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THE CONTRIBUTION OF SATELLITES TO THE EXPLORATION OF THE GLOBAL ATMOSPHERE AND TO THE IMPROVEMENT OF WEATHER FORECASTING*

By B. J. MASON

Summary. Artificial satellites have been assisting weather forecasters for 14 years. Whilst originally satellites were simply used for pictorial representation of cloud distribution, their use has extended via the remote measurement of temperatures of land, sea and cloud surfaces to the reconstruction of complete vertical distributions of temperature and humidity. Together with their usefulness in communicating with automatic weather stations, weather satellites will become major components in any global weather-observing and communication system of the future.

Introduction. Satellites are already playing an important role in observing the weather on a global scale. During the last 14 years the U.S.A. have launched 22 operational polar-orbiting meteorological satellites in the TIROS, ESSA and ITOS series, together with five large NIMBUS research vehicles and two geostationary satellites that are largely devoted to meteorology. Having obtained cloud pictures and radiometric data on an experimental basis from COSMOS satellites since 1966, the U.S.S.R. launched the first of its operational METEOR weather satellites in 1969. So far the emphasis has been on obtaining cloud pictures in both visible and infra-red light, and temperatures of land, sea and cloud surfaces from rather simple radiometric measurements. The latest satellites also carry sophisticated spectrometers and radiometers to determine the vertical distribution of temperature and humidity throughout the whole depth of the atmosphere and so provide, for the first time, quantitative global data of the kind required for numerical weather prediction.

This paper will describe the requirement for global atmospheric measurements, and how these are being obtained and are likely to be obtained in the future by satellites carrying radiometric sensors and interrogation systems. It is probable that the global weather-observing and communication systems will become largely based on satellite technology during the next 10–20 years.

The requirement for global observations of the atmosphere. Each day about 8000 land stations and 4000 merchant ships make regular observations of the weather as experienced at the earth's surface. Conditions in the upper air are recorded at only a few hundred stations which send up balloon-

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borne instruments called radiosondes. The instruments record the air temperature, pressure and humidity as they ascend (and later descend attached to a parachute) and transmit their readings to the ground station or weather ship in the form of coded radio signals. The balloon also carries a reflector that permits its path to be tracked by radar and hence the winds to be measured up to heights of 30 km (100 000 ft) or more. There are more than 600 radiosonde stations in the northern hemisphere which make soundings every 6 or 12 hours, the density of the network being adequate over Europe and North America but too sparse elsewhere, especially over the oceans and the tropical regions. In fact, it is becoming increasingly difficult to maintain the network of ocean weather ships in the North Atlantic. In the southern hemisphere, which is largely occupied by ocean, there are fewer than 100 radiosonde stations altogether. In other words, the atmosphere over at least half the earth is not observed adequately to permit meteorologists to describe and forecast the evolution of even the major weather systems over the entire globe.

Nevertheless, recent research encourages the belief that, given adequate observations and computing facilities, it should be possible within the next few years to produce reliable forecasts of the main weather patterns for 5–7 days ahead and a useful indication of general trends over periods of perhaps 2–3 weeks. Forecasts on these time-scales will require very complex physico-mathematical models of the atmosphere, computers many times more powerful than existing machines, and adequate observations covering at least a hemisphere and perhaps the whole globe.

Additional observations will therefore be needed, especially from the oceanic and tropical areas and the southern hemisphere, and also faster and more reliable methods of communication for the transmission and exchange of these data, together with much more powerful computers than exist at present. The main objective of the World Weather Watch (WWW) is to obtain just these facilities. Plans for the first four-year period (1969–73) called for the establishment of a minimal global network of observations by creating about 40 new fixed radiosonde stations and providing similar facilities on 100 moving ships, and for installing a high-speed global-communication circuit linking the major meteorological centres, which will be equipped with powerful computers for processing the observational data and producing numerical forecasts. However, it is clear that an adequate global system cannot be produced at reasonable cost by simply expanding the current operational facilities, and that the World Weather Watch will ultimately depend largely on satellites for surveillance and remote sensing of the atmosphere, for the location and interrogation of instrumented balloons, ocean buoys and unmanned land stations, and for world-wide communications.

At this stage it is not possible to specify precisely the minimum and optimum standards for the coverage, spatial resolution, frequency and accuracy of the observations. This will be one of the main tasks of the Global Atmospheric Research Programme (GARP), the research component of WWW, which proposes to undertake intensive observations of the global atmosphere over a period of one year in 1978 with a view to determining the stability and limits of predictability of atmospheric behaviour, and the minimum observational and other facilities that will be necessary for the fully operational phases of WWW. GARP also plans to investigate the evolution of the mesoscale tropical weather systems and their role in transporting heat and water vapour into the global circulation, and also the exchange of heat, momentum and water vapour between the oceans and the overlying atmosphere (see Mason[1]).

As far as can be judged at present, it seems likely that, in order to forecast the large-scale dynamical features of the atmosphere that will determine the essential character of the weather everywhere for a week ahead, vertical soundings of temperature, pressure and wind up to heights of 30 km and of humidity up to 10 km will be required once, perhaps twice, daily at an average horizontal spacing of 500 km over the entire globe together with a similar density of the basic surface parameters including sea surface temperature. In terms of present facilities, this would imply an impossible requirement for about 1500 additional upper-air stations, mainly over the oceans, and so adequate global coverage will be achieved only by satellite techniques. Meanwhile, 5–7-day forecasts for at least the middle latitudes of the northern hemisphere might be possible if the present network of upper-air stations could be reinforced over the oceans, particularly at low latitudes, to give an average spacing there of 1000 km. Northern-hemisphere forecasts for 10–20 days will probably require, in addition, a similar density of observations from the southern hemisphere. Regarding the required accuracy of the observations, air temperatures to within 1 degC, atmospheric pressures to within 0·3 per cent (3 mb at the surface), winds to within 1–2 m/s, vapour pressures to within 10 per cent, and sea surface temperatures to within 1 degC may prove adequate, but all these assumptions will need to be tested, first in long-term numerical simulation experiments on the computer and ultimately in predictions using real initial data.

Satellites can provide efficient and economic global observations of meteorological parameters by measuring the intensity, polarization, and angular and spectral variation of radiation emitted and reflected by the earth and the atmosphere. In polar orbit they have the great advantage of being able to survey a large area of the atmosphere at any one instant and to cover the whole globe every 24 hours. In geostationary orbit they can observe a particular area, in fact about one-quarter of the earth, continuously. Despite the distance of satellites from the earth, the difficulties arise not so much in producing instruments that will measure the received electromagnetic radiation with the desired accuracy, resolution and coverage, but rather in discovering and exploiting physical relationships that uniquely relate the measured quantities to the desired meteorological parameters. As will be seen later, it is one thing to measure the spectral distribution of radiation received by the satellite from the underlying atmosphere, and quite another to deduce from these measurements the vertical distribution of atmospheric temperature or humidity with the accuracy required for use in numerical forecasting.

Cloud photography and mapping of the earth's surface. Ever since the first remarkable pictures were transmitted by the TIROS I satellite in 1960, the meteorologist has received an almost continuous flow of excellent photographs from a succession of American satellites. Since early in 1966 the introduction of the automatic-picture-transmission (APT) facility has made these pictures available in real-time to any country that can make, or buy for the equivalent of a few thousand pounds, the necessary receiving and reproduction equipment. More than 60 countries are now so equipped, and the photographs showing the cloud formations, and the distribution of snow on the ground and ice on the sea, are proving a most valuable aid in weather forecasting.

Excellent pictures covering the eastern half of the North Atlantic, western Europe and the Mediterranean are received daily at Bracknell. They show very clearly the organization and structure of cloud systems ranging from large cyclonic vortices 1000 km across to individual shower clouds only 1 km in diameter. Comparison of such photographs and the weather charts has, on many occasions, led to an improved analysis and forecast. Detailed analysis and interpretation of such pictures has provided valuable information on the location of such mesoscale features as hurricanes, thunderstorms, squall lines, jet streams, mountain waves and regions of strong wind shear, often from oceanic and other remote areas where the observing networks are too sparse to make their detection likely by conventional methods. The distribution of sea ice and land areas covered by ice and snow are also clearly shown.

The first television pictures were taken with a 500-line vidicon system which was soon replaced by a more advanced system having three identical cameras at 35° to each other to give overlapping views and so provide contiguous coverage of the globe. The system provides about 1000 pictures each day for storage and transmission in batches of 200 to ground stations. Each camera has a vidicon tube scanned by an 800-line raster of 800 points, the resolution of objects on the ground at the sub-satellite point being about 1 km. In order to cope with the variable illumination of the earth and cloud surfaces, the cameras are fitted with a variable iris-type stop operated by the shaft that carries the solar paddles and whose angular position is related to the solar zenith angles at the surface. The aperture is wide open over the Poles and smallest when the satellite crosses the subsolar point. Calibration of the picture intensity is provided by a uniformly illuminated wedge in the field of view of each camera, so that a stripe ranging from black to white through all shades of grey appears at the side of each photograph.

In the current ITOS (NOAA) satellites, vidicon systems have been replaced by scanning radiometers that produce both visible and infra-red images to give both day and night coverage of the earth. The pictures are built up line by line by scanning the field of view from horizon to horizon, using a mirror rotating uniformly at such a rate that the satellite advances along its orbital path just enough between each scan to provide contiguous cover at the ground. The radiation collected by the mirror is focused by a Cassegrain telescope on to a dichroic beam-splitter, the visible image then falling on a silicon photoelectric detector and the infra-red radiation on a thermistor bolometer. The ground resolution at the sub-satellite point is 4 km in the visible and 8 km in the infra-red.

The ITOS D (NOAA 2) satellite, launched in 1972, carries an additional scanning radiometer with a cooled Cd-Hg-Te infra-red detector that produces very high-quality pictures (see Plate III), with a resolution of about 0·9 km in both visible and infra-red channels.

A geosynchronous satellite, placed in equatorial orbit at an altitude of 36 000 km, rotates in synchronism with the earth and so remains stationary over a particular point on the Equator and thus allows a particular area to be observed continuously. The United States Advanced Technology Satellites (ATS), the first two of which were launched in December 1966 and November 1967 and are still operating, carry a camera (in effect a 5-inch telescope and photomultiplier) which, in scanning laterally while the satellite spins about its axis aligned parallel to the earth's axis, views a wide strip of the earth every

20 minutes. It therefore provides a time-lapse record of the movement and development of cloud systems over nearly one-quarter of the globe. The instantaneous field of view of the telescope is equivalent to 4-km resolution at the surface.

At present one such satellite is poised over the equatorial Pacific and the other over the Amazon but they can be moved if required. Plate I shows a picture taken by the latter satellite which views the whole of North and South America, western Africa and most of the Atlantic Ocean.

The first geostationary satellite designed specifically for meteorology, the United States Synchronous Meteorological Satellite (SMS), launched early in 1974, carries a 16-inch Cassegrain telescope with scanning mirror. Eight photomultiplier detectors in the focal plane of the telescope provide visible images with 1-km resolution, and two Cd-Hg-Te detectors produce infra-red images with 8-km resolution. A rather similar satellite is being developed by the European Space Agency for launching at the end of 1976 and will be one of an international set of five vehicles built by the United States (two), Europe, U.S.S.R. and Japan to provide global coverage during the First Global Observing Experiment of the Global Atmospheric Research Programme in 1978.

Measurement of surface temperatures. In addition to providing images, the radiometers can determine the temperatures of land, sea and cloud surfaces by measuring the infra-red radiation emitted by them in the 10·5–12·5-μm atmospheric window.

The intensity I of the radiation received by the satellite detector when there is no intervening cloud consists of two components, that originating from the surface of temperature T, and that from the atmosphere with mean temperature of T_a.

Thus:

$$I_\nu = \varepsilon\tau B_\nu (T) + (1 - \tau)\, B_\nu (T_a) \qquad \ldots (1)$$

where $B_\nu(T)$ and $B_\nu(T_a)$ are Planck functions appropriate to the frequency ν and temperatures T and T_a respectively, In order to determine T it is necessary to know the emissivity ε of the surface and the transparency τ of the intervening atmosphere. The emissivity of ocean and vegetation-covered surfaces is nearly unity but that of bare rock and soil may be as low as 0·5. Some absorption is caused in the 'window' by water vapour and CO_2 and, being strongly temperature-dependent, is not easy to correct for. In a warm, humid atmosphere the correction may be as high as 5 degC, so the distribution of atmospheric temperature and water vapour needs to be known rather accurately if these corrections are to be properly made. Additional absorption may be caused by dust and other aerosols, especially over land.

The very high-resolution scanning radiometer (VHRR) on ITOS D is able to discriminate equivalent black-body temperature differences of 0·5 K for a 300-K scene, but the degradation that follows transmission and data-processing allows the temperature of land surfaces to be determined to within about 2 K and of ocean surfaces to within 1–1½ K.

Measurements from polar orbiting satellites have been compiled to produce maps of cloud-summit temperatures (see Figure 1) and of temperature anomalies in the oceans, but continuous tracking of the latter is often prevented by intervening cloud. In the case of non-raining clouds at least, interference may

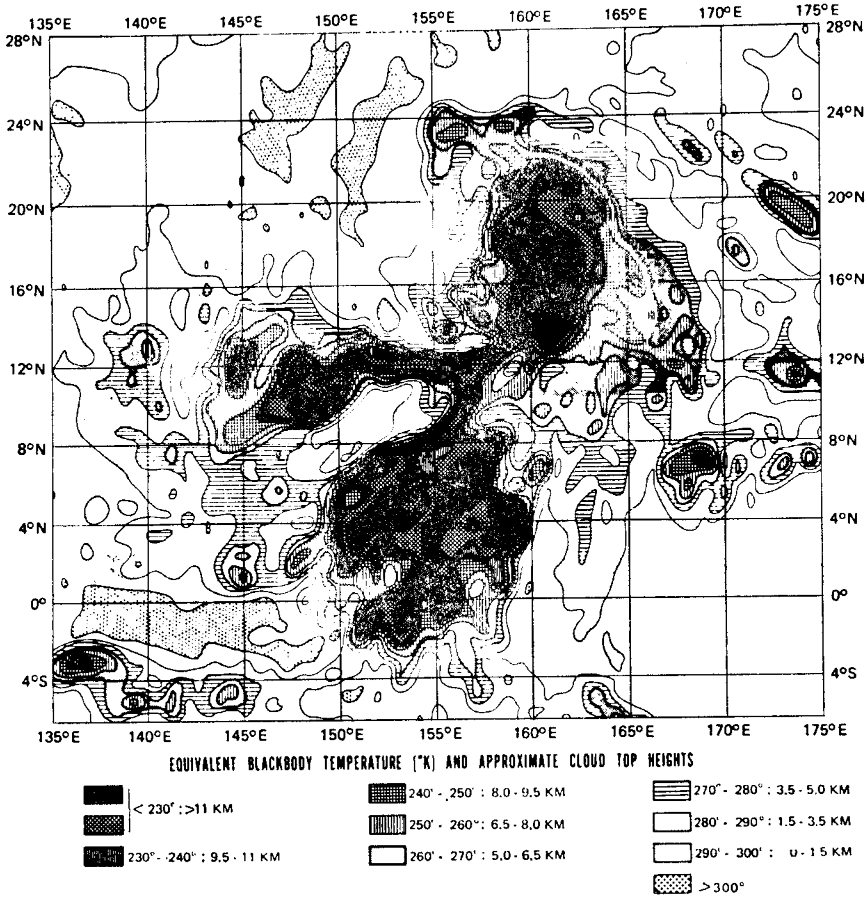


FIGURE 1—THE TEMPERATURE OF THE CLOUD TOPS ASSOCIATED WITH TYPHOON 'MARIE' AND A TROPICAL DEPRESSION, AS DEDUCED FROM A HIGH-RESOLUTION INFRA-RED RADIOMETER ON NIMBUS 2 ON 31 OCTOBER 1966

(From NASA, Nimbus 4 User's Guide)

be largely overcome by using microwaves (e.g. in the 1·6-cm window), but many natural surfaces are not black for microwaves, and their emissivities would have to be determined.

Measurements of radiative flux. The incoming solar radiation, the primary source of energy for driving the atmospheric circulation, can be measured accurately only outside the atmosphere by rocket or satellite. Measurements of the solar flux can be made either with high-resolution spectrometers on sun-stabilized satellites, or with wider-band radiometers on earth-oriented satellites by scanning the sun for, say, 20 minutes during each orbit. At present, measurements of the solar constant have probable errors of about 1 per cent, but the intensity of the ultra-violet portion is much more variable and less well documented. The outgoing solar radiation reflected back to space by the atmosphere and the earth has been measured on American and Russian satellites, but there are difficulties in estimating the total hemispheric flux from narrow-beam measurements and in allowing for angular and spectral variations.

The outward flux of long-wave terrestrial radiation in the 4–30-μm band was one of the first parameters to be measured from a satellite. Existing broad-band radiometers can measure the intensity of radiation received from a given direction with an accuracy of 1 per cent, and with angular resolution of better than 1°. Since the filters and detectors used in radiometers do not permit uniform response over the entire spectral range, and because each area on earth is viewed through a narrow aperture, it is again necessary to use analytical and empirical models to relate the measurements to the total emitted flux over the hemisphere.

Nevertheless, sufficiently accurate measurements of both incoming and outgoing radiation have been made to permit the derivation of useful global maps of the net amount of energy available to the earth and atmosphere and to give some indication of the day-to-day changes in the heat balance of the system. It appears that over a 4–5-year period the net-radiation budget of the entire earth and of each hemisphere separately is in radiative balance to within the limits of experimental error (i.e. better than 1 per cent). Each hemisphere has nearly the same planetary albedo — about 30 per cent — which demonstrates the dominant influence of clouds on the energy exchange with space, since the surface features of the two hemispheres are quite different.

Although the cloud pictures and radiation data from satellites currently provide a great deal of valuable information, it is mainly only qualitative in character and very difficult to incorporate directly into numerical weather-prediction models which require data on atmospheric temperature, pressure, composition and winds. This information can be obtained by remote sensing of the atmosphere from satellites.

Remote sensing of atmospheric temperatures

(a) *Theory of the method.* In contrast to the simple radiometers required for the determination of total fluxes and surface temperatures, a number of very sophisticated and ingenious spectrometers and radiometers are being developed to obtain the vertical distribution of atmospheric temperature from measurements of the spectral distribution of radiation received from constant constituents such as carbon dioxide or molecular oxygen.

The radiation emitted by a layer of uniformly mixed gas in local thermodynamic equilibrium is directly dependent on its temperature. But the intensity of the infra-red radiation reaching a satellite from, say, the carbon dioxide distributed throughout the depth of the atmosphere, even through a window in which absorption by other constituents is negligible, will also be affected by absorption within the gas itself.

Thus relatively little radiation is received from the comparatively small mass of emitting gas in the uppermost layers, and comparatively little also from the lowest layers whose emission is strongly attenuated in traversing the whole depth of the atmosphere. The received radiation therefore comes mainly from the intermediate levels and is weighted according to height (or total pressure), as indicated by a function of the form shown in Figure 2.

The intensity of radiation emitted in a vertical direction from a horizontal slice of the gas of thickness dz in a narrow band of central frequency ν is

$k_\nu dz.B_\nu(T)$, where k_ν is the absorption coefficient. Of this, only a fraction τ will reach the top of the atmosphere where τ is the transmittance.

The total intensity of the radiation at the top of the atmosphere due to all such slices is then:

$$I_\nu = \int_0^\infty B_\nu(T) k_\nu \tau_\nu dz$$

but

$$\tau_\nu = \exp\left(-\int k_\nu dz\right)$$

so that

$$d\tau_\nu = -k_\nu dz.\exp\left(-k_\nu dz\right)$$

and

$$I_\nu = \int B_\nu(T)\, d\tau_\nu = \int B_\nu(T) \frac{d\tau}{dy}\, dy$$

$$= \int B_\nu(T) \frac{d\tau}{d(\ln p)}\, d(\ln p) \qquad \ldots (2)$$

where the weighting function $d\tau/dy$ may be more conveniently expressed in terms of the variable $y = -\ln p$, where p is the total pressure, instead of the height z because this is more nearly independent of temperature. The weighting function for a single frequency ν chosen in the wing of a collision-broadened spectral line (collision broadening is dominant in the lowest 50 km of the atmosphere) is shown in curve A of Figure 2. The value of the pressure p_0 at which the weighting function reaches a maximum depends on the particular wavelength chosen but the half-width of the curve in units of $\ln p$ is independent of wavelength. Since for an isothermal atmosphere, $\ln p \propto z$, the half-width in height units is approximately constant and equal to 10 km.

In practice many of the radiometers designed for temperature sounding in the 15-μm CO_2 band possess a band width of about 5 cm^{-1} and so receive radiation from the wings of several lines in the band. Consequently they do not have the ideal monochromatic response represented by curve A but rather broader weighting functions such as curve B in Figure 2, which give somewhat poorer height resolution.

So far attention has been restricted to a single frequency or a narrow spectral interval for which the altitude of the peak of the weighting function depends on the absorption coefficient at the particular frequency and on the concentration of the emitting gas. Because in any absorption band the absorption coefficient varies rapidly with frequency, different frequencies possess different weighting functions peaking at different altitudes as shown in Figure 3. Thus a set of measurements of the radiation received in several narrow frequency intervals, chosen so that the corresponding intensities each originate from substantially different levels in the atmosphere, provide information on the vertical distribution of temperature.

The weighting functions may be calculated from the optical characteristics of the radiometer and detailed spectral information on the positions, intensities, widths and shapes of the spectral lines emitted by the gas. Alternatively, they may be determined in the laboratory by measuring with the actual satellite radiometer the transmission through a synthetic atmosphere.

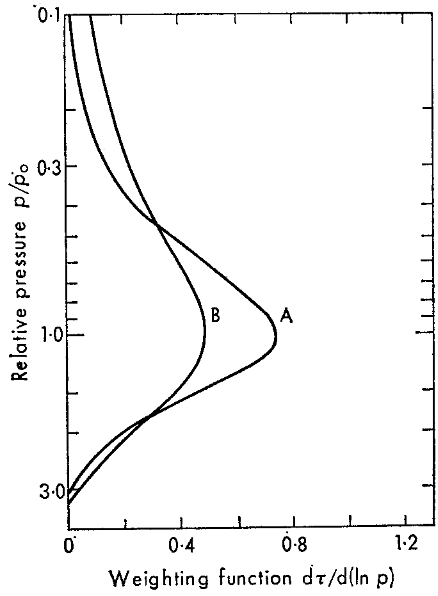


FIGURE 2—WEIGHTING FUNCTIONS FOR A MONOCHROMATIC FREQUENCY IN THE WING OF A COLLISION-BROADENED LINE (A), AND RADIATION RECEIVED FROM THE WINGS OF SEVERAL LINES IN THE CO_2 BAND (B)

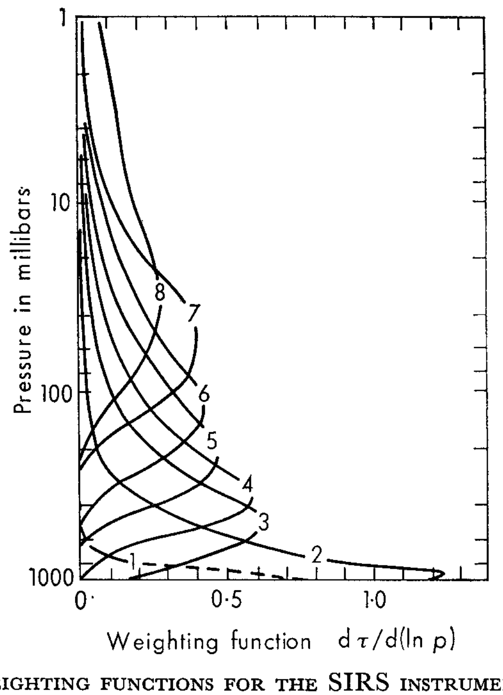


FIGURE 3—WEIGHTING FUNCTIONS FOR THE SIRS INSTRUMENT ON NIMBUS 3

The important quantities which determine the quality of a set of measurements from a vertical-sounding radiometer are the vertical resolutions and the accuracy of measurement. To be useful, measurements of the mean temperature over layers about 200 mb thick need to be made with a probable error of less than 1 K, which means that in the 15-μm CO_2 band radiances have to be measured to better than 1 per cent. The radiance received from a clear atmosphere at a particular frequency represents the appropriate black-body function multiplied by a weighting function of the type shown in Figure 2. The weighting function, which is quite broad, will overlap with similar functions appropriate to other frequencies so that the retrieval of the temperature profile from a set of measured radiances is not a simple matter. Because of the rather coarse height resolution, the overlapping of the weighting functions and the noise in the observations, this retrieval cannot be done exactly and it is important to know the accuracy of a given result.

Although it is possible, in principle, to retrieve the temperature profile from the radiance measurements by, in effect, inversion of the radiative-transfer equations, in practice it has been found more profitable to include statistical information available from conventional (radiosonde) temperature soundings. Thus, in reducing the data from the SIRS instrument on the NIMBUS 3 satellite, the measured radiances are related to atmospheric temperatures through statistical regression equations derived from a large sample of radiosonde soundings, determined for five latitude belts between the North Pole and the South Pole and updated every few days. Equations are derived both for the temperature and for the geopotential height of 13 standard pressure levels between the surface and 10 mb (30 km). Intermediate levels are computed from the hydrostatic equation so that each profile is determined by 25 levels. The radiances are measured over a field of view of 225 km square so that the temperatures represent an average over this area. The eight channels are sampled simultaneously at 8-second intervals during which the spacecraft travels about 50 km. Global coverage is achieved twice each day — at noon and midnight local time. Day-time and night-time observations are obtained with equal precision.

The presence of clouds in the field of view enormously complicates the retrieval of temperature information from the lower atmosphere. With heavy cloud cover, radiometer measurements can be made only above the cloud tops, and the sounding from the cloud top to the earth's surface must be interpolated between satellite-derived temperatures and a known surface air temperature. With partial cloud cover, the radiance measurements are affected by the cloud amount and the heights and constitution of the cloud layers whose optical properties are not well known. In this case, a statistical technique is used to derive a simulated clear-air sounding that SIRS would have obtained had the clouds not been present in the field of view. Data from the more opaque SIRS channels (which measure radiance mainly from higher cloud-free levels) are used with the surface air temperature to obtain a first approximation to the clear-air sounding below the clouds. Data from the remaining channels are compared with the radiance values implied by this first approximation. The departures are used, with a few iterative steps, to improve the approximation to the clear-air sounding in the lower levels, and to produce an estimate of height and amount of one or two cloud layers which could account for the observed departures. This method has been extended to obtain results from the ITPR radiometer on NIMBUS 5, whose much-improved resolution (about 50 km square) allows a large number of neighbouring observations to be made over an area where the temperature profile and cloud height may be assumed to remain constant but where the cloud amount may well vary. The cloud amount may be eliminated from such observations to produce good determinations of temperature profile and cloud height.

An entirely different approach to the cloud problem developed by Rodgers[5] uses the known statistical properties of the atmosphere to derive the most probable temperature profile, cloud height and amount consistent with the set of radiance observations. A different set of statistics has to be used for each season.

Figure 4 shows the historic first temperature sounding derived from satellite measurements and, for comparison, the radiosonde sounding taken from Kingston, Jamaica, about 400 km to the north-west and 4 hours earlier in time. Close agreement between the two is evident. The main difference lies in the middle troposphere, where the SIRS sounding is warmer by 2 or 3 degC. Systematic errors of this type are rather typical and arise mainly from inadequate knowledge of the transmittance functions of carbon dioxide and water vapour. In practice, they may be reduced by using past SIRS observations coincident

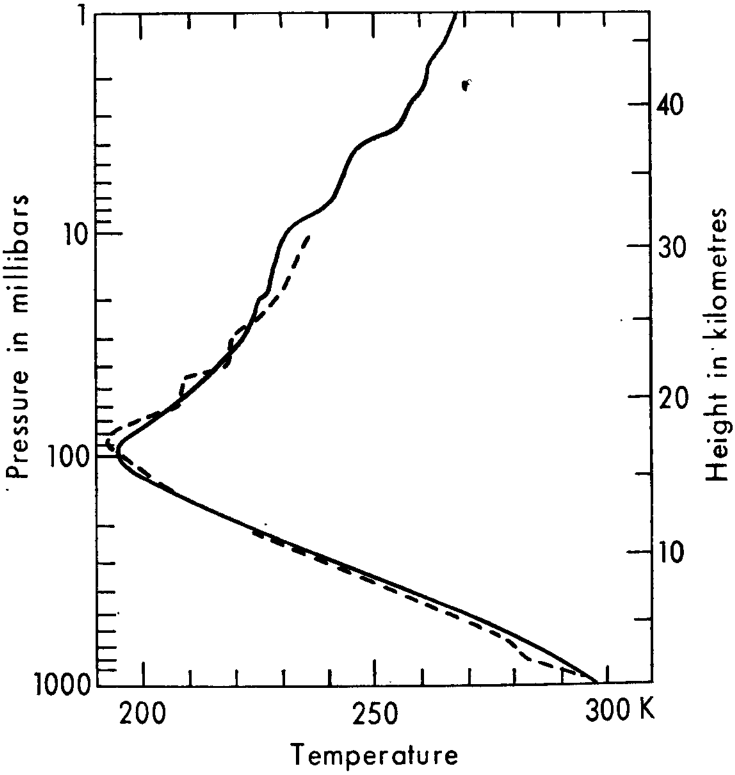


FIGURE 4—COMPARISON BETWEEN SIRS RADIOMETER SOUNDING AND RADIOSONDE ASCENT AT KINGSTON, JAMAICA, ON 14 APRIL 1969

——— SIRS, 16°N 73°W, 1612 GMT, in clear-sky conditions.
- - - - Kingston radiosonde, 1200 GMT.

in space and time with radiosonde data as observed *radiances* in deriving the statistical regression equations, thus avoiding the need to specify the carbon dioxide transmittances explicitly. When these rather empirical methods are used to deduce the temperature profiles, the discrepancies between the SIRS-derived and radiosonde-observed temperatures are between 1·5 and 2 degC for 70 per cent of soundings in the northern hemisphere. Less than 2 per cent of the discrepancies exceed 6 degC, the largest errors occurring in the lower troposphere owing to the influence of clouds. The data for the southern hemisphere are not so good because there are so few radiosonde soundings on which to base the regression equations; here satisfactory methods of inverting the radiative transfer equations are not yet available.

(b) *Instruments.* A radiometer for temperature sounding consists essentially of an optical system for defining the field of view and gathering the energy, a monochromator to select the narrow spectral intervals, and a detector. About six independent spectral channels are required to cover the lowest 50 km of a clear atmosphere but, because of the need to identify surface characteristics, clouds, and water-vapour distribution as well, about twice this number of channels is required in practice. Several techniques have been developed for selecting the frequency intervals and for measuring the radiation received.

The Satellite Infra-red Spectrometer (SIRS), launched in April 1969 on NIMBUS 3, was the first temperature-sounding experiment capable of providing a vertical profile. Eight channels, 5 cm^{-1} wide in the 15-μm band of CO_2, were chosen to cover the atmosphere from the surface to about 35 km. The instrument is an Ebert spectrometer using a fixed grating with slits in the image plane and a rotating-mirror chopper. This is a highly reflecting rotating blade which alternately views the radiations received from the underlying atmosphere and a reflected image of space to produce an a.c. signal which is detected by a thermistor bolometer. Radiometric and wavelength calibrations are made by using an object mirror which allows the instrument to view an internal black-body at the temperature of liquid nitrogen with and without a calibration filter. The field of view is 12°, which gives a resolution of about 200 km at the earth's surface. A further SIRS instrument was launched on NIMBUS 4 satellite in April 1970 but worked for only a limited period.

NIMBUS 3 also carried an Infra-red Interferometer Spectrometer (IRIS), which was essentially a Michelson interferometer scanning the entire spectrum from 5 to 25 μm with a resolution of about 5 cm^{-1}. An improved version on NIMBUS 4 has a still higher resolution of 2·8 cm^{-1}. The spectra provide information on the atmosphere's temperature profile in the 15-μm CO_2 band and also on the distributions of water vapour and ozone. The instrument consists essentially of a multilayered beam-splitter, a moving mirror which advances evenly and without tilt, and a thermistor bolometer detector. A second complete interferometer is incorporated for reference purposes and this uses a discharge lamp as source and a photovoltaic cell as detector. The instrument views the earth via a gold-plated mirror which tilts to view space or an internal black-body when calibration is required.

A simpler instrument, called a Selective Chopper Radiometer (SCR), developed at Oxford and Reading Universities, first flew on the NIMBUS 4 satellite. It employs narrow-band (3·5 cm^{-1}) interference filters to select six channels in the 15-μm CO_2 band and absorption cells containing CO_2 to filter and select further the radiation. For the four channels observing the lower levels of the atmosphere below 30 km, the received radiation passes through the absorbing paths of CO_2, and so these channels are no longer sensitive to radiation originating near the centres of the absorption lines and, therefore, from regions of high altitude. The weighting functions for the lower levels are thereby sharpened, to give increased resolution while allowing the collection of sufficient energy for measurements of adequate accuracy to be made. Weighting functions peaked at high levels are obtained by optically chopping the incoming radiation between two cells, one containing CO_2, the other being empty. An alternating signal is obtained which is dependent only on the radiation absorbed by the CO_2 in the absorbing cell; that is, the system is responsive to just those frequencies absorbed by the CO_2. The resulting weighting functions can be made to peak well in the upper stratosphere. Figure 5 shows the optical design of the SCR on NIMBUS 4. The view through each cell is switched between earth and space by a vibrating mirror, so that an a.c. signal appears at the detector and is amplified by an electronic system tuned to the chopper frequency. The detector is a thermistor bolometer, and calibration is achieved by using an object mirror that views the earth, space

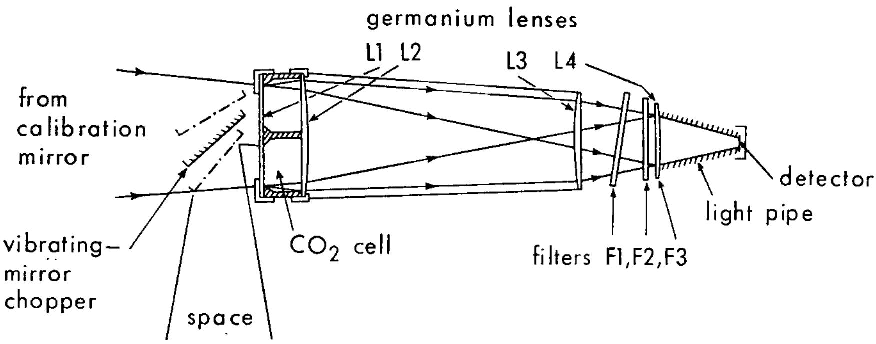


FIGURE 5—OPTICAL SYSTEM OF THE SELECTIVE CHOPPER RADIOMETER (SCR) ON NIMBUS 4

and a black-body of known temperature in turn. With this instrument good temperature retrievals are possible up to 50-km altitude, an example being shown in Figure 6.

The NIMBUS 5 satellite, launched in December 1972, carries a more elaborate SCR with 16 channels — eight CO_2 channels, a channel at 19·2 μm for sounding water vapour, four channels for detecting cirrus clouds, which greatly complicate temperature retrievals, and three window channels. Pyroelectric detectors, having a much better performance than thermistor bolometers, allow the field of view to be reduced to only $1\frac{1}{2}°$, which gives a horizontal field of only 25 km at the earth's surface. This considerably increases the probability of looking through holes in the cloud and of any cloud cover being uniform within the field.

NIMBUS 5 also carries an American-built Infra-red Temperature Profile Radiometer (ITPR) with seven channels selected by filters. Each channel has a separate optical system, four being in the 15-μm CO_2 band, one at 20 μm for water-vapour determination, and two window channels at 11 μm and 3·8 μm respectively. Because of the narrow field of view ($1\frac{1}{2}°$), successive measurements can be made while scanning over a grid containing about 140 elements in a

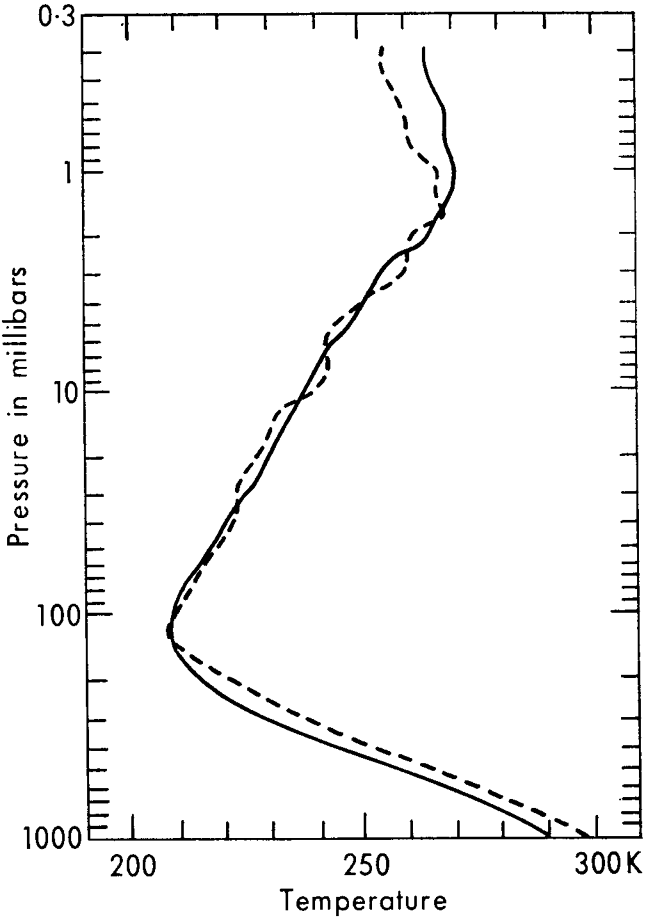


FIGURE 6—COMPARISON BETWEEN TEMPERATURE PROFILES ON 27 AUGUST 1970, RETRIEVED FROM SCR RADIOMETER ON NIMBUS 4 AND DEDUCED FROM RADIOSONDE AND ROCKETSONDE ASCENTS FROM WALLOPS ISLAND

——— SCR on NIMBUS 4.
– – – – Wallops Island radiosonde and rocketsonde.
(From Barnett *et alii*[3])

total time of 64 seconds. On the assumption that the temperature structure is uniform over the area of such a grid while the cloud structure may vary, and by using observations in the two window regions, a retrieval method can be devised that adequately eliminates the cloud structure from consideration.

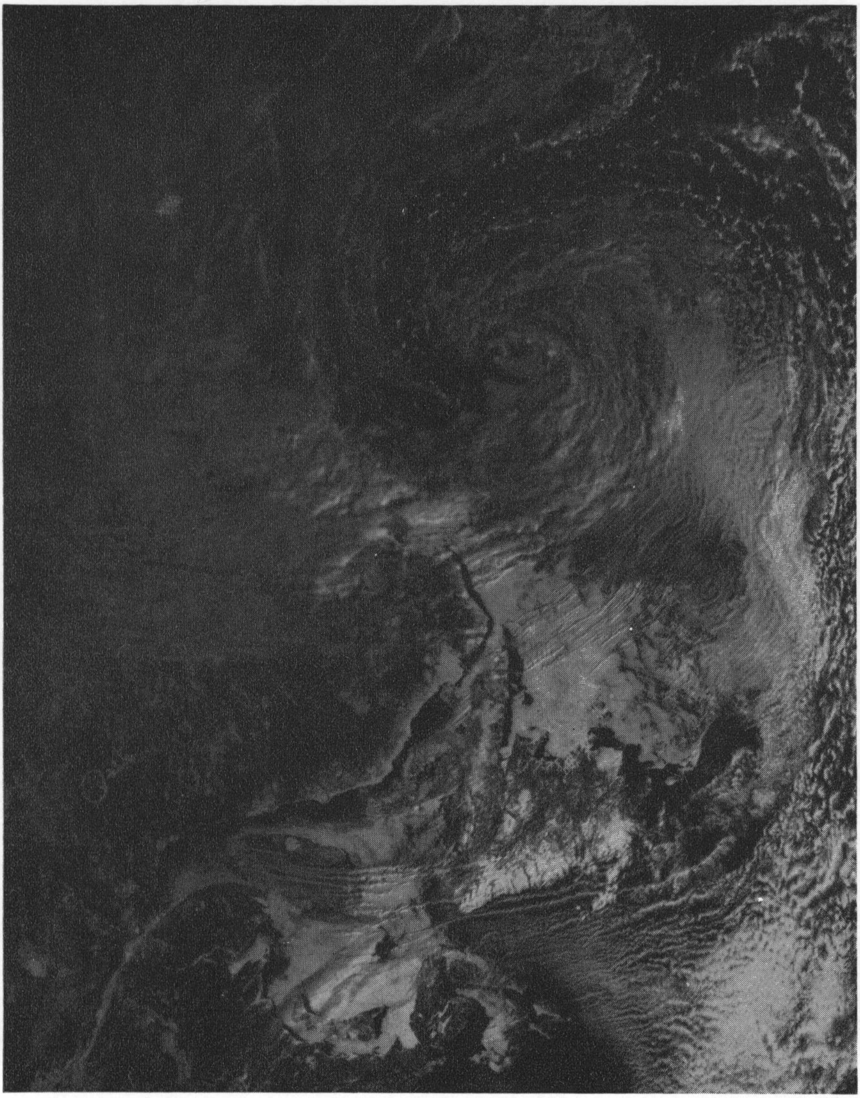
The Pressure Modulator Radiometer (PMR). If with a selective chopper radiometer it is required to select radiation from close to the centres of the lines, i.e. from high altitudes, optical balancing of the double-beam system becomes very difficult. A technique to overcome this employs a cell of CO_2 gas in which the presssure is varied cyclically by a piston. This varies the strength and width of the CO_2 absorption lines so that the radiation falling on the detector is modulated only at frequencies which lie within the absorption

To face page 194

Photograph by courtesy of the United States National Aeronautics and Space Administration

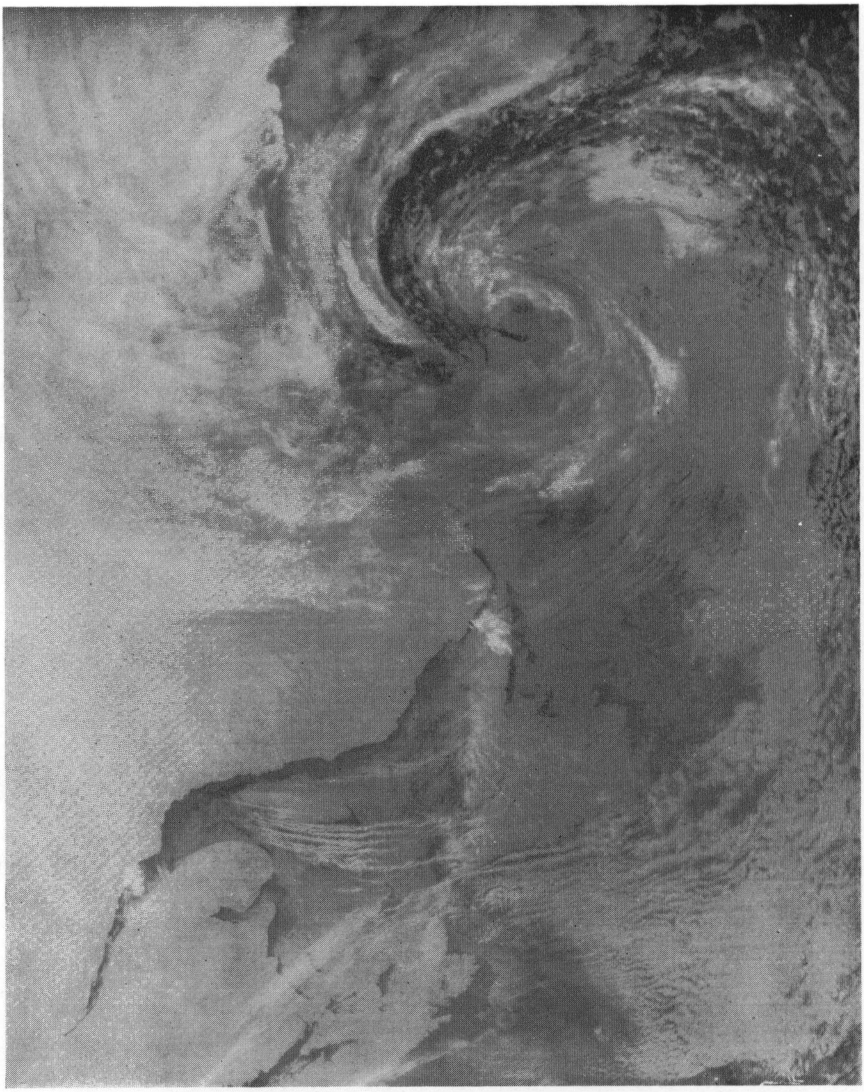
PLATE I—PICTURE TRANSMITTED (ACTUALLY IN COLOUR) FROM THE UNITED STATES ATS-3 GEOSYNCHRONOUS SATELLITE OVER THE AMAZON, SHOWING THE WHOLE OF SOUTH AMERICA, NORTH AMERICA AND WESTERN NORTH AFRICA

Prominent among the many cloud systems are the spiral pattern associated with a small depression off the coast of Morocco, a long line of convective clouds stretching east–west over the southern parts of the North Atlantic and a cold frontal system over Uruguay and north Argentina.



Photograph by courtesy of the United States National Oceanographic and Atmospheric Agency

PLATE II—PHOTOGRAPH TAKEN FROM THE VERY HIGH RESOLUTION RADIOMETER (VHRR) ON THE NOAA 2 SATELLITE SHOWING A DEPRESSION CENTRED SOUTH OF GREENLAND, AND ICE IN THE GULF OF ST LAWRENCE IN VISIBLE WAVELENGTHS



Photograph by courtesy of the United States National Oceanographic and Atmospheric Agency

PLATE III—PHOTOGRAPH TAKEN FROM THE VERY HIGH RESOLUTION RADIOMETER (VHRR) ON THE NOAA 2 SATELLITE SHOWING A DEPRESSION CENTRED SOUTH OF GREENLAND, AND ICE IN THE GULF OF ST LAWRENCE IN THE INFRA-RED

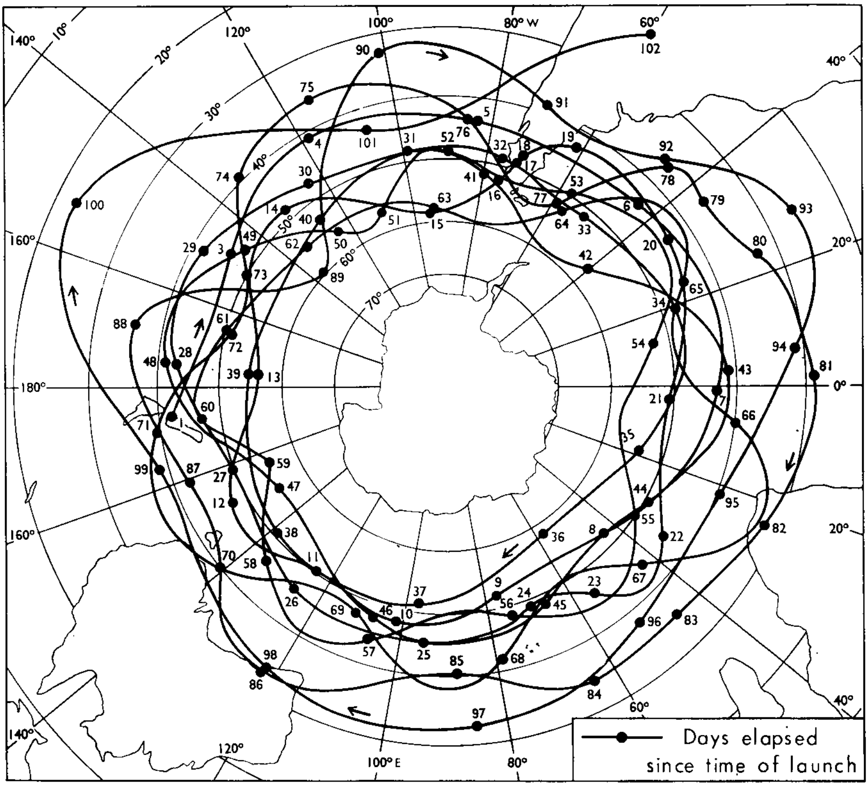


PLATE IV—TRAJECTORY OF A BALLOON RELEASED FROM CHRISTCHURCH, NEW ZEALAND, WHICH MADE EIGHT CIRCUITS AT 200 mb (≈ 40 000 ft) DURING 102 DAYS lines of the gas. The weighting function for the modulated component of radiation passing through such a cell has its peak at a pressure height in the atmosphere proportional to the mean pressure of the gas in the cell, so that by using cells filled to different pressures, weighting functions peaking at different heights can be obtained. Because the wavelength selection and chopping are done by the gas itself, the PMR system is independent of changes in filters, windows and choppers which cause difficulties in other systems.

The piston, mounted on springs, oscillates at a resonant frequency of about 15 Hz with a clearance of only 0·001 in, so that leakage of gas past the piston is not a problem. The PMR is thus a simple, robust instrument and has the great advantage of being sensitive only to energy at the required frequencies while rejecting the rest. Figure 7 shows a diagram of a pressure modulator cell with its optical system. Such an instrument is being built for the NIMBUS F satellite due for launch in 1974 and the Meteorological Office plans to build several similar instruments, each having three channels with a common mirror and black-body, but separate pyroelectric detectors, for the U.S. TIROS N series of satellites that will become operational from 1977 onwards.

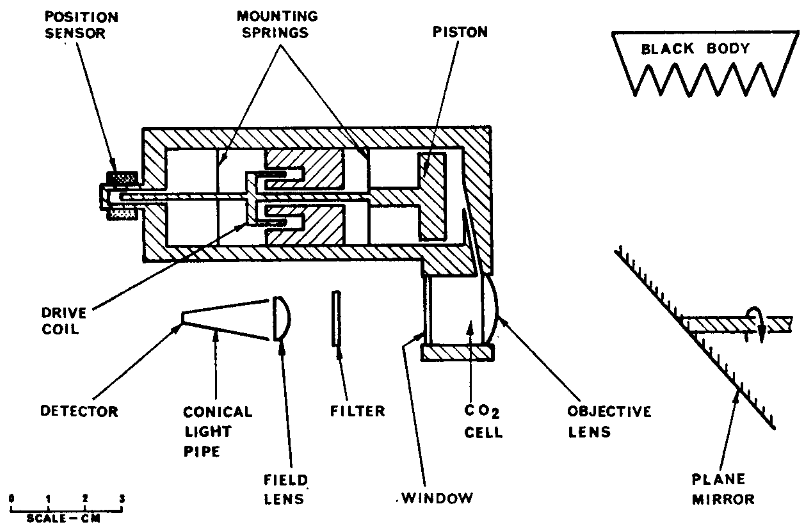


FIGURE 7—SIMPLIFIED DIAGRAM SHOWING ONE CHANNEL OF THE PRESSURE MODULATOR RADIOMETER

(From Abel *et alii*[2])

Microwave radiometers. All instruments described so far observe infra-red emissions from the 15-μm CO_2 band, where the presence of clouds presents a severe problem in the retrieval of tropospheric temperatures. In principle, the cloud problem can be overcome by using microwaves, since all but heavily precipitating clouds are practically transparent to radiation at these frequencies. Oxygen, which is uniformly distributed to high levels in the atmosphere, has suitably strong emission/absorption lines at about 5-mm wavelength and these may be used for temperature sounding. The NIMBUS 5 satellite carries an experimental instrument with five channels, one in a water-vapour absorption band, one in an atmospheric window, and three in the 5-mm O_2 absorption band. The last three are used to obtain temperature profiles from near the ground up to about 20 km. The main disadvantages of the instrument are its weight and power requirements, its rather large field of view, and the fact that the emissivity of the underlying surface varies with the moisture content of the soil and the height of oceanic waves. Nevertheless, the instrument on NIMBUS 5 is working much better than expected and is producing temperature profiles comparable in quality with those obtained from the Infra-red Temperature Profile Radiometer; moreover profiles obtained by using data from both instruments are better than those obtained from each device separately.

Experience with the SIRS, SCR and ITPR instruments has demonstrated convincingly that atmospheric soundings from satellites are feasible. With further improvements in instrumentation and analysis technique (and several are already under development) it should be possible to produce a global coverage of observational data at least as accurate as that now being provided over only limited areas by conventional methods. In the stratosphere, the satellite data are probably already more reliable than radiosonde data, which are subject to large instrumental errors at these levels.

Measurement of water vapour. The simple infra-red radiometers flown on the early TIROS satellites possessed a channel in the 6·3-μm water-vapour band in order to estimate atmospheric humidity. At constant humidity, and in the absence of cloud, the optical depth of water vapour will be a function of temperature only. Consequently, at constant humidity, a roughly constant radiating temperature will be observed in the water-vapour band. Variations in radiating temperature, therefore, arise from variations in the water-vapour content of the tropospheric column. Comparison with the 8–12-μm window region allows correction for the presence of cloud, but with considerable uncertainty because of the strong variation of cloud properties with wavelength in this part of the infra-red spectrum.

More-refined measurements of water-vapour distribution have been made with the IRIS instruments on NIMBUS 3 and 4, and with the SIRS instrument on NIMBUS 4, which included six channels in the rotation band of water vapour between 20 μm and 40 μm. A water-vapour profile produced by the SIRS instrument is shown in Figure 8 and is compared with a nearby radiosonde sounding. The microwave spectrometer on NIMBUS 5 incorporates a single channel near $\lambda = 1{\cdot}35$ cm to determine the total water vapour in a vertical column beneath the instrument, but because of the large and variable emissivity of the underlying land surface the method gives acceptable results only above the oceans. It should be possible to measure the low water-vapour concentrations in the stratosphere by using the pressure modulation radiometer.

The measurement of atmospheric pressure or density. Accurate determination of the vertical temperature distribution would allow the pressure (or density) profile to be calculated from the hydrostatic equation:

$$\frac{1}{p}\frac{\mathrm{d}p}{\mathrm{d}z} = \frac{-g}{RT}, \qquad \ldots (3)$$

provided that the surface pressure p_0 is known. Accurate measurements of the surface pressure on land is readily achieved by modern automatically recording aneroid barometers. The problem is much more difficult over the oceans, where it would be possible but very expensive to mount aneroid barometers on floating buoys that could be located and interrogated by satellites (see page 200). However, this may be rendered unnecessary by the recent development

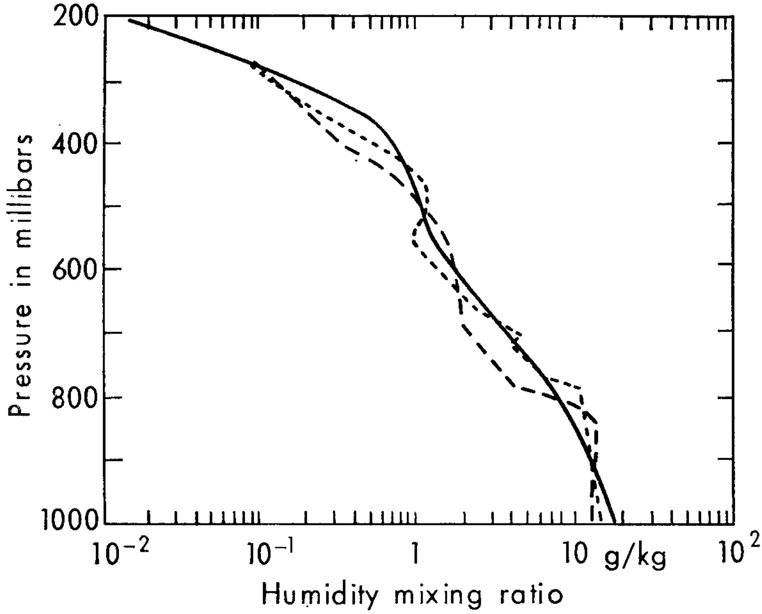


FIGURE 8—COMPARISON BETWEEN WATER-VAPOUR PROFILE RETRIEVED FROM RADIANCE OBSERVATIONS ON NIMBUS 4 (SOLID LINE) AND RADIOSONDE OBSERVATIONS MADE 3 HOURS EARLIER AND 3 HOURS LATER (DASHED LINES)
(From Smith[4])

in the U.S.A. of a simple light-weight radar altimeter which, when mounted on a constant-level balloon (see page 198) at, say, 100 mb ($\approx$ 16 km), can measure the height z of the balloon above the sea surface to within an accuracy of ± 3 m. Hence if the balloon carries instruments to measure the ambient pressure and temperature, the parameters p, T and z in the hydrostatic equation are known, and p_0 may be calculated. Given now the surface pressure, and T as a function of z from the infra-red spectrometer data, the pressure may be determined as a function of height z from equation (3).

Alternatively, the profile of atmospheric density could, in principle, be obtained directly from satellite measurements of the refraction of starlight, the refraction of microwaves, or the absorption of light by the molecular constituents of the atmosphere.

The satellite could make continuous measurements of the angular position of a given star, which depend on the degree of refraction which the light rays suffer in passing through the earth's atmosphere.

A series of such measurements, made between the time when the star is acquired slightly above the horizon until occultation occurs, i.e. over a period of about 30 seconds, could be used to derive a profile of refractive index (and hence air density) at a point where the rays are tangential to the earth on the assumption that the atmosphere is spherically stratified. The method has not yet been tested, but calculations suggest that it should be possible to map the profiles in the lower stratosphere and upper troposphere to within an accuracy of a few per cent. It will probably not be possible to make measurements at lower levels, say, below 5 km, because of atmospheric extinction and occultation by cloud.

It has also been suggested (but not tried), that, since the velocity and direction of propagation of microwaves are functions of the refractive index (and hence density) of the atmosphere, precise measurement of these parameters could be used to determine atmospheric density and its variations. The technique envisages a master satellite followed by five or six slaves in low orbit around the earth. Microwaves transmitted between the master and the slaves would traverse the atmosphere at five or six different levels, and accurate measurement of their velocity and phase would continuously measure the bending and retardation of the waves averaged over the horizontal ray paths at these levels. Measurement of a 1-mb pressure change would require the system to detect a change of 1·4 m in the apparent position of the two satellites, something which could probably be achieved by Doppler measurements if the physical separation of the satellites were known with great precision. In a dry atmosphere it might be possible to derive the pressure field to within ± 1 mb in the horizontal and within ± 5 mb in the vertical, but the presence of water vapour is likely to reduce the accuracy of the method, especially at low levels.

The intensity of radiation reflected from the ocean surface on arriving at a satellite would depend on the total quantity of absorbing gas in its path, i.e. on the total pressure. This suggests that the total (surface) atmospheric pressure could be obtained by measuring the absorption of a beam from a laser on a satellite in its double path to the ocean surface and back. Two nearby frequencies would be used, one in a strong oxygen absorption line and one just outside the line. However, reflections from clouds and absorption by water vapour would probably make it difficult to achieve the required accuracy of better than 0·3 per cent.

Measurement of global winds. No really feasible method has been proposed for sensing winds simultaneously at a number of given levels in the atmosphere from a satellite. Determination of the pressure and temperature fields as described above would allow the winds to be calculated in middle and high latitudes where the winds are closely related to the pressure field through the controlling action of the Coriolis force due to the earth's rotation. This would not be possible in the tropical regions where the horizontal gradients of temperature and pressure, and the Coriolis forces, are all weak, but elsewhere it may well prove possible to derive the large-scale wind field from measurements of surface pressure and vertical temperature distribution only.

Meanwhile, American meteorologists are devoting considerable effort to the extraction of winds from the movement of clouds on the pictures transmitted on successive frames from the spin-scan cameras carried on the geostationary satellites.

Although this technique does not allow one to obtain a complete horizontal coverage of winds, or information at more than about two levels in the vertical, it is producing much useful information in data-sparse areas such as the tropics where there are very few other sources of wind data (see, for example, Plate IV). However, greatest attention has been paid to the measurement of winds by tracking inextensible, constant-volume, super-pressurized balloons that drift with the winds along surfaces of constant atmospheric density. In the United States' GHOST (Global Horizontal Sounding Technique) Project, more than

200 such balloons have been released from Christchurch, New Zealand, and tracked by the signals from a simple telemetering photoresistor device that measures the elevation of the sun. Balloons flying at 100 mb and higher are able to remain aloft for many months and make many circuits of the globe. One has flown for more than 420 days, circling the southern hemisphere more than 25 times at the 100-mb level. Balloons flying at the 200-mb level (40 000 ft) have an average life of about 100 days, Plate IV showing the trajectory followed by one such balloon in making eight circuits of the southern hemisphere over 102 days. Unfortunately balloons drifting at lower levels suffer with varying degrees of severity from the accumulation of frost, ice and snow, which limits their duration to weeks, or even a few days. If the balloon lifetime can be increased, the icing problem overcome, and an electronics package designed that will present no hazard to aircraft, this technique is likely to become an important component of World Weather Watch. Adequate global data on winds and much valuable temperature and pressure data could be supplied by keeping perhaps 6000 balloons circling the earth at altitudes between 3 and 25 km. They would be located and interrogated by a system of satellites and their data relayed to a ground-based computer for analysis.

Three alternative systems are being actively investigated. The IRLS (Interrogation, Recording and Location System) being developed by NASA, will determine the location of a balloon by measuring the propagation time of a two-way radio signal between the satellite and the platform for two positions of the satellite in the same orbit. These two range measurements and the exact time of the measurement in relation to the known geometry of the orbit are all that is required to establish the position of the balloon. A similar determination made during the next orbit, about 100 minutes later, will give the balloon's displacement and hence the average wind over this time interval. Design studies suggest that the total error in range measurement may not exceed 0·5 km, in which case it should be possible to locate a balloon to within ± 3 km and to give average winds to within ± 1 m/s.

The EOLE system, designed by the Centre National d'Études Spatiales of France, will measure the Doppler shift of a signal transmitted from a satellite to the balloon and back again and hence the angle between the propagation path and the tangent to the satellite orbit. Again, measurements taken at two positions of the satellite fix the position of the balloon, and similar measurements during the next orbit yield the wind averaged over the intervening period. The first major trial, involving 500 constant-level balloons each carrying small thermistor thermometers and light-weight aneroid capsules, was carried out in 1972. A target of ± 4 km has been set for the accuracy of location of a balloon.

The OPLE (Omega Precision Locating Experiment) system, designed by NASA, makes use of the very low-frequency (10-kHz) Omega navigational system which, because of its low attenuation and high phase-stability, affords world-wide coverage and very accurate phase measurements. The balloon would receive signals from two pairs, i.e. three, Omega ground stations and retransmit them to a satellite which would then relay them to a computer on the ground for calculation of the balloon's position. Two lines of position (hyperbolic isophase contours) are established by the phase differences between the signals from each of the two pairs of transmitters and the position of the receiver (balloon) is given by the intersection of these two contours. The very long base-lines between the ground stations result in the position contours cutting nearly at right angles to give a fix that is expected to be accurate to within 1 mile by day and within 2 miles at night for almost all geographical locations. The balloon and satellite need carry only a simple transponder, and as the motion of the satellite, which acts only as a relay station, plays no part in determining the fix, it can be geosynchronous. By interrogating on 50 different frequencies simultaneously it might be possible for one geostationary satellite to interrogate a total of 2000 balloons each for 3 minutes every 2 hours. Three such satellites, one with its orbit inclined at 30° to the Equator, could achieve global coverage over each 24-hour period and interrogate a total of perhaps 6000 balloons.

However, because of the severity of the icing problem, to which no solution has yet been found, balloons can be flown economically only above 200 mb, and below 850 mb in the tropics, the most vital part of the troposphere being barred. Accordingly, it seems that the constant-level balloon will play a much less prominent role in World Weather Watch than once seemed likely, and this leaves the difficult problem of obtaining wind data in the tropics unsolved. It has been suggested, however, that a large constant-level balloon flying at, say, 100 mb, might release very light-weight dropsondes carrying transponders and fitted with parachutes that would drift with the wind, and that these could be located and tracked by a navigational system such as Omega. Such a system may be tested later this year.

Automatic weather stations on land, on buoys, and on ships. All three of the satellite systems just described are capable in principle of communicating with automatic weather stations on land, on anchored or floating ocean buoys, and on moving merchant ships. In all cases, identification and precise location will be easier than with balloons.

Several countries are developing automatic stations to report conventional surface weather observations. The Meteorological Office is about to put into operational service stations that measure pressure, temperature, humidity, wind-speed and direction, rainfall, visibility and sunshine, and can be interrogated either by radio or by a telephone call.[6] Similar installations will also be tried out on merchant ships, where the tendency towards greater automation and smaller crews may make it increasingly difficult to obtain all the required information from voluntary observers.

Even so, there will be vast areas of the oceans almost devoid of ships, and here automatic stations on buoys are a possible solution. The Meteorological Office has designed and built an experimental buoy which carries sensors to measure air and sea temperatures, wind speed, humidity and pressure, and has operated satisfactorily in coastal waters for several months.[7] However, the technical problems of making sensing and telemetering systems that will continue to work unattended for long periods on the high seas, and to do this at a cost which will allow them to be deployed in large numbers, are formidable. Major expenditure on buoy development is therefore not likely to materialize until other and cheaper solutions have been thoroughly investigated.

Conclusion. There is little doubt that the developments described in this paper will, over the next decade or two, lead to major changes in the methods and techniques of meteorological observation and measurement, and that the direct measurement of some of the basic atmospheric parameters will be gradually supplemented, and perhaps ultimately replaced, by indirect methods involving the remote sensing of electromagnetic radiations from atmospheric constituents by satellites. For the next 10 years or so, the global observing system will probably consist of a mixture of satellites, conventional radiosondes, dropsondes, balloons released from ground stations and ships and tracked by navigational aids such as LORAN and OMEGA, constant-level balloons carrying accurate radar altimeters, etc. However, satellite methods are likely to become more and more dominant, and although it may be necessary to retain some ground-based sounding stations for the calibration and checking of the satellite systems, it will probably be possible to dispense with many of the radiosonde stations in the northern hemisphere and the weather ships well before the end of the century.

A more detailed account of techniques and instruments for the remote sounding of the atmosphere is given in an excellent review by Houghton and Taylor.[8]

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551.554(267.3+676): 551.577.37

AN EXTREME WIND SPEED IN THE LOW-LEVEL JET-STREAM SYSTEM OF THE WESTERN INDIAN OCEAN

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Summary. This note records an occurrence of very strong winds at one location affected by the low-level jet-stream system of the western Indian Ocean. The maximum speed recorded at 1000 metres above mean sea level exceeded all previously known values, and the strong winds were followed by excessive rainfall on parts of the coast of eastern Africa.

Introduction. Attention has been drawn in earlier papers[1, 2] to the strong air current which circulates at low level over the western Indian Ocean and parts of eastern Africa during the months of the northern summer. The general form of the current is shown in Figure 1 which is a simplified version of a much more detailed analysis.[3] The phenomenon is well marked from April to October every year, but it only protrudes north of the Equator from May until September. It is within the hatched area of Figure 1 that mesoscale low-level jet streams are commonly (though not exclusively) found on a daily basis, orientated in the direction of the major streamline and moving along it.

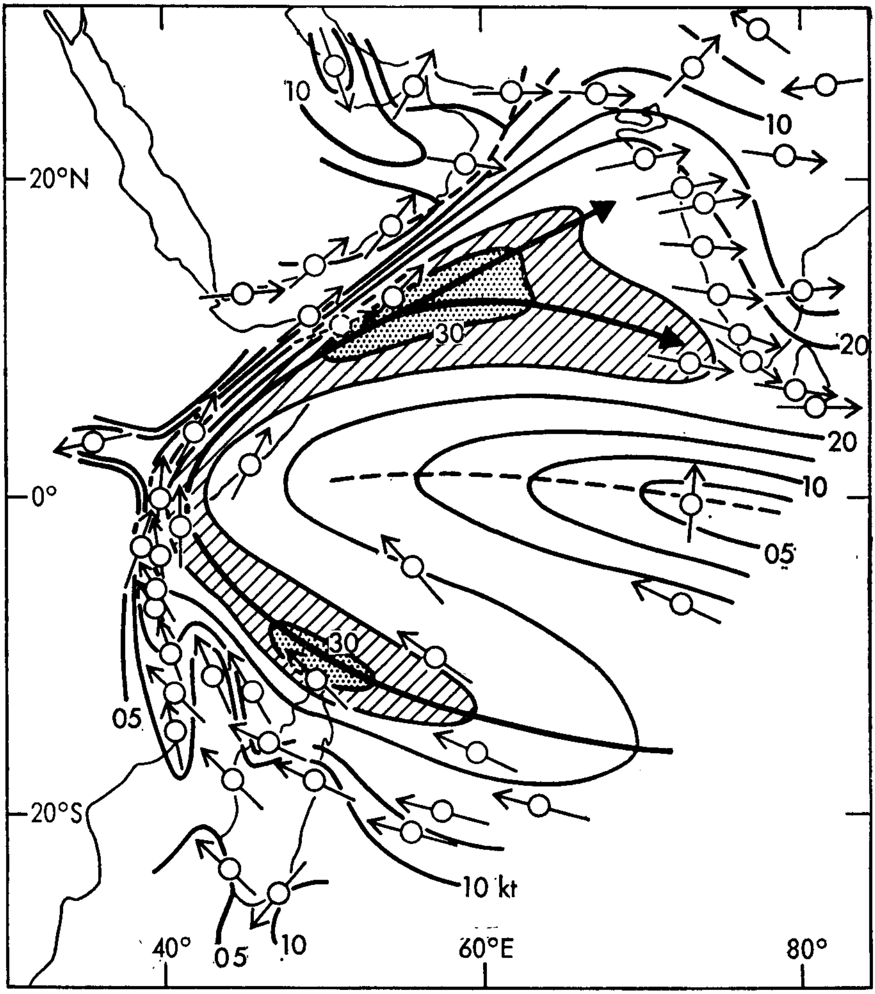

FIGURE 1—MONTHLY MEAN AIRFLOW AT 3000 ft (1 km) IN JULY

——→ Major streamline, axis of maximum flow.
——— Isotachs, at intervals of 5 kt.
- - - - Axis of minimum wind.

The core of the current lies about 1000–1500 metres above sea level and has a mean monthly speed of 25–35 kt* along most parts of its length. This core can, however, attain daily speeds of 50–100 kt or more; the three highest values previously measured were 98 kt by pilot balloon and 100 kt by an aircraft, both over eastern Kenya, and 105 kt by pilot balloon at Ras Asir, Somalia.[4] Now an extreme speed of 126 kt at 1000 metres above mean sea level has been reported from Diego Suarez (12° 21′S, 49° 18′E, 105 m above mean sea level) on the northern tip of the island of Madagascar.

Upper winds at Diego Suarez, 1–4 October 1972. The mean upper wind at 1000 m in July at Diego Suarez is 135 degrees 30 kt. Between April and

* 1 kt = 0·5148 m/s.

October it varies only between 125 and 135 degrees in direction and between 21 and 30 kt in speed.[3] Nevertheless the speed of the core at Diego Suarez can accelerate to very high values at any time during these months. One extreme value is considered here, but the report is credible because of the sequence of upper winds which preceded it.

During this period no cyclonic disturbances affected the area, and the usual broad south-easterly airstream prevailed. Satellite cloud photographs showed a long streak of low cloud orientated south-east to north-west across Diego Suarez, with its origin some hundreds of miles* to the south-east over the Indian Ocean. Calculations of the vertical velocity around the core of this current,[5] where it passes over eastern Africa, have indicated that the air in the core is generally rising, with descent to either side. The core of the current is therefore more likely to be cloudy than areas on its flanks, and such cloud streaks have been found to be helpful in locating zones of high speeds in routine analysis and forecasting.

The upper winds recorded at Diego Suarez are shown in Table I as a time series and the following points are noteworthy:

(a) The direction of the high-speed flow was relatively constant from 130 degrees, and the core of highest speed varied little from a height of 1000 m.

(b) Seven consecutive soundings, including two radar-wind soundings, reported core speeds over 60 kt.

(c) Five consecutive soundings, including one radar-wind sounding, reported core speeds over 80 kt.

(d) Vertical wind shear near the surface was remarkable, even during the afternoons (local time is 4 hours in advance of Greenwich Mean Time).

(e) Wind speeds dropped rapidly during the evening of 3 October 1972, but the direction remained unchanged.

The extreme speed of 126 kt at 1000 m is the highest value known to have been recorded anywhere in the low-level jet-stream system. Although this value may be a little exaggerated, because of possible errors in the pilot-balloon technique, it should be noted that the radar winds (maximum 92 kt) are averaged over deeper layers of air, and most probably undervalue the true maximum speeds, when, as in this case, the cores are shallow and are below the level at which maximum winds are specially reported in the coded message.

Although Madagascar lies aslant the south-easterly airstream, and there is some topographical intensification of the flow, it has been shown earlier[2] that low-level jet streams exist over the open ocean to the east and south-east of Madagascar, and that the phenomenon is not entirely due to topography.

During the period of these very strong winds excessive rainfall occurred on the east African coast near Mombasa (04° 02′S, 39° 37′E), close to the position where the axis of maximum flow approached the coast, although there is no evidence that strong winds at low level occurred over mainland Africa.

The maximum daily fall at Mombasa was 88.0 mm on 5 October, and the maximum three-day fall (3–5 October) was 166.3 mm, also at Mombasa. Figure 2 shows the flow at 1500 m, rather above the level of maximum wind, for 3 October 1972, and the area of heavy coastal rainfall with which the strong wind belt was, in some way, associated.

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* 1 mile ≈ 1·6 km.

TABLE I—TIME SERIES OF SURFACE AND UPPER WINDS AT DIEGO SUAREZ, MALAGASY REPUBLIC, 1–4 OCTOBER 1972

Day in October 1972	01	01	01	02	02	02	03	03	03	04	04	04
Time GMT	0505	1105	2300	0515	1125	2300	0505	1105	2300	0505	1110	2300
Method	P.B.	P.B.	RAWIN	P.B.	P.B.	RAWIN	P.B.	P.B.	RAWIN	P.B.	P.B.	RAWIN
Surface	120 16	100 22	120 19	120 10	120 28	120 26	120 20	100 14	120 10	120 21	100 21	120 06
Height above mean sea level (metres)												
200	126 37	128 70	130 37	146 42	137 77	120 52	134 45	124 60	120 18	135 18	130 25	120 15
500	128 40	130 57	140 65	145 45	**135 94**	**130 89**	136 62	**126 113**	130 35	132 38	135 32	120 26
1000	121 35	143 43	130 73	**129 80**	**134 108**	**120 90**	**128 87**	**127 126**	130 37	132 27	131 42	120 31
1500	113 47	114 32	120 64	107 72	119 60	**120 91**	118 70	**124 85**	140 30	122 43	107 38	120 30
2000			100 37	100 60	100 49	**110 92**	092 68		130 17			120 33
2500			110 30			080 62	076 43		140 10			110 23
3000			110 26			040 41	066 36		130 13			120 10

Station co-ordinates: 12° 21′S, 49° 18′E, 105 metres above mean sea level.
P.B. = Pilot balloon wind. RAWIN = Radar wind.
Winds are given in degrees true and knots. Bold type indicates that the wind speed reached or exceeded 80 kt.

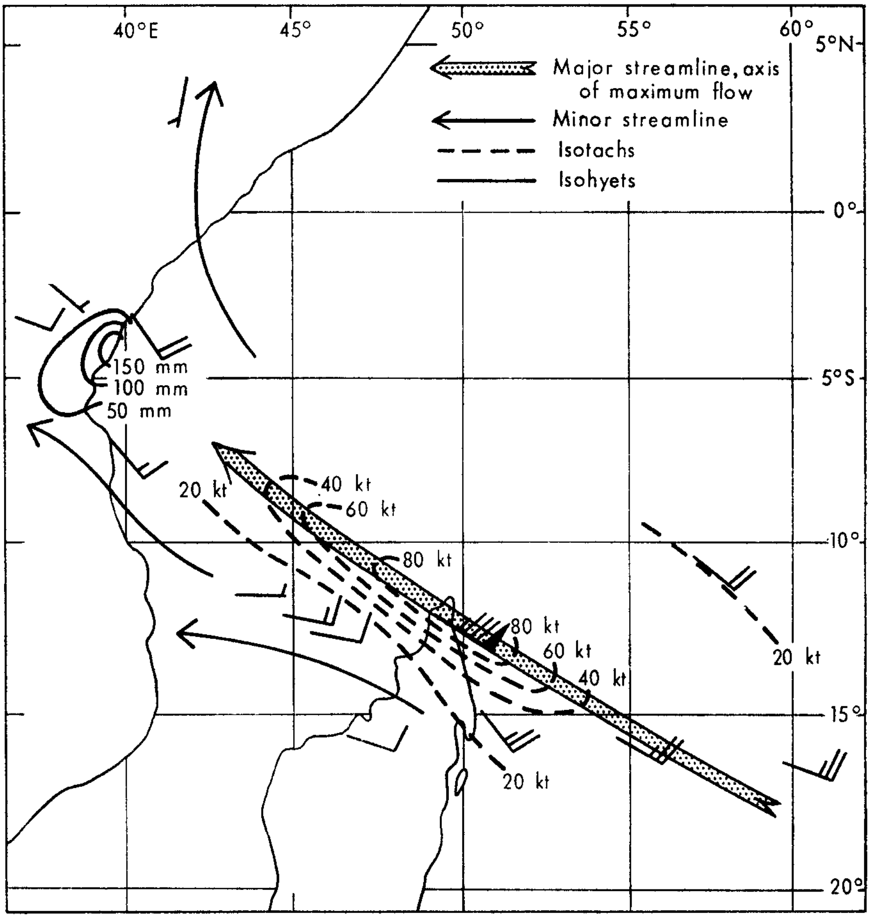

FIGURE 2—WIND FLOW AT 1500 m (850 mb) AT 12 GMT ON 3 OCTOBER 1972
Isohyets are for total rainfall, 3, 4 and 5 October 1972.

Acknowledgements. The assistance of the Director of the Meteorological Service of the Republic of Malagasy, who kindly provided the complete time series of verified upper winds from Diego Suarez, is acknowledged.

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REVIEW

Climatologie—Méthodes et Pratiques, 2e édition, by R. Arléry, H. Grisollet and B. Guilmet. 240 mm × 150 mm, pp. xvii + 434, *illus.*, Gauthier-Villars Éditeur, 24–26 Boulevard de l'Hôpital, 75005 Paris, 1973. Price (paperback): 90 F.

Within its limitations, this is a good book. The authors, three senior members of the French Meteorological Service, state that it is intended as a textbook for scientists intending to work in a national climatological service, and for users of climatological information, and the newcomer in either category who reads and absorbs the contents will find that he has learned a great deal which will stand him in good stead, and not much which he will realize later to have been a waste of time. But it needs to be supplemented.

After an introduction in which the objectives are set out and the definition of 'climate' is discussed, the individual climatic elements are described. In the second part, which makes up about half the book, the statistical methods open to the climatologist are discussed with practical examples, mostly based on French data, which may be new to English-speaking readers. The coverage of methods is excellent, although the chi-square distribution might have been given a little more attention, and there is a good chapter on normals. Tricky points like persistence, temporary oscillations, and loss of degrees of freedom, are brought out into the open and not glossed over, although the reader still has to decide how he deals with them. The third part, on applied climatology, illustrates most of the worthwhile methods of presenting climatological information in assimilable form.

The limitations of the treatment arise because the authors seem to have had no opportunities for working with electronic computers. In consequence, the possibilities which exist for making climatic predictions, and for understanding climatic processes, which depend on powerful means of data processing, are not really envisaged. For example, the method of filtering is treated only sketchily, while principal-component analysis and Monte Carlo techniques do not seem to be considered at all, but there are detailed descriptions of punched-card apparatus which by 1974 should have been retired to a museum. The new concepts involved in computer work, such as the emphasis on a regularly arranged digitized data bank, and modular computer programs to work on the data bank, and on the ability to supply, at low cost, statistics adapted to the customer's need; these ideas are missing from the present treatise, although they must assuredly enter into the mental stock-in-trade of the climatologists of the future.

Apart from the computer topics there are plenty of references, and the authors show familiarity with a great deal of the English-language climatic literature. Possibly for this reason, the whole book is written in a style of French which the reviewer found most pleasant and easy to follow. Taken as a whole, the treatise merits the reflection that if the authors could produce an English translation with the help of a computer-minded collaborator who could add about 100 pages on the computer topics, the result would be valuable to the meteorological community for a very long time to come.

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LETTER TO THE EDITOR

Wet-bulb freezing level as a snow predictor

A paper by Mr B. J. Booth[1] shows a relationship between the wet-bulb freezing level and his index for snow prediction. In a subsequent letter[2] Mr F. E. Lumb says it is unfortunate that I did not include wet-bulb freezing level as one of the predictors examined in my paper[3] on the subject.

The main reason for the omission is given on page 355 of the paper, where I claim that on most occasions the dew-point depression is so small that humidity can be ignored in deciding whether rain or snow is the more likely. On the other hand, Mr Lumb refers to the outstanding usefulness of the wet-bulb freezing level 'on those memorable occasions when snow descends well below' its initial height. This may be true, but the trouble is that such events tend to be memorable because they were not forecast.

It is important to remember that the discovery of an index that is related to the probability of snow may represent only a small contribution to the forecasting problem. Such a predictor is worthless unless it is either (a) a number which is known at the time when the forecast is made or (b) a number which can be forecast with a fair degree of accuracy.

If neither of these conditions is fulfilled a correlation between a weather element and an index does no more than enable the forecaster to state his problem in different terms. An example of such an index is the surface temperature, which might be quite a useful snow predictor were it not for the fact that the temperature itself is affected by whether the precipitation is rain or snow.

Mr Booth is clearly aware that his two papers on snow predictors, like mine, are concerned mainly with establishing correlations. These were correlations between simultaneous elements and were arrived at objectively. It would have been impossible to give them more than an indication of their usefulness as forecasting tools because such assessments are bound to be subjective. Only by experience can the individual forecaster find out what method is the most useful to him.

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Surrey

REFERENCES

1. BOOTH, B. J.; A simplified snow predictor. *Met Mag, London*, **102**, 1973, pp. 332–340.
2. LUMB, F. E.; Wet-bulb freezing level as a snow predictor. *Met Mag, London*, **103**, 1974, p. 59.
3. BOYDEN, C. J.; A comparison of snow predictors. *Met Mag, London*, **93**, 1964, pp. 353–365.

Editor's comment. This correspondence is now temporarily closed pending the forthcoming publication of a full article on this topic by staff of the Forecasting Techniques Section of the Meteorological Office.

NOTES AND NEWS

AUTOMATIC CHART PLOTTING

Following a successful series of field trials, an operational trial of automatic chart plotting was started in November 1973. In this trial most of the three-hourly and six-hourly charts required by the Central Forecasting Office for the period 0900–1800 are being plotted automatically from computer-processed data. Owing to the tight time schedule the automation of some of the charts must await the implementation of the electronic interface between the Telecommunications Branch and the main IBM computer.

PUBLICATION RECEIVED

Sea and air—the marine environment, second edition, by Jerome Williams, John J. Higginson and John D. Rohrbough. 255 mm × 165 mm, pp. xx + 340, *illus.*, Naval Institute Press, Annapolis, Maryland, U.S.A., and Patrick Stephens Limited, Bar Hill, Cambridge CB3 8EL, 1973. Price: £6.00.

OFFICIAL PUBLICATION

British Rainfall Supplement 1961–1965. (London, HMSO. Price: £7.)

This is the first edition of the supplement to *British Rainfall* foreshadowed in *British Rainfall* 1961.

Part I, the Table of Rainfall Stations, lists all stations for which one complete year of rainfall data has been published during the years 1961 to 1965, also the first calendar year with data available for these stations. Complete station particulars are given, some of which have been omitted from the annual volumes of *British Rainfall* since 1961 in order to make way for more rainfall data. Where known, the wettest day on record is included for those stations where daily records are maintained.

Part II of the supplement contains obituary notices of voluntary rainfall observers who have co-operated with the Meteorological Office for 35 years or more.

Part III contains a summary of the work of the hydrometeorological branch of the Meteorological Office during the 5 years.

Part IV deals with heavy rainfall. It contains a summary of the Bilham classification of heavy falls of rain and summaries of heavy falls of rain on rainfall days.

Part V is devoted to special articles by individual authors. There are two articles, 'The presentation of monthly rainfall' by A. Bleasdale and 'Accumulated percentage departures of average rainfall' by P. M. Stephenson.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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