity aircraft. The Canberra aircraft provided low-level Doppler measured winds at 1,000 feet over the same area. The ground-based Doppler radar was used to measure wind fields, the fall speeds of hydrometers, and vertical motions on the 10-20km scale within the precipitation zones. These techniques were expanded and refined during the following 7 years to reveal strong correlations between the patterns of vertical motion and patterns of precipitation and unique information on the dynamics of frontal cloud systems culminating in the now classic three-dimensional conveyer-belt model of middle-latitude depressions, developed by K.A. Browning and T.W. Harrold and simulated in a numerical model by B.J. Hoskins.

These are characterized by an area of fairly uniform persistent rain ahead of the warm front produced by widespread slow ascent, and a series of narrow rainbands of heavier precipitation within the warm sector and also parallel to the surface warm and cold fronts. The main objective of Scillonia was to measure the gentle vertical motions extending over hundreds of kilometres and also the smaller scale (10km) convective motions within the rainbands and of the shower-clouds embedded within them with horizontal dimensions of order tens of kilometres.

In the last and most intense phase of Scillonia, 4 radars operated simultaneously on St. Mary's Island. One radar recorded the distribution of rain in both the horizontal and vertical; a second radar, operating in the Doppler-mode, determined vertical motions on the 10km scale and the size distribution of the raindrops; and two radars measured winds by tracking targets ejected from two aircraft during the passage of frontal systems. Later on radiosondes, dropped from aircraft, allowed temperature as well as wind to be measured and each carried a receiver of the Loran Navigation System so that their movements could be tracked.

Analysis of Scillonia data was completed in 1974. Winds within boxes of 300km by 100km by 4km were determined with an accuracy of ±30cms^{-1} averaged over height intervals of 500m and vertical motions with an accuracy of ±10cms^{-1}. These provide a firm observational framework for the development and testing of numerical models of fronts in collaboration with B.J. Hoskins, at the University of Reading.

An associated project used weather radars at Defford, North Wales and on the Gower peninsular to study the effect of topography on the distribution of precipitation which is considerably influenced by the presence of a low-level jet of enhanced wind speed a few hundred metres above ground in the warm sector of depressions. When the jet is forced up by the hills, increased precipitation results. The organization of frontal precipitation into rainbands is also influenced by topography. Collaborative research with B.J. Hoskins showed that many features of the rainbands can be explained by a type of symmetrical instability in which the release of latent heat of condensation plays an important role.

Structure and Development of Convective Clouds

In the late 1970s and beyond increasing use was made of the new fully instrumented Hercules (C130) flying laboratory to investigate the structure and development of vigorous convective clouds and precipitation, and successful attempts were made to simulate these developments in 3-dimensional numerical models that were constrained by the thermal, humidity and wind fields observed on the larger scales in individual case studies. Model predictions of surface rainfall compared rather well with rainfall measured by radar and raingauge networks.

The high-power, narrow beam (1°) scanning radar at RAF Defford, was used with great effect to study convection and turbulence in the clear air, to delineate the boundaries of incipient shower clouds and the initiation of showers.

Radar Measurements of Rainfall and the Dee Weather Radar Project

In 1968 the Met Office discussed with the Water Resources Board and Plessey Radar the feasibility of using a 10cm radar to measure continuously the rainfall over the hilly Chester-Dee catchment in North Wales. After careful planning and preparatory work, the project became operational in 1971. The radar signals, back-scattered by precipitation particles, were digitized and transmitted to stations remote from the radar site. Mini-computers at the radar site were used to make corrections to the rain echoes for distance and attenuation, to eliminate ground echoes and partial screening of the radar beam by hills, to correct for the radar beam straddling melting snow, and to calibrate the radar against a specially installed raingauge network. It was concluded that a real measurements of rainfall by radar had average errors of less than 20% equivalent in accuracy to that of a network of raingauges spaced 50-100km^2 apart. Unmanned radars would be cheaper to operate than an equivalent raingauge network with the great advantage of providing measurements in real time.

The first unmanned radar was installed in Lanarkshire in 1980. By the mid-1980s weather radars covered much of England, Wales and Northern Ireland, their outputs being combined to produce composite colour-coded maps of rainfall intensity on TV screens. These were transmitted digitally on 2km and 5km squares to forecasting offices where they were combined with satellite images to produce detailed forecasts for a few hours ahead, updated every 5 minutes.

Studies of Stratocumulus Cloud and Fog

During the late 1970s and early 1980s considerable effort was devoted to studies of the formation, structure and dissipation of low stratiform cloud and fog, the forecasting of which is of importance to both aviation and ground transport. I was convinced that the density and persistence of fog involved a delicate balance between the turbulent fluxes of heat and water vapour, rates of condensation under radiational cooling, the growth and sedimentation of cloud droplets.

Careful measurement of these processes and study of their interactions called for an unprecedented and highly co-ordinated observational programme linked to models that would integrate and elucidate the relative importance of the various physical processes. Measurements over land were made over several years by radio-telemetering instruments attached at several heights on the cable of a large tethered balloon at Cardington, and over the sea by the MRF Hercules.

The observations were used to compute radiation, heat and water budgets relevant to the formation and dissipation of nocturnal and daytime marine stratocumulus cloud and of radiation fog. A numerical model of radiation fog was used to predict the occurrence of fog under specified conditions of wind, temperature and humidity. The predictions were consistent with those using empirical rules but the model did not reproduce the large temperature gradients often observed close to the ground. These were later shown to be largely determined by the properties of the underlying surface e.g. soil type, thermal conductivity, moisture content etc, variations of which may often account for patchiness of the fog.

The aircraft observations showed that formation of cloud may cause thermal stratification of a previously well-mixed boundary layer and this profoundly affects the subsequent evolution of cloud. Also revealed are organized convective motions within stratocumulus clouds driven by radiative cooling at the cloud top.

Cloud Micro-physics

During the 1960s and 1970s several aspects of the Imperial College programme on cloud micro-physics were continued but considerable effort was devoted to the development of instrumental techniques for measuring from aircraft cloud droplet and ice-crystal populations and their antecedents, the condensation and ice nuclei.

A new technique for detecting ice nuclei was developed whereby the sub-microscopic nuclei were captured on Millipore filters and then activated and counted as they grew under controlled conditions of temperature and water vapour super-saturation on the cold stage of a microscope. Filter samples were taken in 17 different countries as far apart as the USA, Japan, Australia and Papua New Guinea in 1969 and were posted for activation and analysis to laboratories in Bracknell and Australia. The results were in general agreement with those obtained by other workers using cloud chambers in that ice-nucleus concentrations were highly variable in both space and time but were consistently much lower than those of ice crystals measured at similar temperatures in nearby moderately supercooled clouds so providing *prima facie* evidence for a secondary process of ice crystal multiplication first suggested in my publication in 1955 (Shaw and Mason, 1955).

This led to a continuation of the Imperial College studies on the production of tiny ice splinters during the freezing, expansion and rupture of individual supercooled drops but the crucial experiment was made by Hallett and Mossop (1974) who observed that copious ice splinters were ejected when supercooled droplets of diameter greater than 20µm froze on a simulated hail pellet but only if its surface temperature was in the narrow temperature range -3°C to -8°C. An automatic scanning device was developed to count and measure the diameter of the droplets and to obviate the intensive labour involved in their manual measurements under a microscope.

Since the growth rate dr/dt of a droplet by condensation is proportional to 1/r, cloud droplets grow only slowly when $r>20\mu m$ and progress to raindrop size largely by growing through colliding and coalescing with smaller droplets. The extensive research of the Imperial College Group on the computation and measurement of collision cross-sections for droplet pairs of differing radii and terminal velocities was extended to small droplet sizes and revealed a difficulty in bridging a gap at a radius of 20-30µm beyond which the collision-coalescence would dominate growth by condensation.

Thunderstorm Electrification

In the search for a mechanism which could account for the generation and separation of electric charge in thunderstorms, the experimental work of the Imperial College group was continued during 1965-70. The charges carried away on ice splinters ejected during the freezing of supercooled droplets were measured. Both its number of splinters and the charges carried were found to be considerably smaller than found in earlier experiments in which the more frequent shattering of freezing drops was probably caused by abnormally high concentrations of dissolved carbon dioxide.

A more promising approach was to measure the charges separated when supercooled droplets of diameter 20-100µm made grazing contact with an artificial hail pellet polarized in an external electric field. When the droplet re-bounded from the pellet an electrical pulse was recorded on the hail pellet and an equal and opposite charge on the re-bounding droplet as it passed through an induction ring. The sign and magnitude of the charges agreed with the theory of charge transfer by induction that I had worked out and later incorporated into a quantitative theory of thunderstorm electrification (Mason, 1988).

Exploration of the High Atmosphere

The Met Office started to plan rocket and satellite measurements of temperatures, winds, oxygen and ozone concentrations in the high atmosphere, up to heights of 170km, in the early 1960s.

The first experiment, to measure ozone concentrations above 30km was mounted on the UK satellite ARIEL 2 launched in 1964 but, because of the heavy computation involved, the data were not fully analyzed until 1968. They indicated broad latitudinal and seasonal trends in the ozone concentration above 50km which followed similar trends in air density but with greater variations.

An experiment to measure the concentrations of molecular oxygen at 100-160km was included in the payload of ARIEL 3 launch in May 1967. Measurements were made of the absorption of sunlight as the satellite passed into the Earth's shadow. The most surprising result was of large longitudinal variations in concentrations of O_2, apparently associated with geomagnetic activity, by as much as 50% over distances of a few hundred kilometres. But even the highest concentrations were much lower than assumed in the international Reference Atmosphere.

During the period 1966-1970 several experiments to measure ozone, molecular oxygen and water vapour were carried on Skylark rockets launched from Woomera and Kiruna (Sweden). The un-stabilized rockets were not very suitable, their motions making computation of the concentrations very difficult.

During the period 1965-1980 they were replaced by smaller, specially-designed Skua rockets, kept pointing at the moon, some 300 of which were fired from South Uist (Hebrides), Gan (Indian Ocean), Thumba (India) and Aberporth. Some of these rockets ejected a metalized parachute carrying a temperature sonde or a packet of metalized strips (chaff), all being tracked by radar to provide information on winds, temperature and air turbulence during their descent.

The rocket measurements showed early on that winds up to the mesopause at 85km showed great variability in winter but not in summer. Two sustained winter rocket campaigns at South Uist showed enormous oscillations in the zonal wind component of about 30 days period and a corresponding pressure oscillation which, at 55km, caused the height of isobaric surfaces to vary by 4km! Superimposed on these were shorter-period wind and pressure changes of about 10 days, sometimes linked to disturbances in the lower atmosphere. On one occasion the wind above South Uist changed in 10 days from 175ms^{-1} westerly to 50ms^{-1} easterly. There were considerable differences between the winds at all levels up to 85km between South Uist and Fort Churchill (Canada) at the same latitude.

Another remarkable winter phenomenon was the sudden warmings of the stratosphere in which the temperature rose to as much as 30°C in 24 hours and sometimes led to the complete breakdown of the winter polar vortex with westerly winds in the lower stratosphere replaced by easterlies. The warmings usually start at high level and descend at about 3km per day becoming less intense as they do so and insignificant by the time they reach the troposphere.

In order to conduct similar investigations in the tropical atmosphere, a rocket station was set up on Gan in the Indian Ocean in 1968 and series of campaigns took place during 1968-1973, with some comparative launches from Thumba (India). These revealed alternate layers of westerly and easterly winds up to 50km above which the winds were predominately westerly. The meridional wind also showed large amplitude oscillations associated with atmospheric tides. A series of 24 soundings made at night in order to reduce radiational heating of the temperature element produced a unique data set and revealed the presence and features of gravity waves in the tropical atmosphere. Much of the variability in wind and temperature was associated with large travelling disturbances in the mesosphere below 50km.

During 1976-1980 a number of Skua launches from South Uist were timed to coincide with overpasses of the US satellites NIMBUS 5 and 6 carrying the Oxford University Selective Chopper Radiometer and of TIROS-N carrying the Met Office Stratospheric Sounding Unit in order to check the calibration and stability of these instruments.

The chemical and photochemical reactions leading to the dissociation of molecular oxygen and the formation of ozone lead to the phenomenon of airglow which is the emission of radiation by the ultra-violet excitation of the atoms and molecules involved. The Met Office collaborated with Oxford University to measure the intensity and spectral distribution of the airglow radiations from O_2 in the 30-70km region using Skua rockets launched from South Uist in 1970. The instrument to measure the 1.27µm radiation descended on a parachute and operated satisfactorily.

In 1979 small Petrel rockets deployed sondes to study the diurnal variations of ozone in the 40-70km region, one measuring the attenuation of solar UV and the other of moonlight. All produced excellent sets of observations.

During the 3 years 1981-1983, after the cessation of the rocket programme, effort was concentrated on studying the dynamics of the stratosphere-mesosphere from 10 to 80km. This was a coordinated programme of theoretical studies, numerical modelling and routine daily analyses of the satellite observations from the SSUs on TIROS-N operational satellites. Five years of the satellite data provided a good global archive of data on temperature, geopotential and geostrophic wind from 100mb to 1mb.

A 32-level model of the stratosphere and mesosphere was used to investigate the dynamics. Early simulations demonstrated that the large amplitudes of the longest planetary waves can result from non-linear interactions between different stratospheric waves as well as from upward propagation of disturbances from the troposphere.

The Stratosphere and Mesosphere

As early as 1970-1971 the Met Office formulated a global numerical model of the stratosphere and conducted experiments with a version extending to the mesosphere, with 8 levels in the vertical above 100mb. New problems arose, especially at the uppermost level at about 80km where the flow is dominated by gravity waves and tidal motions. But when concern was expressed, mainly by US scientists, that the emission of pollutants by aircraft flying in the lower stratosphere might significantly alter the constitution of the atmosphere at the these levels and, in particular, deplete the stratospheric ozone, it was decided to test this by adding two more levels to the 11-level general circulation model to simulate the stratospheric circulation as a first step towards constructing a full three dimensional model with the dynamics and the complex ozone photochemistry adequately represented.

In 1972, at the request of the Concorde Division of the Department of Industry, the Met Office undertook a 3-year intensive research programme to study these problems. The research was directed and coordinated by the Committee on Meteorological Effects of Stratospheric Aircraft (COMESA) with R.J. Murgatroyd as the Project Director.

The COMESA Project

The main objective was to determine the chemical composition of the stratosphere and mesosphere and its variations with altitude, latitude, longitude and season with particular attention to the photochemically-active species often present in very low concentrations of only a few parts per billion. Innovative techniques for measuring these concentrations and reaction rates were developed at Cambridge and Oxford Universities. Samples were collected by aircraft, including the proto-type Concorde.

Experiments made with the global model indicated that even large changes in stratospheric composition are likely to produce only very small changes in surface temperature and rainfall, too small to be distinguished from natural fluctuations. Corroborative evidence was provided by the analysis of measurements of total vertically-integrated ozone amounts during the 1950s and 1960s when large quantities of NO_X were injected into the stratosphere by nuclear weapon tests with little discernible effects on total ozone. Moreover, the Bali volcanic eruption of 1963, which injected large amounts of dust into the stratosphere and cause temperatures there to rise by several degrees Celsius, the changes in surface temperature were only a fraction of a degree and were barely statistically significant.

The final report of COMESA, published in 1975, concluded that a very large fleet of stratospheric aircraft would be needed to produce a significant effect either on the amount of stratospheric ozone or on the climate. Consequently no significant effects were to be expected from the smaller number of Concordes and other supersonic aircraft expected to fly in the foreseeable future. As a result the US Congress withdrew objections to granting Concorde a certificate to operate between London/Paris and New York/Washington.

After COMESA the measurement programme was scaled down but modelling studies continued. It was not possible with the available computing power to incorporate the detailed photochemistry involving more than 40 reactions with a full 3-D dynamical model that would compute the transport, dispersion and concentrations of the various species as well as their chemical transformations. A compromise was made by using, *pro tem*, a two-dimensional model in which meteorological parameters from a 3-D model and from observations were averaged round circles of latitude. Alternatively, the detailed chemistry was computed with parcels of air following trajectories in the stratosphere extracted from the 3-D model.

The results of such numerical experiments demonstrated the need to make global-scale measurements of key trace species if their distribution was to be adequately described. It was envisaged that such measurements would be made from satellites and so the Met Office became involved in the Halogen Occultation Experiment (HALOE) to be flown at the end of 1988 on the Upper Atmosphere Research Satellite (UARS).

From 1979 onwards the Met Office developed a 3-D primitive equation model of the stratosphere and mesosphere eventually with 32 layers between altitudes of 16km and 80km with a sophisticated radiation scheme and the lower boundary geopotential height field specified by observations. Early simulations demonstrated that the large amplitudes of the longest planetary waves can result from non-linear interactions between different stratospheric waves as well as from upward propagation of disturbances from the troposphere. The model well simulated the large-scale features of the stratosphere circulation and their seasonal variations as revealed by analyses of data from the Met Office's Stratospheric Sounding Units (SSUs) on board the US TIROS-N/NOAA satellites.

In 1983 a spatially high resolution version of the model was prepared for the CYBER 205 computer and demonstrated that local disturbances of appropriate scale propagated upwards and downstream as wave tracers of Rossby waves which disperse as they move away from the source. Several detailed case studies of sudden stratospheric warmings linked them to these wave tracers and to the growth of particular features in the troposphere. Daily analyses of SSU data for 5 layers between 10mb (30km) and 1mb (~50km) provided an exceptionally valuable archive for studies of the inter-hemispheric and inter-annual variations of the mesosphere circulation.

Tropical Meteorology

Before the RAF withdrew from bases east of Suez, the Met Office had considerable post-war responsibility for providing forecasts in tropical regions, mainly for the RAF operating from bases in Aden, Gan, Diego Garcia, Singapore, and Brunei. Here the problem is considerably more difficult than in middle latitudes for several reasons: (i) routine observations, especially in the upper air, are much more sparse and generally of poorer quality; (ii) poor communications so that the observations could not be transmitted in timely fashion to the forecasting centres; and (iii) the atmospheric motions and weather systems are quite different in structure and behaviour from those at higher latitudes, not least due to the much weaker controlling Coriolis force exerted by the Earth's rotation.

Near the Equator, in comparison with middle latitudes, pressure gradients are usually weak and the winds are less coherent in space and time. The annual weaker pattern of many tropical regions is dominated by the seasonal north-south migration of the Inter-Tropical Convergence Zone, a narrow region of cloud and rain where air masses originating in the two hemispheres converge. Other motions are created by differences in surface heating operating on two distinct scales. On large scales the heating contrast between continents and the oceans creates the monsoons of India and West Africa. On small scales buoyancy forces give rise to convection currents which manifest as cumulus or cumulonimbus clouds often organized within large clusters in the troughs of atmospheric waves.

The concepts underlying weather forecasting in middle latitudes, based on the evolution of baroclinic waves and fronts, are mostly inapplicable in the tropics. The lack of understanding of tropical weather systems, substantially due to a poverty of observations, has wider implications in that the global atmospheric circulation is driven largely from the excess of solar energy received in the Tropics and carried polewards by both atmospheric and oceanic circulations. Even in forecasting for middle latitudes beyond a few days, it is important to include interactions between middle latitudes and tropical systems. The growing awareness of the need to treat the tropical atmosphere as an integral part of the global system, the understanding of which is necessary for understanding of the global climate and for long-range weather prediction, stimulated the Met Office to devote considerable effort to tropical meteorology in the 1970s.

The major elements were to participate in the planning, field phase and analysis of the GARP Atlantic Tropical Experiment (GATE), a major sub-programme of the Global Atmospheric Research Programme (GARP). This was designed primarily to study the physical properties of convective systems over a region of the tropical Atlantic, the organization of small convective clouds into larger cloud clusters, and how these clusters interact with the waves which propagate westwards in the large-scale easterly flow.

The experiment was also intended to provide data against which the validity of numerical weather prediction (NWP) models could be tested in the Tropics. In what was probably the largest and logistically the most complex international experiment ever undertaken, ten nations collaborated during June to September 1974 to measure properties of the atmosphere over the eastern tropical Atlantic in unprecedented detail. Thirty-nine ships, 13 research aircraft, several meteorological satellites and some 5,000 personnel were involved using Dakar (Senegal) as a base. The whole operation was planned over two years by a special international unit established in Bracknell under J. Kueltner (of the USA) and was overseen by an Intergovernmental Board which I chaired.

The UK contribution to GATE included the comprehensively equipped Hercules, already described earlier. The Met Office also contributed 4 weather ships and much of the infrastructure of the operations centre in Dakar. It also undertook the data processing and analysis of the Synoptic Sub-Programme. A tropical modelling group was set-up in 1973 to take advantage of the unique data provided by GATE. It was adapted from a global general circulation 11-level model and covered much of the tropical Atlantic and Africa from 35°N to 10°S with a horizontal resolution of 2°. A new scheme for analyzing the observations and assigning them to the grid used optimum interpolation taking into account the different accuracies of the measurements. The objectively analyzed fields were used as initial data for numerical forecasts which were verified against subsequent objective analyzes.

Besides solving the dynamical and thermodynamical equations for the wind, pressure and temperature fields, other physical processes such as convection, turbulent exchange of heat, moisture and momentum between the atmosphere and the underlying sea and land surfaces, and the transfer of short- and long-wave radiation were represented in the model.

The forecasts were encouragingly good. The 24 hour predictions of winds in the lower troposphere, where the temporal variability is greatest, were generally correct on the movement and development of easterly waves. The predicted patterns and amounts of rainfall were also fairly realistic.

After GATE, when a complex set of observational data became available, the analysis and forecast procedures were improved and were used for testing revised formulations of the physical and dynamical processes in the model. In particular, a new parameterization scheme was developed to provide a more explicit representation of deep convection in cumulonimbus clouds, with entrainment of air from the surface layers, its transport through the depth of the troposphere and detrainment near the tropopause. On the way it is modified by the entrainment of drier, cooler environment air which is compensated by sinking of the surrounding air. The new scheme gave better forecasts of rainfall, and of the movement and development of easterly waves over several days.

The South West Monsoon Region

In 1978 it was decided to displace the tropical model designed for GATE over the Indian sub-continent and surrounding area and use it to examine some characteristic features of the south-west monsoon. This involved appropriate changes to the model's geography and to the underlying surface conditions (sea-surface temperatures, topography, soil moisture and albedo) using appropriate observational data, the boundary conditions for this limited area being provided by a global circulation model. Indeed, the seasonal monsoonal reversal of airflow which affects a large fraction of the globe is a major feature of the atmospheric circulation. It occurs in response to the corresponding reversal of thermal contrast at the Earth's surface. During the Northern Hemisphere winter the Asian land mass is cold relative to the Indian Ocean to the south. The temperature contrast is transmitted to the atmosphere above and induces pressure gradients and associated large-scale flow patterns. During the summer this flow is reversed. The Asian land mass responds quickly to increased solar heating the ocean to the south with its much larger thermal capacity warms much less and the pressure gradient in the atmosphere is reversed.

Over the Indian sub-continent the on-set of the summer monsoon is marked by increase in rainfall towards the end of May. South-Westerly winds are established over the Arabian Sea carrying a plentiful supply of moisture towards the Indian land mass. The monsoon advances from the south-east to the north-west and by early July most of the sub-continent experiences prolonged rainfall and there is an increasing tendency for depressions to develop over the Bay of Bengal and move inland over Bangladesh and India bringing heavy rain. The limited-area tropical model is not suited to simulating the onset and maintenance of the monsoon since it is a relatively large-scale, long-lived phenomenon. It has been successfully simulated by the global circulation models but accurate prediction of the timing of onset and cessation well in advance has yet to be achieved. The tropical model has, however, been used successfully to study the Bay of Bengal depressions and the mechanisms which determine their formation, movement and development, although lack of observations, especially in the upper air over the Bay of Bengal is a handicap. A scaled-down version of GATE in the Indian Ocean, called MONEX, was carried out in 1979 but the Met Office was not a significant participant.

Modelling the Global Climate

In 1965, the year in which numerical weather prediction (NWP) became operational in the Met Office, a research group under G.A. Corby (later designated the Dynamical Climatology Branch) began to study the large-scale basic flow of the atmosphere in the Northern Hemisphere that is dominated by the long planetary waves in the middle latitudes. The hope was that intensive studies of the General Circulation of the Atmosphere (GCA) and its monthly, seasonal and inter-annual fluctuations might lead to the development of numerical models that would simulate and eventually predict these changes and, hence, provide long-range weather forecasts, whilst long-term averages of the global circulation would largely determine the broad features of the Earth's climate. The GCA was the subject of a special topic in the Met Office Annual Report for 1967.

This described preliminary studies of the GCA by plotting time series charts at several levels up to 20km altitude from the routine observations of temperature, pressure and winds, in particular the time evolution and variability of the planetary waves, the other major features such as the breakdown of the circumpolar vortices, the onset of monsoon circulations and the 26-month oscillation.

In parallel with these observational studies, a numerical model was developed to simulate the Northern Hemisphere circulation at 5 levels in the vertical on a latitude-longitude grid of 3° by 5°. By 1968 the model included a radiation transfer scheme, the effects of surface friction, of mountain drag, and of latent heat released during the condensation of water vapour to form clouds. At this stage two hours of computing time on the ATLAS computer were required to advance the model by 24 hours. In 1969 integration of model equations was carried to 35 days, the results showing an encouraging degree of realism. In particular, a detailed study of the structure and development of a fifth-generation cyclone, the 3-dimensional distribution of winds, vertical motion, temperature, humidity and cloud were remarkably realistic even though the sub-synoptic scale processes were only crudely represented. The model also delineated zones reminiscent of fronts.

When the IBM 360/195 computer was installed in 1971, model integrations were made up to 60 days, and in 1972 up to 80 days. These were used to conduct a number of experiments in which the model atmosphere was perturbed by introducing major anomalies in the sea-surface temperature. At this time work started on the development of an 11-level global circulation model with greater horizontal resolution, 10,000 grid points on a 2½° by 3¾° mesh at each level. In 1973 this was extended to 13 levels in order to simulate the stratospheric circulation and the photochemistry of ozone and other trace gases. Early on, the model produced the sudden warmings of the Arctic stratosphere that accompanied the breakdown of the circumpolar vortex at the end of winter. A limited area version of the 11-level model was developed for the tropical regions with a view to using the data collected during the GARP Atlantic Tropical Experiment (GATE) in 1974 and to making the first tropical-area forecasts to guide the huge GATE operations.

In 1975 the 5-level global model was run for hundreds of atmospheric days and produced realistic simulations of seasonal changes of climate including monsoons. A number of numerical experiments were carried out to determine the response of the model atmosphere to major perturbations such as: removal of the Himalayas; making the Sahara wet instead of dry; the ejection of large quantities of volcanic dust into the stratosphere and; concentrating the heat released from all the world's nuclear power stations on two islands, one in the Atlantic and one on the Pacific Ocean.

Responding to the concern of American scientists that the release of nitrogen oxides by several hundred Concordes, flying on average 5 hours per day, would reduce the total stratospheric ozone by as much as 20%, the 13-level model demonstrated that the reduction was not likely to exceed 0.5%. These results later confirmed by American modellers, persuaded the US Congress to grant permission for Concorde to fly to the United States.

The stage was now set to use continuously improved and more complex versions of the global models to simulate the main features of the Earth's climate and its variations and to predict the likely effects of natural and man-made perturbations.

The special topics in the Met Office Annual Report for 1976 was Climate Variability and I chose as the subject of my Symons Lecture to the Royal Meteorological Society, "Towards the Understanding and Prediction of Climate Changes" (Mason, 1976). Here I reported on the use of the 5-level model to test the Milankovich theory that the major ice ages of the last million years were caused by variations in the intensity of the incoming solar radiation as the result of long-term changes in the Earth's orbit on time scales of 20, 40 and 100 thousand years. When orbital parameters appropriate to 8,000BC were incorporated in the model, the Northern Hemisphere summer was about 5°C warmer than at present, in fair agreement with the paleoclimatological record, but since the model did not simulate interaction between the ocean and the atmosphere the result was regarded as indicative rather than definitive.

However, the Milankovich periodicities were soon clearly detected in the analysis of oxygen isotopes in deep ocean sediments and in snow deposited over millennia to form the polar ice caps. The climate changes that followed the Milankovich variations of the incoming solar radiation have also been realistically simulated in more recent and advanced climate models.

At this time (1976) the 13-level model was used to investigate the effect of reducing the total stratospheric ozone by 50% and of increasing the dust content of the stratosphere sufficient to reduce the incoming solar radiation by 4%. Although these perturbations produced a stratospheric cooling of about 10°C, there were no significant changes on the temperature at the Earth's surface.

In 1978 the 5-level global model was used in a first attempt to estimate the climatic effects of doubling the atmospheric concentration of carbon dioxide. The model response in winter was difficult to detect above the natural fluctuations but in the summer hemisphere the temperature increase in average global surface was less than 1°C accompanied by a 5% reduction in rainfall over the oceans. However, no great confidence could be assigned to this result because sea-surface temperatures were held at their current values and no account was taken of the role of the oceans in absorbing, transporting and storing the increased infra-red radiation emitted by the carbon dioxide.

The 5-level model was integrated over 450 days to produce a realistic simulation of the evolution of the annual cycle. In particular, the computed annual variation of the radiative heat flux at the top of the model atmosphere agreed well with values from satellite-borne radiometers.

During the next few years, from 1979 onwards, both the 5- and 11-level models were made more realistic mainly by the improved representation of physical processes. Hitherto the values of sea-surface temperatures, and the distribution of clouds were prescribed by the current climatological values. But if the models were to be used to predict climate changes that might be caused by human activities, it was essential that the clouds and ocean temperatures be predicted by the models themselves in order for them to be consistent with all the other model parameters. Both problems were to prove difficult. In principle cloud extent, height and thickness could be predicted from the computed humidities, temperatures and vertical motions. Some progress was made from 1979 onwards but a satisfactory scheme that would predict also water and ice content of the various cloud types and their influence on both solar and infra-red radiation was several years off.

Although it was recognized that long-term climate changes were almost certainly influenced by the circulation of the deep oceans, the limited power of the IBM 360/195 computer allowed the oceans to be represented only by the well-mixed upper layers of the top 100m. Much attention was given to parameterizing the turbulent transport, by sub grid-scale motions, of heat, moisture and momentum between the Earth's surface and the lowest layers of the atmosphere, but considerable difficulties arose in computing correctly these fluxes at the atmosphere-ocean surface.

By 1980 a new scheme to parameterize atmospheric convection including deep convective clouds in the tropics was incorporated in the 11-level models. Also computations were made of changes in snow cover, and of soil moisture as the difference between rainfall, run-off and evaporation.

The model had now evolved as a principal component of the global climate system consisting of the atmosphere, the oceans, the land surface and the cryosphere (land-based ice sheets and sea ice). A new research group was established to deal with the oceans and the dynamics of sea ice.

By 1979, the model, despite its recognized deficiencies, was sufficiently comprehensive to justify a detailed study of the changes in the model climate induced by suddenly doubling or quadrupling the atmospheric concentration of carbon dioxide after the model climate had reached a new equilibrium. When the sea-surface temperatures were held at their current values, doubling atmospheric CO_2 led to a decrease in precipitation over the oceans and an increase along the eastern coasts of the continents in summer. Land surface temperatures rose on average by only 0.4°C. If, however, CO_2 concentrations were doubled and sea-surface temperatures held 2°C higher than their current values, precipitation increased generally over both oceans and continents although there were some areas of decrease, particularly in the tropics. The land surface temperatures increased on average by 2.8°C. The changes in both precipitation and temperature varied considerably from place-to-place and from season-to-season. Similar experiments were conducted in 1980 with much attention paid to distinguishing the changes due to doubling CO_2 from the model's natural variability.

The development and testing of the global climate models accelerated with the arrival of the CDC CYBER 205 computer, 100 times faster than the IBM 360/195, in 1981. Computing for the 11-level model on a 2° by 3° grid now took only 4 minutes per model day. Research was conducted on including explicit representation of the ocean mixed layer and the dynamics of sea-ice and their interaction with the atmosphere.

During 1982 experiments were carried out to examine the sensitivity of the model climate to the geographical variation of land surface properties such as reflectivity, soil properties, hydrology, vegetation and surface roughness. As stages in the development of an ocean model for coupling to the atmosphere, research continued on the representations of currents throughout the ocean depth, of vertical mixing processes which are very important in the near-surface layers of the oceans, and of sea-ice floating on the surface. Early experiments revealed that the atmospheric simulation must be accurate if the coupling procedure, whereby heat and moisture fluxes, surface wind stress and wind-mixing energy are passed from the atmospheric to the ocean model which, in turn, provides the atmospheric model with the sea-surface temperature field, is to reproduce a realistic seasonal cycle of this field. Further studies with the sea-ice models showed the need to include representations of ice dynamics and of the processes occurring in areas of open water within the ice cover where exchanges of heat and moisture with the atmosphere are particularly high.

By the end of 1983 considerable progress had been made in the development of models to simulate the ocean circulation starting with a 6-layer dynamical model on a 2½° by 3¾° latitude-longitude grid driven by the atmospheric circulation. As a first step towards a fully interactive atmosphere-ocean model, the atmospheric model was coupled to a single-slab mixed-layer ocean model that could respond interactively by storing or exchanging heat. However, the development of a full multi-layer ocean in which heat was transported by internal currents driven by the winds and density differences engendered by differences in temperature and salinity, and which interacted fully with the atmosphere and sea ice, was to take several years. It was only after such coupled models successfully simulated the global climate, its geographical and seasonal variation in the early 1990s was it possible to make reasonably confident predictions of how the climate would respond to gradually increasing concentrations of carbon dioxide and other greenhouse gases (Mason 1993, 1995).

Geophysical Fluid Dynamics

A new laboratory to study the basic properties of a rotating, differentially-heated fluid, fundamental to the understanding the dynamics of, and heat transfer by, the atmosphere, oceans and the molten core of the Earth, was established under the direction of Professor Raymond Hide who joined the Met Office from MIT in 1967. His pioneering work was recognized by election to the Royal Society in 1971 and by the award of major national and international honours, medals and prizes since.

In the most important experiments, the fluid, usually water, was contained in the annulus of a large cylindrical tank heated electrically on the outside and cooled on the inside, and rotated at controlled speed on a turntable. Depending upon the rate of rotation and the radial temperature gradient, the flow develops axisymmetric stable wave patterns with wave numbers 1, 2, 3, ..., reminiscent of the planetary waves in the atmosphere, with much of the flow concentrated in narrow jet streams. The wave number increases as the rate of rotation increases and under certain conditions the wave-like disturbances undergo a regular cycle of changes in amplitude and shape known as vacillation. Under other conditions of rotation and thermal forcing the flow may become highly irregular.

The three-dimensional distribution of temperature and its fluctuations in the fluid was measured by an array of fine thermocouples and the fluid motions at various levels recorded by streak photography of small, neutrally buoyant particles illuminated by a horizontal sheet of light. Variation of the Coriolis force with latitude was simulated by using a rotating tank with a sloping base, and the effects of topography were simulated by placing obstacles of various heights and shapes on the floor.

The conditions under which the wave motions became unstable were intensively studied and criteria established for transitions between the modes in terms of the rotation rate and radial heat-flow. Detailed spectral analysis of the temperature fluctuations allowed precise estimates to be made of the energy transformations taking place in time-varying flows.

It was established that non-linear interactions between the different wave modes determine the amplitudes of the waves and the relationships between their phases. It also appeared that non-linear interactions can promote order rather than disorder in the flow and implies that theories of atmospheric predictability based on the properties of isotropic turbulence are unduly pessimistic.

Some insight into the ordering influence of non-linear interactions was obtained from mathematical studies of solutions and other flows. It appears that the non-linearity enables energy to be fed from the small-scale turbulence to the large eddies and sustains them for long periods. On this basis, Professor Hide accounted for the longevity of the Great Red Spot and smaller features on Jupiter as stable eddies embedded in regions of highly sheared flow, and having a strong resemblance to stable eddies and associated waves and jet streams characteristic of annulus flows in internally-heated systems.

The results of an extensive series of experiments in the rotating annulus were compared with the outputs of numerical models of the flows under comparable external conditions. Many of the observed features, such as the amplitude and structure of the dominant baroclinic wave were well predicted by the models which also simulated some aspects of vacillation.

Experiments were also designed to study the structure and stability of the thermocline in a rotating fluid subjected to heating and cooling at the same level as occurs in the ocean. Others investigated the flow over and around isolated obstacles representing hills and ridges in a rotating system.

Professor Hide devised a new method for determining the radius of the electrically-conducting core of a planet from measurements of the external magnetic field. When applied to the Earth it gave a value very close to that deduced from a study of seismic waves generated by earthquakes.

New work was done on computing the fluctuations of the total relative angular momentum of the atmosphere caused by movements of the large weather systems, which produce tiny but detectable fluctuations in the length of the day. Analysis of global weather charts found irregular changes of up to 15% in the atmosphere's angular momentum over periods of about 10 days and these correlated well with astronomically-determined fluctuations in the length of the day.

Services for Industry and the General Public

In order to provide tailor-made forecasts and warnings for weather sensitive industries such as agriculture, building, transport and public utilities, and detailed local forecasts for the media and general public, Weather Centres were opened in 8 major cities where forecasts were also prepared for local radio and television stations. By 1982, Met Office staff made live TV presentations in Scotland, Wales and Northern Ireland and on 40 radio stations.

© Crown Copyright. Sir John addresses the audience at the televised release of the Met Office's first numerical weather prediction weather forecast on 3rd November 1965.

In 1968 a new service the weather-routing of ships across the North Atlantic became operational. Forecast winds from the computer model were used to forecast the height, direction and growth of wind-generated waves and propagation of the ocean swell, which, given the performance curves of individual ships, allowed a mixed team of weather forecasters and experienced mariners to predict the optimum track over the next 48 hours with updates every 12 or 24 hours. The object was to save time, fuel and damage to ships and cargo. An average time-saving of about 10 hours was soon achieved. In 1970, 350 ships were routed across the Atlantic. The service was extended to the Pacific where tankers sailing between Japan and the west coast of America gained up to 24 hours. The service proved especially helpful to the North Sea oil and gas industry in identifying calm-weather windows for the towing and installation of giant oil rigs, up to 600 feet in height, and for which a forecaster would remain on board during the whole operation. By the mid 1970s special weather forecasts were provided for more than 50 off-shore installations and for helicopters servicing the oil rigs. A new model to forecast waves and swell was introduced in the late 1970s when income from the off-shore industry exceeded £1 million per annum.

Services for Military and Civil Aviation

In 1945 the largest customer for meteorological services was the Royal Air Force, forecasts and personal briefings for aircrews being provided at 54 operational stations in the UK and 24 overseas stretching from Germany to Singapore. The overseas requirement was sharply reduced following UK withdrawal from the East of Suez, leaving stations in Germany, Gibraltar, Malta, Cyprus, Ascension and the Falklands in 1983. However, the total number of aviation forecasts increased from 1.23 million in 1965 to 2.07 million in 1983, reflecting the expansion of civil aviation which culminated in Bracknell and Washington being designated in 1981, as the two World Area Forecasting Centres (WAFCs) providing forecasts and other weather information for airline operations throughout the world.

A major new task arose in 1982 when the Office was requested, at short notice, to support all three Services in the Falklands operation. Within a few days the forecast model was extended to cover the Southern Hemisphere and produced forecasts for the South Atlantic for up to 3 days ahead for the first time. In view of the scarcity of conventional observations much use was made of images from US satellites. A special unit was formed at Bracknell to provide forecasts and other weather information for aircraft flying between Ascension and the Falklands. This involved in-flight re-fuelling for which accurate forecasts of winds and temperatures were crucial. Not a single aircraft was lost. A mobile meteorological unit manned by Met Office staff in uniform was deployed on Ascension within days; a second unit on the Falklands later on.

Services for Agriculture

Agriculture is a large weather-sensitive industry vulnerable in many aspects to changes in meteorological parameters such as temperature, precipitation, humidity, soil moisture, wind and solar radiation on time scales ranging from hours to seasons and beyond. These affect the quantity and quality of agricultural production through their influence on the planting, growth and harvesting of crops, the outbreak, severity and spread of crop and animal diseases and vectors, the use of fertilisers and pesticides, the internal climate of animal houses and crop storage facilities. The Met Office has provided relevant forecasts and advice on all these aspects, the meteorologists working with agricultural scientists and farmers through six regional offices of the Ministry for Agriculture, Food and Fisheries Advisory Service. These were supported by a central unit formed in Bracknell in 1966 which held the relevant data on computer and compiled, for example, a weekly bulletin of evaporation and soil moisture under a variety of crops, from which the demand for irrigation was concluded.

The number, variety and complexity of agricultural problems referred to the Met Office increased substantially between 1966 and 1983. Of particular importance were the outbreak and spread of foot and mouth disease in cattle and pigs, of Newcastle disease in poultry, liver fluke in cattle and sheep, potato blight, apple scab, cereal mildews and rusts and virus yellows in sugar beet. Working closely with pathologists studying the life cycles of parasites and carriers of the diseases it was often possible to judge when inoculation of animals and spraying chemical agents on crops would be most effective.

The Met Office investigated the origin and spread of the serious epidemic of foot and mouth in 1967. A detailed analysis of air-mass trajectories excluded the possibility that the infection was airborne from Europe or North Africa. The evidence indicated that it was the spread within the UK by particles carried downwind from infected sites, especially from burning carcases, and deposited again after capture by raindrops. As a result, the official report recommended that burning should not be used in future outbreaks, but this was ignored in the 2001 epidemic. A new method of calculating the downwind spread of the virus was devised in 1980 to provide a more accurate indication of where to concentrate control measures. This was tested when outbreaks were discovered in Brittany, Jersey and the Isle of Wight and provided valuable guidance to the epidemiologists within hours of confirmation of the disease in the UK, so the spread was very limited. These lessons were apparently forgotten 20 years later.

Developments in Hydrometeorology

Hydrometeorology is concerned with problems and processes that are common to meteorology and hydrology, in particular, the measurement of rainfall, run-off, evaporation and soil moisture. That these are of major importance in agriculture provided the rationale for establishing a new Met Office Branch for Agriculture and Hydrometeorology in 1967. Before that date collaboration between the two disciplines was limited because meteorological operations and research were highly organized and integrated within one government agency whereas hydrology was very fragmented among many small agencies such as river authorities, local authorities and university departments with no central core and no national strategy for planning and management of water resources, the control of rivers and the warning and mitigation of floods.

Considerable improvements followed the establishment of the Water Resources Board in 1964 to coordinate and regulate 29 new river authorities having increased powers regarding the use, quality and conservation of water. It reported to the Department for the Environment (DoE) on operational matters while research was concentrated in a new Institute of Hydrology (IoH) under the Natural Environment Research Council (NERC). The Board was surprisingly abolished in 1973 and replaced by ten Regional Water Authorities under the DoE. At the international level, where responsibility for both operational matters and research lay unhappily with UNESCO, considerable progress followed transfer of the former to WMO and research to the International Association for Scientific Hydrology (IASH) in 1975.

Acquisition of powerful computers by the Met Office made it possible to establish a comprehensive rainfall data bank involving the transfer of data from millions of punched cards and manuscripts to digital format on magnetic tapes and discs and the introduction of error detection and correction. The basic rainfall data and derived quantities from about 5,500 daily- and about 1,000 monthly-read raingauges were archived and readily accessed for the first time and led to rationalization and better design of the network. At the same time the quantity and continuity of observations were improved by the installation of automatic, magnetic-tape recording raingauges.

Major projects involving close collaboration between the Met Office and the Institute of Hydrology were:

- Studies of relationships between point measurements of rainfall and estimates over an area, highly relevant to the design of urban storm-water drainage systems and the regulation of dams and reservoirs.
- A major report on Flood Studies in the UK was initiated by the Institution of Civil Engineers in 1966, commissioned by the NERC in 1970, and produced by the Met Office and the Institute of Hydrology in 1975.

The Met Office used its data bank to estimate the frequency and probability of return periods of floods, and also the probable maximum precipitation at specified sites and over catchment areas for return periods ranging from 6 months to 1,000 years.

In Conclusion

In concluding this memoir, I offer my profound gratitude to all my colleagues whose expertise, loyalty and dedication enabled us, working together, to establish one of the most advanced, best equipped, and most effective National Meteorological Service in the world. It was a pleasure and privilege to lead them into the computer and satellite age.

At the same time, and with their encouragement, I was able to continue research in cloud physics, serve as Treasurer and Vice-President of the Royal Society for ten years, and as Chancellor/President of two Universities. These were the happiest and most productive years of my life, shared with my beautiful wife and two fine sons.

I close by expressing my warmest thanks to Professor Paul Hardaker and his staff (especially Andrew Picken, Sue Brown and Kathy Maxwell) for preparing my hand-written manuscript for publication.

Sir John with Professor Chris Collier, the then President of the Royal Meteorological Society, at the first Mason Gold Medal Award Ceremony in 2006.

Sir John with Professor Anthony Illingworth, the 2009 Mason Gold Medal winner, at the Awards Ceremony in 2010.

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Glossary of Acronyms

AERE	Atomic Energy Research Establishment
AMSU	Advanced Microwave Sounding Units
ATSR	Along Track Scanning Radiometer
COMESA	Committee on Meteorological Effects of Stratospheric Aircraft
DoE	Department of the Environment, UK Government Department
ERS	Earth Resources Satellite
ESA	European Space Agency
ESRO	European Satellite Research Organization
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Programme
GATE	GARP Atlantic Tropical Experiment
GCA	General Circulation of the Atmosphere
GTS	Global Telecommunications System
HALOE	Halogen Occultation Experiment
IASH	International Association for Scientific Hydrology
IoH	Institute of Hydrology
MIT	Massachusetts Institute of Technology, Boston, USA
MONEX	Monsoon Experiment
MRF	Meteorological Research Flight
MRU	Meteorological Radar Unit
NASA	National Aeronautics and Space Administration
NCAR	National Centre for Atmospheric Research, based in Boulder, Colorado, USA
NERC	Natural Environment Research Council
NWP	Numerical Weather Prediction
UNESCO	United Nations Educational, Scientific and Cultural Organization
RAF	Royal Air Force
RMC	Regional Meteorological Centre
RTH	Regional Telecommunications Hub
SSU	Stratospheric Sounding Unit
TIROS	Television Infrared Observation Satellite
UARS	Upper Atmosphere Research Satellite
WAFC	World Area Forecast Centre
WMO	World Meteorological Organization
WWW	World Weather Watch

> *"Sir John's contribution to both cloud physics and to meteorology more widely over his long and distinguished career has been truly astounding."*

Professor Paul Hardaker, Chief Executive of the Royal Meteorological Society

> *"I applied to the Met Office after my PhD (in theoretical physics). I knew nothing about meteorology at the time, but had heard rumours that the Office was an interesting place to work, and that the governor was himself a pretty formidable scientist. Although this encouraged me to apply, I thought my chances of success were minimal. To my great surprise I was successful, and discovered subsequently that this was because Sir John had given instructions to the interview team to find him the best young scientists regardless of background. I sometimes wonder if I would have fared as well in today's environment. For this, for his subsequent guidance and encouragement, I owe Sir John an enormous thanks for giving me the best career anyone could wish for."*

Professor Tim Palmer, DSc, FRS, President of the Royal Meteorological Society

Sir John at his desk on his first day at the Met Office on 1st October 1965.

Sir John with Her Majesty the Queen during her visit to the Met Office in Bracknell.

> *"Sir John's presence was felt throughout the Office - he was a giant of a man, both physically and intellectually. We were in awe of him! He gathered around him some of the best young scientists, many of whom have gone on to be leaders themselves. His legacy is the world-leading status that the Met Office still holds in weather and climate research and prediction."*

Professor Julia Slingo, OBE, DSc, Met Office Chief Scientist