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# THE METEOROLOGICAL MAGAZINE

Vol. 100, No. 1184, March 1971

## RETIREMENT OF DR R. FRITH, O.B.E.

Dr R. Frith retired from the Meteorological Office on 31 December 1970 after more than 34 years' service. Joining the Office in 1936, Dr Frith was for ten years engaged either in forecasting duties or in the organization of forecasting services to the Royal Air Force.

In 1946 Dr Frith was appointed as Senior Meteorological Officer of the Meteorological Research Flight and under his direction the flight carried out a number of important investigations. The dryness of the stratosphere was established and the small-scale variability of the temperature and humidity throughout the troposphere extensively studied. Under Dr Frith's guidance the Meteorological Research Flight also demonstrated that clearly observed effects could be produced by seeding stratocumulus cloud.

Dr Frith was appointed an Officer of the Order of the British Empire in the 1951 Birthday Honours List. In the same year he took charge of the instrument development branch and later occupied various other directing posts on the research side of the Office. In 1960 he was appointed Assistant Director in charge of the newly formed branch for High Atmosphere Research. Under his direction a small but very active team established themselves rapidly as one of the effective groups undertaking experiments from outer space. Successful experiments to measure ozone and molecular oxygen were flown on the British satellites ARIEL 2 and ARIEL 3. Several complementary experiments were also conducted on large rockets fired from Woomera, Kiruna and other ranges. A Meteorological Office programme for exploring the mesosphere and upper stratosphere was also developed using the specially developed SKUA rocket and Dr Frith and his team demonstrated the remarkable variability of the high atmosphere over the British Isles in winter.

In 1968 Dr Frith was promoted to the post of Deputy Director (Physical Research) and assumed responsibility for the experimental and observational research of the Office, applying to this task his remarkable ability to pick out the essential aims of an experiment and to ensure that the true objectives are achieved.

Dr Frith has been an active member of a number of national and international committees concerned with physical meteorology. In particular he has been a much valued member of Working Group VI of COSPAR (Committee for Space Research) which has been largely responsible for demonstrating how the requirement for world-wide observations for a Global Atmospheric Research Programme (GARP) can be formulated in a manner which is practicable by satellite techniques.

Dr Frith's colleagues in the Meteorological Office wish him health and happiness in his retirement.

J. S. SAWYER

551·515·53:551·577·31

# DIURNAL INCIDENCE OF RAIN AND THUNDER AT ASMARA AND ADDIS ABABA, ETHIOPIA

By D. E. PEDGLEY
Anti-Locust Research Centre, London

**Summary.** Diurnal variations of rainfall and thunder have been tabulated for Asmara and Addis Ababa on a monthly basis for the five-year period 1958–62. In the absence of autographic data, conventional data on the occurrences of rain and thunder were used for the eight three-hourly periods of each day. Contemporaneous afternoon peaks in incidence of rain and thunder at both places indicate the dominance of day-time convection on the development of precipitation. Persistence of essentially non-thundery rains after midnight at Addis Ababa suggests the presence of a diurnally varying mechanism of mass ascent over the Ethiopian plateau. A broad-scale anabatic circulation with a period comparable to one day is a possible mechanism, evidence for which has already been suggested by the diurnal rainfall régime over the Nile valley in neighbouring Sudan.

**Introduction.** In a previous paper,[1] concerned with the diurnal incidence of monsoon rainfall over the Sudan, evidence was given to indicate that a large-scale circulation, set up each day over the Ethiopian plateau, was able to inhibit afternoon convection over the Nile plains of the Sudan. If such a circulation exists there should be a corresponding promotion of rainfall over the plateau. Some evidence is presented in this note, based on an examination of the diurnal incidence of rain and thunder over the plateau, which supports the existence of a broad-scale circulation of an anabatic type.

Whereas the Sudan study was based on records from autographic gauges, such records are not available from Ethiopia over a period sufficiently long for analysis. As an alternative, station registers of observations were consulted, and occasions of rain were noted in each of eight three-hourly periods daily during the five years 1958–62. For convenience, the eight periods have been named as in the previous paper. For example, using local times, 12–15 h has been called 'early afternoon', and 15–18 h 'late afternoon'. Rain is considered to have fallen during the early afternoon, for example, if it was recorded either at 15 h or at some time during the previous three hours, but not at 12 h. During the years 1958–62 only two stations in Ethiopia kept a continuous 24-hour watch — the international airports at Asmara (15° 17′N 38° 55′E, altitude 2325 m) and Addis Ababa (09° 00′N 38° 44′E, altitude 2324 m). See Figure 1 for their locations. Whereas during the day-time observations were hourly, at night-time they were three-hourly, so it is possible that some light night-time falls were missed. Occasions of thunder were noted similarly.

Table I lists, for each three-hour period, the number of periods during which rain fell; similarly, periods with thunder are listed in Table II.

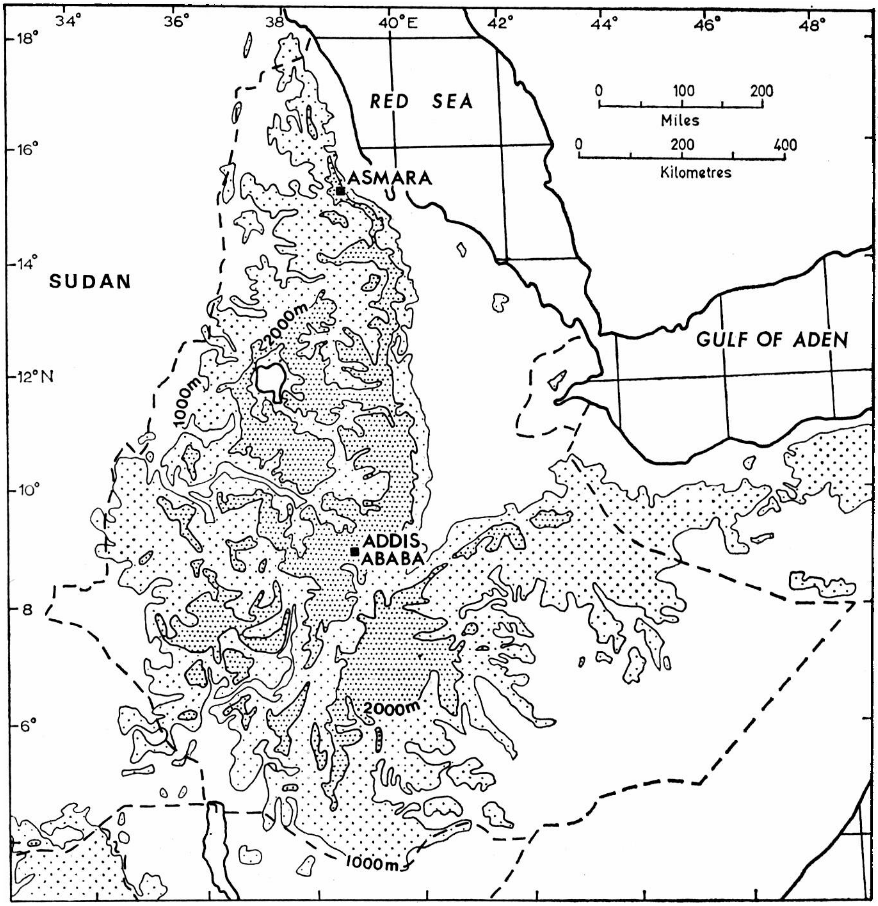


FIGURE 1—MAP SHOWING LOCATION OF ASMARA AND ADDIS ABABA ON THE PLATEAU OF ETHIOPIA

**Rain at Asmara.** In most years there are two rainy seasons at Asmara[2] — the 'little rains', approximately March to mid-May, and the 'long rains', approximately mid-June to mid-September. The period mid-September to February is essentially rainless, but in some years significant rains fall in late October and November. Between the two rainy seasons there is usually a short dry spell, but its timing varies from year to year. For convenience, the year has been divided into : March–May, 'little rains'; June–September, 'long rains'; October–November, 'late rains'; and December–February, 'dry season'.

Table I shows that the little rains have a sharp frequency maximum in the early and late afternoon; falls can be expected on average about 2–4 days per month during each of these two three-hourly periods. Falls decrease rapidly in frequency during the evening, and very seldom occur during the night or morning. In March, falls are almost entirely confined to the afternoon.

TABLE I—NUMBER OF OCCASIONS WHEN RAIN FELL IN EACH OF THE EIGHT THREE-HOURLY PERIODS DURING THE YEARS 1958–62 AT ASMARA AND ADDIS ABABA

| Local time | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *(a)* ASMARA | | | | | | |
| 00–03 | 0 | 1 | 1 | 4 | 4 | 0 | 12 | 9 | 2 | 0 | 5 | 0 |
| 03–06 | 0 | 1 | 0 | 0 | 2 | 0 | 9 | 8 | 3 | 0 | 0 | 0 |
| 06–09 | 1 | 2 | 0 | 1 | 2 | 0 | 12 | 22 | 3 | 0 | 0 | 0 |
| 09–12 | 2 | 1 | 0 | 1 | 6 | 3 | 13 | 23 | 4 | 1 | 0 | 0 |
| 12–15 | 2 | 5 | 12 | 21 | 15 | 18 | 65 | 54 | 16 | 6 | 18 | 2 |
| 15–18 | 4 | 7 | 12 | 22 | 19 | 15 | 84 | 58 | 15 | 9 | 22 | 7 |
| 18–21 | 3 | 3 | 1 | 12 | 9 | 6 | 32 | 23 | 2 | 1 | 5 | 1 |
| 21–00 | 2 | 3 | 1 | 9 | 4 | 2 | 15 | 10 | 1 | 0 | 4 | 1 |
| | | | | | | *(b)* ADDIS ABABA | | | | | | |
| 00–03 | 8 | 5 | 14 | 7 | 5 | 11 | 33 | 36 | 21 | 2 | 5 | 2 |
| 03–06 | 4 | 5 | 12 | 12 | 5 | 10 | 38 | 46 | 32 | 6 | 6 | 0 |
| 06–09 | 3 | 3 | 13 | 3 | 2 | 5 | 49 | 56 | 33 | 4 | 7 | 4 |
| 09–12 | 4 | 3 | 5 | 6 | 4 | 5 | 42 | 39 | 25 | 7 | 6 | 3 |
| 12–15 | 2 | 7 | 19 | 25 | 25 | 60 | 49 | 62 | 75 | 21 | 3 | 1 |
| 15–18 | 5 | 6 | 27 | 24 | 31 | 57 | 67 | 76 | 49 | 11 | 9 | 2 |
| 18–21 | 7 | 5 | 18 | 19 | 15 | 23 | 33 | 36 | 25 | 5 | 6 | 3 |
| 21–00 | 9 | 5 | 17 | 15 | 9 | 13 | 23 | 32 | 12 | 3 | 7 | 4 |

During the long rains, falls are more frequent and not so strongly peaked about the afternoon, but there is still a maximum at that time of day, with 8–10 days per month during the early afternoon and also the late afternoon periods. Falls are least frequent in the early hours (about one per month).

Diurnal incidence of the late rains is very similar to that of the little rains, with falls largely confined to the afternoon — 2–4 days per month.

From December to February, falls are few and occur mostly in the late afternoon, but even at that time of day they are observed only about once per month.

**Thunder at Asmara.** Table II shows that during the little rains thunder is almost entirely confined to the afternoon (4–5 occasions per month in both

TABLE II—NUMBER OF OCCASIONS WHEN THUNDER WAS HEARD IN EACH OF THE EIGHT THREE-HOURLY PERIODS DURING THE YEARS 1958–62 AT ASMARA AND ADDIS ABABA

| Local time | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *(a)* ASMARA | | | | | | |
| 00–03 | 0 | 0 | 0 | 2 | 2 | 0 | 1 | 4 | 2 | 0 | 2 | 0 |
| 03–06 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 06–09 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| 09–12 | 0 | 0 | 0 | 1 | 3 | 4 | 16 | 11 | 4 | 0 | 1 | 0 |
| 12–15 | 1 | 6 | 7 | 25 | 23 | 19 | 81 | 73 | 22 | 9 | 18 | 2 |
| 15–18 | 2 | 8 | 9 | 25 | 27 | 20 | 75 | 68 | 25 | 10 | 24 | 3 |
| 18–21 | 1 | 6 | 1 | 13 | 9 | 4 | 21 | 24 | 3 | 4 | 6 | 1 |
| 21–00 | 0 | 1 | 0 | 7 | 1 | 1 | 3 | 7 | 1 | 2 | 4 | 0 |
| | | | | | | *(b)* ADDIS ABABA | | | | | | |
| 00–03 | 5 | 0 | 4 | 1 | 1 | 1 | 4 | 14 | 5 | 0 | 0 | 0 |
| 03–06 | 0 | 0 | 2 | 0 | 0 | 1 | 0 | 2 | 6 | 0 | 0 | 0 |
| 06–09 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 |
| 09–12 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 4 | 3 | 2 | 0 | 0 |
| 12–15 | 0 | 0 | 4 | 8 | 14 | 46 | 23 | 39 | 43 | 7 | 0 | 0 |
| 15–18 | 0 | 3 | 15 | 15 | 9 | 40 | 39 | 45 | 40 | 9 | 1 | 0 |
| 18–21 | 4 | 1 | 15 | 11 | 7 | 10 | 11 | 15 | 16 | 3 | 1 | 1 |
| 21–00 | 2 | 2 | 10 | 6 | 3 | 2 | 6 | 12 | 6 | 0 | 0 | 0 |

April and May), but there are also one or two occasions per month with thunder in the early evening. As the season progresses, the chance of thunder in the late morning increases, but is still less than once per month in May. During the long rains, thunder is heard more widely during the day, but there is still a sharp maximum in the afternoon (about 15 days per month during the early afternoon and also during the late afternoon). In this season, thunderstorms develop earlier than during the little rains (there are 2–3 days per month with thunder during the late morning), and they are also heard in the early evening (3–4 days per month). During the late rains, diurnal incidence of thunder is much the same as during the little rains.

**Rain at Addis Ababa.** There is really only one rainy season, March to October. From November to February, falls are few and they are distributed fairly evenly through the day — about once per month in each of the eight three-hour periods. In March, the incidence of rainfall shows a maximum in the late afternoon (about 5 days) but there are also 2–3 days per month with falls in most of the other periods. In April and May, the diurnal variation becomes more pronounced although there is little increase in frequency. A maximum occurs in the afternoon (about 5 days per month in the early afternoon and also in the late afternoon), and a minimum in the early morning (less than once per month).

At the height of the rainy season, in July and August, the diurnal incidence is less-strongly peaked. There is a maximum in late afternoon (15 days per month) and a minimum in the late evening, whilst a noticeable secondary maximum in frequency of falls occurs in the early morning (10 days per month). By September, the diurnal variations become stronger again, with a maximum in the early afternoon (15 days per month) and a minimum in the late evening (2 days), whilst a secondary maximum still occurs around dawn (6 days per month, in the early hours and also in the early morning). October resembles May, with a maximum in the early afternoon (4 days per month), and a minimum around midnight.

**Thunder at Addis Ababa.** From March to May, thunder is heard progressively earlier in the day. During March there is a distinct frequency maximum near dusk (3 days per month during late afternoon and also during early evening), but by May it has moved to early afternoon. June shows a big increase in frequency of thunder, which is heard most often in mid-afternoon (8–10 days per month during the early afternoon and also during late afternoon). There is little thunder at night in June and it is almost unknown in the morning.

From July to September, thunder occurs at almost any time of day, but in each month there is a strong frequency maximum around mid-afternoon (8–10 days per month in the early afternoon and also in the late afternoon), whilst it is almost unknown around dawn. October resembles the early part of the rainy season, with a maximum in the late afternoon (2 days per month). From November to February, thunder is almost unknown.

**Discussion.** The afternoon maximum of rainfall frequency in all rainy months, at both Asmara and Addis Ababa, can clearly be identified with convection released by day-time insolation; contemporaneous peaks in both rainfall and thunder incidence support this conclusion. At the beginning and end of the rainy season at Addis Ababa, thunder frequency rapidly decreases during the night, as might be expected with progressive decay of convective storms starting in the afternoon, but rains are more persistent. Such rains are either the remnants of previous days' storms, or they are the result of another mechanism that produces widespread stratiform clouds at night. Although some of the rains occurring up to midnight are likely to be the residues of earlier convective storms (the ratio of frequencies of rain and thunder does not change much until after midnight), some of the rains during the early hours and the morning (not thundery, and falling from stratiform clouds) are more likely to be the result of widespread uplift. Synoptic disturbances seem unlikely to account for these rains for such disturbances are not expected to have any significant diurnal variation in incidence. The tendency for rains to decrease in frequency from midnight to midday suggests a lifting mechanism with a diurnal variation in intensity, weakening from midnight to midday. Such a mechanism is a broad-scale anabatic flow towards the Ethiopian plateau that is to be expected as a result of day-time insolation. Because of the breadth of the plateau, this circulation would have a life-cycle comparable to one day, and it might well reach a maximum intensity after dusk. Accompanying subsidence over neighbouring plains would be expected to inhibit afternoon and evening convection there. Some evidence for this inhibition over the Sudan has been already presented.[1]

Night-time thunderstorms at Addis Ababa during the height of the rainy season could be attributed to the release, by widespread anabatic ascent, of potential instability known to be present. However, this mechanism cannot account for the early-morning secondary maximum in rainfall incidence. This occurs at a time of minimum thunder frequency and is associated with stratiform clouds. Similar secondary maxima are observed widely during the monsoon rains over West Africa,[3] the Sudan[1] and East Africa,[4] and do not appear to be linked to topography. They are probably associated with the thermal tide which produces a maximum in lower tropospheric convergence around 07 h.[5]

A broad-scale anabatic circulation which, it is suggested here, affects the incidence of rain and thunder at Addis Ababa, would be expected to be less effective at Asmara, where the plateau is much narrower and the circulation consequently shorter lived. The persistence of rain and thunder into the night should be much less pronounced and, in fact, as the tables show, Asmara has a characteristically sharp afternoon maximum of both rain and thunder in all rainy months. Only during the long rains is thunder relatively frequent in the early evening; it is during this season that individual convective storms are largest and most persistent.

There is little evidence for the tidal effect at Asmara. In this respect, the diurnal incidence of rain is similar to that at the beginning and end of the rains at Addis Ababa. The relatively few occurrences of rain and thunder from midnight to early morning at Asmara are probably associated with unusual synoptic disturbances, but during the long rains, drizzle from low, stratiform clouds forming in the moist monsoon (deflected to a north-westerly over the plateau) accounts for most of the falls in the early morning.

During the dry season, the infrequent rains at Addis Ababa, falling at any time of day, probably mostly come from stratiform clouds accompanying synoptic disturbances, but even at this time of year some of the falls from late afternoon to late evening are convective, as indicated by a few occurrences of thunder. The rarity of night and morning falls at Asmara in this season suggests that synoptic disturbances do not strongly influence the occurrence of rainfall.

**Conclusions.** Apart from the obvious effects of insolation on the diurnal incidence of rain and thunder, there is some evidence to support the hypothesis that a broad-scale anabatic circulation develops between the Nile plains and the Ethiopian highlands. Such a circulation would account for the observed enhancement over the highlands of afternoon convective rains and of night-time rains from stratiform clouds. Evidence for a corresponding inhibition of rains over the neighbouring plains of the Sudan has already been presented. Once again, an interaction of local and broad-scale convective systems has been suggested; the role of synoptic disturbances remains to be explored.

**Acknowledgements.** Sincere thanks are due to the Director and Staff of the Meteorological Service of the Imperial Ethiopian Government for kindly making available original records used in this study. Mr R. G. Wilson assisted in the extraction and tabulation of the records, and the results are published with the permission of the Director, Anti-Locust Research Centre.

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551·509·313:512·9

# TWO DECOMPOSITION THEOREMS FOR THE MEAN VECTOR VELOCITY OF AN AREA IN A TWO-DIMENSIONAL FLOW FIELD

By R. DIXON

**Summary.** Two integral equations are derived which may be viewed as decomposition theorems for the mean vector velocity within a plane fluid area. One of the theorems sheds some light on the difference between wind fields as used in primitive equation models and those used in vorticity models.

It is a familiar fact that the vorticity ($\zeta$) and the divergence (Div $\mathbf{V}$) may be expressed in terms of the spatial derivatives of the velocity vector $\mathbf{V}$ having components $(u, v)$ as

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \quad \text{Div}\,\mathbf{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}. \qquad \ldots (1)$$

Less familiar to meteorologists are relationships which relate vorticity and divergence to the undifferentiated velocity field. Two such relationships

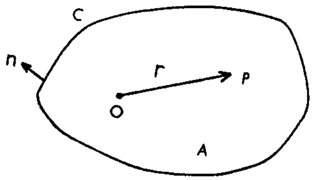


FIGURE 1—DIAGRAM OF CURVE $C$ AND AREA $A$

may be derived by considering a plane area of fluid, $A$, bounded by a closed curve $C$, Figure 1. Let any point P in the area $A$ be defined by a position vector $\mathbf{r}$ with respect to some origin O. If use is made of some well-known vector formulae, Weatherburn,[1] the following may be obtained

$$\nabla (\mathbf{V} \cdot \mathbf{r}) = \mathbf{V} + \mathbf{r} \cdot \nabla \mathbf{V} + \mathbf{r} \times \zeta \mathbf{k}, \qquad \ldots (2)$$

$$\nabla \cdot (\mathbf{r}\, \mathbf{V}) = 2\mathbf{V} + \mathbf{r} \cdot \nabla \mathbf{V}, \qquad \ldots (3)$$

$$\nabla \times (\mathbf{r} \times \mathbf{V}) = -\mathbf{V} - \mathbf{r} \cdot \nabla \mathbf{V} + \mathbf{r}\, \mathrm{Div}\, \mathbf{V}. \qquad \ldots (4)$$

From (2) and (3) it follows that

$$\mathbf{V} = \nabla \cdot (\mathbf{r}\, \mathbf{V}) - \nabla (\mathbf{V} \cdot \mathbf{r}) + \mathbf{r} \times \zeta \mathbf{k}, \qquad \ldots (5)$$

where $\mathbf{k}$ is the unit vertical vector and now, by integrating (5) over the area $A$ and using Gauss's Theorem relating to the integral round curve $C$, there follows

$$\int_A \mathbf{V}\, dA = \oint_c (\mathbf{n} \cdot \mathbf{r})\, \mathbf{V}\, dc - \oint_c \mathbf{n}\, (\mathbf{V} \cdot \mathbf{r})\, dc + \int_A \mathbf{r} \times \zeta \mathbf{k}\, dA, \qquad \ldots (6)$$

where $\mathbf{n}$ is the outward unit normal vector to the curve $C$.

By dividing through by $A$ and by combining the first two terms on the right-hand side the following may be obtained

$$\mathbf{V}_m = \frac{1}{A} \left\{ \int_A \mathbf{r} \times \zeta \mathbf{k}\, dA + \oint_c (\mathbf{n} \times \mathbf{V}) \times \mathbf{r}\, dc \right\}, \qquad \ldots (7)$$

where $\mathbf{V}_m$ is the mean velocity over the area.

If, instead, the same sequence of manipulations is carried out on equations (3) and (4) there results

$$\mathbf{V}_m = \frac{1}{A} \left\{ \oint_c (\mathbf{n} \cdot \mathbf{V})\, \mathbf{r}\, dc - \int_A \mathbf{r}\, \mathrm{Div}\, \mathbf{V}\, dA \right\}. \qquad \ldots (8)$$

The point of selecting (2) and (3), and (3) and (4) for these manipulations is to eliminate the term $\mathbf{r} \cdot \nabla \mathbf{V}$, which contains the spatial derivatives of $\mathbf{V}$, thereby obtaining expressions for Div $\mathbf{V}$ and $\zeta$ which do not involve these derivatives. However, in the event, the resulting expressions are more readily interpreted as decomposition theorems for the mean vector velocity over an area.

Equation (7) may be written as

$$\mathbf{V}_m = (\mathbf{r} \times \zeta\, \mathbf{k})_m + \frac{1}{A} \oint_c (\mathbf{n} \times \mathbf{V}) \times \mathbf{r}\, dc, \qquad \ldots (9)$$

showing that the mean velocity vector is made up of a component due to the mean moment over the area of the vertical vorticity vector $\zeta\,\mathbf{k}$ about the origin, plus a component due to the moment of the tangential component of the velocity on the bounding curve (note that the effect of the operation $\mathbf{n} \times$ in the second term of (9) is to eliminate the normal component of $\mathbf{V}$ and to rotate the tangential component into the vertical).

Equation (8) may be written as

$$\mathbf{V}_m = \frac{1}{A} \oint_c (\mathbf{n} \cdot \mathbf{V})\, \mathbf{r}\, dc - (\mathbf{r}\, \mathrm{Div}\, \mathbf{V})_m, \qquad \ldots (10)$$

and this shows $\mathbf{V}_m$ composed of an areal mean involving Div $\mathbf{V}$, together with a boundary contribution depending on the component of $\mathbf{V}$ normal to the boundary.

By combining (9) and (10), or else by starting the manipulations with (2) and (4), an expression for $\mathbf{V}_m$ involving both Div $\mathbf{V}$ and $\zeta$ may be obtained. It is also possible to find an expression corresponding to (7) and (8) which expresses $\mathbf{V}_m$ in terms of the deformation field.

Equations (9) and (10) shed considerable light on the relationship which must exist between conditions on a boundary and the flow in the interior of an area. For example in the numerical forecasting suite of programmes, as currently used in the Meteorological Office, the wind field for the vorticity model is obtained by ellipticizing and solving the balance equation in the form

$$f\zeta + 2J(u, v) - \mathbf{k} \cdot \mathbf{V} \times \nabla f - g\nabla^2 h = 0, \qquad \ldots (11)$$

subject to the condition

$$\mathbf{V} = \mathbf{k} \times \nabla\psi, \qquad \ldots (12)$$

which implies that

$$\mathrm{Div}\, \mathbf{V} = 0. \qquad \ldots (13)$$

It follows directly from (12) that in this case the mean velocity vector is determined by the boundary conditions, and this is confirmed by (10) in view of (13). However, in determining the wind field for the unfiltered primitive equation model the more general form of the balance equation may be used

$$f\zeta - (\mathrm{Div}\, \mathbf{V})^2 + 2J(u, v) - \mathbf{k} \cdot \mathbf{V} \times \nabla f - g\nabla^2 h = 0. \qquad \ldots (14)$$

and the theorem (10) applies in full. Thus (10) pin-points an essential physical difference between the wind fields used in a vorticity model and those used in a primitive equation model.

Truesdell[2] states that the formula (9) was first established by J. J. Thompson for the case of the three-dimensional flow of an incompressible fluid. Truesdell also shows that (9) may be obtained as a special case of a very general form of Gauss's Theorem. A slight slip in his algebra leads Truesdell to say that (9) is only true if Div $\mathbf{V} = 0$, but this is not so, as the above derivation shows. Westberg[3] obtained (9) for the special case of irrotational motion. The author has not been able to trace (10) in the literature.

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551·515·3

# THE CYPRUS WATERSPOUTS AND TORNADOES OF 22 DECEMBER 1969

By R. N. HARDY

**Summary.** The transformation of a waterspout on crossing the coastline into a highly destructive tornado appears to be an extremely rare phenomenon. A case which occurred in Cyprus is discussed.

**Introduction.** On the afternoon of 22 December 1969 the southern coastal region of Cyprus was the scene of very active convection and waterspouts. On the eastward passage of a trough line a series of six intense waterspouts hit the shore line and several continued inland as tornadoes. Of these, one continued as a tornado across the centre of the Akrotiri peninsula, creating considerable damage (e.g. to married quarters) before it faded out. Another crossed the tip of the peninsula, traversed the bay, and then, as a tornado some 200 yards* in width, it cut through the west and north of Limassol and continued inland up into the hills. The loss of life (one at Akrotiri, three in Limassol) was remarkably low considering the havoc. Past records are very scanty in Cyprus but this family of tornadoes is the most destructive known to the author. The fact that they originated as waterspouts makes this occurrence of great interest.

**Description of the waterspouts and tornadoes.** The map at Figure 1 shows the town of Limassol on the south coast of Cyprus together with Akrotiri lying on a low peninsula to the south-south-west and Episkopi to the west. Limassol is the second largest town in Cyprus.

In the early afternoon the weather took on a very threatening appearance and by 15 hours (13 GMT) waterspouts were seen out to sea appearing to be roughly in line and orientated east–west, although this cannot be verified. The number visible at any time varied between two and seven and whilst some appeared to persist others decayed and new ones formed. Towards

* Distances and heights are given in traditional British units.
Conversion factors to metric units are : 1 foot = 0·3048 m; 1 mile = 1·6 km; 1 knot ≈ 0·5 m/s.

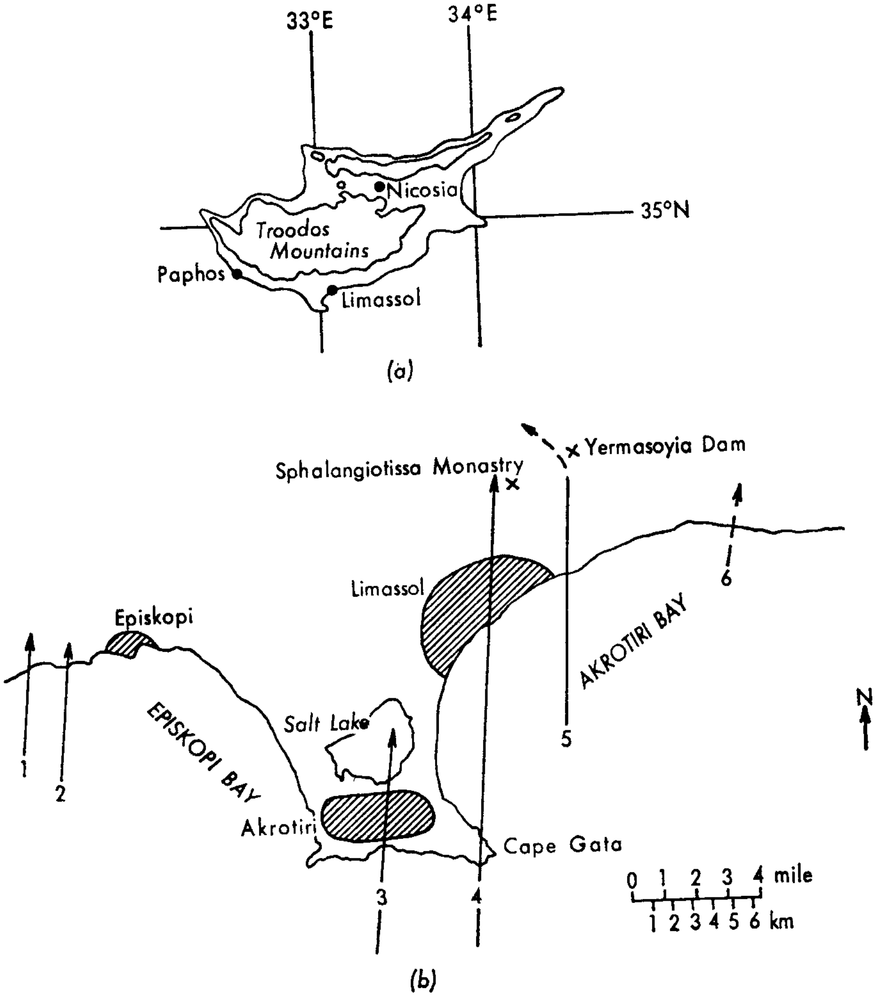


FIGURE 1—WATERSPOUTS AND TORNADOES IN SOUTHERN CYPRUS ON 22 DECEMBER 1969

*(a)* Map of Cyprus *(b)* Approximate tracks of waterspouts and tornadoes

1530 hours (1330 GMT) most waterspouts were hidden from view by an intense hailstorm accompanied by thunder, which, it transpired, was just one part of an extremely large storm which affected much of southern Cyprus. The hail was most intense in the eastern sector; a report from a motorist (a trained meteorologist) 10 miles south of Nicosia speaks of visibility being reduced to two or three yards in hail, halting all traffic. Paphos in the west had thunder but no hail.

Out of this storm a family of waterspouts emerged each travelling in a direction of approximately 010° and striking the coastline. No. 1 crossed the coastline about one mile west of Episkopi and travelled up a narrow steep-sided valley before dying away at the valley head some 600 yards inland. No. 2 struck the headland some 400 yards nearer to Episkopi but did not penetrate inland. Then a gap occurred of several miles to the extremely active group of Nos. 3, 4 and 5, spaced over about two miles, of which the middle one (No. 4) struck the coastline just west of Cape Gata. This was followed by a further wide gap to No. 6 about eight miles east of Limassol, which was similar to No. 1.

**Episkopi.** The hail shower was short at the Main Meteorological Office at Episkopi and it was noted that two distinct types of hailstone fell simultaneously. About 80 per cent were spherical with the appearance of frosted glass and of almost uniform size about 8 mm diameter ($\frac{3}{8}$ inch). The remainder were jagged where it appeared that two and sometimes three of the former type had partially melted and joined together. A few had fractured and showed several onion-like layers. The jagged stones were mostly larger than the rime-ice covered hailstones, the maximum axis measuring up to 15 mm ($\frac{5}{8}$ inch).

When the hailstorm finished, two waterspouts came into view, clearly visible against the brightening sky to the south though the cloud was still black overhead (Plate I). Both waterspouts were moving at about 25 kt but when the nearer one (No. 2) reached the cliffs the progress of the base appeared to be completely arrested whilst the part near the cloud base continued forward. The result was a stretching and a lateral contraction until it resembled a long black rope, see Plate II. The lower portion weakened quickly, first becoming a transparent sheath in the lowest hundred feet or so, and then wobbled as it quickly contracted and disappeared. Soon afterwards the cloud edge crossed from the south.

**Akrotiri.** No. 3 and No. 4 struck the Akrotiri peninsula after a short but intense hailstorm. From a cine-film sequence taken at the time it seems that the hailstones were mostly larger than those at Episkopi; observers report that there were mis-shapen ones where two or more had joined together at some stage in their development. No. 3 crossed the coastline about 4 miles west of Cape Gata, surmounting a cliff 100 feet high before continuing forward through a housing estate, some offices, scrubland and a helicopter pad before reaching the salt lake where it decayed. Damage was severe in places, especially to roofs and prefabricated buildings; a helicopter was damaged, whilst the private car shown in Plate III *(a)* had been lifted over the bungalow and deposited in the back garden. No. 4 turned out to be the most powerful. It struck the Akrotiri peninsula about 2 miles to the east of No. 3 in an area of low scrub and rock and proceeded for about a mile across this sort of terrain before, as it emerged into Akrotiri Bay, it destroyed the Sub-Aqua Club building (Plate III *(b)*). It crossed the bay, struck Limassol town and went on inland for some 4 miles with only a very slight deviation from a straight path throughout.

**Limassol.** Plate IV *(a)* shows waterspout No. 5 before it became a tornado. After a hailstorm, waterspouts No. 4 and No. 5 struck the Limassol coastline. No. 5 crossed the eastern outskirts of Limassol, where the population is relatively sparse, but it added considerably to the confusion by bringing down large trees across the main Nicosia road, effectively cutting off Limassol. This somewhat weaker tornado was channelled about 30 degrees to the left of its original track along a small valley when it encountered the Yermasoyia dam about $3\frac{1}{2}$ miles inland.

The records of weather in Cyprus are extremely scanty before the British occupancy commenced in 1878. The tornado which started as waterspout No. 4 is the most intense in living memory in southern Cyprus and it struck near the centre of Limassol with its crowded streets near the waterfront and more modern spaced-out development inland. It crossed the waterfront just west of the harbour into the Turkish quarter and immediately demolished several houses built of mud bricks and removed the top half of a brick-built minaret, see Plate IV *(b)*. It continued thereafter in an almost straight line slightly east of north leaving a path of damage up to 300 yards wide for a distance of about 4 miles, and finally dissipated when it came up against a steep escarpment where it caused some damage to the Sphalongiotissa Monastery at an altitude of 600 feet.

It is clear that the density of buildings reduced the damage at ground level, for where it crossed open ground the adjacent buildings were more severely affected and cars overturned, see Plate IV *(c)*. Some idea of the destructive power of the rotating air can be gauged from the fact that water-filled tanks of roof-top solar heaters weighing two or three hundred pounds were lifted and carried away; some of the larger debris in Plate V* may consist of these heaters. The noise of the vortex was described as equivalent to several jet aircraft flying low overhead.

**Synoptic situation.** Any analysis of weather in the eastern Mediterranean is hampered by lack of data, especially when so-called mesoscale phenomena are involved. This difficulty is accentuated by the effects of local topography which often mask air-mass characteristics.

A frontal low deepened markedly over Italy on 19 December and with a stationary high persisting over north-east Europe, a long easterly low-level flow was established from central Russia into the circulation of the depression. This cold low-level flow helped to maintain the area of low pressure, and a mobile warm-sector depression approaching the British Isles from the west was deflected north-eastwards by the weak block over Europe. The resultant veering of the strong high-level flow from the North Sea to Italy soon resulted in a cut-off upper low just west of Greece coincident with the surface-low complex. Figure 2 shows the surface analysis for 12 GMT on 21 December. There was widespread thundery activity from western Turkey to the coast of north-west Libya. The two troughs extending southwards from the centres were based on little evidence but were shown to be real features on subsequent charts. The occlusion was intense and active east of 20°E but west of that the colder air to the north was dry. Central pressure in the low area was rising slowly with warming at all levels. Another feature of the chart that may be significant is that the weak low-level south-easterly from the Persian Gulf had brought moist air to much of Iraq.

A change in the upper flow became evident in the next 12 hours. The 300-mb low centre had moved slowly north-eastwards since it first formed at 12 GMT on 20 December, see Figure 3; but at midnight on 22 December it became apparent that a second centre had formed some 150 miles west

* This is number 21 of a remarkable sequence of photographs taken by Sgt D. L. Pownall of RAF Episkopi. The sequence starts with waterspouts well out to sea, continues with shots of a tornado approaching and ends with pictures of damage to the house opposite.

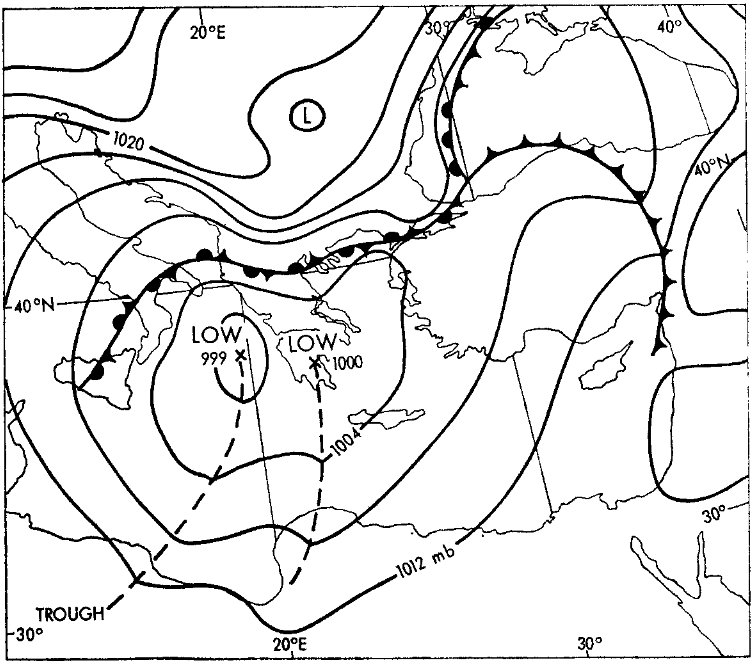


FIGURE 2—SURFACE ANALYSIS, 12 GMT ON 21 DECEMBER 1969

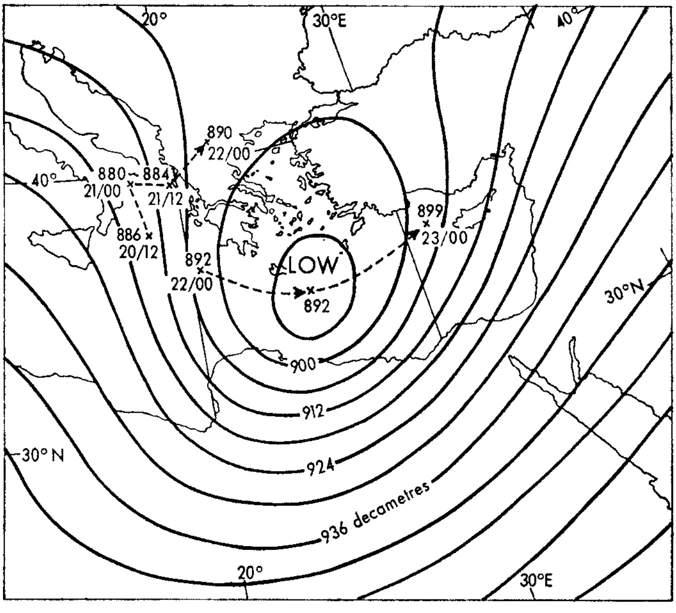


FIGURE 3—CONTOURS AT 300 mb, 12 GMT ON 22 DECEMBER 1969

x – – x Track and pressure of centre, with date/time (GMT) of Crete. This seemed to mark a resumption of mobility at these latitudes and perhaps also the genesis of the severe storm. Subsequently the 300-mb centre moved eastwards at about 20 kt and the surface low also accelerated east towards Cyprus.

From the time-section of upper winds at Episkopi and the hodograph of winds at 12 GMT on 22 December shown in Figure 4, can be seen the gradual

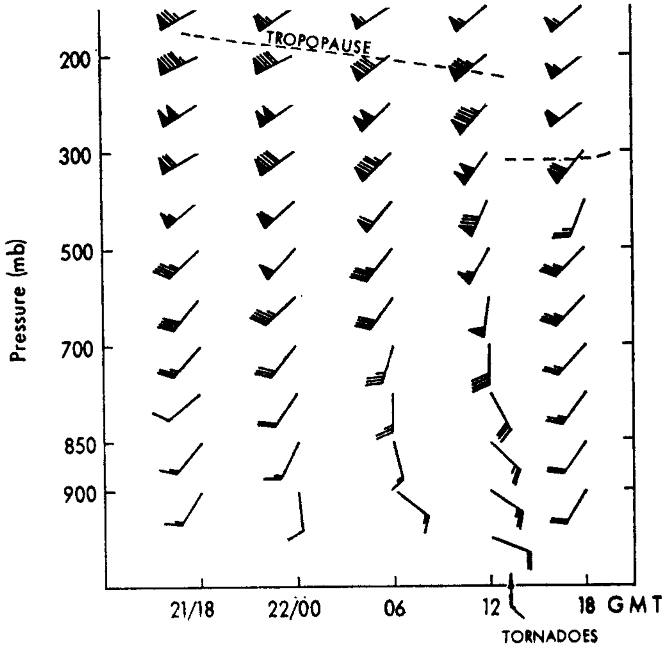


FIGURE 4 *(a)*—SEQUENCE OF UPPER WINDS AT EPISKOPI, 18 GMT ON 21 DECEMBER TO 18 GMT ON 22 DECEMBER 1969

Wind directions and speeds are in the normal international symbols.

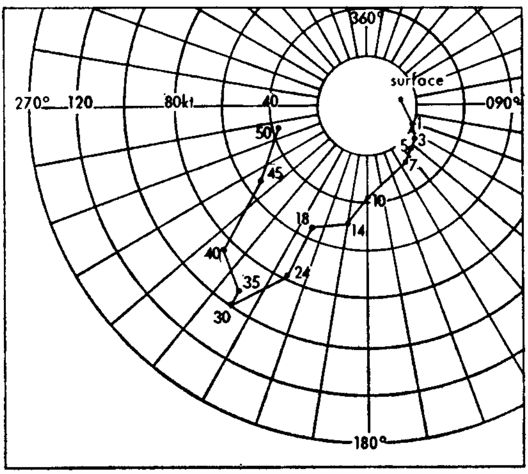


FIGURE 4 *(b)*—EPISKOPI WINDS, 12 GMT ON 22 DECEMBER 1969

Heights in thousands of feet (10 000 ft = 3048 m).

setting up and intensifying of the wind shear and how strong this was near the time of the tornadoes. The radiosonde ascent from Episkopi at 12 GMT on the 22nd is shown in Figure 5 together with the temperatures 12 hours before and 12 hours after. The severe storm that gave birth to the tornadoes is believed to be shown at A in Plate VI *(a)* though its orientation at the time that the satellite ESSA 8 picture was taken, 0727 GMT, does not correspond with the observed clearance from the south. At 0815 GMT, less than one hour later, the NIMBUS photograph (Plate VI *(b)*) showed the same feature but now with a more dense section having developed. The analysis for 12 GMT on the 22nd is shown in Figure 6.

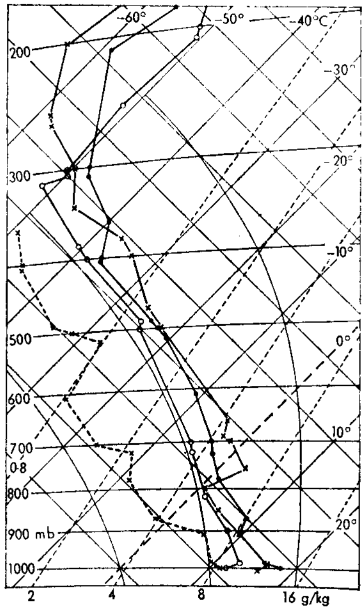


FIGURE 5—EPISKOPI UPPER AIR ASCENTS, 22–23 DECEMBER 1969

x ——— x Temperature at 00 GMT on 22nd
· ——— · Temperature at 12 GMT on 22nd
x – – – x Dew-point at 12 GMT on 22nd
o ——— o Temperature at 00 GMT on 23rd

**Discussion.** Perhaps the most interesting aspect of these tornadoes is their rarity. Tornadoes are not unknown in Cyprus but are usually comparatively weak summer features associated with the sea-breeze front, an example of which was recently recorded by McGinnigle.[1] The only other severe storm tornado reported since the last war was recorded in 1946 when several aircraft were damaged by hail and wind at Nicosia. Waterspouts are more common and may be seen several times in most years by a keen observer, but never before have waterspouts been known to have developed to such an intensity and crossed the coast to cause widespread damage well inland. It should be noted however, that these waterspouts/tornadoes struck heavily built-up areas, whereas over 90 per cent of the southern Cyprus coast is unpopulated; thus it is quite possible that previous occasions have passed unremarked.

*To face page 80*

***Photograph by R. J. Drury***

PLATE I—WATERSPOUTS NOS. 1 AND 2 APPROACHING EPISKOPI CLIFFS, 22 DECEMBER 1969

***Photograph by Mr. Harper***

PLATE II—DECAYING STAGE OF WATERSPOUT NO. 1

PLATE III(*a*)—DAMAGE CAUSED BY WATERSPOUT/TORNADO NO. 3

PLATE III(*b*)—THE SUB-AQUA CLUB BUILDING DESTROYED BY NO. 4

*Photograph by A. Cox*

PLATE IV(*a*)—WATERSPOUT NO. 5 APPROACHING EASTERN LIMASSOL

PLATE IV(*c*)—LIMASSOL DAMAGE FURTHER INLAND

PLATE IV(*b*)—TRAIL OF DAMAGE IN LIMASSOL FOLLOWING NO. 4

Note minaret.

*Photograph by Sgt D. L. Pownall, RAF*

PLATE V—TORNADO NO. 4 IN LIMASSOL MOVING TOWARDS CAMERA

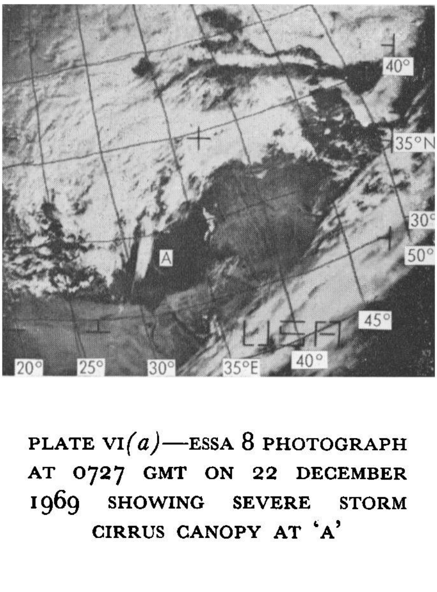


PLATE VI(*a*)—ESSA 8 PHOTOGRAPH AT 0727 GMT ON 22 DECEMBER 1969 SHOWING SEVERE STORM CIRRUS CANOPY AT 'A'

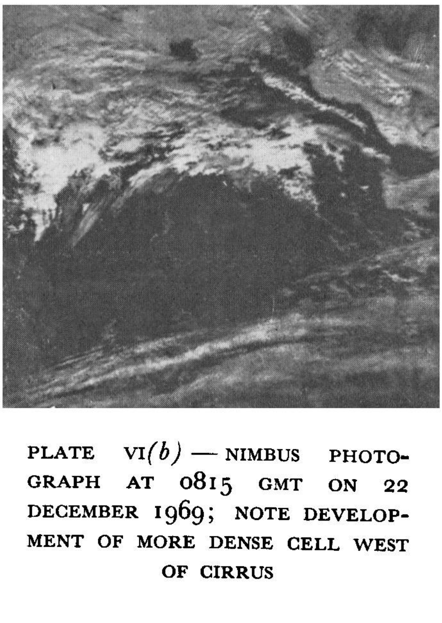

PLATE VI(*b*) — NIMBUS PHOTOGRAPH AT 0815 GMT ON 22 DECEMBER 1969; NOTE DEVELOPMENT OF MORE DENSE CELL WEST OF CIRRUS

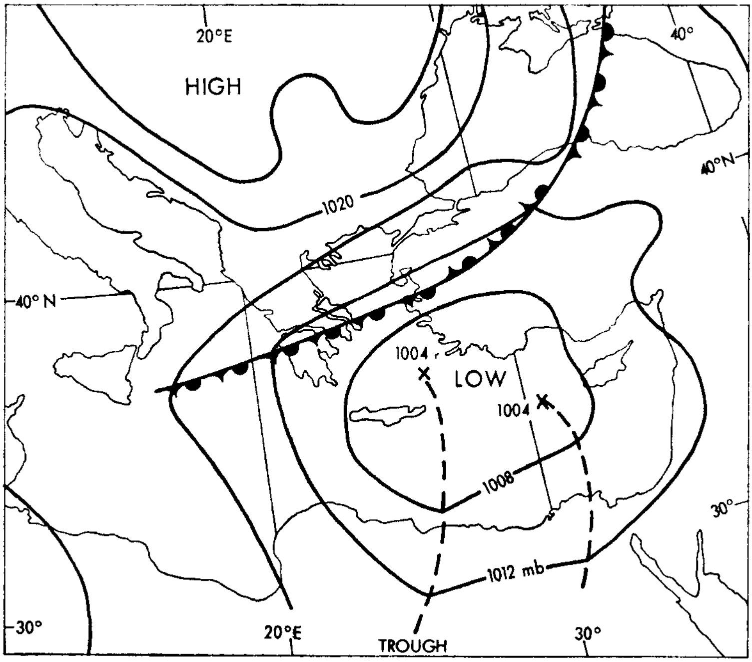


FIGURE 6—SURFACE ANALYSIS, 12 GMT ON 22 DECEMBER 1969

Many features of this occasion were similar to those recorded at Malta on 14 October 1960[2] which, in turn, agreed with tornado reports outside the Mediterranean area. These are :

(i) A dry stable layer above a moist, potentially unstable surface layer: can be seen near 900 mb in Figure 5.

(ii) Pronounced vertical wind shear in the lower layers.

(iii) Cold dry air above the stable inversion layer.

(iv) The occurrence of hail.

It seems certain that the Cyprus tornadoes were associated with a severe storm on the lines of the model described by Browning.[3] A great deal of work has been done, particularly in the U.S.A., regarding the physical processes involved in the production of tornadoes; nevertheless, the reasons for tornado genesis are still not fully understood.

It may be that one reason tornadoes are mostly associated with severe self-perpetuating storms is the large area covered by the low-level convergence field. This will be much greater than that associated with the more common thunderstorm, because of both the low-level inversion and the long life-cycle of the severe storm. If the low-level flow has any shear in the horizontal this could lead to vorticity and angular momentum becoming concentrated at the storm centre.

There are many similarities between the synoptic events which led up to the tornadoes of 22 December and events leading to occasions of severe low-level clear-air turbulence near Cyprus, one of which was discussed by

Jefferson.[4] It is clear that the forecaster in Cyprus concerned with aviation must recognize that an area of strong vertical wind shear ahead of a cold front or trough can be associated with extreme conditions.

**Acknowledgements.** The author is grateful to the Chief Meteorological Officer, HQNEAF, for his helpful suggestions, to Mr D. Imrie of the Main Meteorological Office, RAF Episkopi, for his help in collecting data, and to the many other people in Cyprus who supplied photographs, cine films and eye-witness reports.

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# A PRESSURE-ACTUATED RELEASE FOR METEOROLOGICAL BALLOONS

By H. CHARNOCK, A. I. REES and P. K. TAYLOR
Department of Oceanography, University of Southampton

**Introduction.** This note describes a pressure-actuated release used to separate two parts of a balloon-borne instrument train. It was developed originally for use over the sea. A ship disturbs the lower atmosphere and it is difficult to launch a slowly ascending balloon from it. When low-level measurements of the atmosphere are needed the method adopted is to use two balloons to send the instrument train rapidly to a predetermined pressure where one balloon is released so that the instruments sink slowly back to the sea. This allows undisturbed measurements to be made down to very near the sea surface.

A number of methods have been used to effect the release. Systems involving pressure-actuated electrical circuits are known but they are relatively expensive, heavy and unreliable. Other methods which act after a preset time interval are better on all these grounds. The cheapest seems to be a length of slow-burning fuse, but this is dangerous to use with hydrogen balloons. Small clockwork timers have been found to work reasonably well for periods of about 30 minutes but are difficult to make sufficiently reliable.

The device described here uses the atmospheric pressure directly to perform the release. It is cheap to make and if carefully tested before use is very reliable.

**Description.** The device (Figure 1) is a chamber of plastic which can be partially evacuated so that the lid is held on by the excess atmospheric pressure. It is used to join the two parts of the balloon train. When the train has risen to the height where the external pressure equals that inside the chamber, the lid comes off and the train separates.

The device weighs 150 g and will withstand complete evacuation. When evacuated so as to release at 850 mb it will stand a tension of about 10 kg at sea level.

**Results.** The device has been used on 34 occasions, 11 at the Meteorological Office Station at Shanwell, Fife, 15 during the June 1970 cruise of R.R.S. *Discovery* in the trials for the Royal Society's U.K. Air–Sea Interaction Project and 8 from the weather ship *Cumulus* during the same period. Of these, 33 operated satisfactorily, the other is thought to have leaked.

Figure 2 shows the atmospheric pressure at release, derived from radar or radiosonde observations, plotted against the preset internal pressure. With the one exception all agree within the limits of measurement.

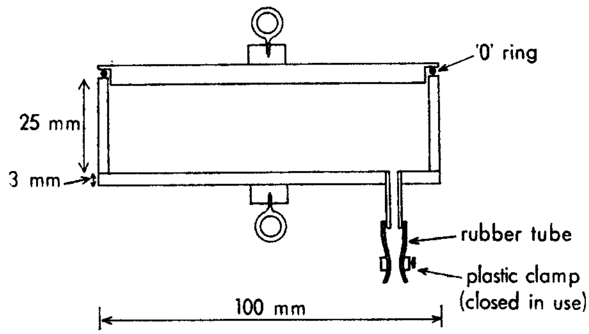


FIGURE 1—CROSS-SECTION OF PRESSURE-ACTUATED RELEASE

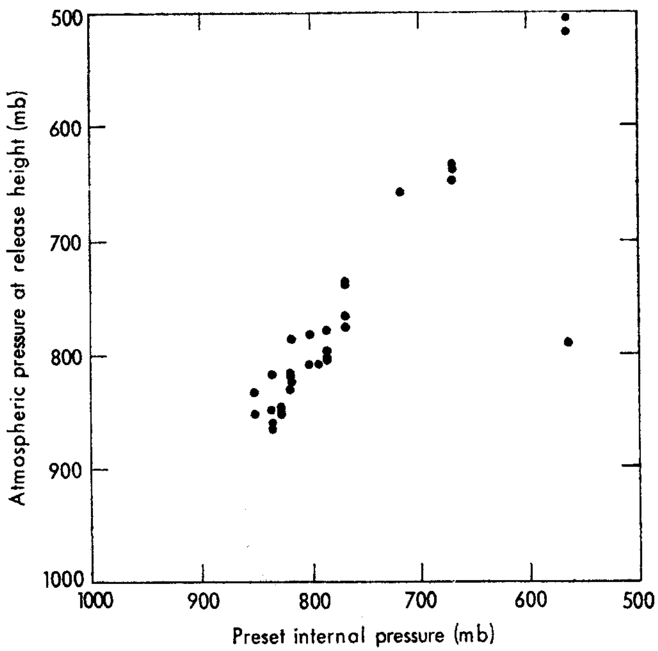


FIGURE 2—ATMOSPHERIC PRESSURE AT RELEASE, DERIVED FROM RADAR OR RADIOSONDE OBSERVATIONS, PLOTTED AGAINST THE PRESET INTERNAL PRESSURE

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# PERIODIC FLUCTUATIONS IN EQUATORIAL STRATOSPHERIC TEMPERATURES AND WINDS

By R. A. EBDON

**Summary.** The 50-mb and 30-mb temperature and wind data for Canton Island (02° 46′S 171° 43′W) are analysed by means of a band pass filter technique to determine the relative importance of the quasi-biennial, the annual and the semi-annual oscillations. It is shown that the quasi-biennial oscillation dominates the behaviour of the zonal wind components and is important as far as temperatures are concerned. The annual variation becomes important when considering temperatures but the semi-annual variation is of little significance with both temperatures and winds.

During the last decade much interest has been shown in, and many papers have been written about, the behaviour of stratospheric winds and temperatures in the equatorial stratosphere. In the early 1960s[1,2] attention was first drawn to the approximately 26-month or quasi-biennial oscillation in winds and temperatures and there is now a very extensive literature on that subject, although there is still no completely satisfactory explanation for the existence of the oscillation.

In more recent years[3,4] interest has been focused on another interesting feature in the stratosphere — namely the 6-monthly or semi-annual oscillation which is now known to exist in the higher stratospheric winds and temperatures. When the climatology of the stratosphere is studied the problem to be faced is the determination of the relative importance of the quasi-biennial (approximately 26 months), the annual (12 months) and the semi-annual (6 months) oscillations. Angell and Korshover[4] point out that for zonal wind components the quasi-biennial oscillation is at a maximum near 30 km over the equator, the annual is at a maximum near 60 km over middle latitudes and the semi-annual is at a maximum near 50 km over the equator.

For temperatures they show that the maximum of all three oscillations is to be found in polar regions; the quasi-biennial near 35 km, the annual near 40 km and the semi-annual at the stratopause. They also indicate the existence of a weaker maximum in the semi-annual temperature oscillation between 30 and 40 km in equatorial regions.

In this paper attention is restricted to the equatorial region. The wind and temperature data at the 50-mb and 30-mb levels (approximately 20·5 km and 24 km respectively) for Canton Island (02° 46′S 171° 43′W) for the 12-year period January 1955 – December 1966 are analysed by means of a band pass filter technique as described in detail by Craddock[5] and as used by Geraldine Edmond in an earlier article on this subject.[6]

Figures 1*(a)* and 1*(b)* show the monthly mean temperatures and zonal wind components for Canton Island for the period 1954 to 1967 (when radiosonde ascents there ceased). From these curves it can be seen that the so-called 'approximately 26-months' or 'quasi-biennial' oscillation is a very important feature and many of the now well-known facts concerning the oscillation are apparent on studying the curves.

The zonal wind component curves at both levels show that the quasi-biennial oscillation is the dominant feature and it is also clear that there is considerable variation in the length of the period. The temperature curves show that there is a well-marked annual variation at 50 mb and the presence

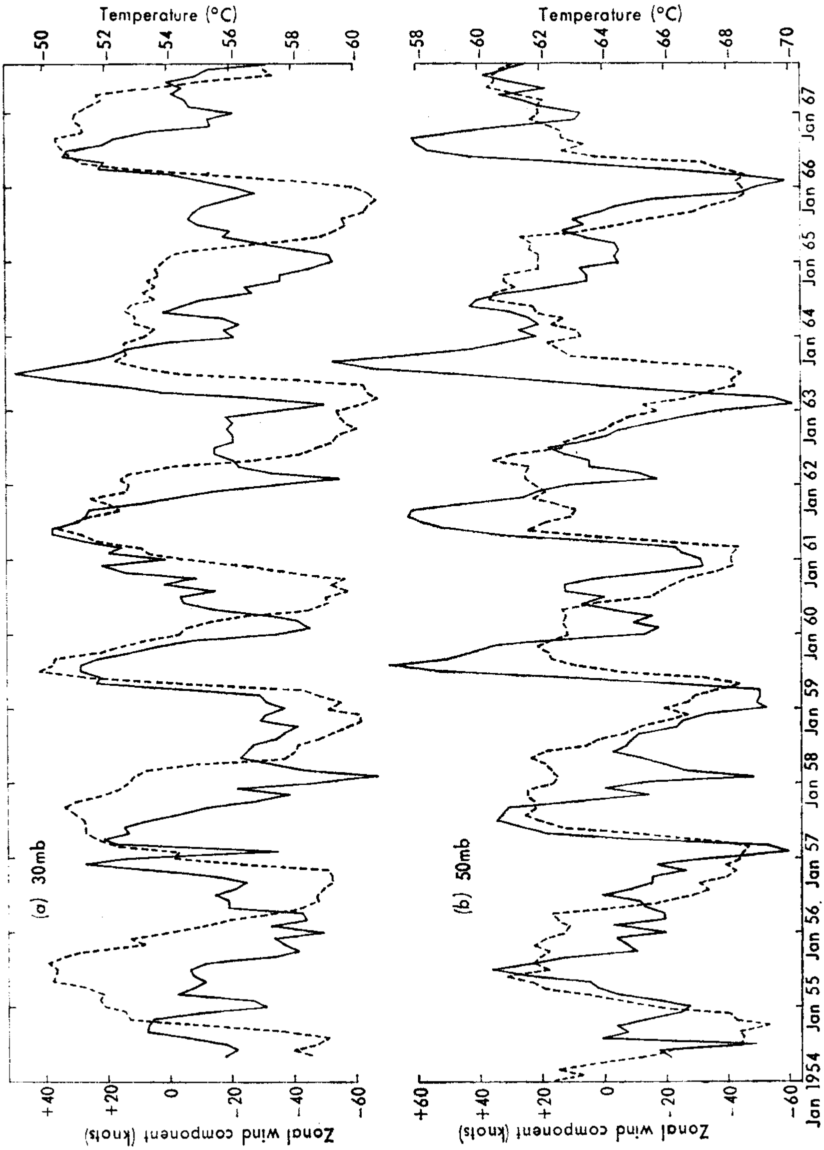


FIGURE 1—MONTHLY MEAN ZONAL WIND COMPONENTS AND TEMPERATURES AT CANTON ISLAND

—— monthly mean temperature - - - - monthly mean zonal wind component
(components towards the east are positive)

of the quasi-biennial oscillation is shown by the regular variations in the level of the annual maxima and minima. This regularity is upset during the period 1964–66 and it has been suggested that the cause of this disturbance in the behaviour of the oscillation could have been the volcanic eruption at Mount Agung, Bali (8°S 115°E), on 17 March 1963.[7] At the 30-mb level the monthly mean temperatures show the existence of both the quasi-biennial and the annual variations but there is also a suggestion of a shorter-period oscillation.

Figures 2*(a)* and 2*(b)* show the correlograms of the 50-mb and 30-mb data and from these it is clear that as far as the zonal wind components are concerned the main feature is certainly the quasi-biennial oscillation. The temperature correlograms, although highlighting the approximately 26-month oscillation, also suggest an important annual oscillation, particularly at 50 mb. None of the correlograms give a clear indication of a 6-monthly oscillation.

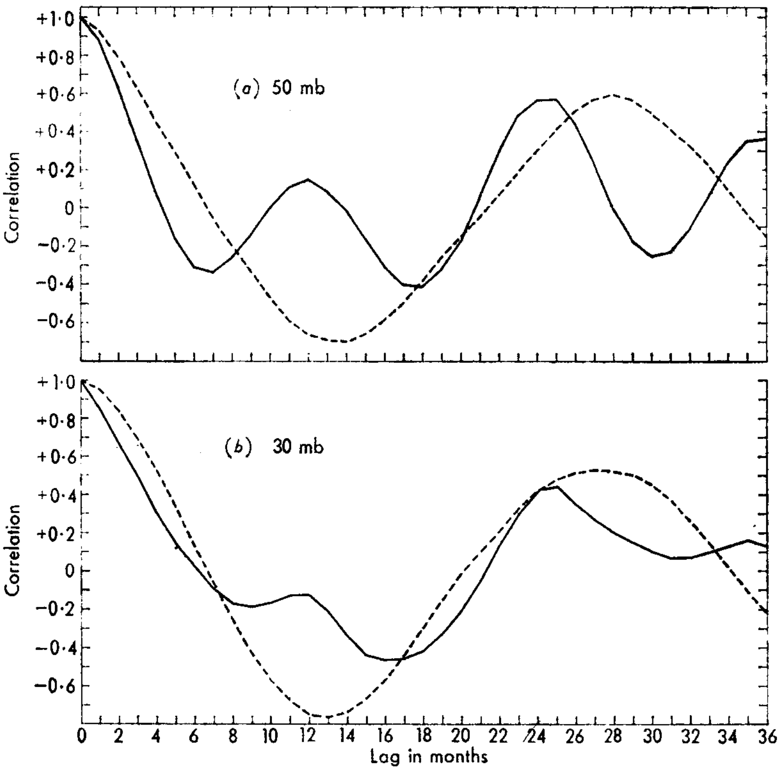


FIGURE 2—CORRELOGRAMS OF MONTHLY MEAN TEMPERATURES AND ZONAL WIND COMPONENTS AT CANTON ISLAND FOR JANUARY 1955–DECEMBER 1966

——— monthly mean temperature  – – – – monthly mean zonal wind component

In order to determine the relative importance of the three oscillations at the 50-mb and 30-mb levels, thirteen 25-point filters designed by Craddock[8] were applied to each set of data. The curves of the filtered values are shown in Figures 3 and 4, and Table I gives the percentage of the total variance

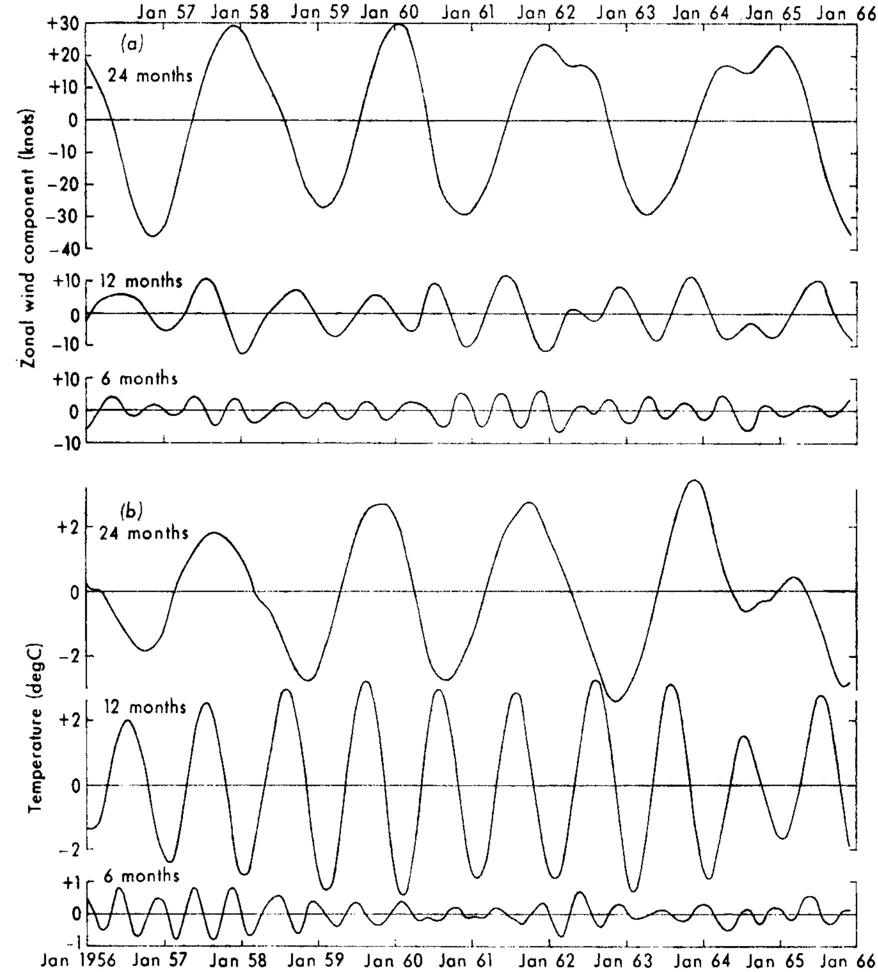


FIGURE 3—MONTHLY MEAN ZONAL WIND COMPONENTS AND TEMPERATURES AT 50 mb AT CANTON ISLAND FILTERED TO SHOW OSCILLATIONS, WITH VARIOUS PERIODS

*(a)* Monthly mean zonal wind components (components towards the east are positive)
*(b)* Monthly mean temperatures

TABLE I—VARIANCES OF FILTERED SERIES OF TEMPERATURES AND ZONAL WIND COMPONENTS AT 50 mb AND 30 mb AT CANTON ISLAND

| Peak period of oscillation | Effective range of period | Percentage of total variance occurring in each band | | | |
|---|---|---|---|---|---|
| | | Temperatures at | | Zonal wind components at | |
| | | 50 mb | 30 mb | 50 mb | 30 mb |
| *months* | *months* | | | | |
| 24 | 48–16 | 33 | 46 | 65 | 70 |
| 12 | 16–9·6 | 42 | 23 | 6 | 4 |
| 6 | 6·9–5·3 | 1 | 5 | 1 | 1 |

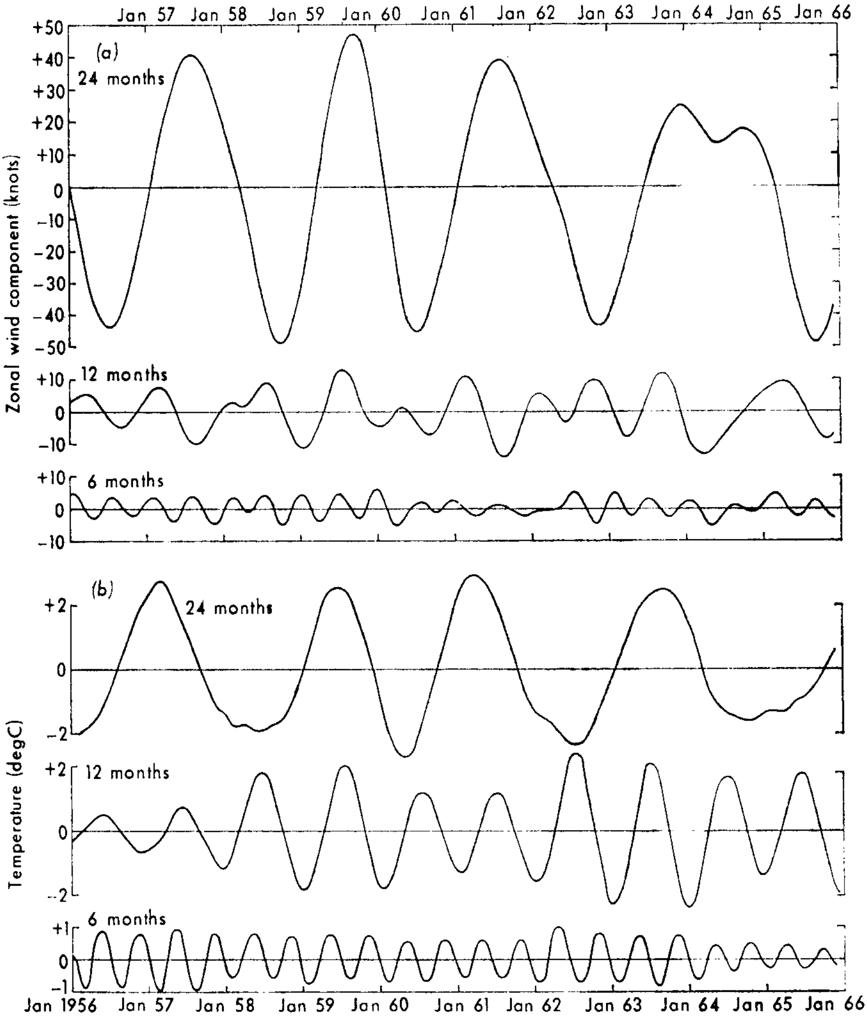


FIGURE 4—MONTHLY MEAN ZONAL WIND COMPONENTS AND TEMPERATURES AT 30 mb AT CANTON ISLAND FILTERED TO SHOW OSCILLATIONS, WITH VARIOUS PERIODS

*(a)* Monthly mean zonal wind components (components towards the east are positive)
*(b)* Monthly mean temperatures

covered by each oscillation. The zonal wind component curves show that most of the variance can be attributed to the quasi-biennial oscillation — at 30 mb this oscillation accounts for 70 per cent and at 50 mb for 65 per cent of the total. The annual oscillation is very much less important and accounts for only 4 per cent and 6 per cent respectively while the semi-annual oscillation accounts for only about 1 per cent of the total variance.

The temperature curves in Figure 4 show that at 30 mb the quasi-biennial oscillation accounts for nearly half (46 per cent) of the total variance, the annual oscillation for about a quarter (23 per cent) and the semi-annual is much less important, contributing only 5 per cent. At 50 mb the quasi-biennial and the annual oscillations are of almost equal importance with values of 33 per cent and 42 per cent respectively but the semi-annual contribution accounts for only 1 per cent of the total variance. In order to test the significance of these results two sets of random numbers within the range −50 to −60 were generated and processed in the same way as the wind and temperature data. The corresponding filtered values are shown on the curves in Figure 5. For these numbers the percentage of total variance occurring in each of the three bands was within the range 7–12 per cent for

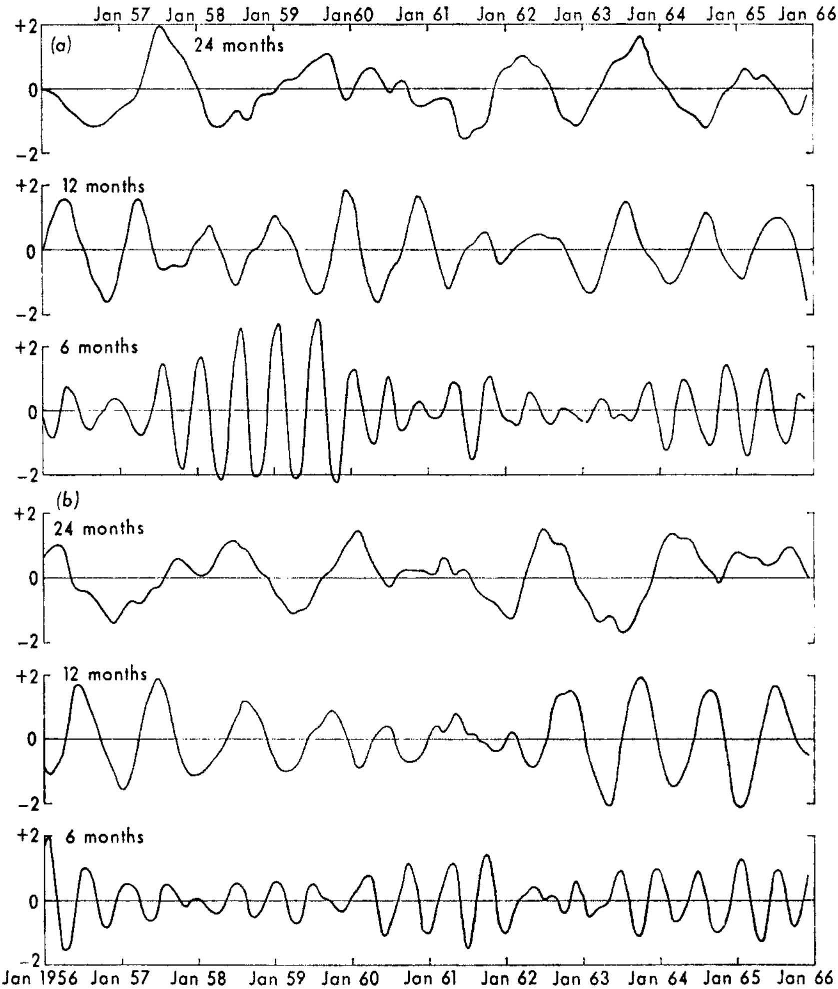


FIGURE 5—RANDOM NUMBERS IN THE RANGE −50·0 to −60·0 (ONE BLOCK OF 144) FILTERED TO SHOW OSCILLATIONS, WITH VARIOUS PERIODS

*(a)* Set 1 *(b)* Set 2

one set and 6–12 per cent for the other set, indicating that the six larger percentages in Table I are appreciably greater than could be expected by chance.

This analysis confirms that, as far as zonal wind components at the 50- and 30-mb levels in the equatorial region are concerned, the quasi-biennial oscillation is the dominant feature and the annual and semi-annual oscillations are relatively unimportant. However, with temperatures the annual variation assumes increasing importance and in the lower stratosphere (50 mb) accounts for rather more of the total variance than is attributable to the quasi-biennial oscillation. The data show that, at these levels, the 6-monthly oscillation is of little significance although it must be remembered that these results are for only one station and can be regarded only as representative of the equatorial region. It would be of interest to obtain results for other levels and from stations in other latitudes where long and homogeneous records of stratospheric wind and temperature are available.

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# A COMPARISON OF THE McKENZIE AND SAUNDERS METHODS OF FORECASTING NIGHT MINIMUM SCREEN TEMPERATURES

By W. G. RITCHIE

A test of three methods of forecasting night minimum screen temperatures was carried out at Mildenhall and was reported in the *Meteorological Magazine* of June 1968.* The methods were those due to Craddock and Pritchard, McKenzie, and Saunders using Menmuir and Tinney's cooling curves. The test showed that the McKenzie and Saunders methods gave the best results, and that there was little to choose between them. In view of the speed

* GORDON, J. and VIRGO, S. E.; Comparison of methods of forecasting night-minimum temperatures. *Met Mag, London*, **97**, 1968, pp. 161–164.

and simplicity of the McKenzie method this result seemed surprising, and it was decided to see if the same thing applied to Wyton which is 40 km west of Mildenhall.

Continuous observations for Wyton are available from January 1954. McKenzie constants were computed from observations for the years 1954 to 1967, the number of suitable nights being 386. The constants are shown in Table I.

TABLE I—VALUES OF McKENZIE'S CONSTANT FOR WYTON

| Average surface wind speed | Average low-cloud cover in oktas | | | | |
|---|---|---|---|---|---|
| | 0 | 1–2 | 3–4 | 5–6 | 7–8 |
| *knots* | *degrees Celsius* | | | | |
| Calm | 7 | 6 | 5 | 4 | 3 |
| 1–3 | 6 | 5 | 4 | 3 | 2 |
| 4–6 | 6 | 5 | 4 | 3 | 2 |
| 7–10 | 5 | 4 | 3 | 2 | 2 |
| 11–16 | 4 | 3 | 2 | 2 | 1 |
| 17–21 | 3 | 2 | 2 | 1 | 1 |
| 22–27 | 2 | 2 | 1 | 1 | 1 |

A comparison of the McKenzie method using the constants computed for Wyton, and the Saunders method using Menmuir and Tinney's cooling curves was carried out at Wyton during the two years ending on 30 November 1969. As at Mildenhall this was a true forecasting test done with real forecasts before the event. The test was not done at week-ends or on nights during which there was precipitation. The total number of suitable nights was 392.

The root-mean-square error was 2·6 degC for both methods, and the distribution of errors was similar. To see if the distribution of errors was normal, a normal frequency-distribution curve was drawn for 392 observations with a standard deviation of 2·6. The distribution of errors about the mean was plotted for both methods (Figure 1), and both distributions appeared to be a reasonable approximation to the normal — as was the case at Mildenhall.

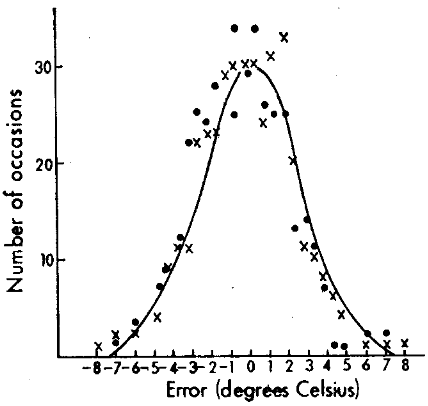



FIGURE 1—DISTRIBUTION OF ERRORS BY THE McKENZIE AND SAUNDERS METHODS

——— Normal frequency-distribution curve
x Errors by McKenzie method
. Errors by Saunders method

The nights were then divided into two seasons, April to September (summer), and October to March (winter). The root-mean-square errors were as follows :

| | Winter | Summer |
|---|---|---|
| | *degrees* | *Celsius* |
| McKenzie | 2·8 | 2·4 |
| Saunders | 2·9 | 2·2 |

This test confirms the Mildenhall conclusions that there is little to choose between the methods as far as accuracy is concerned. Examination of the daily results showed that, as for Mildenhall, when large errors occurred they were common to both methods.

## REVIEWS

*Hydrometeorology*, by C. J. Wiesner. 255 mm × 190 mm, pp. viii + 232, *illus.*, Chapman and Hall Ltd, 11 New Fetter Lane, London EC4 (New York, Barnes and Noble Inc.), 1970. Price: £3·00.

This book is written primarily for hydrologists and in particular for those interested in the estimation of probable maximum precipitation (PMP), and is purposely restricted to the study of the atmospheric phase of the hydrological cycle.

The first eight chapters outline the meteorological aspects. Chapters 1 and 2 describe the hydrological cycle and the atmospheric heat-balance; Chapters 3 to 8 give a brief account of the general circulation and the meteorological elements — temperature, water vapour, wind, pressure, air masses and fronts. What is needed in this section is a chapter on world climatology, with special reference to the climatology of heavy falls of rain. This could have been done with a simplified map of Köppen's classification, illustrated by climatological statistics from a selection of representative stations, giving, as well as monthly mean rainfall, temperature and dew-point, observed extremes of temperature and dew-point, and of monthly and daily rainfall, and giving also for daily rainfall the mean annual maximum fall and the fall with, say, a 50-year return period. This is the fundamental background knowledge wanted by the typical reader.

Chapter 9 gives an account of evaporation and its measurement, with a worked example of Penman evaporation. But data of potential evaporation in different parts of the world should have been given as background information.

Chapter 10 deals with the interrelationships between rainfall depth, duration and return period at a given point, and gives regional formulae for these, with some examples of relations with other parameters such as annual rainfall and thunderstorm days; but only one set of data is given, of annual maximum 5-minute falls for Sydney. How much better if similar sets for different durations had been given for Sydney, and these displayed on extreme probability paper, instead of the blank diagram Figure 10·8, and on a depth-duration diagram instead of the unspecified data of Figure 10·10; and the data used to illustrate the formulae.

Chapter 11 gives a satisfactory account of estimation of areal rainfall, and of depth-duration analysis of storms using the data from an actual Australian storm.

Chapter 12 gives a brief summary of the few useful methods of estimation of snow melt.

Chapters 13 to 15 give a good account of estimations of available water for precipitation and their application to the most useful elementary storm models. Chapter 16 illustrates the estimation of PMP using these models; a case-study for a given area would have made the chapter more lively.

Chapter 18 gives a current list of the world's greatest observed rainfalls for durations from one minute to two years; and maximum depth-duration-area data for the United States, and justifies the generalization of these to make preliminary PMP estimates for other parts of the world. An outline is also given of the Hershfield statistical method for estimating PMP.

The book unfortunately seems to be orientated more towards the university student than to the working hydrologist; but it is the first to cover this field and is welcome.

A. F. JENKINSON

*The value of the weather*, by W. J. Maunder. 220 mm × 145 mm, pp. xxiv + 388, *illus.*, Methuen and Co. Ltd, 11 New Fetter Lane, London, EC4 (New York, Barnes and Noble Inc.), 1970. Price: £3·75 (University Paperback edition £2·00).

At a time when world-wide emphasis is being placed on the importance of the environment and the conservation of those environmental features that are essential to our well-being, it is appropriate that a book of this kind should be available. It is concerned with the involvement of the weather and climate in the affairs of mankind.

In the opinion of James D. McQuigg, writing in the Foreword, the book is important because it clearly emphasizes two important ideas :

'Man is affected both by the atmosphere *and* by information about the atmosphere.

Man is not just a passive object, subject to weather events without recourse, but he can and does react to the atmosphere through his ability to make decisions.'

The author's purpose is 'to bring together, for the first time, the most significant and pertinent associations between man's economic and social activities, and the variations in his atmospheric environment' and he expresses the hope that the book will 'bridge the gap between the physical, dynamical and descriptive aspects of the atmosphere, and the economic, social, political and legal aspects of man and his environment'.

The Introduction, which is but two pages long, stresses the concept of the atmosphere as a 'resource' — 'we have to learn how to live within our climatic income'. Subsequent chapters and their approximate contents are as follows :

*Weather variations*

The natural atmosphere (violent storms, precipitation extremes).

The modified atmosphere (air pollution, atmospheric modification).

*Economic activities*

Primary activities (agriculture, forestry, fishing).

Secondary activities (manufacturing, construction).

Tertiary activities (transportation, utilities, commerce).

*Sociological and physiological aspects*

Human aspects (weather and human behaviour, human classification of climate).

Health aspects (human biometeorology, effects of weather on certain ailments, weather and mortality).

Recreation and sport.

*Economic analysis of weather*

Evaluation of weather and climate (problems of identification and measurement, econoclimatic models).

Applications (regional, national, international).

*Weather knowledge: benefits and costs*

Weather information (types, use, value).

Weather forecasting (atmospheric predictability, presentation of weather forecasts, economic and social value of weather prediction, decision making, benefits and costs of weather forecasting services, foreseeing the future: problems and prospects).

World Weather Watch (history and formulation, the World Weather Watch plan, potential benefits of World Weather Watch).

The modified atmosphere (weather knowledge and modification, economic and social aspects, engineering aspects, medical aspects, controlling the urban environment).

*Political, planning and legal aspects*

Politics and policies (politics and the atmosphere, policies towards weather modification).

Planning aspects (the importance of atmospheric resources, man the modifier).

Legal aspects (the law and the atmosphere, the law and weather modification).

This list of contents has been given as the best means of emphasizing the value of this book which consists principally in its comprehensive sweep over a whole range of disciplines and activities. Examination of particular aspects shows that the treatment is often superficial but the wide bibliography — some 750 references of which more than 400 have appeared since 1965 — offers sufficient inducement for anyone desiring further information.

In the reviewer's opinion, the title of the book, useful though it may be as a means of attracting readers, has its difficulties. There are ambiguities involved in 'value' which, coupled with the additional concept of the atmosphere as a 'resource', lead to minor irritations for the reader.

This book will be of greatest value to forecasters and others with basic knowledge who wish to see weather in its broadest context. Present tendencies are for forecasters to become less involved with the making of forecasts (because of the impact of numerical techniques) and more involved with their application to the needs of the customer. This book will be useful to them in making the necessary adjustments of outlook.

It is hinted in the book that science (as opposed to geography, economics and sociology) is not sufficiently concerned with many of the aspects dealt with, in particular with the changing environment. Readers may therefore wish to note that the International Council of Scientific Unions (ICSU) is setting up a 'Scientific Committee on Problems of the Environment (SCOPE)' which will be concerned with the promotion of environmental monitoring, evaluation of the effects of environmental disturbances, simulation modelling and predictions, and the study of the social effects of man-made changes in the environment.

T. H. KIRK

*Atmospheric circulation systems, International Geophysical Series, Volume* 13, by E. Palmén and C. W. Newton. 230 mm × 160 mm, pp. xvii + 603, *illus.*, Academic Press Inc. Publishers, 111 Fifth Avenue, New York, New York 10003, U.S.A. 1969. Price $26·00.

The aim of this book has been to provide a comprehensive account of atmospheric circulations on all scales from thunderstorms to the mean global circulation of the troposphere and lower stratosphere. In each case the principal observed features and basic structure are described in some detail and a large number of synoptic examples are presented and discussed. Many diagnostic studies, based largely on a thorough review of modern literature, but also supplemented by new work by the authors, are also included and used to illustrate and interpret the roles of the different systems in forming the general climatology and producing the observed weather. Interrelations between the different scales are discussed and emphasis is also given to their budgets and transfers of energy, momentum and water vapour.

The first three chapters are concerned with global mean wind and temperature structures, their seasonal and spatial variability and the mechanism of the general circulation in terms of energy and momentum exchanges. The principal air masses, fronts, jet streams and tropopauses are described in Chapter 4 and the development of the polar front theory in Chapter 5. The next six chapters include detailed treatments of the large-scale extratropical systems, i.e. the planetary waves in the middle and upper troposphere, anticyclones, depressions, jet streams and fronts. These are interrelated and their principal features analysed and linked using theoretical ideas based on baroclinity and vorticity considerations, divergences and computed vertical windfields and three-dimensional trajectories. In addition the conditions for their formation, evolution and dissipation are discussed at some length. The complex relations between the disturbances and weather phenomena are considered in Chapter 12 — and organized convective systems and severe-storm phenomena in middle latitudes are the subject of Chapter 13. The authors then turn in the next two chapters to circulations in the tropics and critically assess modern research and present knowledge of tropical systems including cyclones, hurricanes and typhoons. Chapter 16 is devoted to the general problem of energy conversions in circulation systems and finally

Chapter 17 provides an extended summary of the global picture given in the preceding sections. Some readers may prefer to read this first to obtain an overall view before studying the earlier chapters in detail. Altogether this coverage adds up to a very large amount of subject matter. Many American and some European case studies, which are all well documented and illustrated with several figures, are also included.

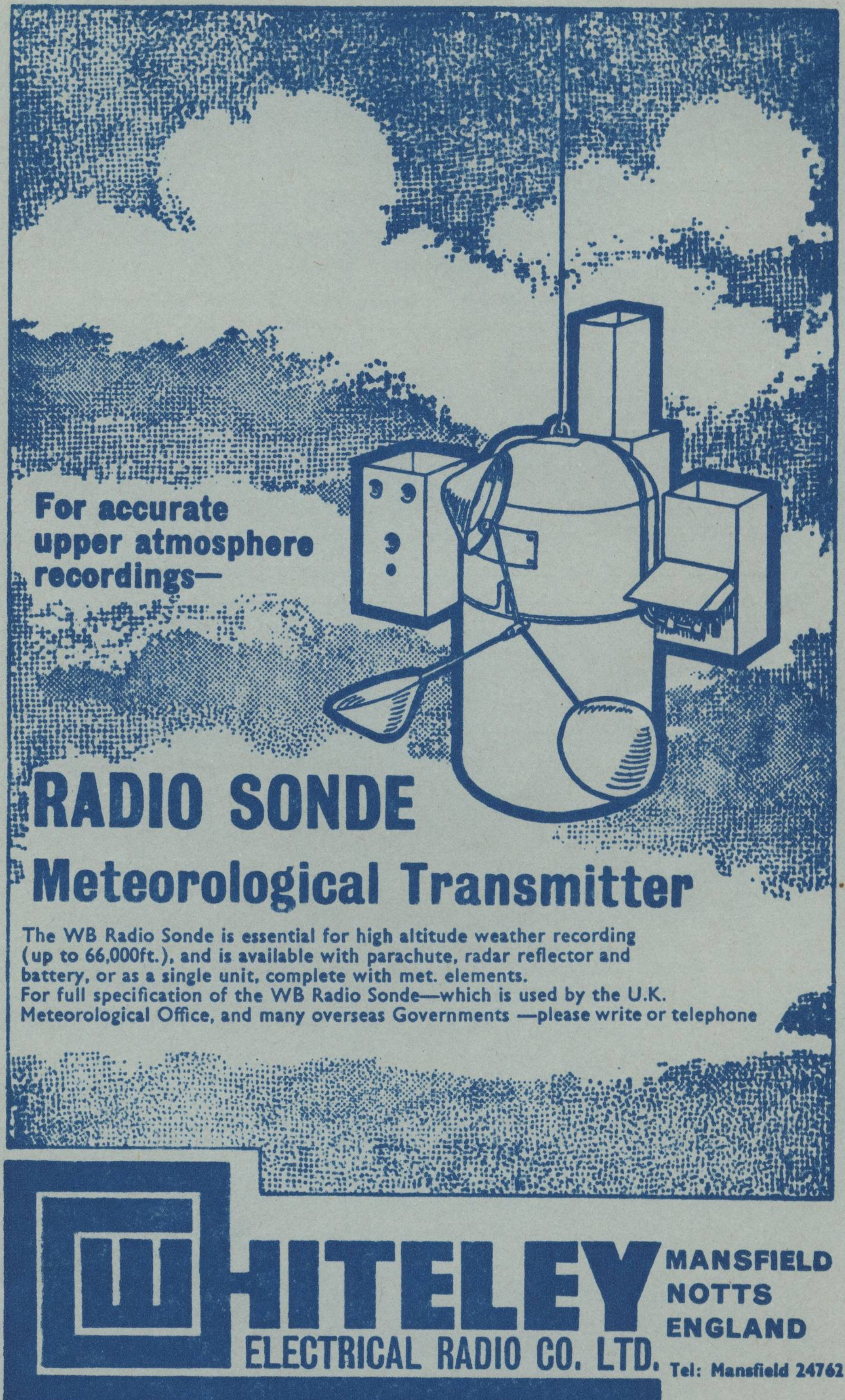
The authors, who are world authorities in this subject, have clearly produced an outstanding addition to the meteorological literature now available to research workers, students and professional meteorologists concerned with understanding and forecasting the movement and development of atmospheric circulation systems. The recent research effort in synoptic and dynamical meteorology has tended to centre on numerical forecasting models and the modern, theoretically well-grounded, diagnostic studies discussed in this book have probably not attracted in recent years the attention they deserve. However, it is these studies, largely expanded and developed in the decade or so following the Second World War and systematically continued over recent years, that have elucidated the main features of atmospheric structure that the models must simulate. The synthesis of results of the diagnostic studies so admirably introduced and presented in this book will be of considerable help to anyone seeking insight into the mechanisms at work. Numerous references are also given for further reading.

Although much of the text is descriptive and non-mathematical a basic knowledge of dynamical meteorology is essential before many of the explanations and interpretations can be fully appreciated. Since the descriptions of the case studies are very detailed (perhaps sometimes excessively so) the reader will often need considerable time and patience before he can fully assimilate many of the conclusions and their implications. Although the production is very good (only a very few minor errors were noted) some of the diagrams are necessarily very complicated and they will also need much detailed study. This, however, will not deter the serious student and in many sections even the casual reader will quickly learn a good deal about the atmosphere from this book. It is certain to come into constant use for a long time by meteorological libraries, universities, and similar organizations concerned with the detailed understanding and study of the atmosphere.

R. J. MURGATROYD

## OBITUARY

It is with regret that we record the death on 29 November 1970, of Mr J. H. S. Manson, Scientific Assistant, Lerwick.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