Zeitschrift: Verhandlungen der Schweizerischen Naturforschenden Gesellschaft. Wissenschaftlicher und administrativer Teil = Actes de la Société Helvétique des Sciences Naturelles. Partie scientifique et administrative = Atti della Società Elvetica di Scienze Naturali

Herausgeber: Schweizerische Naturforschende Gesellschaft

Band: 147 (1967)

Artikel: Global atmospheric research

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DOI: https://doi.org/10.5169/seals-90668

Global atmospheric research

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1. Introduction

I would like to talk to you today about the way in which meteorology has developed as a science, to appraise the present position, and thereby attempt to define the major problems now calling for solution. I would then like to tell you how meteorologists are thinking and planning to tackle these problems over the next five to ten years. In all that I shall say my attention will be directed primarily at the global atmosphere considered as a single physical system. But, as will appear, a physical understanding of the behaviour of the global atmosphere demands that we have an appreciation of the working of its many component parts and how these parts are geared together to form a single system. We commonly call this study the study of the general circulation of the atmosphere. The accent is thereby thrown on the motion of the atmosphere, the implication being that only by understanding its motion shall we understand its overall structure. That is indeed the case.

2. The development of meteorological science

Meteorology, like other physical science, effectively began in the 17th century. Soon after the invention of the barometer, HOOKE (1664) was able to write to BOYLE that he had found the barometer to "most certainly predict rainy and cloudy weather when it falls very low . . . I hope it will help us one step towards the raising of a theoretical pyramid, from the top of which, when raised and ascended, we may be able to see the mutations of the weather at some distance before they approach us, and thereby being able to predict, . . . many dangers may be prevented, and the good of mankind very much promoted". Further observation did not allow this optimism to be fully sustained. Yet barometric pressure has remained with us as a well-nigh indispensable element in the study of weather—though we are not immediately conscious of it as we are of wind, temperature, cloud and precipitation.

The first main task in an observational science is to systematize the observations—that is, to create the system, which means to describe behaviour in some integral manner. HOOKE recognized this need in meteorology, but HALLEY (1688) was the first notable exponent with his map (fig. 1) of the Trade and Monsoon winds of the tropical oceans. HALLEY's description was possible because the winds he depicted blew

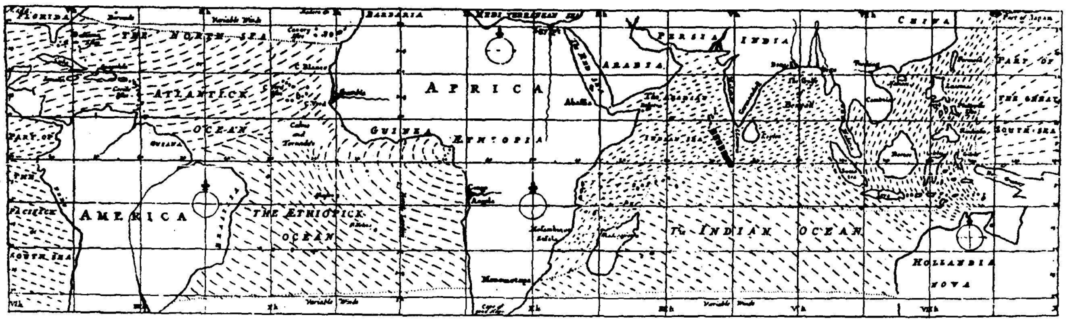

Figure 1

HALLEY's map of 1688 of the Trade and Monsoon winds of the tropical oceans.

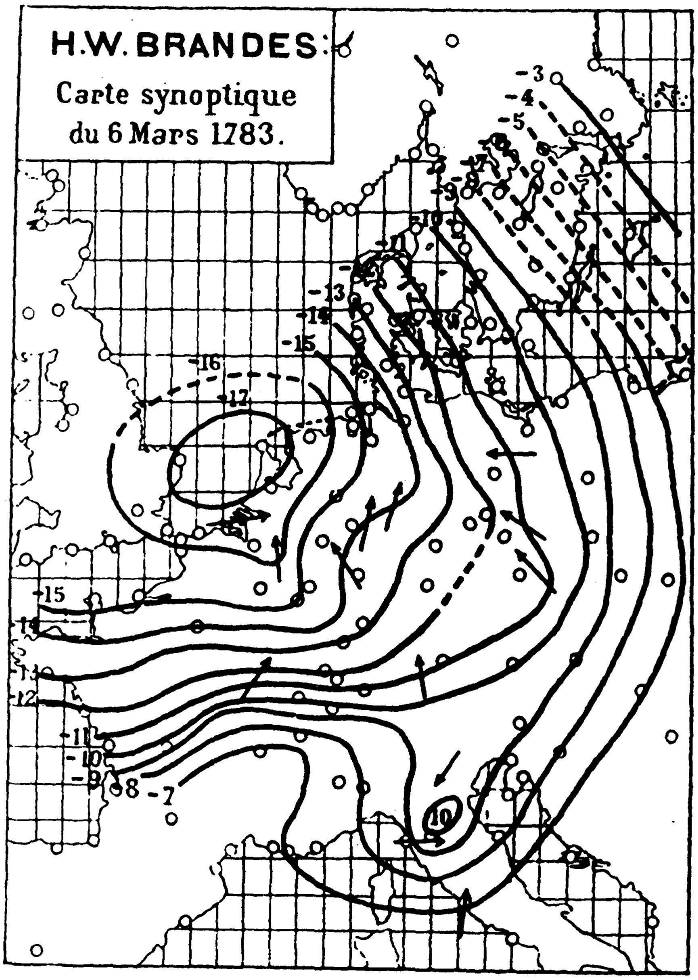

Figure 2

Reconstruction of one of the first (1783) synoptic charts, by BRANDES. The lines show equal deviation of pressure from normal and the arrows give the surface wind direction. A centre of low pressure is situated over the southern North Sea.

with such steadiness that there was little problem in distinguishing signal from noise. In higher latitudes, where westerlies predominated, it was otherwise. Here the disturbances in speed and direction were so large that a physically meaningful description was much slower to emerge. However, following the work of pioneers like BRANDES in the first decades of the 19th century, a *synoptic* meteorology of extra-tropical latitudes was slowly created. The existence of travelling cyclonic and anticyclonic pressure systems was recognized (fig. 2) and some relation with their weather established. Thus BUYS BALLOT (ca. 1850) was able to enunciate his empirical law that, in the northern hemisphere, lower pressure is to be found to the left of the wind and higher pressure to its right. Others were concerned to develop structural models of these weather systems, particularly of the cyclone which was the system of inclement and dangerous weather, and great was the controversy attending such model development from about mid-century onward. For with the invention then of the electric telegraph it became possible to organize observational networks reporting immediately and regularly to centres from which forecasts might be issued for the advice of mariners and other users. Many state meteorological services were in fact created at that time and a model of the cyclone however imperfect was an almost indispensable framework for their observations and the forecasts made empirically from them.

I shall not detail the development of these models. They were, to begin with, necessarily based on surface observations only (but exploiting the observed motions of clouds), though by the end of the century the observations made from balloons, at first manned and then unmanned, and from kites were adding some knowledge to what could be inferred from the surface observations alone. This extended period of cyclone modelling culminated at the end of World War I in the Norwegian model of the frontal cyclone. It is illustrated, in horizontal structure and in temporal evolution, in figure 3. This model remained current until and after World War II.

Now the point I wish to make strongly at this stage is that the developments I have so briefly described were developments of description. That is not to say that they were made without regard to the laws of physics, but they were certainly not shown to be any logical necessity arising from those laws, except in certain details of behaviour. Yet if meteorology is to be a physical science, the structure and evolution of the atmosphere must be regarded as springing inevitably from the laws of physics and such *given* data as the solar radiation incident on an atmosphere of basic composition overlying a lithosphere and hydrosphere.

Of course, from Newton onwards, many physical laws had been shown to be in operation in the atmosphere. Thus, DELUC, followed by LAPLACE, had demonstrated the necessary rate of decrease of pressure with height in an atmosphere without accelerations comparable with gravity—the hydrostatic equation. DALTON had shown that the formation of cloud was primarily due to the cooling of moist air by expansion as it rose from

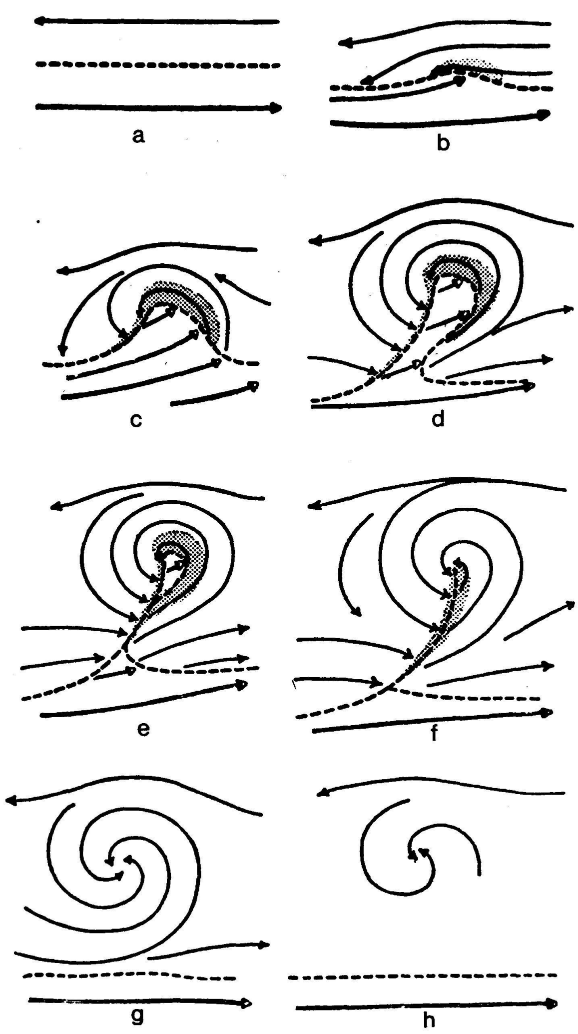

Figure 3

Evolution of extra-tropical cyclone and its fronts according to J. BJERKNES and SOLBERG (1922). Thick arrows show warm air, thin arrows cold air, and the dashed lines the boundaries (fronts) between them. Rain areas are shaded.

a lower level (higher pressure) to a higher level (lower pressure), taking cognizance of the variation of the saturation vapour pressure of water with temperature. The precise rate of cooling (or warming) of a parcel of air, saturated or unsaturated, when displaced upwards (or downwards) adiabatically had also been determined from the First Law of thermodynamics in the 19th century. Again, and of great importance, the equations of motion of a fluid on a rotating earth and the equation expressing the conservation of mass of the fluid were known from well back in the 19th century and HELMHOLTZ and others had applied these equations to certain kinds of motion which could arise in the atmosphere. By the end of the century something also was known about the operation of the laws of radiation in the atmosphere, both for solar (short-wave) radiation and for self-excited (long-wave) radiation in the atmosphere and at the earth's surface.

But no one before V. BJERKNES in the first decade of this century appears to have had the scientific vision to see that it was appropriate to try to apply physical laws quantitatively and deductively to the atmosphere; thus to demonstrate the *necessity* of trades and westerlies, that cyclones and anticyclones of inferred structure must form, and that the atmosphere should evolve in the way it was observed to do, with its clouds and rain here today and there tomorrow, and the fields of wind and temperature all a necessary part of an integral physical system. There was indeed a good reason why the vision was slow to emerge; namely that the differential equations which were known to express, with more or less approximation, the physical determinism of the system were nonlinear, so that, as V. BJERKNES said, "an exact analytical integration of the system of equations is out of the question". There was also the formidable technical and economic problem of obtaining a sufficiently accurate and comprehensive knowledge of the three-dimensional state of the atmosphere at the initial time of a particular integration of the equations, whether performed deductively or from experience. This was before the days of radiosondes, ocean weather ships and other advanced but expensive technology.

V. BJERKNES was a giant in formulating the principles of a deductive treatment of atmospheric behaviour, but he found no very good recipe for carrying out the necessary integration of the equations. However, another genius appeared upon the scene in the second decade of this century—L. F. RICHARDSON. He had been doing very original work on the approximate solution of nonlinear differential equations by finite difference methods—methods which have now become commonplace in this age of electronic computers—and he began to dream of applying his new-found techniques to the problem before us. From 1913 to 1921 he developed the equations of motion, conservation of mass and energy, in suitable form, designed a computing scheme (necessarily manual at that time) to provide their solution, and worked out himself a sample forecast for a particular 6-hour period.

The forecasting plan, described by RICHARDSON in his classical monograph *Weather Prediction by Numerical Process* (1921), involved the division of the global atmosphere into 5 layers each about 200 mb deep and the layers into "squares" about 200 km on the sides, observations of the meteorological variables being required at the initial instant at the centres of the squares. Finite difference increments in each of the dependent variables could then be computed from the appropriate equations and the process repeated with the new values of the variables again and again for as long as the equations or the mathematical technique could be expected to retain validity.

About this scheme, involving 3200 atmospheric columns and requiring on RICHARDSON'S estimate about 64000 computers if they were to keep usefully ahead of the weather, he wrote as follows:

> After so much hard reasoning, may one play with a fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the antarctic in the pit. A myriad computers are at work upon the weather of the part of the map where each sits, . . . The work of each region is coordinated by an official of higher rank. Numerous little "night signs" display the instantaneous values so that neighbouring computers can read them. . . . From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; . . . One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide rules and calculating machines. But instead of waving a baton he turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand.
>
> Four senior clerks in the central pulpit are collecting the future weather as fast as it is being computed, and dispatching it by pneumatic carrier to a quiet room. There it will be coded and telephoned to the radio transmitting station.
>
> . . .
>
> In a neighbouring building there is a research department, where they invent improvements. But there is much experimenting on a small scale before any change is made in the complex routine of the computing theatre. . . . Outside are playing fields, houses, mountains and lakes, for it was thought that those who compute the weather should breathe of it freely.

RICHARDSON's sample forecast related to the central part of an area in Europe (fig. 4) over which V. BJERKNES had previously prepared a three-dimensional analysis for a particular period of the structure of the atmosphere in respect of pressure, temperature, humidity, wind velocity, cloud and precipitation. The sample computation was made in France "in the intervals of transporting wounded in 1916–1918. During the battle of Champagne in April 1917 the working copy was sent to the rear, where it became lost, to be rediscovered some months later under a heap of coal"! How hard it must have been for RICHARDSON to find that his sample forecast gave a catastrophic change of surface pressure of 145 mb in 6 hours, while in reality there was negligible change. The reasons for that were partly realized by RICHARDSON himself, but they are another story.

And so we arrive at the post-World-War-II period, RICHARDSON's work having lain practically dormant in the interval. Much new information

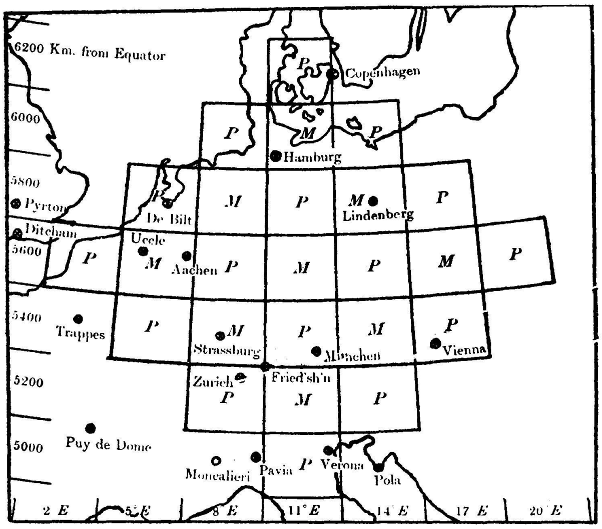

Figure 4

The grid used by RICHARDSON for a six-hour sample forecast from data for 7 GMT, 20 May 1910. The forecast referred to property changes in the vertical column overlying the "square" containing München.

on the ways of the atmosphere had emerged, largely under the pressure of war, radiosondes having largely provided it. But another giant, ROSSBY, was showing how to regard it with a more discerning dynamical —we might say inertial—eye, while SUTCLIFFE and others were directing attention away from fronts (discontinuities) in the body of the atmosphere to seek the causes of major developments in the larger scale horizontal gradients of temperature. Then the electronic computer appeared on the scene and a diminished version of RICHARDSON's dream began to appear to be practical politics. By 1950, CHARNEY with others was showing that a numerical scheme of weather prediction, using simplifications of the equations deriving from ROSSBY, had great potential (fig. 5). His methods were taken up and adapted by a number of meteorological services to obtain useful forecasts over limited areas and extending to about two days ahead of the initial observations. This was indeed a milestone in our science, vindicating the vision of V. BJERKNES and L.F. RICHARDSON that physical laws could and should be applied to the quantitative evaluation of atmospheric structure and evolution.

The triumph was not, however, so great that the theorist and the service providing the forecasts could be content. The limitations in space and time of the integrations were severe and that not only because of computer capacity and blanks in the observational network. The model of the atmosphere which was represented by the equations was so much simplified compared with the real atmosphere that it did not possess the potential for long-term evolution. In particular it lacked the sources and sinks of heat which any engine, however good its fly wheel, must possess if it is to go on running. These sources and sinks of heat arise from solar

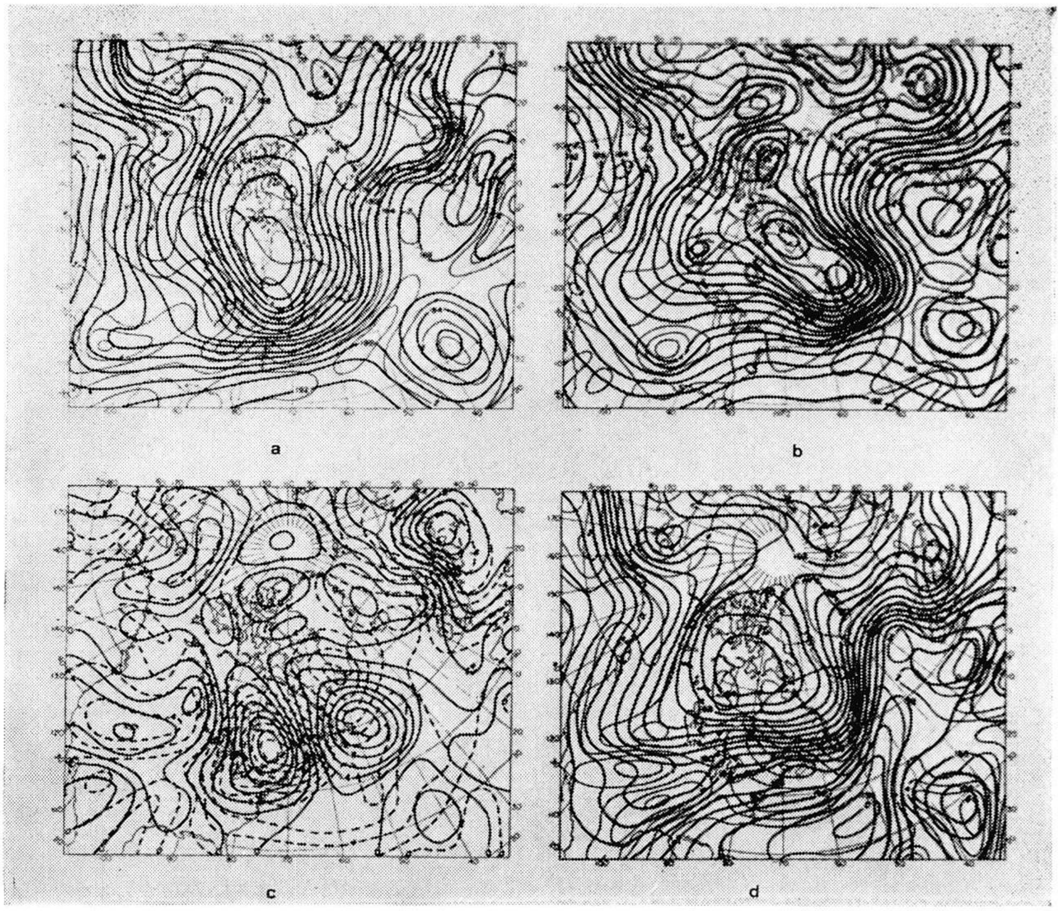

Figure 5

An example of one of the first numerical forecasts. The upper charts (a, b) show the observed flow fields at the 500-mb level (5 km approximately) at 03 GMT, 30 and 31 January 1949, by means of the heavier lines which are contours of the 500-mb surface and are, approximately, streamlines. Chart (d) gives the forecast flow field for comparison with (b) and chart (c) gives the observed (full lines) and computed (broken lines) 24-hour height changes of the 500-mb surface. (After CHARNEY, FJÖRTOFT and VON NEUMANN.)

radiation and the self-emission of radiation from the atmosphere which are themselves determined by the atmosphere's evolution.

In this situation PHILLIPS in 1956 carried out what he called a numerical experiment on a model two-layer dry atmosphere stretching from near the equator to near the pole. He made it start from rest at a uniform temperature but gave it more or less realistic sources and sinks of heat and computed its evolution. After "jolting" it, he found it developed disturbances, with structures much like our familiar cyclones and anticyclones, which travelled in a belt of westerlies with surface easterlies on their warm equatorward and cold poleward sides (fig. 6). *It was the first demonstration of the necessity for something very like the observed general circulation of the atmosphere.* With this great impetus SMAGORINSKY and then

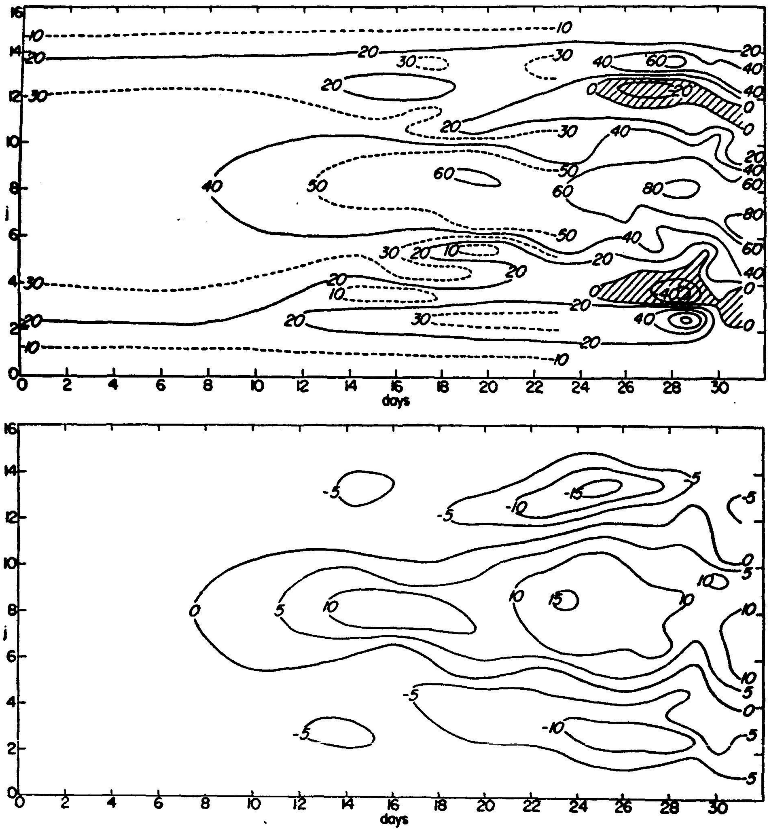

Figure 6

Variation of zonal wind speed (m/s, westerlies positive) with latitude *j* (arbitrary scale) and time following perturbation of the system. The lower portion shows surface winds, with easterlies on the equatorward and poleward sides of mid-latitude westerlies; the upper portion shows winds (easterlies shaded) at the 250-mb level (upper troposphere), with a westerly jet developing in middle latitudes. (After PHILLIPS.)

MINTZ have made more realistic and complex models but still with a number of processes oversimplified. The results (figs. 7 to 10 show examples) have however been so encouraging that they have brought us back to the full problem posed by RICHARDSON, namely to observe the whole atmosphere on a suitably spaced network of points so as to determine its physical evolution on the scale of the network over as long a period as possible from some chosen initial instant. We may now indeed say that theory waits on observation for its further development and exploitation. But the problems posed are formidable: in developing the governing equations so as to represent all important physical processes and boundary conditions; in computer science and technology since this part of the enterprise for the models envisaged is much beyond current capabilities in this field; and not least in designing a system of global observation which will be adequate for the models and within man's economic resources. This enterprise has been formulated by the Committee on Atmospheric Sciences of ICSU/IUGG in cooperation with the

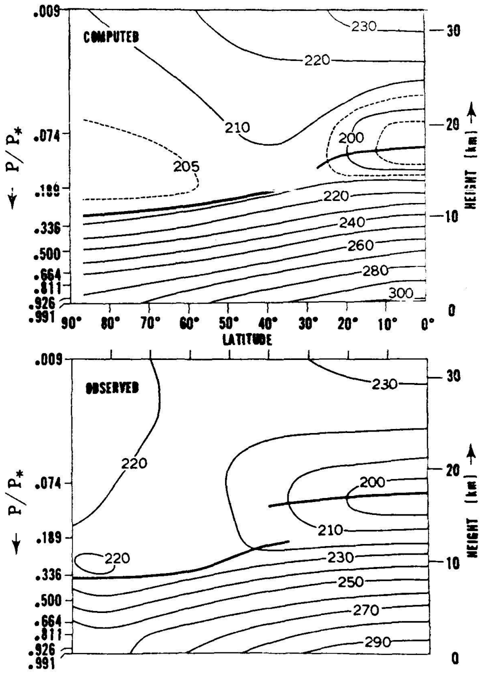

Figure 7

Comparison of computed (above) with observed (below) mean temperature (°K) as function of latitude and height. The heavy lines show the tropopause. The scale on the left shows the layers into which the model atmosphere was divided (P = pressure, P_* = surface pressure). (After MANABE, SMAGORINSKY and STRICKLER.)

World Meteorological Organization (WMO) and has been named the Global Atmospheric Research Programme (GARP). It is an experiment which, with preliminary subprogrammes satisfactorily carried out over the next few years, is expected to be achievable in the mid 1970's. If reasonably successful, it can be expected to usher in a new era in extended and long-range forecasting.

3. The scientific nature of GARP

Before discussing what may be implied operationally by GARP, it is appropriate to restate the scientific problem which is at issue. *It is to determine the predictability of the global atmosphere in regard to the evolution of its structure on a horizontal scale upwards of a few hundred kilometres given a full description of that large-scale structure at an initial instant.* Thus there will be no attempt to observe or to predict the many smaller scale atmospheric systems as "individual" entities—systems such as cumulonimbus storms, sea breezes, tornadoes, valley winds, fronts, etc., all of which affect weather more or less notably in their areas. But insofar as such systems involve processes which react on the larger scale systems, the tropical and extra-tropical cyclones, the long waves in the westerlies, the trades, and so forth—and the scientific delight and

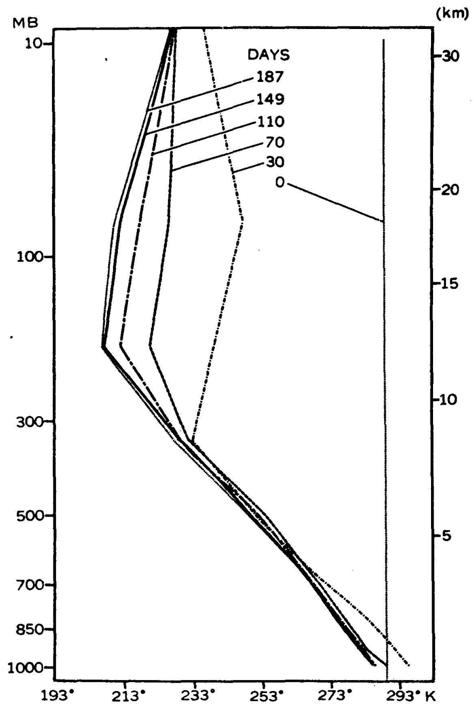

Figure 8

Variation of the vertical distribution of temperature of a model atmosphere with time at 45° latitude. (A quasi-equilibrium temperature profile is reached after about 150 days, but more rapidly in the troposphere.) (After MANABE, SMAGORINSKY and STRICKLER.)

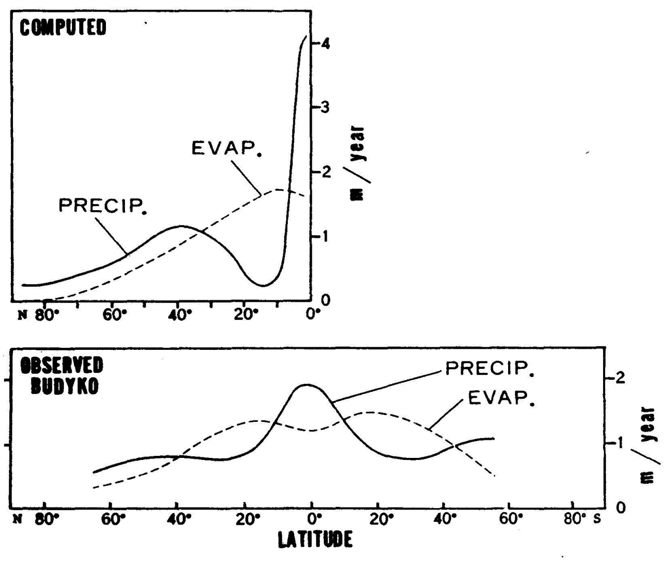

Figure 9

The latitudinal distributions of precipitation and evaporation as computed for a model (above) and as inferred for the real atmosphere (below). (After MANABE, SMAGORINSKY and STRICKLER.)

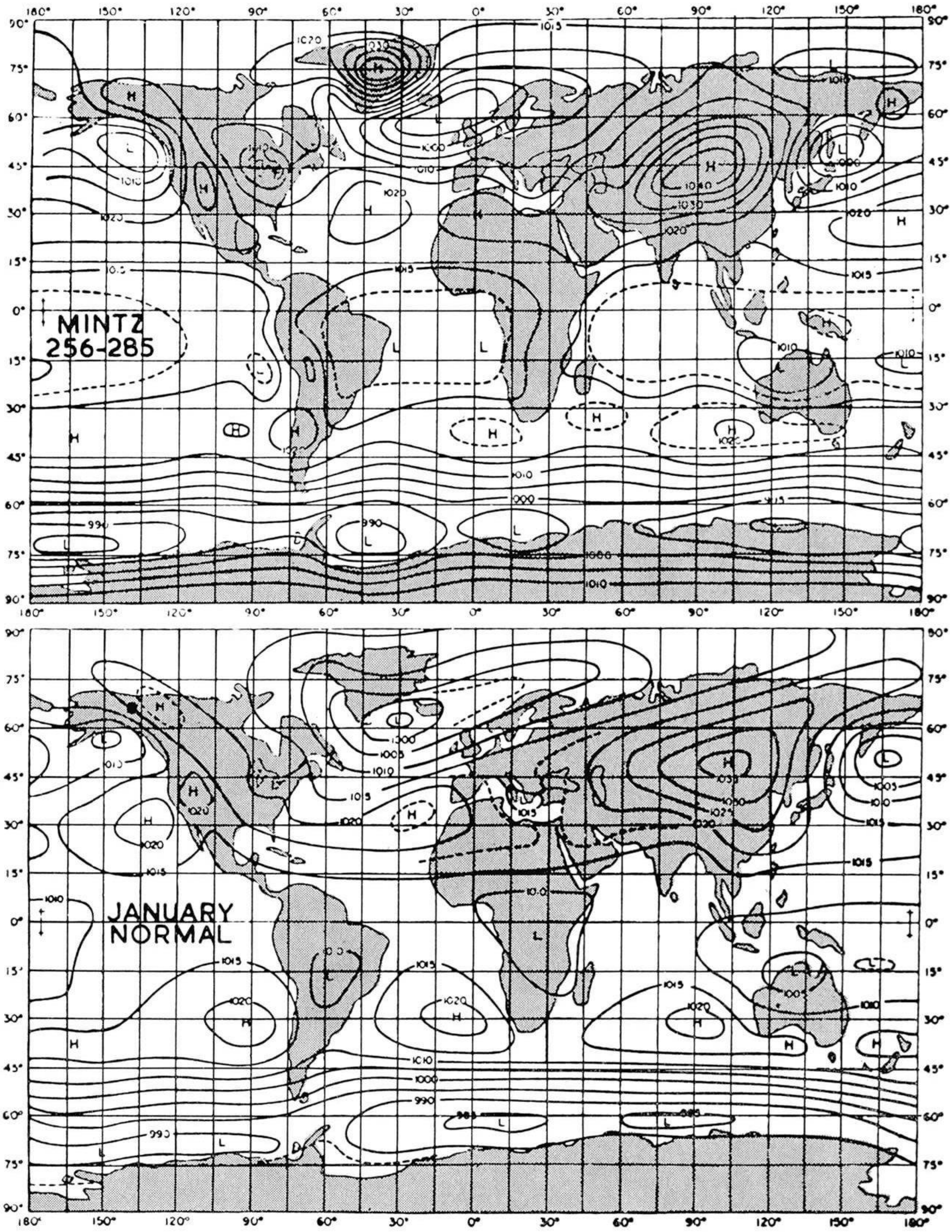

Figure 10

Comparison of computed (above) with observed (below) mean surface pressure (mb) for January. Note general agreement but presence of spurious anticyclone over Greenland in model atmosphere. (After MINTZ.)

subtlety of much atmospheric science is that the atmosphere is full of such feed back—then these processes must be represented parametrically and in bulk on the scale of the grid, i.e. in terms of the large-scale

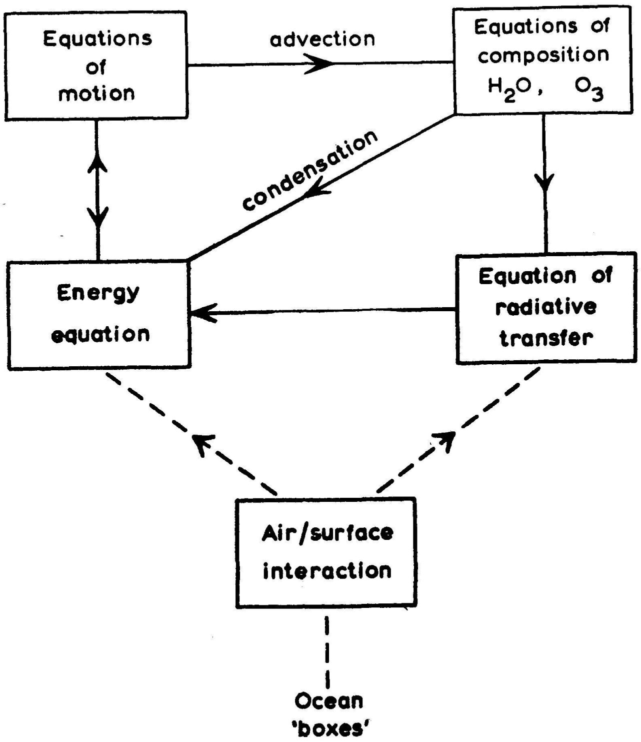

Figure 11

A schematic diagram showing the physics involved in an extended integration of the equations which determine the evolution of the atmosphere. Each box represents equations deriving from basic physical laws (of momentum, energy, etc.) and the interplay of one process with another is indicated by arrows between boxes. Not all operative interactions are shown.

parameters. To provide an analogy—if we are interested in a particular kind of laminar flow of a gas, we do not attempt to describe the flow directly in terms of the motions of the individual molecules of the gas. But the transfer properties arising from these individual motions are represented in the governing equations by a coefficient of viscosity, thermal conductivity, etc. of the gas, multiplied by a gradient of the bulk flow. It is the need for realistic parameterisation of processes like air/sea interaction, the transfer of momentum, heat and water vapour in the turbulent boundary layer of the atmosphere, by cumulus-like convection and frontal action, and the transfer of heat by radiation, that now poses some of the biggest problems in atmospheric modelling. It is for the determination and test of methods of parameterising such processes that important GARP subprogrammes will be needed preliminary to the main GARP programme itself.

The computed evolution of the atmosphere by integration of the model equations (fig. 11) requires observational data for the initial time only of the integration. But to determine the predictability of the model, not just once but over a representative range of inital conditions, e.g. as between summer and winter in a particular hemisphere, will require that the observational system be maintained for a lengthy period, for comparison with the predictions of the model. It has been decided therefore that the observational system should be operated for one year to provide a satisfactory experiment. Some particular observations will however not necessarily be required continuously over the whole globe in order that certain features of the model may be adequately tested.

Much thought has already been given to the likely limits of predictability of the atmosphere in the sense defined, for one should have some grounds for regarding a big experiment of this kind to be worth while operationally as well as scientifically. One important limitation must arise from errors in the initial observations, or from effective errors arising from the method of smoothing the initial observations in a way regarded as appropriate to the model and the grid over which it is to be applied. When the effect of such errors has built up in time to a stage that the predicted atmosphere departs from the actual by as much as two actual atmospheres chosen at random differ from each other, the model will have lost predictive value. Present, necessarily tentative, research along these lines suggests that realizable models should have predictive value for a *minimum* of about 20 days. But I wish to stress once again that the aim of GARP is to determine this period for the atmospheric models and observation systems which can be developed in the next five to ten years.

4. GARP—Observational system

4.1 General

The upper limit of the atmosphere for the purposes of GARP is taken to be 30 km or 10 mb which is the present practical ceiling of radiosondes. There is of course some atmosphere ($\sim 1\%$ by mass) above this level, but it is thought that its effect on the atmosphere below, or conversely, is very small and can be represented by suitable boundary conditions. The model requirement is then to obtain suitably averaged data for each point of the 3-D network into which the atmosphere is divided, which may be at 10 to 20 levels in the vertical and every few hundred km in the horizontal.

The present number and distribution of aerological stations is quite inadequate to satisfy the data requirements—about 1000 existing stations against a need for about 10000 if they were to be of the same sort. Moreover the big gaps in the existing network occur in the deserts and nonindustrialized countries and over the oceans and ice caps where conventional aerological stations are very difficult to set up and maintain.

The difference between the present and the required density of data points has led WMO to aim to achieve in due course a true World Weather Watch (WWW). Some filling in of the more serious gaps will be attempted over the next few years using more or less conventional techniques, but it is realized that new and cheaper techniques will have to be developed in order to achieve the complete observing system. Fortunately there are a number of developments involving space techniques which hold consider-able promise and I shall now say something on these possibilities. They involve the use of satellites either as communication and location devices or as platforms on which indirect sensors of atmospheric structure can be carried.

4.2 Horizontal "sounding" techniques (GHOST/EOLE)

The most important new development in the direct sensing of atmospheric structure for global application involves the use of superpressurized constant-volume balloons which float at a number of selected constant-density levels. The winds are given by the translation of the balloons over given periods, and the pressure, temperature and humidity of the air are provided by sensors suspended from the balloons. One form of the technique under development in the USA is termed the Global Horizontal Sounding Technique (GHOST) and another form under development in France is termed Project EOLE.

If the balloons could be suitably injected into the atmosphere, remained at more or less constant separation in their flight surfaces, and had infinite life, we should have a well-nigh perfect global sensing system.

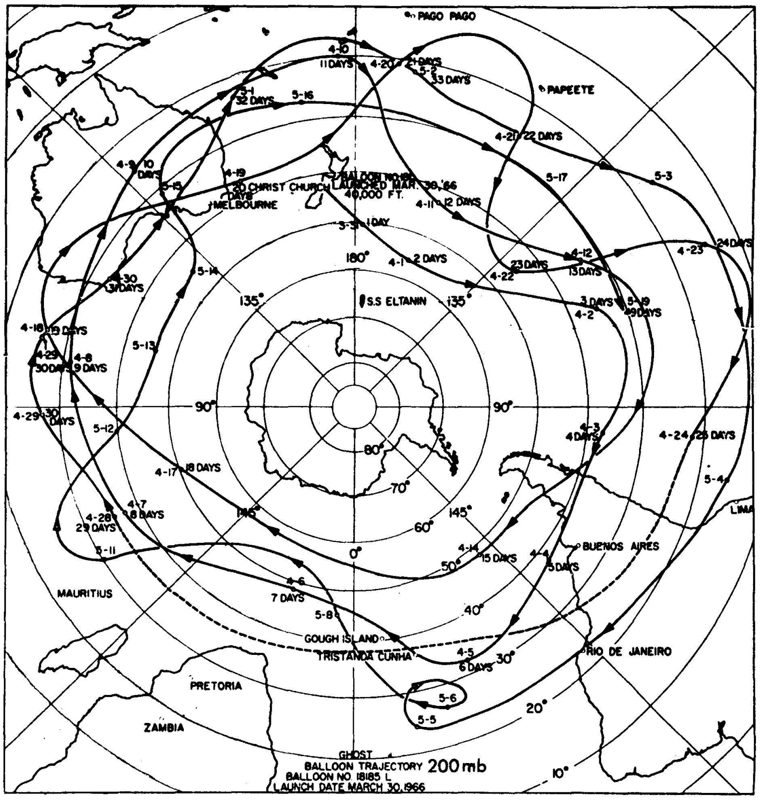

Figure 12

A sample trajectory of a GHOST constant-volume Milar balloon released 30 March 1966 from New Zealand and flown at a constant-density level near 12 km altitude. This is not an air trajectory, because the balloon does not partake of the vertical motion of the air. (After LALLY.)

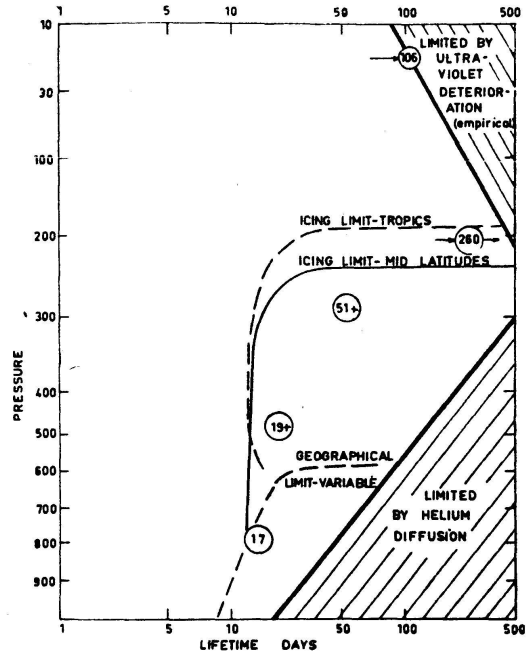

Figure 13

GHOST balloon life (log scale) as function of height (pressure in mb) of flight level. Shaded areas in lower and upper right show theoretical limits from diffusion loss and ultraviolet deterioration respectively. Circled figures show realized lives and additional lines probable limits from icing and mountain loss. (After LALLY.)

Of course the balloons will do none of these things, but tests have been and are being carried out to determine actual performance.

Figure 12 shows a trajectory of a GHOST Milar balloon released, as one of a series, from Christchurch, New Zealand, on 30 March 1966. It flew at about 200 mb (12 km) for 49 days, circumnavigating the southern hemisphere 4 times. In this series the balloons were tracked by solar navigation. There was a photoelectric solar-elevation sensor on the balloon which carried a radio transmitter powered by solar cells to transmit in code the sun angle to one of three ground receivers. The relation of actual to possible life of these Milar balloons is shown in figure 13. The possible life is limited at lower levels by diffusion loss of gas and at upper levels by ultraviolet deterioration. In the stratosphere the possible life appears to be readily realizable, but at the lowest levels there are earlier losses from mountain range capture and in the middle and upper troposphere there are serious losses from balloon icing. It is however possible to prevent the latter loss by hanging a float on the balloon so that when it descends to the surface under its weight of ice it remains suspended until the ice melts and it then returns to flight level. It would then give a vertical sounding of the atmosphere and indeed might be equipped to undertake such Yo-Yo action under radio command.

Regarding the variation of balloon separation, numerical experiments

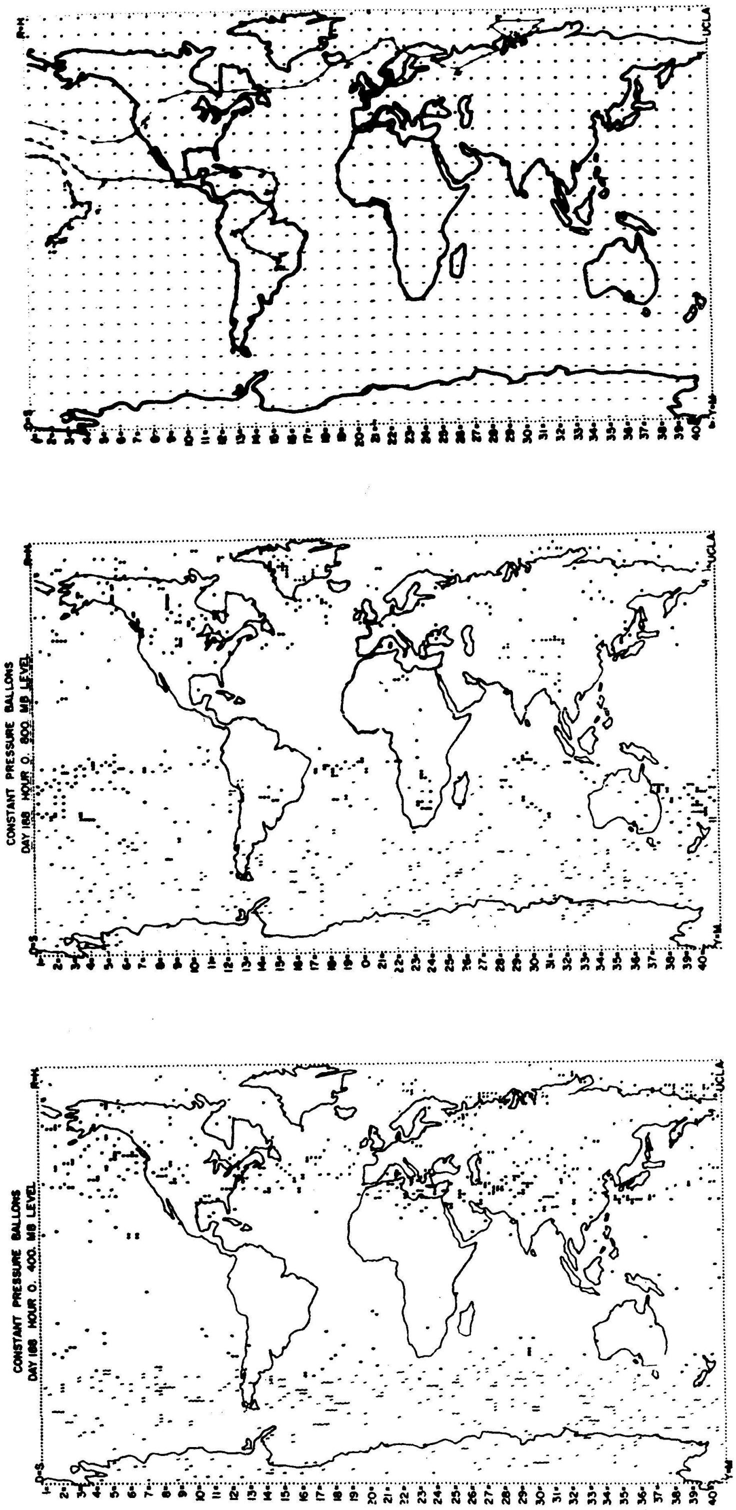

Figure 14

Results of a numerical experiment on balloon clustering. Top diagram shows the points at which balloons were "released". The middle and bottom diagrams show balloon positions after 32 days of flight at 800-mb and 400-mb levels respectively. (After MINTZ.)

have been conducted with a dynamical model of the atmosphere in which hypothetical balloons were "released" at a given time from all grid points and their later positions (and loss by mountains) determined. The results, after 32 days, for flights at the 800-mb and 400-mb levels, are shown in figure 14. There are notable losses from the northern hemisphere tropics at 800 mb and from the whole tropical region at 400 mb. The losses are however almost certainly exaggerated by defects in the model for low latitudes. From these and other such tests it is tentatively concluded that between 25 and 50 launch sites would be adequate to provide global coverage, with balloon replacements being required at an average of one or two per launch site per day, to combat losses and clustering in a seven- or eight-level system.

In a global GHOST/EOLE system techniques are required for locating the several thousand balloons with sufficient accuracy for wind measurement and to provide data acquisition, storage and read out. This is a formidable problem but one which appears to be thoroughly soluble by satellite technology.

The balloons would carry electronic equipment which would enable them to respond to an address when interrogated by the satellite, to transmit information translatable as range, and to telemeter values of the meteorological parameters. One or perhaps two polar orbiting satellites at 1000 km height would have the capacity to carry out this interrogation and data acquisition for the whole balloon system. [It would also be used for interrogation of and data acquisition from automatic surface stations on the ocean (buoys) and at remote land stations.] With one satellite, balloons would be interrogated on two successive satellite passes 110 minutes apart, and twice per day (day and night sides of the earth).

The associated ground data-handling system is necessarily complex—it re-programmes the satellite, reduces the balloon data received from the satellite into a form suitable for numerical analysis, and provides instructions to launch sites on balloons to be launched and addresses to be set. It is shown schematically in figure 15.

Apart from further tests in 1967/68 of constant-volume balloons for this system, a test of a satellite, observation platform, ground control system called IRLS (Interrogation, Recording and Location System) will be made using NASA's NIMBUS-B satellite in late 1967 or 1968. The EOLE system is also due for test, using 500 constant-volume balloons in low latitudes and a French satellite FR-2, in 1969/70, and there will be further tests of the IRLS system in 1969/70 using NASA's NIMBUS-D satellite.

It would be foolish to minimize the difficulties to be overcome in order to develop the GHOST/EOLE system to full operational status. Moreover the balloon system must not present a significant hazard to aircraft—but the limits seem likely to be met. In the next two or three years we should know whether it is indeed a viable observational system for the intended purpose, with or without other systems apart from a basic network of conventional aerological stations.

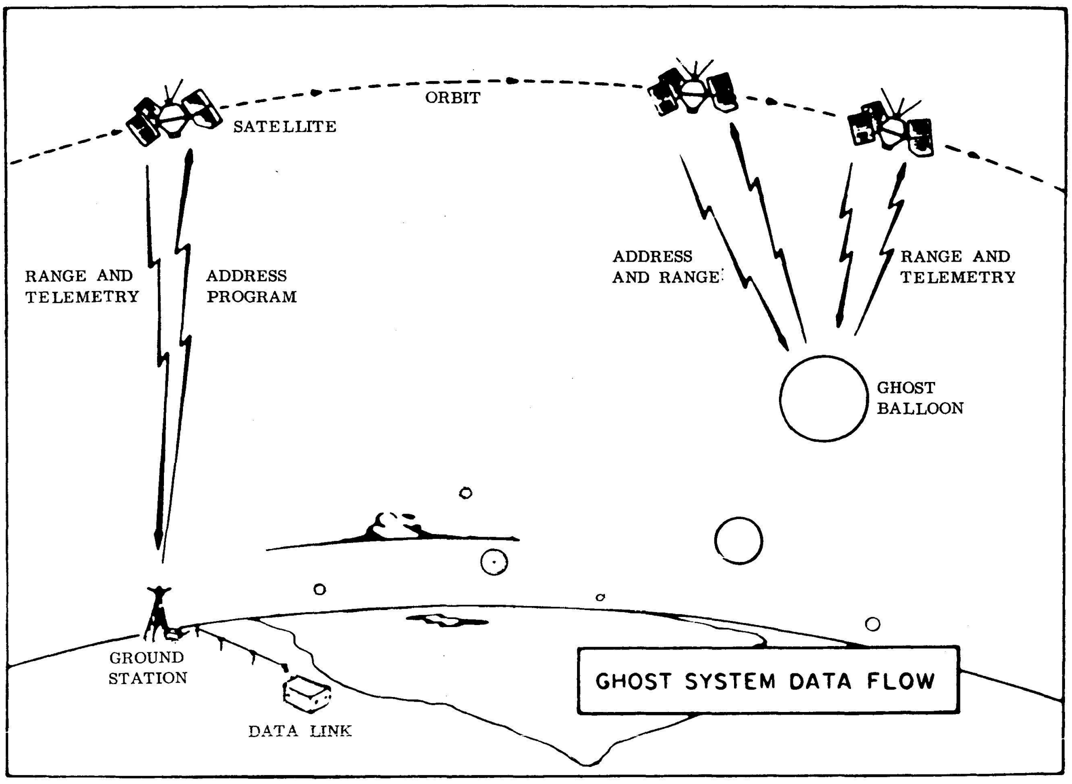

Figure 15

Schematic picture of GHOST interrogation, location, instruction and data-flow system.

4.3 Indirect atmospheric sensing from satellites

Given a satisfactory remote sensor of some atmospheric property, the artificial satellite provides the most effective instrumental platform for obtaining the global distribution of the property as a function of time. It is of course for this reason that satellites have already been much applied to meteorological ends and you will all probably be familiar in particular with the television pictures of clouds from the TIROS series of satellites.

There are broadly two kinds of satellite orbit suited to global meteorological survey, the sun-synchronous polar-orbiting satellite making two passes per day over all places on the earth at the same local times, and the geosynchronous satellite looking down from a given longitude over the equator and capable of continuous observation over its earth-fixed field of view. The former orbits at around 1000 km height in 110 minutes, the latter at about 36000 km, and views something less than a hemisphere. Clearly the great difference in orbit distance implies very different problems in instrument resolution on the two kinds of vehicle.

The remote sensing of the atmosphere from a satellite is carried out by making observations in appropriate wavelengths of the radiation proceeding upward from the earth. This radiation is for practical purposes either scattered solar radiation within the wave band $0.3\,\mu$ to $3\,\mu$

(near ultraviolet, visible and near infrared) or self-emission from the atmosphere, its clouds, and the underlying earth in the far infrared and microwave region, from 3 μ to 3 cm. Additionally, some sensing may be carried out by means of observations of absorption and refraction at near glancing incidence on the sun and stars. The whole field is a very big one technologically and I shall only attempt to indicate some of the more important achievements and possibilities.

First, regarding observations in the visible, there have been almost continuous satellite television observations of clouds over large parts of the globe since TIROS I was launched in April 1960. There are many problems in the interpretation of these cloud pictures, as to cloud type, height and depth, etc., but the horizontal structures of cloud *systems* has been very informative and of great importance in day-to-day synoptic analysis, particularly where conventional observations are sparse. It is now possible for anyone with quite simple means to acquire cloud information over an area of about 2000 km × 5000 km by local read out from the Automatic Picture Transmission (APT) system flown on ESSA polar-orbiting satellites. Figure 16 shows the ground aerial and figure 17 a sample record from the facsimile recorder.

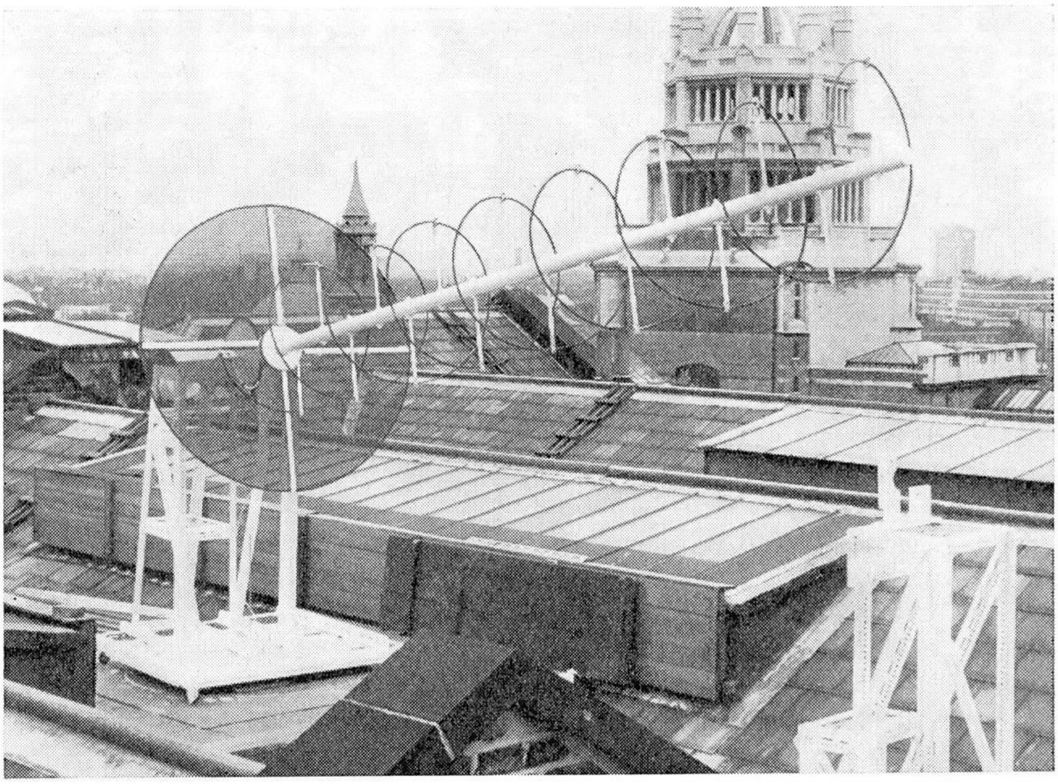

Figure 16

The simple aerial system (on the roof of the author's department) which is used to receive the Automatic Picture Transmissions (APT) from ESSA's polar-orbiting weather satellite.

Figure 17

An example of the cloud and earth pictures received in a single pass of an APT satellite. Record of 09 GMT, 6 May 1967. Observe the clear anticyclonic area to the north of the British Isles with Scandinavia marked by low cloud, and the cloud systems associated with a cyclone centred to the west of Ireland. Spain and the Pyrenees are at bottom right centre, cloud- or snow-covered.

Even more striking are the photographs recently taken by the NASA Application Technology Satellite (ATS-I) in geostationary orbit over the central Pacific. This uses a 13-cm diameter, 25-cm focal length reflecting telescope which with 2000 scans in north-south steps and 100 rev./min of the satellite takes 20 minutes to complete a picture (fig. 18) of very high resolution.

There is no significant absorption in a clear atmosphere in the band 3.4 μ to 4.2 μ and only very little in the so-called atmospheric window from 8 μ to 12 μ. The earth's surface and clouds of more than minimal thickness are however black in the infrared, so that emission measurements

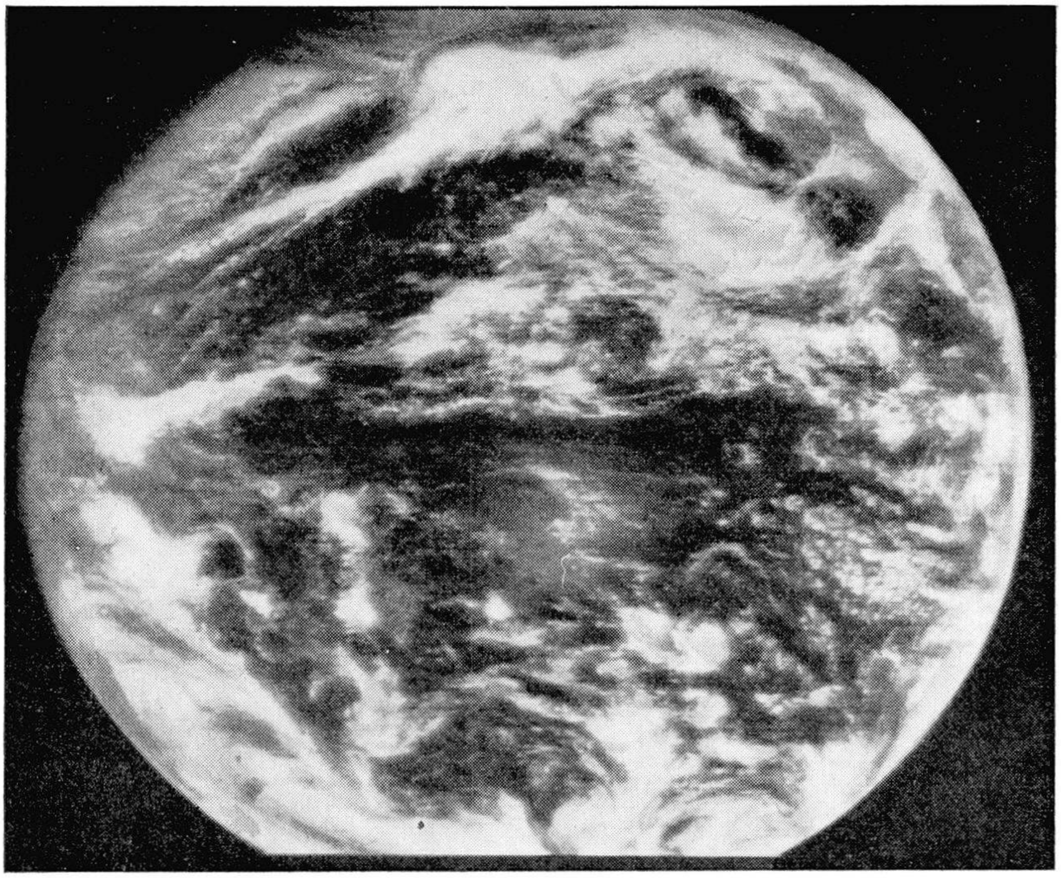

Figure 18

A scan photograph of the sector of the earth seen from a geostationary ATS satellite over the central Pacific. California appears at upper right and eastern Australia at lower left.

in these two wave bands give the temperature of the earth's surface or of cloud top in the field of view (at night only for the shorter wave band because of solar interference). Present measurement accuracy is about 1 to 2 °K. Figure 19 is a picture of surface and cloud top temperature shown by shades of grey for a large area of the Pacific taken by NIMBUS-I satellite using the 4-μ emission. The large-scale structure is very impressive. From temperature one can readily transform to approximate height of cloud and so obtain materially greater information on cloud structure than is given in the visual pictures. Such measurements of cloud and surface temperature could be a very important part of a global observation system, though greater accuracy of ocean surface temperature is desirable.

Moving now to infrared wavelengths in which there is absorption and therefore emission by atmospheric gases, we are concerned with CO_2 which is uniformly mixed with air, and with H_2O and O_3 which have variable mixing ratios. CO_2 has absorption bands at 4.3 μ and 15 μ, the former on the edge of the blackbody emission curve and therefore with little absolute emission but large temperature dependence, the latter

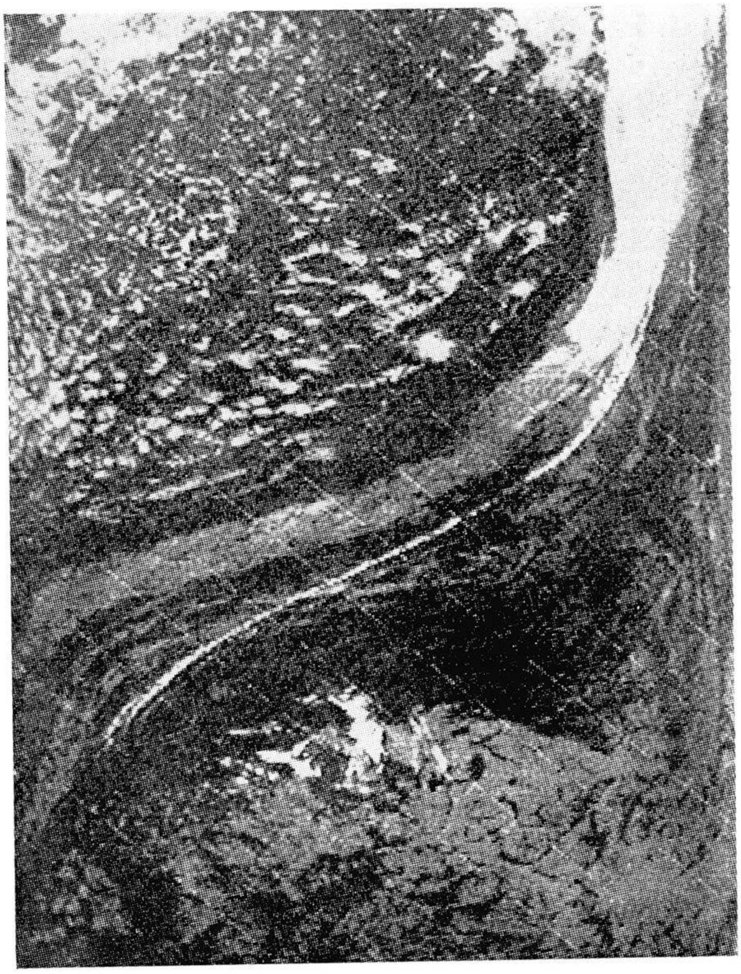

Figure 19

High-resolution infrared (HRIR) 4-μ emission picture of clouds and earth surface in the north Pacific from NASA's NIMBUS I satellite on 16 September 1964. Latitude range 25° N to 50° N, with Hawaiian Islands at bottom left. The intensity of emission (temperature) is shown by the shade of grey—lower temperature bright, higher temperature dark. Note the change of ocean surface temperature from warm (dark grey) below to cool (lighter grey) above; also the broad low altitude and narrow cold high-troposphere bands of cloud extending across the centre and merging with high-troposphere cloud in a storm area in upper right. (After NORDBERG and PRESS.)

where emission is relatively large. We consider the use of satellite spectrometry in the 15-μ band to provide vertical profiles of temperature beneath the satellite. Because of LAMBERT's law and the decrease of density with height the relative contribution to the radiation in any one wavelength at the satellite from the different atmospheric levels beneath is given by a weighting function curve such as any of those in figure 20—the larger the absorption coefficient, the higher the weighting function will peak. Then by using different wavelengths of different absorptivity a range of weighting functions is obtained as in figure 20. The radiation of given wavelength emitted by a thin layer at any level depends on its temperature

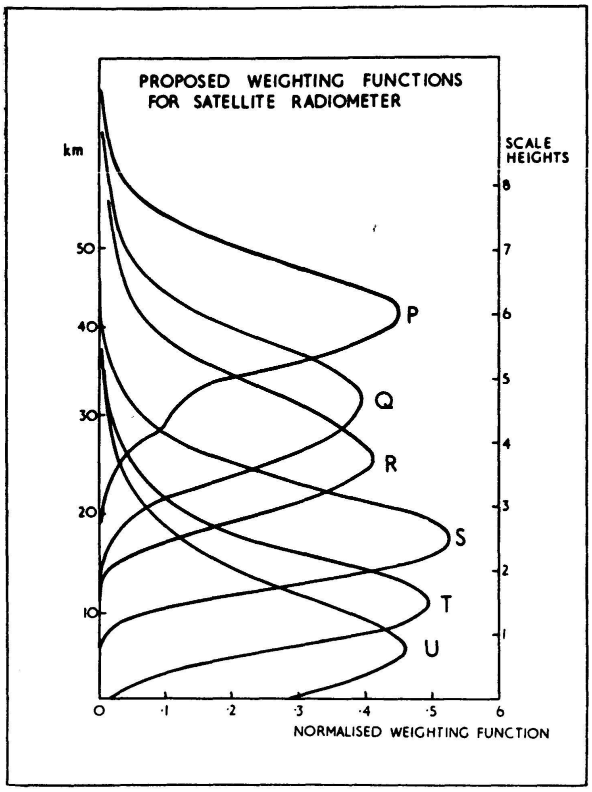

Figure 20

Weighting functions versus height for CO_2 upward emissions at different wavelengths (absorptivities) in the 15-μ band. The height of the maximum weighting increases with increase of absorption coefficient. (After HOUGHTON.)

according to KIRKHOFF-PLANCK principles and so it is possible, by a so-called inversion technique which is itself quite sophisticated, to infer the vertical distribution of temperature from the radiation received in the different wavelengths at the satellite. The results of a balloon test of this technique are shown in figure 21 and are evidently encouraging. We now wait on two tests of the technique which are to be made with satellite NIMBUS D in 1969/70, one group in the USA employing conventional but refined infrared spectroscopy, the other group from the UK employing a very original system of interference filters and selective CO_2 chopping.

There may be a very serious limitation to this otherwise very promising technique, in that clouds are opaque in the infrared so that the temperature profile can only be determined down to cloud-top level where clouds are present. If this proves to be a serious limitation, it is possible that a similar technique but using the O_2 microwave band at 0.5 cm could be exploited, for clouds are almost transparent to this radiation.

Passing now to the H_2O and O_3 infrared bands, if the temperature profile is known, then spectroscopic measurements of the emission of these two gases at selected wavelengths could lead, by methods akin to

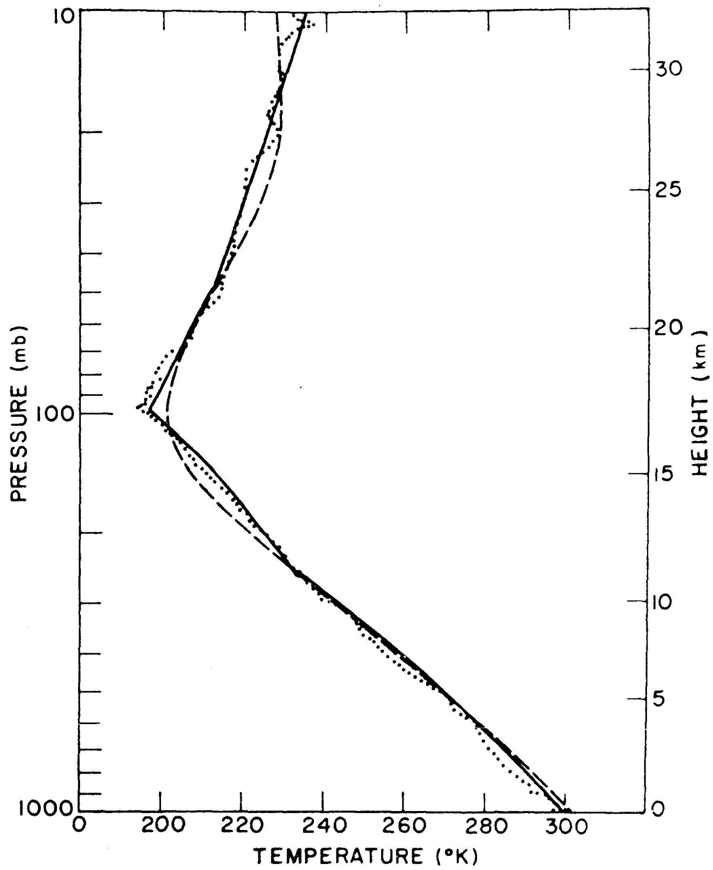

Figure 21

Comparison of temperature soundings made by conventional radiosonde (dotted line) and from the radiations received at a balloon from upward emissions in five wavelengths from CO_2 in the 15-μ band (dashed and solid lines) by two different inversion techniques. (After WARK.)

those just described, to the vertical profiles of these two gases. They are both important in determining the radiative sources or sinks of energy in the atmosphere, H_2O in the troposphere particularly and O_3 in the stratosphere. Additionally, the phase transformation of vapour is of outstanding thermodynamic significance. Some progress has been made with H_2O.

Regarding total radiation, if we measure from a satellite all that passes upwards from the top of the atmosphere, that is scattered sunlight and atmospheric and earth emission, and subtract this from the solar input (given by the solar constant, 2.0 cal cm^{-2} min^{-1}), we obtain the distribution in space and time of the net energy source/sink for the atmosphere and underlying earth. Some of this energy is stored (and transported) in the oceans, but the overall quantity is of major climatological importance. Preliminary measurements of its distribution have already been made on US TIROS and USSR COSMOS satellites.

4.4 Appreciation of the problem of global observation

You will see that I have talked rather of possibilities for a global observation system rather than of any agreed plan for its realization. I hope, however, I have convinced you of the big opportunities before us, but also of the big technological problems which remain. That is a very healthy state for our science to be in. In the next few years we shall have to decide, in the light of tests now under way or planned, how the global observation system should be implemented and then convince our treasuries that they should provide the pecuniary means, not only for the observational system but for the computer and data-handling facilities and, not least, for the scientists and technologists who will be required for the realization of GARP. The programme is the biggest in international collaboration in science that has yet been attempted. I believe it should and will succeed and I hope European nations will contribute notably to it.