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Scientific Paper No. 21

Estimation of rainfall using radar—a critical review

by T. W. Harrold, B.Sc., D.I.C.

This publication contains a critical review of the possibilities of using a weather radar to measure rainfall over an area, such as a river catchment, as it falls. Two methods are discussed.

By relating the power reflected from the rain to the rate of rainfall it is possible to estimate the rainfall amount, the probable error in such an estimate being 25 per cent. To achieve this accuracy a narrow beam width and a wavelength greater than 5 cm are necessary. In winter in the United Kingdom the error will be larger since the beam passes above the rain into snow at larger ranges. The circuitry required to provide automatic measurements is discussed.

An alternative method is to measure the attenuation of radiation, of wavelength about 1 cm, and to relate this to the rate of rainfall. Although theoretically more accurate, practical considerations, such as the size of a reflector required at larger ranges, make this a less satisfactory method of estimating rainfall compared with measuring the reflected power.

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A RADIOMETER SONDE

By D. G. JAMES, D. W. S. LIMBERT and J. C. McDOUGALL

Summary.—A radiometer designed by Suomi and Kuhn[1] for use on balloons has been adapted to the requirements of the Meteorological Office radiosonde ground receiving equipment by the construction of a fully transistorized electronics package. Measurements of net radiation near the ground were compared with those made simultaneously with a Kew net flux radiometer. Systematic differences between these results led to a recomputation of an equivalent thermal conductivity through the instrument, the value obtained being significantly different from that given by Suomi and Kuhn. This difference is thought to be due to a change in instrument construction. Three flights of the radiometer are described and a short discussion of the results is presented.

Introduction.—In attempting to produce a numerical forecast for periods in excess of 1 or 2 days, it is essential to know how and where heat is put into and taken from the atmosphere by non-adiabatic processes. Furthermore, since it is usual in these forecasts to divide the troposphere into several layers, it is necessary to obtain the rate of heating or cooling of each individual layer. In this paper we will be concerned only with the loss of heat by long-wave radiation from the atmosphere.

Measurement of net outgoing radiation is necessary since its calculation can only be obtained approximately even when all the radiating atmospheric constituents are known. A radiometer has been developed by Suomi and Kuhn[1] which is sufficiently light to be carried aloft by an ordinary radiosonde balloon, and sufficiently inexpensive to make regular daily soundings a practical proposition. Dr Kuhn was kind enough to present us with a dozen of his radiometers, and in this paper we describe the design and construction of an electronics package which allows us to use the Meteorological Office Cintel equipment to measure the appropriate variables of the radiometer. It should be remembered that the Suomi-Kuhn radiometer is a proven instrument, and has been flown many hundreds of times in the U.S.A. The accuracy of the measurements obtained there has been limited by the accuracy of the telemetry system of the American radiosonde (Bushnell and Suomi[2]), and so we have set ourselves to improve on this by obtaining an accuracy in temperature measurements of 0·1 degC. This is the bulk of the paper. We also present three test flights just to prove that the instrument behaved satisfactorily, though we would not claim high accuracy for the results presented, since, for example, no allowance has been made for the lag of the instrument. But this is not a difficult problem.

We now feel that the radiometer and our electronics package will give accurate measurements of nocturnal rates of cooling over layers of the atmosphere of 100 mb or so, and could, for example, be used in determining the rate of cooling against height profile in large quasi-stationary anticyclones.

The Radiometer.—Only a brief description of the instrument is given here, a fuller description may be obtained from Suomi and Kuhn[1] or Suomi, Staley and Kuhn.[3] The radiometer sonde is shown in Plate I.

Essentially the radiometer consists of two parallel sheets of mylar (strong plastic sheet) insulated from each other by thin layers of air and polystyrene and held in position by a circular polystyrene former (Figure 1). (Note that our diagram does not agree with that given by Suomi, Staley and Kuhn.[3])

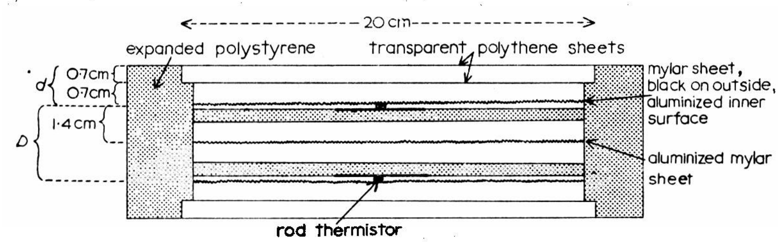


FIGURE 1—VERTICAL SECTION THROUGH RADIOMETER

The surfaces of the outward facing mylar sheets are black but the inward facing surfaces are aluminized as are both sides of another mylar sheet across the centre of the instrument. Convection at the black surfaces is reduced to a minimum by the use of two layers of thin transparent polythene sheet. The temperatures of the two black surfaces are measured by rod thermistors cemented directly beneath the mylar, and are calibrated — one spot temperature and resistance — by the manufacturer. At room temperature these resistances are of the order of 10 K ohms increasing exponentially to about 1 M ohms for temperatures in the region of –80°C, the sort of temperature expected at the top surface of the instrument in the stratosphere.

The temperatures of black surfaces are determined by :

(i) The incoming long-wave radiation from the earth, clouds or sky modified by absorption and reflection at the polythene windows.

(ii) The outgoing long-wave radiation from the black surfaces themselves also modified by the windows.

(iii) Heat conducted through the polystyrene former to or from the environment, and also by the air from each black surface to its corresponding polythene shield.

(iv) Heat conducted through the radiometer from one black surface to the other.

(v) Heat transferred by convection inside the instrument and also from the black surfaces to the polythene sheets. These terms are small compared with the other variables influencing the heat balance according to Suomi, Staley and Kuhn.[3]

Following these authors the downward and upward streams of long-wave radiation ($R\downarrow$ and $R\uparrow$) may be expressed as

$$R\downarrow = \sigma T_t^4 + A(-C_i - C_t + \lambda\left(\frac{dT_t}{dt}\right) + E_t) \qquad \ldots (1)$$

and

$$R\uparrow = \sigma T_b^4 + A(C_i - C_b + \lambda\left(\frac{dT_b}{dt}\right) + E_b), \qquad \ldots (2)$$

where subscripts t and b refer to top and bottom black surfaces and $\frac{d}{dt}$ denotes differentiation with respect to time and

σ = Stefan-Boltzmann constant

T_t, T_b = temperatures of the top and bottom surfaces

A = constant depending on the absorptivity of the black mylar surface (0·85) and the reflectivity of the polythene sheets (0·16)

λ = constant depending on the thermal inertia of the surfaces

E_t, E_b = errors introduced by the various simplifying assumptions made

C_t = $k_t \frac{T_a - T_t}{d}$ and $C_b = k_b \frac{T_a - T_b}{d}$ = conduction terms from the black surfaces to air

and C_i = $k_i \frac{T_b - T_t}{D}$ = heat conducted between the surfaces, where k_t, k_b and k_i are thermal conductivities, T_a = air temperature, d = distance from the black mylar surface to the outside polythene sheet and D = distance between the inner surfaces of the main mylar sheets.

The net flux of long-wave radiation R_n can now be obtained by simple subtraction.

Furthermore, rates of cooling over a layer p_1 to p_2 can be written as

$$\frac{dT}{dt} = \frac{-g\,(\,(R_n)_2 - (R_n)_1\,)}{c_p\,(p_2 - p_1)} \; . \qquad \ldots (3)$$

where p_2, p_1 are the pressures at top and bottom of the layer, $(R_n)_2$, $(R_n)_1$ are the corresponding net radiations, g is acceleration due to gravity and c_p is specific heat at constant pressure.

Near the ground the radiation terms and conduction terms are about equal in size in the expression for net radiation but at higher levels and certainly in the stratosphere the conduction terms become the greater by a factor of 3 or 4. The evaluation of k_t, k_b and k_i is thus of considerable importance. Suomi *et alii*[3] suggest that the same value — namely the thermal conductivity of air at temperature $\frac{1}{2}$ $(T_b + T_t)$ — be used for all three terms. However, with the variation in design of the instrument mentioned earlier there is some reason to doubt the validity of this assumption.

Some spot checks on the accuracy of the instrument at ground level were obtained by mounting it alongside a net flux radiometer at Kew Observatory and making simultaneous measurements of the temperatures of the top and bottom surfaces and of the net flux. The comparisons were performed on two nights when the presence or absence of cloud cover was expected to give quite different results. Evaluation of the net radiation, as measured by the Suomi radiometer using the constants given in the 1958 paper,[3] showed systematic differences from the readings of the Kew net flux radiometer. These differences could be explained by an error in k_i, the internal thermal conductivity. The instrument was sectioned — it was at this stage we discovered the change in design — and from accurate measurements of the thicknesses of the layers of air and polystyrene a new k_i was calculated for the appropriate temperature. Table I presents the results of the comparison using the new value of k_i.

TABLE I—COMPARISON OF KEW RADIOMETER WITH THE SUOMI-KUHN RADIOMETER USING A NEW VALUE FOR k_i

Kew net flux radiometer	Suomi-Kuhn radiometer		
Net radiation *mW/cm²*	Top temperature	Bottom temperature	Net radiation *mW/cm²*
	degrees Celsius		
7·23	0·8	7·6	7·26
7·13	0·1	6·8	7·18
7·13	−1·2	5·6	7·13
4·64	9·0	13·2	4·69
4·97	7·6	11·9	4·64
4·68	6·4	10·8	4·66

Telemetry.—The design of the telemetry package was determined by six basic requirements. These were :

(i) Four parameters must be measured, namely air temperature, the temperatures of the top and bottom surfaces of the radiometer and a standard resistance acting as a calibration check.

(ii) The audio-frequency oscillator periodicity must vary with the resistance change of the thermistors in such a manner that a linear temperature change gives a near-linear change of periodicity over the range +30°C to −80°C the expected range of temperatures of the surfaces.

(iii) A good radio-frequency oscillator is already available and has been test flown in the rocketsonde. The audio-frequency oscillator must therefore be designed to be compatible with this.

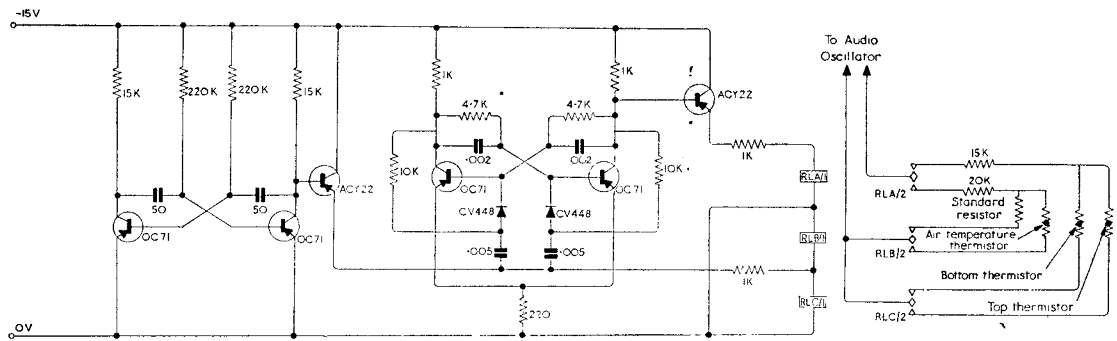
(iv) Temperatures must be known to an accuracy of ±0·1 degC.

(v) Any temperature or voltage drift in calibration must be uniform throughout the whole periodicity range 950 to 1500 microseconds (μs) so that the one calibration standard resistance is representative for the whole range.

(vi) Power supplies must be as convenient and as small as possible.

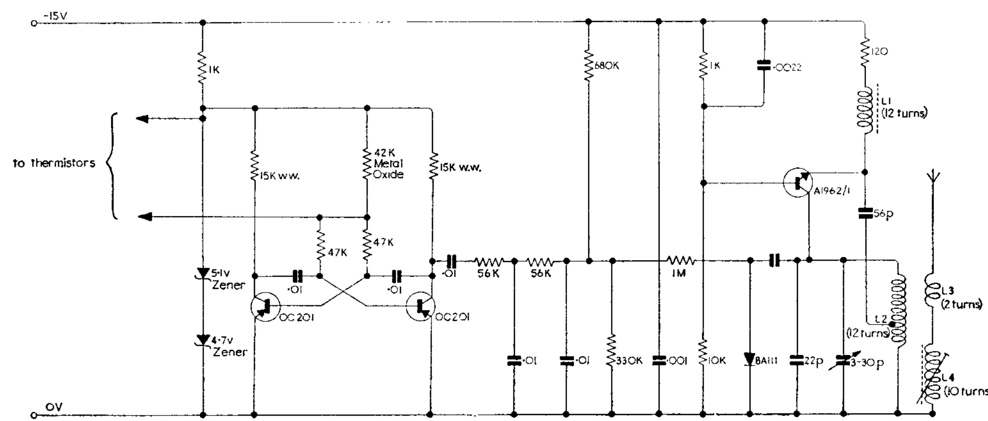
Windmills as used with Mk 2 radiosondes are unsuitable for switching because of the proposed slow rates of ascent, 600–800 feet per minute, and also because it was hoped to float a balloon at one level. Our present solution is a long-period multivibrator with suitable binary coupling acting on three miniature relays (Figure 2). Each position is held for about 15 seconds.

The audio-frequency oscillator is a multivibrator (Figure 3) with a variable resistance in the RC coupling. In such a circuit, resistance/periodicity changes



(*a*) Primary multivibrator (*b*) Binary circuit (*c*) Relay connexion

FIGURE 2—SWITCHING CIRCUIT



(*a*) Audio-frequency oscillator (*b*) Transmitter circuit

FIGURE 3—AUDIO-FREQUENCY OSCILLATOR AND TRANSMITTER CIRCUIT

are linear. The exponential variation of thermistor resistance with temperature can be converted to near linearity by a combination of resistors in series and parallel with the thermistor. The actual change in the thermistor resistance of 20 K ohms at +30°C to 1 M ohms at −80°C is made to produce a net resistance change of 19 K ohms to 40 K ohms. The standard resistor is a stable 80–K ohms wire-wound resistor in parallel with 42 K ohms.

Compensation for changes of temperature in the circuit is essential for keeping a constant slope for the calibration curve of periodicity/thermistor temperature, and is achieved by using wire-wound, carbon, and metal-oxide resistors whose temperature coefficients oppose each other (Figure 3). Between +20°C and −20°C the drift of periodicity throughout the whole range is usually less than 10 μs ±1 μs. The drift is given by the standard resistor. The slope of the periodicity/thermistor temperature characteristic of the audio-frequency oscillator is 10 μs/degC but only half this value at the ends of the range so that the maximum error there is ±0·2 degC. In practice the known drift has rarely exceeded 2 μs with an error correspondingly reduced to about ±0·2 μs, i.e. less than 0·1 degC. The rocket transmitter (Figure 3), a proven system developed for the SKUA rocket, is powered by two 9-volt PP6 batteries in series, which will sustain a current drain of 20 milliamps for 2 to 3 hours. The transmitter has the advantage that it will perform satisfactorily even when the voltage has fallen by half. Interaction between the transmitter on one hand and the audio and switching circuits on the other is avoided by giving the latter circuits a separate 15-volt supply. This is dropped to a zener-stabilized 9·8 volts across the audio circuit.

The electrical components are mounted on a circuit board of 4·8 × 5·8 inches and enclosed together with the batteries inside a cavity roughly 6 × 6 × 6 inches hollowed from a 1-foot cube of expanded polystyrene. The radiometer itself is mounted on three wooden supports cemented into the base of the instrument and also into one of the vertical sides of the polystyrene cube. The radiation reaching the radiometer from the complete package is thus negligible, so also is that from the balloon when the radiometer is a hundred feet or more below it. In flight this long suspension ends in a bridle fitted round the package and adjusted such that the radiometer freely hangs with its surfaces horizontal. The whole package including the radiometer weighs about 2 kilogrammes.

In an early radiometer flight the switching rate increased rapidly and then ceased altogether. We suspected that this was caused by the cooling of the transistors in the switching circuit. Experiments conducted using a 12-inch cube polystyrene box with 3-inch walls similar to that enclosing the package of electrical components showed that the internal cooling rate is 20 to 25 degC per hour provided that the temperature gradient across the walls is in excess of 30 to 40 degC. The cooling rate is roughly the same by day or by night but in the daylight flights the cooling rate high in the stratosphere decreased almost to zero. In the night flights the box continued to cool at the rate quoted. To combat this, a simple heater consisting of a 10-ohm 10-watt resistor is strapped to the back of the mounting of the electrical unit and supplied with 4·5 volts from a bell battery. This also keeps the audio oscillator warm. Since using this system we have experienced no trouble from changing frequency of switching.

Calibrations.—The temperatures of the black surfaces of the radiometer are measured by two rod thermistors cemented directly below the surfaces. The resistance of the thermistor may be expressed as

$$\text{Res} = \text{Res}_0 \, e^{\beta/T}$$

where Res_0 and β are constants depending respectively on the size of the element and its composition. The manufacturer gives one value of resistance and temperature, usually room temperature, and β. These values were checked by us for several of the radiometers by constructing the full log Res against $1/T$ curve from $+30°$ to $-40°$C and were found to be accurate within the limits of experimental error. Subsequently only one point was checked at room temperature.

The ambient air temperature is measured by a thermistor bead strapped between two of the radiometer supports. The thermistor has a resistance of about 10 K ohms at 0°C with a β of 3100°K. Each of these was checked at room temperature as well.

The resistance/periodicity calibration curve of the whole unit is constructed in detail by the use of numerous known resistors, 10 K to 1 M ohms, in place of the thermistor detectors. This calibration is performed soon after construction and is checked over the whole range (but not in such detail) immediately before a flight. We estimate that all of our temperatures are known to within 0·1 degC.

Data reduction.—The telemetered data are recorded on the ground by the Meteorological Office Cintel equipment, the signals being presented as periodicities on a moving paper chart graduated from 0 to 100 μs. Although there is some noise on the trace we estimate that our readings are accurate to better than 0·5 μs. This corresponds to about 0·05 degC on the steepest part of the calibration curve (–20 degC to –50 degC) and 0·1 degC elsewhere. Each sensor on the radiometer is interrogated for 15 seconds at a time which corresponds to a displacement of about ¼ inch on the Cintel chart. Generally this is ample time in which to determine the periodicity — indeed under certain conditions, for example through inversions or just above cloud top, considerable changes in temperature have been observed during one interrogation.

The first step in reducing the data from periodicity to temperature is to correct for any systematic variation in signal as disclosed by the standard resistor. In all cases this correction has been small, less than 2 μs, but has been applied nevertheless. In order to obtain the net radiation, R_n, at a given point, the upward and downward radiation streams must be evaluated simultaneously at this point. Our telemetry is single channel so that the temperatures of the surface are separated by 15 seconds, perhaps 50 metres in height. Therefore the observed periodicity must be converted to temperatures and plotted against time so that

$$T_a, \quad T_t, \quad T_b, \quad \frac{dT_t}{dt} \quad \text{and} \quad \frac{dT_b}{dt}$$

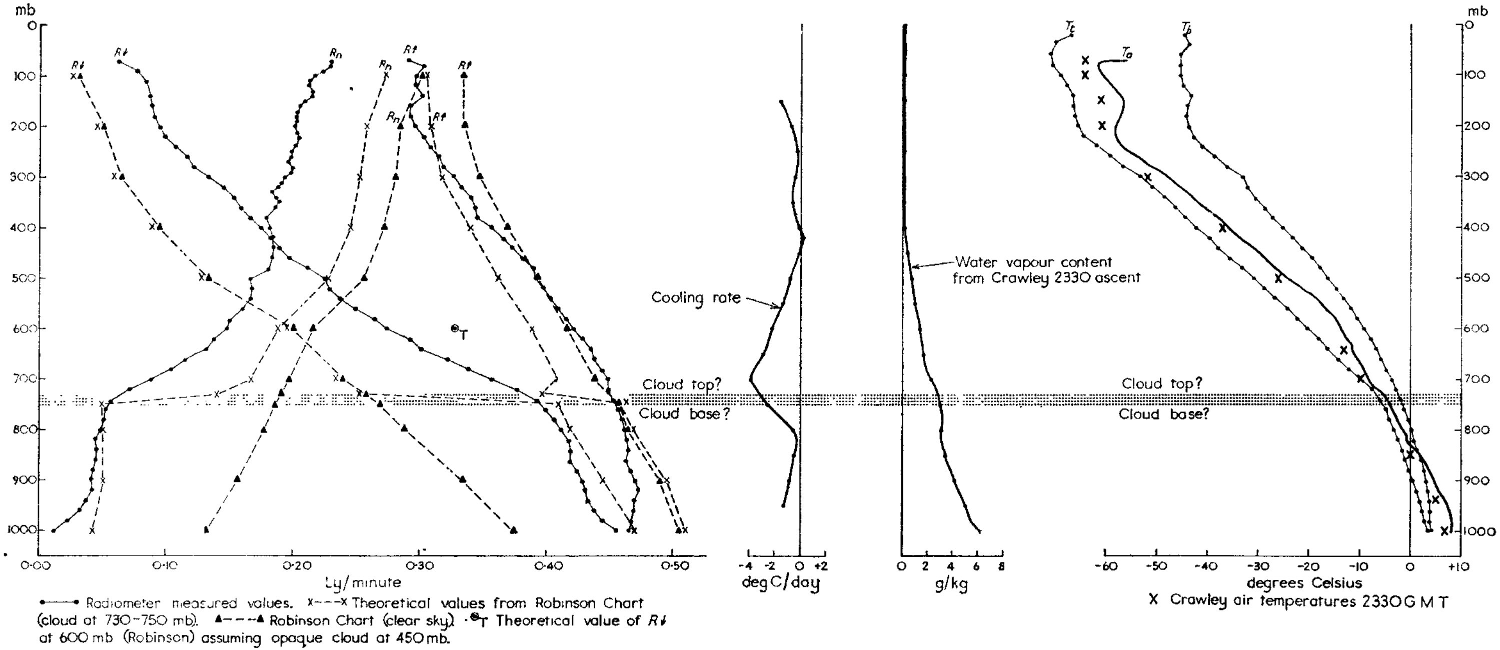
can be obtained simultaneously at selected pressure intervals, usually 20 millibars.

Rates of cooling may be calculated from equation (3). However, since these involve second order differences of temperature it is desirable to keep the pressure interval as large as possible. We have used 100 mb layers in the discussion following.

Discussion of the flight results.—Although the three balloon flights described here were intended mainly as test flights for the performance of the instrument there is some merit in a closer examination of the results if only to compare them with each other, with similar ascents described in the literature and also with simple calculations based on one of the well-known radiation charts. Figures 4(*d*), 5(*d*) and 6(*d*) present flight data from the three ascents. Each figure shows the temperature T_t, T_b of the top and bottom surfaces plotted every 20 millibars together with the air temperature T_a. Also included are temperatures and water vapour contents from the nearest radiosonde sounding, the 2330 GMT Crawley for all cases. The left side of the figures shows the downward and upward radiation streams as obtained from equations (1) and (2) together with the net out-going radiation ; units are Langleys (Ly) per minute. On two of the dates it was possible to obtain a net flux measurement at the surface from Kew Observatory ; these too are plotted on the figures. Finally in the centre of the diagrams we have cooling rates in degrees Celsius per day evaluated every 50 mb over thicknesses of 100 mb. Although it was intended to fly the radiometer only when there was no cloud so that the analysis would be simplified, on two of the three occasions there was some stratocumulus, 8/8 on 13 September and, we suspect, a patch on 29 April. On all three dates there is evidence that cirrus cloud was also present but we cannot be certain about its height or its density. Thus we can only compare the three flights in the broadest of terms. We hope to carry out flights in the future in conjunction with aircraft of the Meteorological Research Flight when accurate measurements of frost-points and reliable cloud heights will be obtained.

On all three ascents the temperatures of the black surfaces decreased with height through the middle and upper troposphere, T_t falling rather faster than T_b, but became relatively constant in the stratosphere. The tops of any low cloud showed up clearly as a sharp decrease in T_t but cirrus cloud could not be detected in the same way. The rates of cooling of 100 mb thicknesses (calculated from equation (3)) are 1 to 2 degC per day in the lower troposphere falling to about zero in the upper troposphere and lower stratosphere but 3 to 4 degC per day near the top of the stratocumulus cloud. This is in good agreement with values quoted in the literature (for example Kuhn, Suomi and Darkow,[4] Staley[5]) but for a more detailed analysis of results we will treat each case separately.

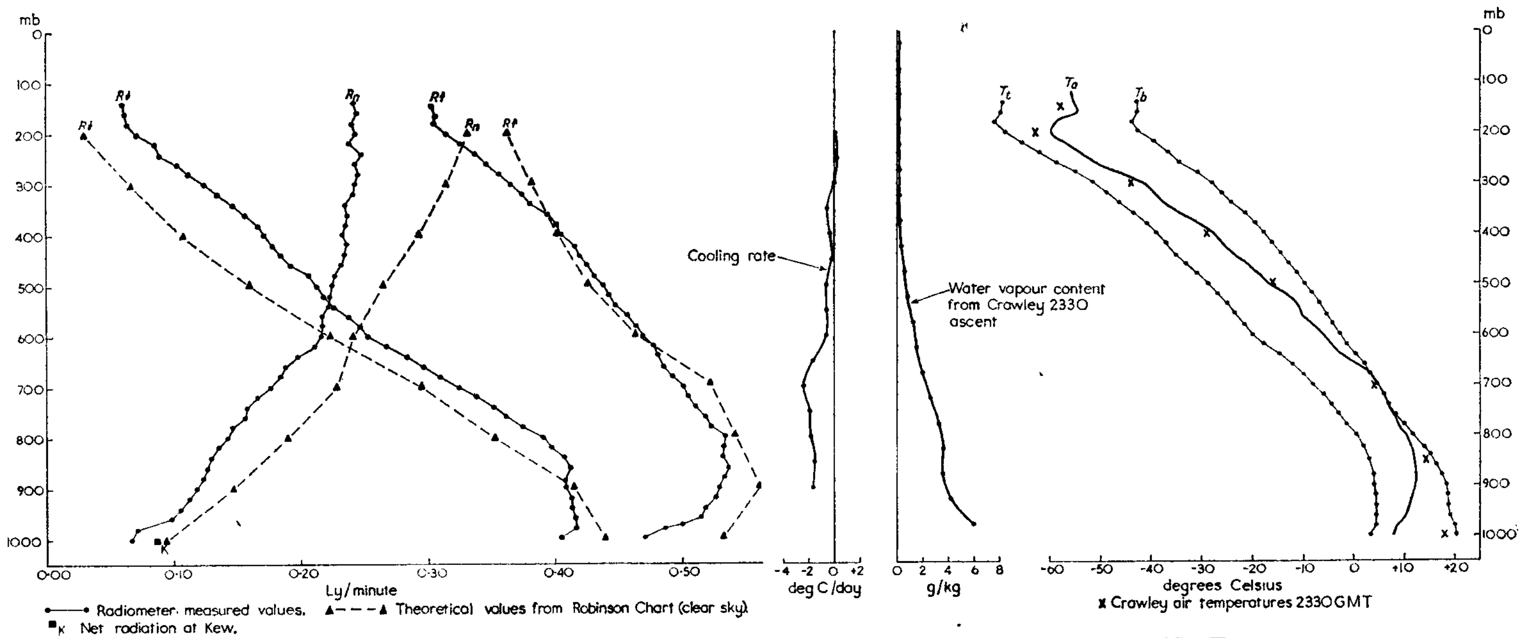
Flight of 29 April 1965.—A slack pressure gradient existed over the British Isles between a depression to the west and an anticyclone near Scandinavia. The day was one of sunny periods and at dusk the sky was clear apart from high cirrus. A final check calibration of resistance/periodicity was made before the polystyrene box was sealed and taken outside where it was allowed to cool in the clear night air. The sonde was launched at 2200 GMT from the Meteorological Office Experimental Site at Easthampstead,



(*a*) Radiation data (*b*) Cooling rate (*c*) Water vapour content (*d*) Temperatures

FIGURE 4—RADIOMETER FLIGHT ON 29 APRIL 1965

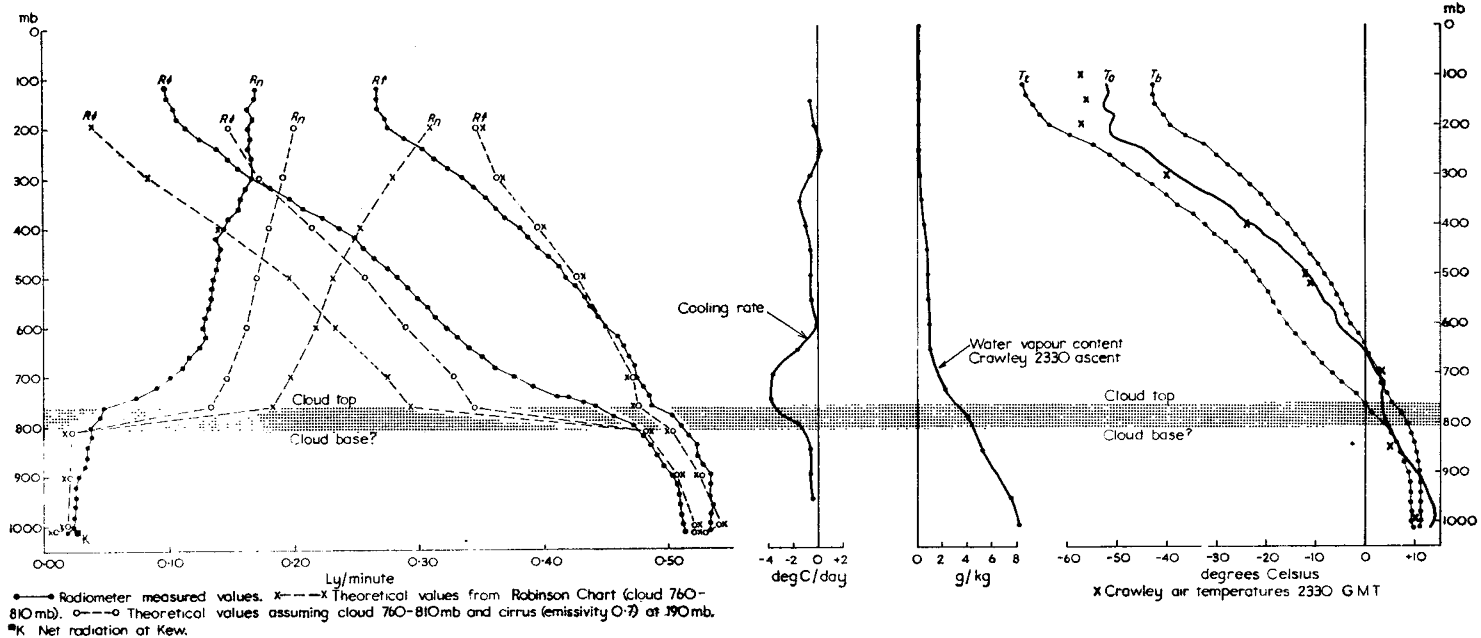
T_a=temperature of air, T_t, T_b=temperatures of the top and bottom surfaces.



(*a*) Radiation data (*b*) Cooling rate (*c*) Water vapour content (*d*) Temperatures

FIGURE 5—RADIOMETER FLIGHT ON 13 MAY 1965

T_a=temperature of air, T_t, T_b=temperatures of the top and bottom surfaces.



(*a*) **Radiation data** (*b*) **Cooling rate** (*c*) **Water vapour content** (*d*) **Temperatures**

FIGURE 6—RADIOMETER FLIGHT ON 13 SEPTEMBER 1965

T_a=temperature of air, T_t, T_b=temperatures of the top and bottom surfaces.

Berkshire. Throughout the flight all instruments functioned well. Heights were obtained by radar ranging and the rate of ascent was found to be about 4·5 m/s, rather higher than intended. The balloon burst after 105 minutes at a height of about 25 mb. A few days later the sonde was recovered from a farm in Essex ; it was found to be in a workable condition and a check calibration showed very little difference from the pre-flight calibration.

The interpretation of the results of this flight (Figure 4) is complicated by the presence of cloud with a top close to 730 mb. Although there were no reports of low cloud in the immediate neighbourhood there is no doubt that it existed. The net radiation is relatively constant at 0·04 Ly per minute up to 750 mb and then increases sharply mainly because of a decrease in $R\downarrow$. The cooling rate at 700 mb is 4 degC per day and calculations at points 25 mb above and below this level substantiate this figure. Between 375 and 475 mb the net radiation remains roughly constant at 0·18 Ly per minute, indeed there is a slight decrease in R_n leading to a slight warming near 400 mb. Although this warming is not significant when compared with the probable errors of observation the fact that R_n is constant over a depth of 100 mb certainly makes this a significant feature of the sounding.

In order to compare our results with a simple calculation of net outgoing radiation the nearest radiosonde sounding was used to obtain temperatures and optical path-lengths (although no frost-points were given above 400 mb we have assumed a linear decrease of frost-point to −78°C, i.e. mixing ratio of 2·5 parts per million at the tropopause and a constant mixing ratio above — water vapour content is shown in Figures 4(*c*), 5(*c*) and 6(*c*)). Figures 4(*a*), 5(*a*) and 6(*a*) show the results of these computations using the Robinson radiation chart. In Figure 4(*a*) we have calculated the outgoing radiation assuming an opaque cloud, base 750 mb and top 730 mb, and also assuming no cloud. Below cloud (except very close to the ground) our measurements of $R\uparrow$ and $R\downarrow$ are in good agreement with those calculated, but above cloud there are quite large differences in $R\downarrow$, the observed values being the greater at all levels. That this may be due at least in part to the presence of cirrus cloud can be shown by assuming a black body at 450 mb, when $R\downarrow$ at 600 mb increases from 0·20 to 0·33 Ly per minute (the measured value is 0·27). The differences in $R\downarrow$ also show in R_n, which above cloud is about 25 per cent less than that calculated from the radiation chart.

Flight of 13 May 1965.—The British Isles lay in a ridge of high pressure between depressions in mid-Atlantic and over Scandinavia. The day was warm and sunny and at dusk the sky was clear apart from spreading contrails. The flight was conducted as before and all instruments functioned well until one of the relays stopped switching after 95 minutes and the flight was abandoned. At this time the sonde was at a height of about 120 mb having ascended at about 2·5 m/s. Later the instrument was recovered from the River Itchen at Southampton but owing to corrosion of the electronics a calibration check was impossible.

On this occasion there was no low cloud but 2/8–3/8 cirrus at 20,000 feet was reported and persistent contrails were seen near sunset. The air temperature as measured by our thermistor shows a very steep inversion, 10 degC in 20 mb, near the ground but then follows closely the 2330 GMT Crawley sounding. The upward radiation increases slowly to 850 mb and then decreases steadily to the tropopause. The net radiation near the ground, 0·074 Ly per minute, agrees well with the Kew value of 0·082 Ly per minute. From here to about 450 mb it increases steadily to 0·24 Ly per minute after which it remains relatively constant. Calculation of the radiation streams using the Robinson chart (Figure 5(*a*)) shows good agreement — except near the ground — with the measured $R\uparrow$ and a systematic difference from the measured $R\downarrow$ above 900 mb, the measured values once more being the greater. This could again be due to the non-opaque cirrus at high levels.

Flight of 13 September 1965.—The British Isles lay in a ridge of high pressure at the surface with a generally north-westerly gradient at upper levels. The day was dry but mainly cloudy although at times towards dusk the cloud threatened to break. The sonde rose at about 4 m/s to about 110 mb after 66 minutes and appeared to float at this level for a further 24 minutes after which it passed out of radar range near the Channel coast. It has not been recovered.

On this occasion there was 7/8–8/8 stratocumulus, and an aircraft landing at London (Heathrow) Airport gave the base and top of the cloud as 6500 feet and 8000 feet respectively. The height of the cloud top is clearly shown by the temperature at the top surface to be at 760 mb agreeing with the aircraft observation, but since the moon was clearly visible through the cloud at Easthampstead the cloud was unlikely to have been much thicker than 500 feet. This is verified further by R_n which continues to decrease as the sounding approaches cloud base. Nevertheless, in the following calculations we have assumed that the cloud base is 6500 feet as given by the aircraft.

Figure 6(*a*) compares the measured radiation streams with those calculated from the Crawley 2330 GMT ascent on the Robinson radiation chart (pecked lines with crosses). There is good agreement at all levels in the upward radiation streams and also below cloud for $R\downarrow$ but above cloud the measured value of $R\downarrow$ is consistently greater than that calculated. This must be due in part to cirrus cloud ; during the afternoon cirrus cloud could be seen faintly through gaps in the lower cloud deck. Zdunkowski *et alii*[6] give probable particle densities and transmissivities of cirrus clouds 1 kilometre thick and for the want of better observations we assume that the cirrus cloud in this example falls into their category. For a visible cirrus cloud, particle concentrations of 0·1 to 1·0 per cm^3 are quoted leading to emissivities of 0·7 over the total long-wave spectrum. Using this value for a cirrus cloud at 200 mb we have recalculated the radiation streams. There is now very much better agreement above cloud though the measured values are still somewhat higher.

Conclusions.—We have designed, constructed and test-flown a transistorized sonde which when used with a Suomi-Kuhn radiometer gives a reading of four parameters over each period of 60 seconds. The circuit is insensitive to quite large changes in battery voltage and only slightly sensitive to temperature.

Initial calibration of the radiometer and sonde disclosed a systematic difference between values of net radiation as measured by the sonde and as given by the Kew net flux radiometer. This difference was eliminated when the internal conduction term was recalculated.

Although the test flights indicated that the instrument behaved satisfactorily there is considerable uncertainty in the interpretation of results because of lack of accurate cloud observations. Furthermore direct comparison with radiation calculations based on one of the well-known radiation charts is hampered by uncertainties in the water vapour measurements at all levels.

Acknowledgements.—We are indebted to Dr P. M. Kuhn of the U.S. Weather Bureau who donated the radiometers which started this project. Also, we must acknowledge the work of Mr J. M. Nicholls who was responsible for most of the calibrations.

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NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1965

By J. PATON

Table I contains a summary of displays of noctilucent clouds that were visible over western Europe during 1965.

The approximate overhead geographical position of the clouds, determined by the method described in an article in the *Meteorological Magazine*[1] is given in the third column. On occasions when the absence of low cloud allowed observations to be made when the cloud mass was illuminated to its southern border, the latitude of the overhead position of this border is given to the nearest degree. When such observation is not possible, the elevation of the highest portion of the noctilucent clouds above the northern horizon observed in a stated latitude is given under the 'notes by observers'. The extension in longitude is given to the nearest 5°.

While the frequency of occurrence of the clouds was only slightly less than that during 1964,[2] the displays were generally much weaker. In the latter half of the season, during July, they consisted mainly of veils, usually containing some weak bands or waves.

The most striking display occurred during the early morning of 5 July. This display remained visible in the south-western sky at a station in latitude 56°20′N until 0247 Universal Time (UT), when the depression of the sun below the horizon was 5°10′, the lowest at which the clouds have been discernible. Unfortunately, prevailing low cloud on this night prevented observation at stations south of latitude 55°N.

A short-lived display observed in Denmark during the early morning of 27 June did not extend sufficiently far west to be visible in Britain. This was the only display in which 'whirls' were reported.

The clouds were first seen in 1965 10 days earlier than in 1964 and the northwards recession, usually observed to take place towards the end of July, also began rather earlier. The clouds have never been seen in central Scotland later than 3 August ; in 1965 they were last seen there on 20 July.

Weak noctilucent clouds in the form of a veil were seen at Danmarkshavn, Greenland (77°N 341°E) at 0230 UT on 21 September, reaching an elevation of 6° at azimuth 355°. Bright bands with wave structure and veil, which may have been noctilucent clouds, were reported overhead at Tingmiariut (62°N 318°E) at 2320 UT on 24 October.

Suspected noctilucent clouds in the form of a veil were observed at Stanley, Falkland Islands, South Atlantic (52°S 58°W) at 0015–0020 UT on 28 November up to an elevation above the southern horizon of 55°.

The analysis recorded in Table I has been compiled from observations made (*a*) by observers at meteorological stations in Ireland and the U.K., (*b*) by voluntary observers in the U.K. and in Denmark, and (*c*) by aircrews in civil and military aircraft. We wish to thank all who have taken part in this work, either by organizing or making the observations.

These synoptic studies will continue, and we invite the co-operation of observers who may be prepared to contribute to them. Notes on observation and photography of the clouds may be obtained from the Balfour Stewart Laboratory, The University, Drummond Street, Edinburgh 8.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1965

Date — night of	Times UT	Approximate geographical position Latitude*	Longitude	Notes by observers
30–31 May	2230–2315		5°W	Weak bands seen through gaps in low cloud in latitude 55° at elevation of 5° above northern horizon.
2–3 June	2300–0035	58°	5°E–15°W	Very faint bands showing fine wave structure.
8–9 June	2240			Weak display low on northern horizon seen in latitude 56°. No details available.
12–13 June	0050–0240	55°	15°E–20°W	Compact mass of cloud of moderate brightness, the lower portion consisting of cirrus-like streaks, while regular waves appeared in the upper portion.

* Of southern border, when measurable.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1965 — *continued*

Date—night of	Times UT	Approximate geographical position Latitude*	Longitude	Notes by observers
13–14 June	0130–0200		10°E–5°W	Weak bands to elevation 10° seen in latitude 53°.
26–27 June	2355–0050	55°	25°E–5°E	Seen in Denmark. None seen in U.K. though skies there were also clear. Began as single greenish band in the north, later spreading over whole eastern sky to south of the zenith. Colour described as 'milky to light green with touch of blue' and form 'like sheeps' wool and in other parts like bunches of rays'.
27–28 June	2300–2315		5°E–10°W	Bands seen through breaks in almost continuous low cloud to elevation 25° in latitude 56°, to 20° in latitude 55° and near the northern horizon in latitude 50°.
29–30 June	0150–0240	54°	5°W–15°W	Pale whitish-blue bands.
30 June–1 July	0245–0257	54°	5°W–15°W	Pale white bands visible overhead near dawn in Isle of Man.
4–5 July	2350–0247	<55°	15°E–20°W	Brilliant display of bands and waves with fine structure and veil background.
5–6 July	2245–0310		5°E–10°W	Veil with faint streaks seen up to elevation 32° in latitude 56°.
7–8 July	2330–0105		5°E–10°W	Faint veil with occasional fine structure observed up to elevation 70° in latitude 55°.
9–10 July	2330–0050		5°E–10°W	Faint veil along northern horizon seen in latitude 55°.
10–11 July	2105–2250		15°E–10°W	Bands seen to elevation 30° from Jutland, Denmark, at 2105 UT and later from Scotland. Obscured later by low cloud.
13–14 July	2312–2330		5°E–10°W	Veil with weak isolated filaments seen to elevation 9° in latitude 55°.
15–16 July	2245–0055		5°E–10°W	Veil with ill-defined horizontal bands seen to elevation 7° in latitude 58°.
16–17 July	2245–0250		5°E–10°W	Thin veil with patches showing weak bands seen to an elevation of 57° in latitude 55° at 0250 UT.
19–20 July	2230–2330		15°E–10°W	Small patches of diffuse horizontal bands seen first in Jutland, Denmark, and later in Scotland, at elevations between 20° and 35° in latitude 58°.
26–27 July	2300–0050		5°E–10°W	Faint patches of veil with delicate cirriform structure seen to elevation of 11° in latitude 58°.
28–29 July	Not known			Clouds seen from Lerwick, Shetland Islands. No details available.
30–31 July	2255–0040		10°E–0°	A bright but not extensive display of horizontal parallel bands seen to elevation of 10° in latitude 61°.

* Of southern border, when measurable.

REFERENCES

1. PATON, J.; Noctilucent clouds. *Met. Mag., London*, **93**, 1964, p. 161.
2. PATON, J.; Noctilucent clouds in 1964. *Met. Mag., London*, **94**, 1965, p. 180.

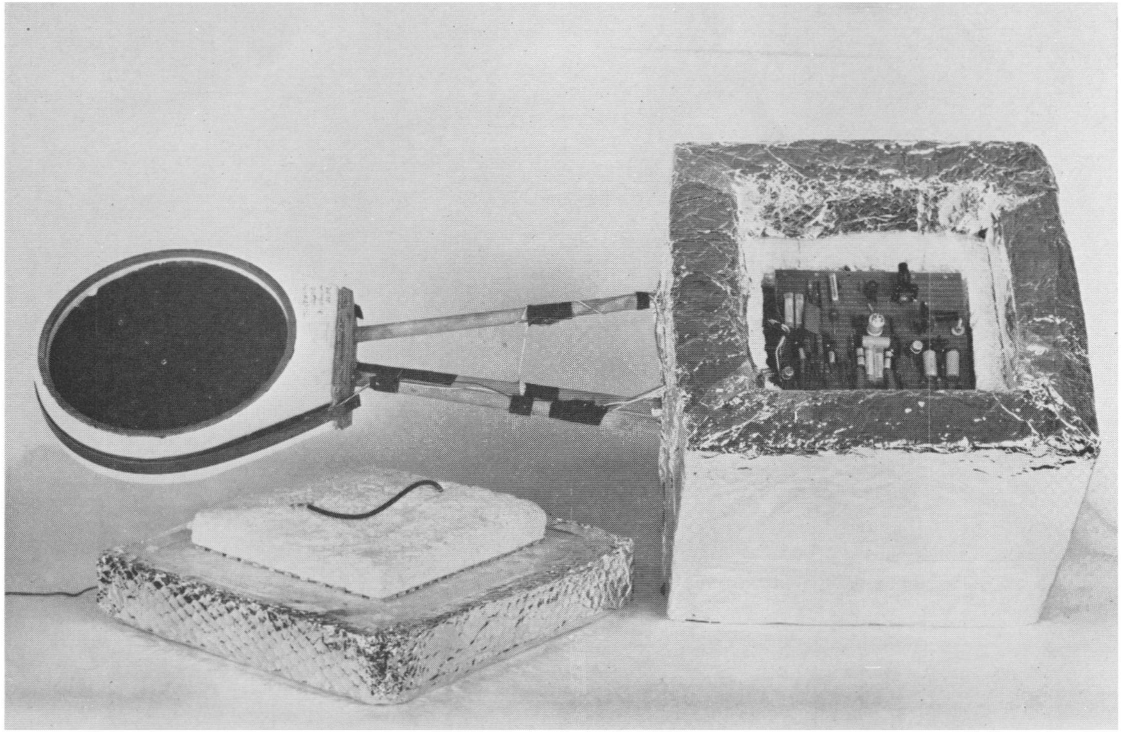


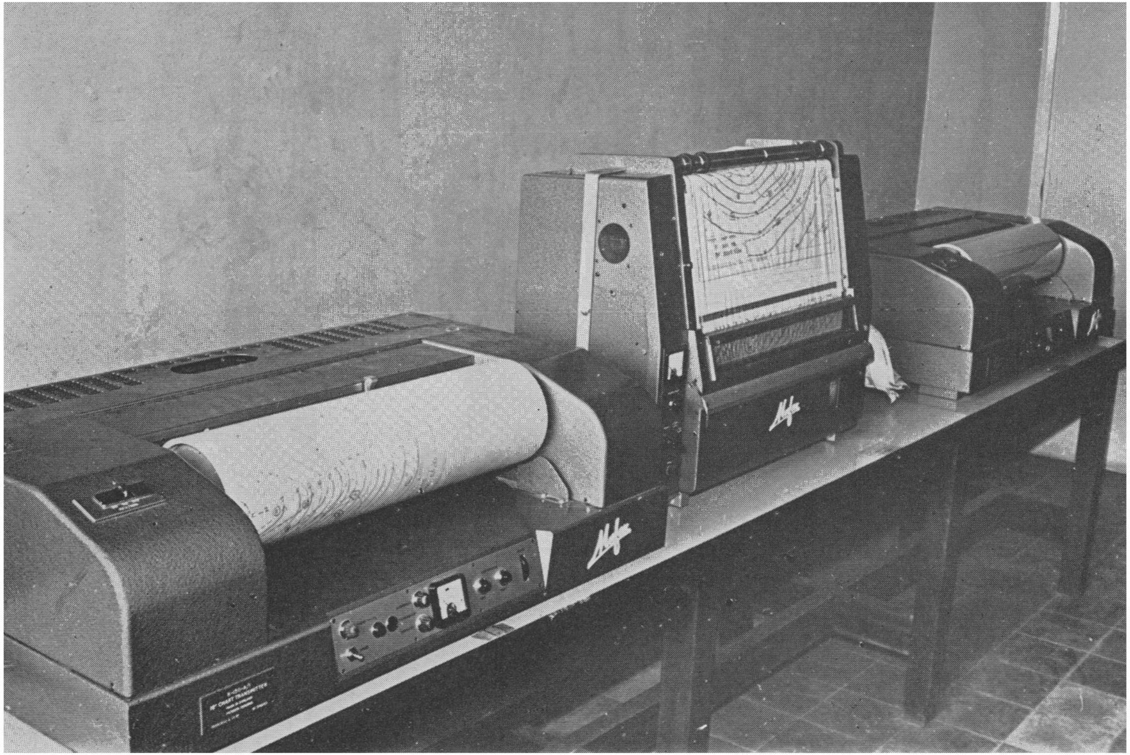
PLATE I—RADIOMETER SONDE

The close-fitting polystyrene cover has been removed exposing the electronics card. The thermistor for measuring air temperature is shown suspended between two of the wooden supports for the radiometer at the left of the picture (see page 162).

Photograph by G. J. Jefferson

PLATE II—METEOROLOGICAL FASCIMILE ROOM AT THE MAIN METEOROLOGICAL OFFICE, RAF EPISKOPI, CYPRUS

Spot wind chart of London (Heathrow) Airport origin being received.



Photograph by G. J. Jefferson

PLATE III—METEOROLOGICAL FACSIMILE ROOM AT THE MAIN METEOROLOGICAL OFFICE, RAF EPISKOPI, CYPRUS

Upper level forecast chart being transmitted and monitor copy on monitor recorder in centre.

Ta face page 177

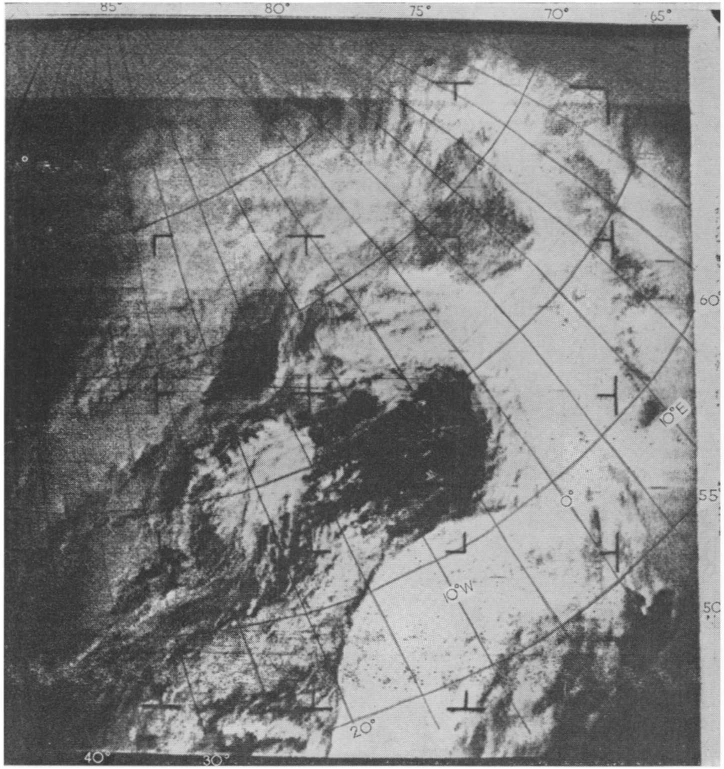


PLATE IV—SATELLITE PICTURE TAKEN AT APPROXIMATELY 1100 GMT ON 5 MARCH 1966
See page 177.

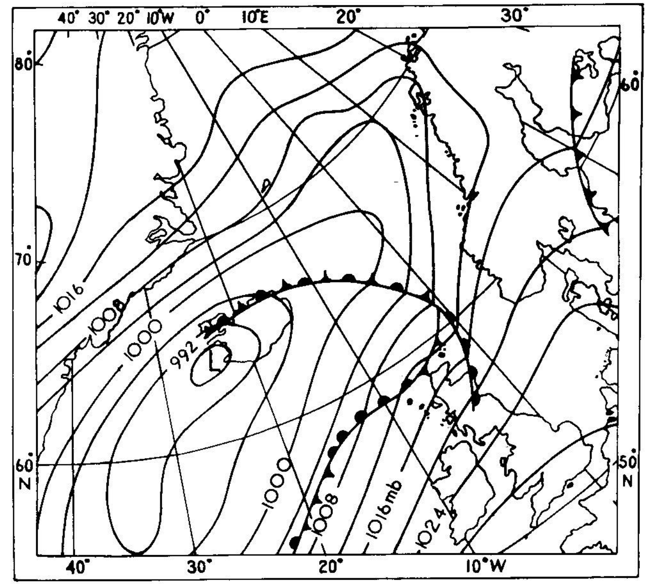


FIGURE I—SYNOPTIC CHART FOR 1200 GMT ON 5 MARCH 1966

551.507.362.2:37:778

TIROS OPERATIONAL SATELLITE

By T. H. KIRK

The first of the TIROS Operational Satellites (TOS) to incorporate the Automatic Picture Transmission (APT), ESSA II, was launched from Cape Kennedy on 28 February 1966. The satellite is in a near polar orbit of inclination 101 degrees and period 113·42 minutes. The height of perigee is 1353 km and of apogee is 1413 km and the nodal period is 28·38 degrees. The facsimile transmission is on a frequency of 137·5 megacycles/second and pictures are taken at intervals of 352 seconds with a 30 per cent overlap. Further details of the satellite programme are available in a previous article.* It is now possible for anyone with suitable ground equipment, of relatively modest cost, to acquire cloud pictures on a current basis.

An example is shown in Plate IV of a picture taken on 5 March 1966 with the equipment illustrated in the *Meteorological Magazine* of December 1964. The corresponding synoptic chart covering approximately the same area is shown in Figure 1.

In the technique of APT there are three distinct aspects ; firstly, the plotting of the satellite orbit to determine the times during which it will be possible to receive pictures ; secondly, the gridding of the pictures so that each point on a picture can be given its exact geographical location ; lastly, the interpretation of the photographs. All three of these aspects are essential parts of the work but the photographic interpretation has the greatest interest for meteorologists and requires the greatest experience for its successful practice.

In preparation for the new TOS system, the Environmental Science Services Administration of the United States Department of Commerce recently organized an APT Training Course which was held in the National Environmental Satellite Center, in Suitland, Maryland, near Washington D.C., from 6 to 10 December 1965. There were 63 participants, mostly United States Army, Air Force and Weather Bureau personnel, but also some representatives of foreign services, including the Meteorological Office.

Participants were welcomed by Mr D. S. Johnson and Mr A. W. Johnson, representing the Administration, and short introductory talks were given by Mr D. W. Holmes and Mr P. E. Lehr. Most of the instruction on orbital computation and gridding techniques was given by Mr A. Schwalb while Mr Vincent J. Oliver, Chief, Applications Group, and his staff lectured on photographic interpretation and its synoptic significance for the forecaster. Students had the advantage of hearing expert comment on some hundreds of photographs chosen to illustrate different aspects of weather and technique.

The impact of the satellite on meteorology in Europe and elsewhere outside the United States has as yet been limited because pictures on a current basis have not been available and because the nephanalyses (i.e. coded or facsimile analyses of the organization of clouds), disseminated by the U.S. Weather

* JAMES, D. G. and POTHECARY, I. J. W. ; Some aspects of satellite meteorology. *Met. Mag., London*, **94**, 1965, p. 193.

Bureau, have been received too late to be of great significance for routine forecasting. With the introduction of the APT in the current TOS programme it will be possible for forecasters to utilize cloud photographs to an ever increasing extent in their routine work and to become expert in their interpretation.

The photographs will provide not only factual information of immediate value but also increased insight into the structure of depressions and frontal systems. One can look forward to the integration of this new information into the present system of analysis and, ultimately, to the data from satellites being used as essential input data for the computer in its preparation of short- and medium-range forecasts.

551.586:631(04)

PHYSICAL LIMITATIONS TO CROP GROWTH

The 1965 Middleton Memorial Lecture was given at the Wellcome Institute on 8 December by Dr J. L. Monteith of the Physics Department, Rothamsted, who chose for his subject the above title. He started by giving a brief historical survey of the relationships between weather and crops.

The main emphasis of his talk was on the effect of weather on the size and efficiency of the photosynthetic system. When the leaves of a plant assimilate carbon dioxide from the air around them, energy for running the photosynthetic machine is supplied by quanta of visible radiation absorbed by chloroplasts in leaves. Only a fraction of this absorbed energy is stored chemically in the final products of photosynthesis. In ideal conditions, the maximum storage of energy is equivalent to about one fifth of visible radiation in the wave band from 0·4 to 0·7 μm, constituting about half the total energy in the solar spectrum at the earth's surface. In terms of total incident radiation as measured with a conventional solarimeter, the maximum possible efficiency of photosynthesis is about 8 per cent. Because this figure represents an upper limit set by the nature of the photosynthetic process, it holds for all species that synthesize carbohydrate in daylight. The amount of energy available from solar radiation is the ultimate physical factor limiting crop growth when all other restrictions are removed.

Assuming this value of 8 per cent, Dr Monteith calculated the fastest possible rates at which dry matter could be produced from three different crops (sugar beet in England, sugar cane in Hawaii and maize in California). From these he assessed the percentage efficiency of growth. The results are shown in Table I.

TABLE I—THE CONVERSION OF RADIANT ENERGY TO CARBOHYDRATE

	Sugar beet	Sugar cane	Maize
Length of growing season (months)	6	18	4
Mean solar radiation in growing season (cal/cm² day)	260	500	620
Carbohydrate production at 8 per cent energy conversion (g/m² day)	60	104	140
Relative dry matter production — per cent			
(i) maximum for experimental plot	52	41	37
(ii) seasonal mean for experimental plot	30	22	22
(iii) seasonal mean for commercial farming	15	10	7

The last three lines of Table I represent the percentage efficiency of production. Limiting factors on plant growth can be listed as :

(i) energy available for photosynthesis ;

(ii) amount of carbon dioxide available ;

(iii) leaf behaviour—in early stages, too few leaves to intercept all the incoming radiation, and in later stages inability of leaves to assimilate carbon dioxide quickly in very bright light and

(iv) factors such as lack of water or fertilizer, pests and diseases, poor husbandry, waste in harvesting due to adverse weather.

Carbon dioxide variation is therefore obviously important and long-term change is of interest. There is evidence that an increase has taken place in the last hundred or so years, from 280 parts per million (ppm) to about 314 ppm, and that unless future needs for fuel are met largely by the development of nuclear power, the growing consumption of coal, gas, and oil may increase atmospheric carbon dioxide to almost 400 ppm by the year 2000. By itself, this change might be expected to increase crop yields by 10 to 20 per cent, but it is difficult to predict whether changes in the absorption of radiation by carbon dioxide will lead to changes in the earth's climate large enough to be welcomed or deplored by farmers. At the concentration of carbon dioxide prevailing in the atmosphere, the dependence of photosynthesis on light intensity follows a law of diminishing returns. In weak light, the photosynthesis of all crop plants increases linearly with light intensity, but as the light gets stronger the efficiency of photosynthesis decreases, and in full sunlight many species behave as if they were saturated with light. However, some species such as maize, sunflower, cotton and several tropical grasses seem better adapted to many climates because their leaves are not saturated with light even at the maximum intensity of tropical sunshine.

Plant growth can normally be regarded as occurring in three phases : a juvenile phase during which the ability to produce dry matter increases rapidly as the leaves expand to intercept more and more light ; a second (mature) phase when there are enough leaves to absorb all the available light and the rate of production may stay nearly constant or even decrease slightly because the rate of synthesis by a sunlit leaf gets slower as the leaf ages ; a third (senescent) phase, with production declining rapidly as the leaves die. The rate of germination depends on temperature, with the optimum range usually between 15 and 25°C. Some growth progress is however likely down to as low as 3°C in some cases and up to as high as 33°C. In Israel where germination may be inhibited by soil that is too hot, experiments in covering the soil with magnesium carbonate in the form of a white powder to reflect radiation have been successful ; at 2 cm depth a decrease of 5–10 degC was maintained for a period of several weeks.

Leaf-area growth is complex depending upon a number of factors ; up to 25°C, higher temperature gives more rapid growth — a function of temperature rather than illumination. Growth rates can be of the order of 13 per cent per day at 20°C for sunflowers and up to 45 per cent for potatoes ; the growth rate decreases by a factor of two or three when a 10 degC temperature fall takes place. Figure 1 brings out quite well the difference in development which even 2 degC make in progress ; the ordinate in this figure is the leaf-area index, which is the ratio of leaf area (counting one surface only) to the

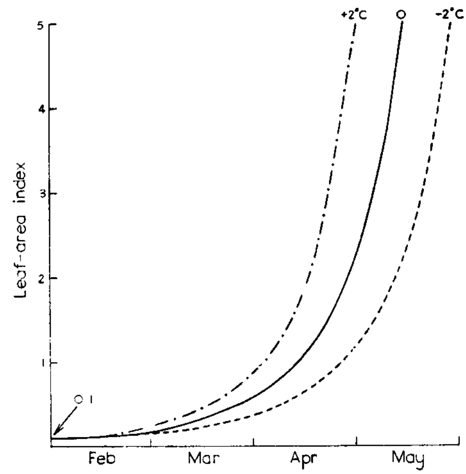


FIGURE 1—CHANGE IN RATE OF GROWTH OF LEAF-AREA INDEX IN WARM, AVERAGE AND COOL SPRINGS

—·—·— Warm spring (+2 deg C from average)
——— Average spring - - - - Cool spring (−2 deg C from average)

area of underlying ground. A decrease in relative humidity slows down the rate of leaf expansion, presumably because of greater transpiration into drier air with associated greater water stress in the leaves. Wind speed too is important; for example a laboratory experiment produced a total leaf-area growth of 330 cm^2 in an airflow of 1 m.p.h., whereas in a wind of 33 m.p.h. a seedling grew only to 20 cm^2 in the same time.

Once the leaves of a field crop have expanded to form a closed canopy intercepting all the available light, the gross rate of photosynthesis becomes independent of leaf area and is therefore independent of the physical factors governing leaf area. The rate at which plants produce dry matter then depends on the balance between carbohydrate formed by photosynthesis and destroyed by respiration. Laboratory experiments show that the rate at which leaves assimilate carbon dioxide depends mainly on their illumination and on the concentration of carbon dioxide in the surrounding air. The rate of photosynthesis is much less sensitive than leaf expansion to changes of temperature and in many species the rate is relatively constant between 10 and 30°C. It has recently been shown that photosynthesis at temperatures between 0 and 10°C can be greatly increased by treating plants with a chemical which makes leaf cells more permeable to carbon dioxide — a technique which may have important implications for cold climate agriculture.

Another factor of importance is the angle of the leaves with respect to the source of light. To intercept 95 per cent of incident light, crops like clover and kale, with relatively horizontal leaves, need a leaf area three to four times the area of the field below them, whereas cereals and grasses with leaves hanging more vertically need a leaf-area index of eight or nine.

A final factor of some importance concerns the respiration. All plant organs respire carbon dioxide while they are growing, and any increase in the rate of respiration decreases the amount of dry matter remaining at harvest.

The main physical factor governing the rate of respiration is temperature and for any plant at a given stage of development an increase of temperature by 10 degC is expected to double the respiration rate. Comparatively little is known about the respiration of whole plants as distinct from individual cells, and still less is known about respiration of crops in the field.

The above account is necessarily a very abbreviated report on Dr Monteith's lecture, which will in due course be printed in full in *Agricultural Progress.*

G. W. HURST

NOTES AND NEWS

551.583.2:061.3:551.481

African lake-level changes, world rainfall pattern anomalies and related aspects of climatic change in the 1960's

Mr H. H. Lamb spoke at a colloquium given in the lecture theatre at the Headquarters of the Meteorological Office, Bracknell, on 9 February 1966. Extracts from the lecture and the discussion which followed are given below.

Since gauge measurements were begun in 1896, the level of Lake Victoria, a sheet of water between ½°N and 3°S comparable in size with the southern North Sea, has varied by as much as a metre over a period of a few years. Many studies have been aimed at predicting these variations from their apparent, but unfortunately inconstant, relationships to the sunspot cycle. Since 1960, however, the level of the lake has risen abruptly by 2 metres and now appears to be varying about a new level. The other great lakes in East Africa have risen by a similar, or greater, amount. The damage to waterside activities and installations involves very big money values, and the construction of a new spillway at a cost of £2 million to make it possible to run off more of the water of Lake Victoria into the Nile is under consideration. The flow of the river Nile has also reached great heights in the 1960's.

Mr Lamb's investigation of this problem reveals principally that

(i) the changes since 1960 appear to represent an abrupt return to the climatic régime that prevailed for some long time before 1895 and

(ii) the related changes in the world distribution of rainfall for the years 1961–65 indicate a change in the prevailing mode of the large-scale wind circulation that has the following characteristics :

(*a*) Weaker zonal flow and increased prominence of meridional flow over extratropical latitudes in the northern and southern hemispheres, combined with changes in the locations of most frequent (surface) polar outbreaks. These effects probably indicate shorter wave-length than before in the upper westerlies.

(*b*) Intensified development of the zonal character of the equatorial trough which, however, undergoes smaller seasonal displacements north and south, and perhaps also smaller day-to-day wanderings, than formerly.

These characteristics have gone with intensified equatorial rainfall, sometimes over a quite narrow zone near the equator, whilst the sub-tropical anticyclones have been weaker and somewhat nearer the equator than formerly, at least over Africa and, from the rainfall evidence, also over other sectors.

Serious droughts have been reported in low-latitude parts of the arid zone and in well-separated parts of the temperate zones where changes in the prevailing positions of the upper cold troughs have made cyclonic rain or snow situations less frequent since 1960. Wet or snowy years have been experienced in other longitudes in the temperate zones. Corresponding changes of prevailing upper air temperatures at those stations where the series may be considered nearly homogeneous appear interesting, the greatest changes since the 1940's being (i) falls of temperature over middle and higher latitudes — though greatest near the tropic — and (ii) rises of upper air temperature in and near the equatorial rain belt.

Surface temperatures in regions affected by more frequent polar outbreaks, including Britain, also register sharp changes in the 1960's.

With so many significant changes of climatic figures in different parts of the world, meteorology is being confronted with inquiries from industry and from government agencies that amount to a demand for climate forecasting, for which no adequate scientific basis exists as yet. This demand places upon us a responsibility to extend and deepen our knowledge of the facts of climatic behaviour in the past and of the processes that appear to be involved. Among the latter must now be included indications of very slight long-term changes in the energy of the solar beam ; and in order that these may be investigated further it may be necessary to encourage quicker and more regular production of data on solar faculae from the fine series of daily heliophotographs maintained by the Royal Greenwich Observatory since 1874 and continued at the present date.

In the discussion, Mr Bushby asked to what extent the changed level of Lake Victoria could be attributed to a single disastrously heavy rainfall season in the second half of 1961 combined with the effect of the Owen Falls Dam in limiting outflow. Mr Lamb agreed that that rainy season was extreme, but there had been other very heavy rains since, especially in early 1964 and late 1965, and from 1961 to date rainfall over the catchment area averaged 25 per cent above the previous 30-year mean. Dr Forsdyke described the nature of the outlet from Lake Victoria as a steep-sided channel with a considerable fall ; water was expected to overflow the dam in high-water periods and was thought to have done so. The Nile floods at Cairo must be largely a separate matter : most of the water in the flood months around September comes from the Blue Nile which is fed by the summer monsoon rains over the mountains of Ethiopia. Also about 90 per cent of the water entering Lake Victoria is lost in evaporation and only the remainder goes down the Nile. Dr Forsdyke thought that a more reliable measure of changes of the régime in the upper air is given by the observed upper winds over the temperate zones than by the observed temperature. Mr Lamb commented that the central European mountain-top observatories provided a record of such changes since 1880–1900, but one must recognize in them changes of prevailing upper wind direction, associated with shifts of the troughs and ridges in the upper westerlies, as well as changes of prevailing wind speed. Mr Craddock made a plea for filter analysis to be applied to the African lake-level data to sort out the time-scale of fluctuations.

Miss Timpson believed that when the Owen Falls Dam was built around 1950 it was expected to raise the water-level in Lake Victoria. Mr Lamb replied that it did not in fact rise materially until 1961, and this was undoubtedly due to the rainfall increasing : Mörth had found a correlation coefficient of +0·96 between rainfall over the preceding 12 months over the catchment area and the level of the lake, from the data for 1938 to 1964, years which straddled the building of the dam and the major change of rainfall in 1961. Miss Timpson also remarked that most of the rain in East Africa was thought to come from upper westerly winds. There was no specific information on this since 1961 (Mr Lamb replied) except in so far as local East African evidence was reported to indicate an intensified development of the equatorial trough zone, apparently with the same structure as previously supposed, though possibly over a slightly narrowed range of latitudes. Commenting on a question by Mr Bushby about the economic implications, Mr Lumb who had lately returned from Nairobi told of jetties and railway sidings submerged in Lake Victoria and a considerable loss of land around the flat shores. Professor Sutcliffe took up the question of the economic importance of climatic changes and remarked that there was enough serious investigation and research required to warrant a special institute. There was more to the understanding of this problem than the extrapolation of trends or cycles. It seemed as if the climate was also subject to step-like abrupt changes, which were fortunately rare but changed the climatic prospects and should not (or should not necessarily) be regarded as part of a trend. Was this change since 1960 such a step or had we merely experienced a few anomalous years? The reply was that the various anomalies of the years since 1961 discussed by Mr Lamb appeared statistically significant, and no such run of years had occurred this century ; it looked like one of the four or five biggest steps in the climatic record in the last 250 years.

The paper on which this colloquium was based is to be published in full in the *Geographical Journal* (June 1966).

H. H. LAMB

Address by Professor P. M. S. Blackett, P.R.S.

On 15 March 1966, Professor P. M. S. Blackett, P.R.S. visited Bracknell at the invitation of Dr B. J. Mason, Director-General, to address the staff of the Meteorological Office on the subject of continental drift and the climates of past geological epochs. The address was given in the excellent theatre of the S. E. Berkshire College of Further Education at Bracknell, thanks to the kindness of the Principal, Mr H. B. Toft, and members of the college were able to attend.

Professor Blackett opened with a review of the history of the drifting continents hypothesis before study of rock magnetism began, a study which has added vital new evidence in the last decade or two. As early as 1620 Francis Bacon noticed the correspondence in shape between South America and South Africa and speculated that they might once have been together : this observation was made quite soon after these two continents had been reliably outlined on maps for the first time. In 1858 Snider pursued the idea further with an imaginative map showing the two continents brought together, with some distortion, lapping Tierra del Fuego round the Cape of Good Hope. About 1910 Wegener, Du Toit and Taylor, working separately, demonstrated a number of corresponding tectonic features and palaeoclimatic evidence in the two continents. They directed particular attention to striated rocks and other evidence of a major glaciation in the Permo-Carboniferous epoch on both sides of the South Atlantic and as far away as India and Australia also. The ice flow was from south in India and Australia, from north-east in South Africa and apparently from some easterly direction in South America—all in terms of modern orientation. These directions of ice flow convey unmistakable impressions of how the land masses should fit together and where the centre of the ice-cap was. This great glaciation of 250 million years ago baffled explanation in terms of the older geology that denied continental drift. Holmes pointed out that there was not enough water in the world to make an ice-cap, of the thickness indicated by the eroding effects, covering all this vast area. This led directly to the suggested explanation in terms of a single great Urkontinent, 'Gondwanaland', in which all the land masses concerned were together around the South Pole.

The study of rock magnetism developed independently. It had been known since the beginning of this century that when Mt Etna lava cools, magnetism is induced in the iron oxide compounds (ferrites) in it in line with the earth's magnetic field. The iron compounds in sedimentary rocks are also magnetized in line with the earth's field at the time of deposition. Study of the weak remanent magnetism in the rocks today may therefore be taken as a fossil compass indicating the direction of the earth's field at the time of deposition. No difficulty is encountered in measurements on rocks less than one million years old, but 50 per cent of the measurements on older rocks are just 180° out. The earth's magnetic field appears from this to have reversed many times in the course of geological time — to have 'flicked over' at intervals of about a million years. This is difficult to explain, but because it appears as a precise reversal it is no hindrance to measurements of the former latitude at the time when the rocks formed : these depend on the fact that in a dipole field the tangent of the angle of dip is twice the tangent of the latitude. Moreover this angle of dip makes clear which hemisphere the place was in, regardless of the polarity at the time.

Triassic rocks in Britain (about 200 million years old) — e.g. the red sandstones much used in architecture — are magnetized with a shallow dip corresponding to latitude 20°N. In Cheshire, as in Germany, salt deposits 100 feet or so thick underlie this sandstone. Salt deposits are produced by evaporation in shallow seas in low latitudes — e.g. today only in a zone that extends about as far from the equator as the Caspian and the Dead Sea. Deeper in the rock structure of Europe lie the coal beds, formed apparently from tropical forest trees without annual growth rings, i.e. evidence that here, as in North America, the Carboniferous climate (of 250–300 million years ago) was producing the vegetation of the equatorial rain forest. The magnetism of the Carboniferous rocks in these areas shows no dip, in conformity with an equatorial origin. It appears that Europe has drifted from a position near 20°S around 450 million years ago more or less steadily northwards to its present position.

By contrast, the lands with evidence of Permo-Carboniferous glaciation have, to judge by the magnetic data, drifted more rapidly and not always linearly. India appears to have moved fastest, points now at 20°N having been at 50°S only 130 million years ago and possibly south of the Antarctic circle in the Permian. Rock magnetism in the Alice Springs area of central Australia, now at 20°S, shows a more complicated course from around 10°N 500 million years ago, crossing the equator at 330 million years, proceeding to 70°S about 160 million years ago and returning from there — a course consistent with the much earlier suggestion, made from a geologist's study of the rocks, of rapid refrigeration between 300 and 200 million years ago.

The most striking result of all may be the way in which all this evidence points to permanency of the zoning of climate by latitude. This has sometimes been disputed by geologists in the past ; but it now appears unnecessary to propose (as some classical geology did) the occurrence of epochs when the whole earth was hot or cold, wet or dry, and without any semblance of climatic zones. It also appears that the earth has always behaved as a magnetic dipole, and that the strength of the earth's magnetic field has not changed by more than a factor of two over hundreds of millions of years. Wandering of the poles (i.e. of the earth's rotation axis) is not sufficient to explain the rock magnetism palaeo-latitude data because of the evidence of relative motions of the different land masses and of some slewing of them. From rocks over 50–100 million years old the pole positions indicated from Europe, America, Australia and India are all different.

Coral is another good indicator of climate, since most corals will only grow in the warm seas within 20° of latitude from the equator. The corals of 250 million years ago are not related to the present equator but along a band from U.S.A. to Greenland, the British Isles and northern Europe, central Asia and Australia. Thus one can derive and plot latitudes of the geological past from (*a*) magnetic dip, (*b*) salt deposits, (*c*) corals and (*d*) coal beds. A plot of the palaeomagnetic latitude, the 'salt latitude' and the 'coral latitude' of Paris through the last 700 million years showed good general agreement.

Returning to the evidence from continental shape, Professor Blackett described the result of Sir Edward Bullard's statistical study of best fit between the edges of the continental shelves of South America and South Africa. This had produced a mean error of under 50 miles along 4000 miles of coast.

Finally, Professor Blackett considered what theories and evidence were available as to the causation of continental drift and the forces at work. Study of the distribution of epicentres of earthquakes revealed the systematic pattern of volcanically active mid-ocean ridges, notably that running through the Atlantic from Iceland to Tristan de Cunha and round into the Indian Ocean and Red Sea. These were zones of ever-opening fissures and abnormal heat flux from the earth's interior. Iceland was crossed by innumerable parallel fissures and its eastern and western parts were calculated to be drifting asunder at a rate of 1 to 5 cm a year. Other straight fault lines, such as Scotland's Great Glen and the San Andreas Fault in California, could be similarly understood though there lateral shear was also active. Earthquakes occurred when tension was suddenly released by failure of the elasticity of the rocks to hold the relative motion that was slowly going on on either side of the fault. The theory that seemed most acceptable, illustrated by a diagram model proposed by Holmes, was that there were slow convection currents in the earth's mantle due to heat generated either by radioactivity or by chemical changes — e.g. from one silicate to another. The concept of viscous state of the mantle was supported by isostatic movements — e.g. Scandinavia's slow rebound, as yet little more than half completed, from its depression by ice-load in the Würm ice-age. According to the model the continents float like islands on the mantle and drift apart as the rising convection currents in the mantle diverge. Such convection cells appear to have a characteristic life span of the order of 250 million years and are followed by the development of new cells.

G. A. BULL

H. H. LAMB

Burma Meteorological Department

Dr Po E, Director-General of the Burma Meteorological Department, retired on 3 March 1966 and has been succeeded by Dr Tun Yin.

Meteorological Service of Portugal

Dr Antonio Silva de Sousa has succeeded Professor H. Amorim Ferreira as Director of the National Meteorological Service of Portugal.

Meteorological Service of Uruguay

Capitan de Navio Carlos F. Castro Pelaez has succeeded Capitan de Navio don Eduardo A. Laffitte as Director-General of the Meteorological Service of Uruguay.

REVIEWS

The climate of Africa, by B. W. Thompson. 20 in × 18 in, pp. 132, *illus.*, Oxford University Press, Amen House, London, EC4, 1965. Price: £9 8*s*.

This is the second of two substantial climatic atlases of Africa published in the last five years. The other is of course the 'Climatological Atlas of Africa'* (CAA), published by the Commission for Technical Co-operation in Africa South of the Sahara, and produced in collaboration with the World Meteorological Organization (WMO) African Regional Association. It may claim to be regarded as the model for a set of atlases, which, under WMO sponsorship, would ultimately cover all land areas of the world. One's first reaction, naturally, is to ask 'Why a second atlas?' This question is not specifically answered in the new atlas, but it is stated (in the Introduction) that the purpose of the work is to present maps which describe and assist in explaining the main elements of the climate of Africa, and (in the Preface) to assist in the training of the new generation of African meteorological personnel. In the reviewer's opinion, and in the light of these objectives the production of the new atlas is worth while, because firstly, it was wider in scope than the CAA, and secondly, it was printed entirely in black and white so that the meteorological services of the developing African countries could afford to distribute it more widely than the beautifully produced but presumably costly CAA.

* Lagos, Commission for Technical Co-operation in Africa South of the Sahara. Climatological Atlas of Africa. Lagos, 1961.

The atlas contains 132 charts; 75 of them on the scale 1:22M depict solar radiation, sunshine duration, rainfall, temperature and humidity for the African mainland and the Malagasy Republic. The remaining charts depict winds, contours, temperature and humidity at the standard upper levels from 850 to 200 millibars ; in order to show Africa in relation to somewhat wider aspects of the general circulation these maps are on the scale 1:30M and extend over a large part of Europe, southern Asia and the Indian Ocean.

Apart from the shading of land over 1000 metres on all except the charts of rainfall amount, no physical features are shown. Missing are the great lakes and rivers which are so helpful for spotting locations on the map of Africa. There is no latitude and longitude grid, except for a single line representing the equator ; the labelled marks at 5-degree intervals in the frame of each map are hardly adequate for precise location. But it should be said that to include these aids to location would have caused confusion, certainly on the more complicated maps.

Surprisingly, the only charts of surface elements for which the CAA and the new atlas have identical specifications are those of rainfall amounts, one chart of annual rainfall and one for each of the 12 months. Only some of the isopleths are common to both works, and it is good to note that with one or two minor and local exceptions the two atlases agree, even in detail so far as can be judged from sets of charts on different scales — greatly different scales for the annual charts.

The climatic factor of greatest economic importance to many parts of Africa is rainfall, and it is therefore appropriate that the charts of rainfall amount should be supplemented by others. These include monthly and annual charts showing the mean number of days for which the rainfall exceeds 1 mm. There is also a new set of charts showing the first month of the year and the numbers of subsequent consecutive months for which the rainfall exceeds certain specified amounts. These are particularly germane to the need for adequate rainfall at the time of planting of crops and during their subsequent period of growth. From the purely climatological aspect the charts clearly depict the seasonal distribution of rainfall. One would like to see, however, some information on rainfall variability.

Temperature is shown by isopleths of average maximum, average minimum, and mean daily temperatures for the four months January, April, July and October. Values are for station level and thus give a true comparison between the coastal and plateau areas. Charts for the same months show actual values of relative humidity near sunrise and midday. As with rainfall, these temperature and humidity charts give only broad pictures ; their small scale and complications of pattern prohibit the giving of detailed information, or the use of interpolation, in rugged country, but these are not the object of the work.

Monthly and annual charts of total radiation and bright sunshine are features which do not appear in the CAA. For these the author is to be commended. The radiation charts in particular are perforce based on scanty data, but give a useful first picture which doubtless could be reconsidered when more data become available.

The upper air charts mentioned earlier in this review are mean charts for the months of January, April, July and October. An indication of the heterogeneous nature of the data and perhaps also of some degree of subjectivity in interpretation is provided by comparison with the corresponding charts of the CAA. This is possible only for the contour charts for 850, 700 and 500 mb; the CAA has no charts for higher levels. At first sight, except outside the tropics, there are big differences between the contour patterns of the two atlases. Closer scrutiny however shows that where there are spot height differences they do not as a rule exceed 10 metres. The pattern differences, which arise mainly from showing a col in place of a closed system with a single contour, are therefore more apparent than real, especially considering that in low latitudes the contours are not closely related to the streamlines.

The 14-page Introduction is a clearly written description of the charts with a critical appraisal of the methods used in their preparation. It also contains a useful summary of the synoptic features of the tropics including the model contour patterns introduced into East African forecasting practice in the late 1950's by Johnson and Mörth.

The production of this atlas was made possible by the generosity of the Munitalp Foundation which bore the entire cost.

A. G. FORSDYKE

Computing methods by I. S. Berezin and N. P. Zhidkov. Vol. 1 and Vol. 2 (separate) 9¼ in × 6½ in, pp. xxxiv + 464 in Vol. 1 and pp. xv + 679 in Vol. 2, *illus.*, (translated from the Russian by O. M. Blunn). Pergamon Press, Headington Hill Hall, Oxford, 1965. Price : £10 (for both).

Computing is not new in meteorology. Almost fifty years ago, in 1916, The Computer's Handbook appeared as an official Meteorological Office publication and ran into a second edition in 1921. While much of it was rather bread-and-butter stuff, such as computing barometric corrections, there was a lengthy chapter on computations associated with probability theory, backed up by practical meteorological examples. About the same time methods were being developed for correcting the trajectories of shells for the variations of the ambient meteorological conditions from standard values, involving the numerical solution of sets of ordinary differential equations, and not long afterwards computations were carried out in connexion with the partial differential equations of turbulence. Desk machines were used in all these computations. When electronic computers became available about fifteen years ago, the Meteorological Office was among the first users ; the volume and variety of computation now carried out are sufficient to warrant a computing laboratory based on the powerful KDF9 electronic computer. Meteorological problems require a great deal of computing skill, especially as many of them must necessarily be solved in a short time. Any new book on computing methods or techniques is therefore welcome.

The advent of electronic computers has inspired a lot of research into numerical analysis, multiplied the number of journals concerned with this particular aspect of mathematics and led to the publication of a great number of textbooks, all of them excellent in one way or another. As new methods became available textbooks which aimed at being comprehensive became rather large and lately the tendency has been to write monographs on particular aspects of numerical analysis, so that there is a fairly complete coverage in the English language and a foreign text must have some particular appeal to make its translation worthwhile. In this case the translation is welcome because it gives an overall picture of computing methods in Russia.

There are two large volumes of the book by Berezin and Zhidkov, which aims at being comprehensive while realizing that it is not possible to include all worthwhile methods of attacking a problem ; it is based on a course of lectures given in Moscow State University, for specialists in computer mathematics, and is intended to cover a great deal of ground in a way that suggests methods of solving problems, rather than presenting algorithms for immediate use.

The date of original publication of the book is not given ; it is important since developments in some parts of numerical analysis have been rapid. From the contents the book was probably completed about 1960, so that some recent developments are not included as is inevitable in any publication like this.

The first volume is concerned with the problem of interpolation and the related problems of numerical differentiation and integration. It starts with an excellent chapter on how errors due to various causes can affect simple calculations. Then follows a long chapter, basic to this volume, on interpolation, which is marked by its clarity of exposition and illustrated by numerical examples. All the common interpolation polynomial formulae are dealt with — Lagrange, Newton, Gauss, Stirling, Bessel, Everett and Hermite — as well as interpolation theory for periodic functions and for more than one independent variable. This is rather a formidable chapter, as are the fifty or so problems at the end. One of the difficulties of reading texts on numerical analysis is the variation in notation adopted by different writers ; the notation used here is self-consistent but may look a little unfamiliar to some of us.

The next chapter deals with numerical differentiation and integration and is based on the interpolation formulae that have been obtained. Many integration formulae are given, the corresponding weight coefficients are given explicitly and there is also a section on how to deal with improper integrals and estimation of multiple integrals. The volume ends with two chapters on the approximation of a function by some more easily computed function and fitting by least squares.

The second volume is concerned with problems that perhaps are more familiar to meteorologists, the numerical solution of matrix problems and of differential equations. There is also a very useful chapter on solving non-linear equations. Since some of the classical methods of attacking matrix problems and of integrating differential equations are necessarily included in the text many of the familiar names, such as Runge-Kutta, Gauss-Seidel, etc., are to be found. When the developments are more recent the differences between this text and those which are written in English become more marked. Matrix methods associated with the names of Givens, Householder and Francis are not mentioned and do not appear to be given under any other name ; alternating direction implicit methods do not appear. On the other hand material developed by Russian mathematicians, which is not readily available in English texts as far as I know, is given in detail. Like the first volume the text is carefully written and well illustrated by numerical examples both worked out and for solution.

These two large volumes will serve as a reference book and must surely be in the library of any computing unit. There are advantages in having a unified text rather than monographs, especially as regards notation and lack of repetition. Perhaps the volumes will be of more use to the professional computer user than to the occasional user, who now finds that the method employed for the solution of his problem is dictated more by the variety of library programmes available on the particular computer that he uses than by its suitability.

The books are beautifully produced and great care must have gone into the translation.

E. KNIGHTING

Chasseurs de typhons by Pierre André Molène. $8\frac{1}{4}$ in × 6 in, pp. 316, *illus.*, Flammarion, éditeur, 26 Rue Racine, Paris, 6e, 1964. Price : 14F.

To M. Molène, as perhaps to any readers of this magazine, a typhoon or hurricane was just something one read of in the newspaper, a severe storm in distance places, a curious tropical phenomenon. But on his travels as an Air France navigator he found that to the inhabitants of those considerable parts of the world where typhoons pass they are terribly real, a recurrent threat of appalling disaster. So he set out to learn all he could about them and their effect on human life. His book, which is the result of his studies, tries to convey to others a vivid impression of what he found.

He saw and talked to meteorologists and others in Japan and visited the various American weather centres in the Pacific responsible for typhoon warnings. Later he was permitted to fly from Guam on weather reconnaissance flights with both the Typhoon Chasers of the USAF who penetrate typhoons in their Super-fortresses, and the U.S. Navy Typhoon Trackers with their massively-equipped radar-watch aircraft. As an experienced navigator he was well able to appreciate the task these men have and the success they achieve. Finally, he read all the books he could on the subject.

His book is, rightly, a popularization, not a scientific treatise. It is journalistic in style, and loaded, overloaded perhaps, with forceful statements and emotive adjectives. The accounts of his flights into and around typhoons are technically of interest, and to the layman they must be truly astonishing. As to typhoons in history, the origin of the emotive, to the Japanese, name 'Kamikaze' — 'Heavenly Wind' — was a typhoon that destroyed an invading Mongol fleet sent by Kubla Khan in A.D. 1281. Many other historically significant tropical cyclones are also described from the time of the Discoveries to World War II. However, M. Molène goes rather too far afield in his search for typhoon history, by including some winds that are not remotely appropriate. He mentions other effects of typhoons also, such as islands which, when short of rainwater, bless the storm that passes near, but not too near, and harmlessly refills the water tanks.

For one who has never experienced more than a severe gale the most potent illustration is perhaps the square-law relationship between the pressure exerted by the wind and its speed, and the account of the physical effects of winds of 150 to 200 knots. The rain and the wind-driven tides do almost as much damage. In our temperate climate, however restless, we may be thankful for that qualifying adjective. By 'moderation in all things', we miss not only the best but also the worst.

D. G. HARLEY

OFFICIAL PUBLICATIONS

The following publications have recently been issued :

Ice accretion on aircraft. Meteorological Reports No. 9, 2nd edition. London, HMSO, 1965. Price 4*s*.

This is a revised edition of the publication of the same title which first appeared in 1951. It takes much the same form as the earlier edition but has been brought up to date, particularly with respect to some further investigational data which are included.

Modern aircraft design, equipment and operational techniques have much reduced the hazards of icing, but the subject still retains considerable importance. The publication can be easily read and understood by the informed layman and should be of interest and value to all airmen.

SCIENTIFIC PAPER

No. 22—*The solution of atmospheric diffusion equations by electrical analogue methods*, by J. B. Tyldesley, B.A.

A method of solving the two-dimensional diffusion equation by means of a resistance-capacity network is described, and an application to a continuously emitting cross-wind line source is given. This introduction to the basic analogue of diffusion is followed by a description of a more comprehensive computing method using a general-purpose analogue computer.

Methods of obtaining solutions for the continuous line source, continuous point source, and instantaneous line source are given, and some preliminary results are shown. A proposed extension of the method to deal with the instantaneous point source (cluster) is outlined. The variation with height of the parameters is not restricted to simple analytical forms.

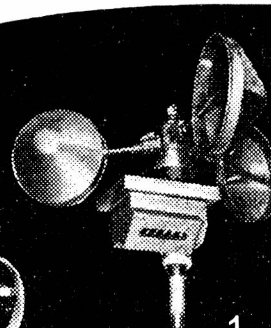
Daily Aerological Cross-sections at Latitude 30°*N during the International Geophysical Year Period.* London, HMSO, 1966. Price 55*s*.

These daily vertical cross-sections round the earth at latitude 30°N and from sea- or ground-level to 10 millibars (about 30 kilometres) show isotachs of south-to-north wind component, numerical values of west-to-east wind component and isopleths of temperature, potential temperature and humidity mixing ratio. The level of the tropopause is also indicated. The daily charts are followed by a mean chart for the month showing the same parameters. To facilitate their use the charts are printed in three colours.

This volume, for the month of March 1958, is the first of a series of four and June, September and December will make up the other three volumes.

CORRIGENDUM

Meteorological Magazine, March 1966, Plates III and IV should be interchanged.



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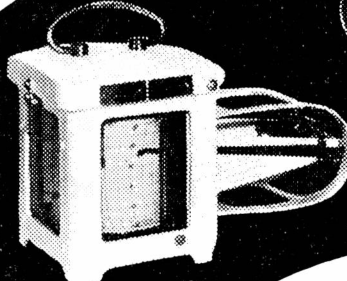

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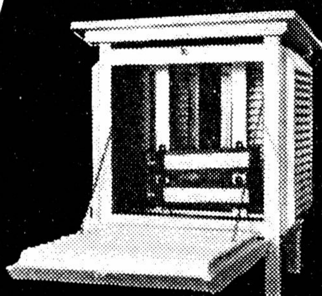

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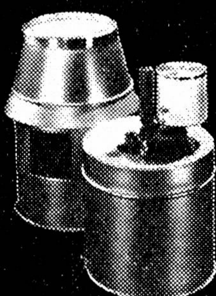

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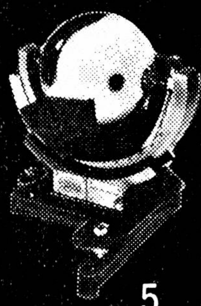

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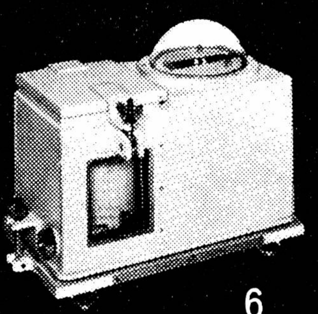

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