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PROBABILITY OF AIRCRAFT ENCOUNTERS WITH HAIL

By J. BRIGGS

Summary. Estimates of the probability of aircraft encounters with hail are presented; they depend on several assumptions and cannot do more than indicate probabilities of hail within about a factor of 10. Nevertheless, comparisons made with actual aircraft experience are encouraging. The comparisons are least satisfactory for aircraft flying at the highest levels considered and so the extrapolation to the levels of most concern to supersonic transport may be less realistic, though at these levels the estimates seem more likely to be pessimistic than optimistic as regards the probabilities of large hail being met.

Introduction. Assessments of the chances that aircraft will meet hail are necessary for design purposes. It seems reasonable to base such assessments on meteorological variables for which long-term records are available and which can take account of the regional differences which undoubtedly exist. This note presents estimates of hail probabilities which are based on the incidence of thunderstorms at points on the ground, though it is necessary in obtaining these estimates to make several assumptions, notably concerning the typical hail-cell dimensions as well as variations in the probability of hail occurrence which are due to differences in height. Some comparisons with actual aircraft experience suggest that the estimates are reasonably realistic and can give a fair indication of likely experience of hail encounters supposing that avoiding action, based (say) on airborne or surface radar, is not taken.

Method. If the probability of hail at a point on the ground, or on a particular height level, is P_p and the corresponding probability of hail at any point inside an area of unit radius is P_a then, taking the average hail-cell radius as R $(R \ll 1)$,

$$P_a \approx P_p/R^2.$$

If now no avoiding action is taken, the chance of an aircraft encounter with a hail cell of radius R somewhere during the crossing of an area of unit radius is given by

$$\frac{4P_a\,R}{\pi} = \frac{4P_p}{\pi R}.$$

But if the aircraft speed is V then the time taken to cross the area is $2/V$ and so the chance of a hail encounter in unit time is

$$\frac{2VP_p}{\pi R}. \qquad \ldots (1)$$

Now, suppose the number of thunderstorms per year at a point on the ground is N and that the average duration of hail at the point is t whilst the probability of occurrence of hail of diameter x inches or more during the storm is P_x, then for stones of diameter x or more

$$P_p = \frac{NP_x t}{8760} \qquad \ldots (2)$$

(t in hours). Crossley[1] suggests t as about 1/10 hour.

So, taking V as 500 knots,* equations (1) and (2) indicate that the number of encounters with hail of diameter x or more per flight hour, assuming no avoiding action, is given by

$$3{\cdot}6\times 10^{-3}\,\frac{NP_x}{R}. \qquad \ldots (3)$$

In equation (3) N will vary with the locality whilst P_x will vary with the locality and height.

Variations with locality. Long-period records provide incidence of thunderstorm-days on a world-wide basis, so relative values of N are given almost directly by the number of thunderstorm-days. On the other hand there are few data on which estimates of P_x can be based.

Topographical and other factors play important parts in the production of hail and there are some regions where hail occurs fairly frequently whereas others in the same general climatic régime only rarely have hail. Reports of hail are much less reliable than those of thunder, though isopleths of hail incidence can be produced for most areas. Relative values of P_x for different places can be obtained by consideration of the relative values of the hail-day/thunderstorm-day ratio though this approach has to be used with care for there is no unique hail/thunder relation even for a given place (e.g. at London/Heathrow Airport the peak incidence of hail is in April whereas that for thunder is in June). However, if any small hail is excluded and if comparisons are restricted to places with similar temperature régimes then the hail/thunder ratio can give a good estimate of the P_x variation.

Beckwith[2] used a network of 79 stations in the vicinity of Denver, Colorado, over a period of 10 years. He had 829 reports of hail of which about 80 referred to hail of diameters one inch or larger. These figures suggest that $NP_1 = 0{\cdot}1$. Another estimate applicable to central areas of the United States is due to Souter and Emerson.[3] During flights through thunderstorms they found that 800 traverses were required for each occurrence of one-inch diameter hail or larger. So at the flight levels around 12 000 ft (1000 ft = 305 m) $P_1 = 0{\cdot}00125$. These two estimates agree if $N = 80$ and since

* 1 kt≈ 0·5 m/s

this is in close accord with the reported storm incidence for the Denver area it may be assumed that in this area $N = 80$ and $P_1 = 0{\cdot}00125$ for levels from the ground to about the middle troposphere.

In the tropics, values of N are often large but hail incidence at the ground is usually low. Frisby and Sansom[4] indicate for central Africa and Malaysia values of the hail/thunder ratio which are usually less than 1/5 of the Denver values. This suggests that even for the worst places in these areas P_1 is about 0·00025 in the lower troposphere.

For north-east India, values of thunderstorm and hail incidence are both near the values for the central plains of the U.S. Indeed, these two areas appear to have about the highest incidence of hail in the world. The Denver value of P_1, 0·00125, can be taken as typical of these two areas.

In the United Kingdom hail/thunder ratios are higher than for Denver but, as indicated above, small hail is a complicating factor. It seems unlikely that P_1 values for the United Kingdom will be higher than those for Denver, at least at usual flight levels and indeed it is considered that the Denver value of P_1 can be used for all temperate inland areas, though the values of N will generally be considerably reduced.

For high latitudes and for temperate latitudes over the sea all the evidence indicates that though small hail is relatively frequent large hail is almost unknown. No reliable values for P_1 are available but it is suggested that United Kingdom values will be reduced by a factor of 10 or more.

Variations of P_x with hailstone size. There is little reliable information on the variation of P_x with x. Estimates have been made of the probable size distribution of hail using reasonable assumptions as to equivalent rainfall rates, and of the distribution of the ice-mass amongst stones of different sizes. These estimates (R. F. Jones — unpublished) indicate broadly that the chance of a stone of given size decreases by a factor of 10 for each doubling of the stone diameter. Summers and Paul,[5] reporting on Alberta hail studies in the period 1957–66, show that for stones of diameter exceeding about ½ inch (12·7 mm) the doubling of size is equivalent to a frequency decrease of nearly 10 times. A formula which fits these data well is $P_x = P_0 10^{-x}$ (x in inches). This formula will be assumed here for each area considered. Thus in the lower troposphere and for the Denver/north-east India areas it will be assumed that

$$P_1 = 0{\cdot}00125, \qquad P_2 = 0{\cdot}000125, \qquad P_3 = 0{\cdot}0000125.$$

Variations of P_x with height. The process of hail formation is not yet understood fully but it seems certain that large updraughts are needed, and the stronger the updraughts the more probable are large stones. In a storm cloud the strong currents are likely to penetrate the bulk of the cloud, dying away only towards the cloud top. Thus, in a particular cloud which generates large hail, the chance of a stone of given size occurring at a particular level may be expected to remain fairly constant until towards the cloud top and then to diminish rapidly.

Radar studies of the precipitation content of storm clouds give support to this idea of the distribution of hail. For example, Donaldson[6] found that the median profiles of radar reflectivity for hailstorms over New England showed a concentration of precipitation at 20 000/25 000 ft with a rapid fall-off in precipitation above this region. Similarly, Marshall *et alii*,[7] averaging over summer storms around Montreal, found that the hours in excess of a given intensity of precipitation decrease by about a factor of 10 for each rise of 10 000 ft through the upper levels of a storm.

Radar reflectivity is a measure of the numbers and sizes of large raindrops and hailstones so that reflectivity profiles do not readily indicate the way in which hailstone occurrence varies with height. However, as a first estimate it is reasonable to consider that the chance of a stone of given size is closely indicated by the average reflectivity profile.

Another factor which must affect the overall probability of hail at a given height is the chance of the cloud reaching that height. All clouds which generate large hail are likely to reach near to or beyond the tropopause but even so the frequency with which these cloud tops occur is likely to decrease sharply as the height concerned approaches and exceeds the tropopause. For example, studies (Moore — unpublished) of the height of the highest radar echo in the vicinity of Singapore showed the following percentage frequencies :

TABLE I—PERCENTAGE FREQUENCY DISTRIBUTION OF THE HEIGHTS OF THE HIGHEST RADAR ECHOES NEAR SINGAPORE

Height *km*	Frequency *per cent*	Height *km*	Frequency *per cent*
> 9	85·1	>16	16·6
>10	83·0	>17	9·7
>11	77·7	>18	4·0
>12	68·2	>19	1·4
>13	53·2	>20	0·5
>14	40·2	>21	0·2
>15	27·6		

These figures for cloud-top echo frequency suggest that the probability of occurrence of a hailstone of given size is likely to decrease even more rapidly with height than is indicated by the radar reflectivity profiles. However, for planning purposes the radar profiles may be taken as safely indicating the variation of the hail probability (P_x) with height. Thus, P_x may be taken as constant up to a height in the region 20 000–30 000 ft but then it decreases by a factor of 10 for each rise of 10 000 ft. The depth of the near-constant layer must be related to the average storm depth and so to the tropopause, the lower value (20 000 ft) corresponding to temperate latitudes and the higher value (30 000 ft) corresponding to tropical latitudes. On this basis the variation of the probability of one-inch hail, P_1, with height for the various areas discussed will be assumed as follows :

Denver		United Kingdom		Singapore/central Africa	
0–25 000 ft	0·00125	0–20 000 ft	0·00125	0–30 000 ft	0·00025
35 000 ft	0·000125	30 000 ft	0·000125	40 000 ft	0·000025
45 000 ft	0·0000125	40 000 ft	0·0000125	50 000 ft	0·0000025

Comparison with aircraft experience. British Aircraft Corporation (BAC) height and speed profiles for several aircraft can be combined with the assumed values for N, P_x and R to determine the probable hail experience of the aircraft and to compare with the actual hail experience. In these comparisons the radius (R) of the typical hail cell will be taken as 1 n. mile ($\approx$ 2 km) since the average hail-cell diameter is 1–3 n. miles (Crossley[1]).

(a) *Britannia aircraft.* BAC height and speed profiles indicate the following breakdown of each 30 000 flight hours :

Flight hours	Height range *feet*	Speed *kt*
2 000	0–10 000	300
14 000	10 000–20 000	300
14 000	20 000–30 000	350

With Denver/north-east India values of N and P_x, equation (3) then gives the following probabilities for one-inch hail encounters in 30 000 hours :

Height range *feet*	Probability
0–10 000	0·4
10 000–20 000	3·0
20 000–30 000	2·9
	Total 6·3

Thus, every 30 000 hours flight over Denver/north-east India areas should give 6 encounters with one-inch hail. Similarly there should be 0·6 encounters with two-inch hail or about 16 encounters with two-inch hail in 800 000 hours.

Similarly, United Kingdom values of N and P indicate 1·9 encounters with two-inch hail in 800 000 hours whilst Singapore/central Africa values indicate about 5 encounters in the same time.

Britannia experience over all routes is 2 encounters with two-inch hail in 800 000 hours.

(b) *Viscount aircraft.* BAC profiles indicate all flights between 0 and 20 000 ft at speeds averaging about 233 kt. Table II gives the number of encounters with three-inch hail in $5{\cdot}5 \times 10^6$ hours for specified areas and as actually experienced by Viscounts.

TABLE II—NUMBER OF ENCOUNTERS WITH THREE-INCH HAIL

Denver/north-east India	9
United Kingdom	1¾
Singapore/central Africa	2
Actual Viscount experience	1

(c) *Caravelle aircraft.* The distribution of each 30 000 flight hours is as follows :

Flight hours	Height range *feet*	Speed *kt*
2 000	0–10 000	about 300
2 000	10 000–20 000	about 350
2 000	20 000–30 000	about 425
24 000	30 000–40 000	about 450

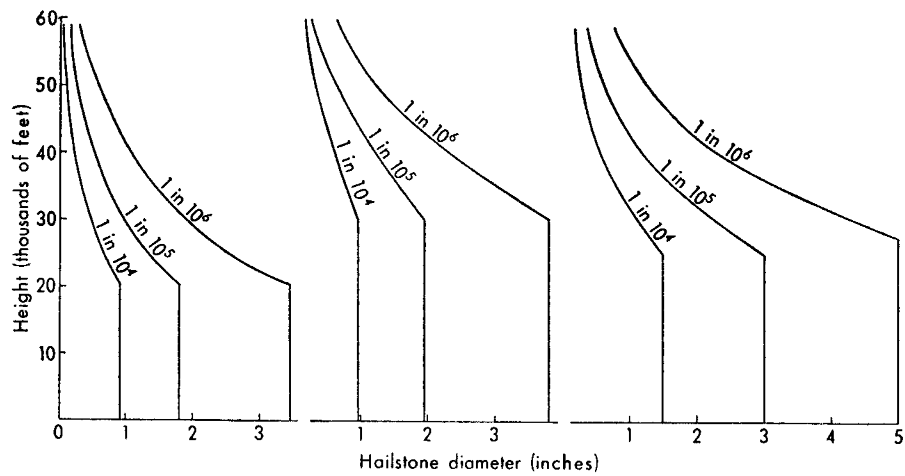
Table III gives the number of encounters with one-inch hail in $0{\cdot}9 \times 10^6$ hours for specified areas and as actually experienced by Caravelles.

TABLE III—NUMBER OF ENCOUNTERS WITH ONE-INCH HAIL

Denver/north-east India	66
United Kingdom	7
Singapore/central Africa	30
Actual Caravelle experience	2

The hail risk is extremely variable from region to region so that the above comparisons are of very limited value without more knowledge of the route histories of the aircraft concerned. For example, the hail risk must be extremely low over most sea areas and over areas such as north Africa and the Middle East. Nevertheless, the comparisons indicate that probabilities based on United Kingdom values are reasonably close to overall experience whilst probabilities for the worst hail areas are likely to be above overall experience by a factor of 10 to 10^2.

Estimates for supersonic transport. Concorde height and speed profiles have been used together with the appropriate values of N and P_x to estimate the hailstone diameter which corresponds to one encounter in 10^4, 10^5 and 10^6 hours of flight at a given level. Figure 1 presents these estimates and shows how the size of stone varies with height for the areas of the United Kingdom, Singapore/central Africa and Denver.



(a) United Kingdom (b) Singapore/central Africa (c) Denver, Colorado

FIGURE 1—ESTIMATED HAILSTONE DIAMETER FOR ONE ENCOUNTER IN 10^4, 10^5 AND 10^6 FLIGHT HOURS (ALL HOURS AT LEVEL OF INTEREST)

REFERENCES

1. CROSSLEY, A. F.; Hail in relation to the risk of encounters in flight. *Met Mag, London*, **90**, 1961, pp. 101–110.
2. BECKWITH, W. B.; Hail observations in the Denver area. Denver, Colorado, United Air Lines, Meteorology Circular No. 40, 1956.
3. SOUTER, R. K. and EMERSON, J. B.; Summary of available hail literature and the effect of hail on aircraft in flight. Washington, National Advisory Committee for Aeronautics, *Tech Note* 2734, 1952.
4. FRISBY, E. M. and SANSOM, H. W.; Hail incidence in the tropics. *J App Met, Lancaster, Pa*, **6**, 1967, pp. 339–354.
5. SUMMERS, P. W. and PAUL, A. H.; Some climatological characteristics of hail fall in central Alberta. Montreal, McGill University, Stormy Weather Group Scientific Report MW-57, 1967, pp. 17–26.
6. DONALDSON, R. J.; Radar reflectivity profiles in thunderstorms. *J Met, Lancaster, Pa*, **18**, 1961, pp. 292–305.
7. MARSHALL, J. S., HOLTZ, C. D. and WEISS, M.; Distribution of rain shower intensity as a function of height. Boston, *Proc Twelfth Conf Radar Met*, 1966, pp. 473–478.

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10 YEARS OF WEATHER OBSERVATIONS FROM MOUNT OLYMPUS, CYPRUS

By J. B. McGINNIGLE

Summary. The auxiliary meteorological station on the summit of Mount Olympus, Cyprus (1936 metres above MSL), completed 10 years of continuous observation cover in March 1971. The development of the station and its equipment are described. Some statistics are presented to assist in the description of the weather there and these are compared with the lower-level Cyprus statistics.

Introduction. Cyprus is a large island which lies at the eastern end of the Mediterranean Sea, at a latitude of around 35°N. The island and its topography can be seen in Figure 1. Cyprus enjoys a good reputation for fine, warm weather and is a popular tourist area. However, the difference between the lower-level weather of the island and the conditions experienced in the mountains is generally not appreciated, although skiing is an advertised attraction during winter. In fact, the winter conditions on the upper slopes of the Troodos Mountains are frequently severe, with high winds, sub-zero temperatures and several feet of snow and ice, often accompanied by freezing fog as cloud caps the peaks. Snowdrifts of up to 12 feet (about 4 m) have been reported.

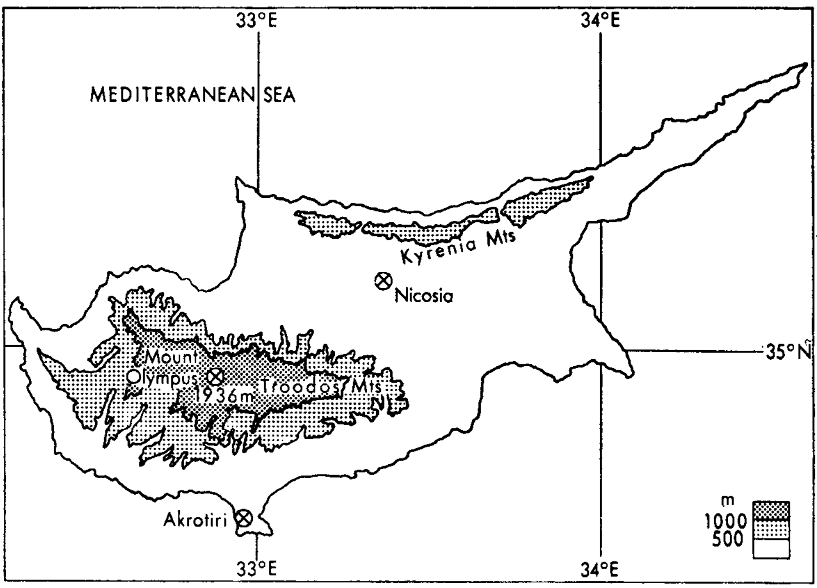

FIGURE 1—MAP OF CYPRUS

The highest summit in Cyprus is Mount Olympus, 1936 metres above MSL, and observations have now been made there for a period of 10 years. The writer has recently compiled statistics from these observations and has also photographed some of the weather conditions there.

The Mount Olympus observing station. The observing station was set up in 1958 and is located just four metres below the summit. By 1959, observations were being made three times daily on most days, at 06, 12 and

16 GMT, but there was no cover between these times or at any other time of the day or night. In March 1961, the commitment was taken over on a voluntary basis by the Royal Air Force Police, who increased observation cover to 24 hours, consisting of the normal 8 routine 3-hourly reports plus a continuous weather watch. At the same time, maximum/minimum thermometers and a rain-gauge were installed and measurements from them were included with the appropriate routine reports. Wind direction was obtained from a simple wind vane while the speed was measured by a standard Meteorological Office cup-generator anemometer mounted on the top of a 10-m pole (1942 m above MSL). The thermometers were housed in a small thermometer screen and rainfall was measured by a Meteorological Office 5-inch rain-gauge and measure.

The observations are telephoned to the Main Meteorological Office in Cyprus for use and dissemination. The form of observations is a little more simple than the standard Meteorological Office product but each observation covers dry- and wet-bulb temperatures, surface wind, cloud cover, state of ground and weather in progress (selected from 10 classifications). Additionally, maximum/minimum temperatures and rainfall are measured.

Plate IV shows the current position of the thermometer screen, which is situated across the road from the guardroom, where the anemometer dials are located. The photograph was taken on a typical summer day in 1970, while the 09 GMT observation was being made.

When the standard cup-generator anemometer was installed in 1958, it very quickly became apparent that the system was of no use for a large part of the year because the cups were frozen solid for most of the winter. A special heated anemometer was developed and this was installed on top of the 10-m pole in December 1963. However, this instrument was only partially satisfactory and icing problems persisted, amply demonstrating the severity of the winter conditions. Many wind observations were lost because of the failure of the anemometer and also because of damage to the wind vane when it was subjected to mean winds of up to 75 knots (1 kt$\approx$ 0·5 m/s).

A new heated anemometer* has since been developed and this was installed in January 1969. The operation of this new instrument has been successful. During 1970, the exposure of the anemometer equipment was improved by mounting an electric wind vane at 1959 m on top of a lattice tower and subsequently moving the heated anemometer to the same position. The latest addition to the anemometer system has been a roll-chart anemograph, suitably modified to operate from the heated anemometer head. This equipment was installed in March 1971 and is now operating satisfactorily.

It is clear from the above that records of wind are incomplete and unreliable and it should also be noted that this applies to other elements, particularly precipitation which it is not always possible to measure and wet-bulb temperature which tends to be reported as equal to dry bulb in freezing conditions. Nevertheless, the observations are of very considerable value for forecasting in Cyprus.

Weather and statistics. In comparison with the lower-lying areas of Cyprus, Mount Olympus weather is markedly colder, precipitation amounts

* HARTLEY, G. E. W.; A heated anemometer. *Met Mag, London,* **99,** 1970, pp. 270–274.

are greater, surface winds are stronger and the annual frequency of fog (often freezing fog in winter) is high because of cloud covering the peak. Winter snow depths are often several feet, with packed ice below and snowdrifts can be up to 12 feet in depth.

Plate V shows typical winter conditions at Mount Olympus; this photograph was taken on 26 March 1971 (the photographs published in the December 1962 *Meteorological Magazine* are also of winter conditions at Mount Olympus, Cyprus). Plate V shows that the snow depth was around three feet (1 m), with packed ice underneath and heavy drifting was observed in the area. At the time, the station was in freezing fog with a temperature of −1°C and a wind speed of 22 knots.

Table I (a) lists some basic climatological statistics for Mount Olympus. Column 1 shows the highest mean winds which have been recorded during the 10-year period. Gust information is not available. It can be seen that winter winds are generally stronger and this is borne out by frequency statistics which have been compiled (not reproduced here).

TABLE I—WEATHER STATISTICS FOR MOUNT OLYMPUS, CYPRUS, APRIL 1961 TO MARCH 1971

(a) Wind, temperature, rainfall and weather

	1	2	3	4	5	6	7	8	9	10	11
	Extreme wind	Mean day max.	Highest day max.	Mean night min.	Lowest night min.	Rainfall: Wet days*	Rainfall: Ex. wet days†	Weather: Fog	Weather: Snow/hail	Weather: Rain/drizzle	Weather: Columns 9+10
	kt	*degrees Celsius*						*percentage frequency*			
Jan.	SW 55	1·7	14	−2·9	−16	11	3	33·8	11·8	3·4	15·2
Feb.	S SW 60	2·2	11	−3·0	−12	8	2	31·3	10·3	1·8	12·1
Mar.	S 72	5·2	16	−1·0	−11	7	1	18·8	7·9	1·8	9·7
Apr.	SW 52	9·7	23	2·3	−08	5	2	9·5	3·3	3·3	6·6
May	SW 47	14·1	25	6·4	−02	5	2	6·2	0·9	3·2	4·1
June	N 51	19·6	27	10·7	03	<1	<1	1·2	0·0	0·3	0·3
July	N 60	22·6	28	13·6	05	1	<1	0·3	0·0	0·3	0·3
Aug.	NE 50	22·7	29	13·9	06	<1	<1	0·2	0·0	0·3	0·3
Sept.	N 42	18·9	28	10·3	02	1	<1	3·7	0·0	0·8	0·8
Oct.	NE 52	13·1	21	6·0	−03	6	2	7·5	0·4	4·7	5·1
Nov.	SW 65	9·5	17	3·3	−10	6	2	12·7	2·3	5·1	7·4
Dec.	SW 75	3·7	16	−0·9	−10	13	5	28·2	11·0	7·0	18·0

* Wet day ⩾ 1·0 mm/24 hours
† Extremely wet day ⩾ 10·0 mm/24 hours

(b) Snowfall

	First snowfall	Last snowfall	Last snow on ground
Mean date	3 December	9 April	24 April
Extremes	21 November	23 March	2 April
	16 December	4 May	7 May

Columns 2 and 3 list maximum-temperature information. The midwinter mean maxima are shown to be not far above freezing, although the extremes indicate that mild spells have occurred, with temperatures rising to above 10°C. Summer temperatures are quite high with the extreme having risen as high as 29°C.

Night minima are shown in Columns 4 and 5 and these indicate how cold it can be on the summit of Mount Olympus. The mean values for 4 months of the year are below freezing and the extremes warn that the temperature may fall below freezing on any night during 8 months of the year.

Columns 6 and 7 show the distribution of 'wet days' and 'extremely wet days'. The definitions of these terms are given below Table I (a). Because the rain-gauge is sometimes buried under deep snow and ice, it has not been possible to calculate mean monthly rainfall figures for the winter months. Columns 6 and 7 show that precipitation is frequent in winter and is of very high intensity on several days in these months. Midsummer precipitation is infrequent but tends to be of high intensity (convective) when it occurs.

Columns 8 and 9 give the percentage frequencies of fog and freezing precipitation. These figures indicate that the peak is likely to be covered with cloud for almost one-third of the time during January, with almost as high frequencies in December and February. The frequency becomes progressively less towards summer, being quite low (0·2 per cent) in high summer, before increasing again towards winter.

A similar seasonal pattern applies to freezing precipitation, although the frequency figures are less, ranging from 12 per cent in January to no occurrence in summer. However, it is evident from Column 10 that non-freezing precipitation occurs throughout the year, though rather rarely in summer. The percentage frequency of precipitation of any type is shown in Column 11, indicating that December is the month in which there are most reports of precipitation.

Finally, mean snowfall information is reproduced in Table I(b). Snow is relatively late in coming to Mount Olympus but, once started, it persists into spring and is reported as covering the ground to some degree for almost 5 months.

Comparison with lower-level climate. Table II lists the results of a comparison of the Mount Olympus readings with those taken in the central plain just west of Nicosia (Figure 1) at an altitude of 220 metres. The Mount Olympus mean monthly maxima and minima appear to bear a conservative relationship with those of Nicosia. The mean difference in the mean maxima is 13·2 degC with a range of only 1·6 degC, while the comparable information for the minima is 8·0 degC and 1·7 degC.

The rainfall comparisons, for both amount and frequency, confirm a statement of greater rainfall at Mount Olympus. With the one exception of June, the mean monthly rainfall of the peak is greater than that of Nicosia — usually more than double. The June anomaly is also reflected in the frequencies as the only positive value, albeit only one day.

Concluding remarks and acknowledgements. While midsummer conditions at Mount Olympus can be very attractive — when, for instance, the temperature in the central plain is rising above 35°C every day — the summit experiences severe weather at times during most of the year. In particular, the midwinter conditions are very bad, and great credit is due to the many Royal Air Force policemen who have been voluntary meteorological observers during the last 10 years, working at times in the most difficult of conditions.

The writer would like to thank the Officer Commanding, Royal Air Force, Mount Olympus, for his permission to photograph the observing station, and also the Officer Commanding 230 Sqn (Det) Helicopters, Royal Air Force, Nicosia, for his valuable co-operation which enabled the writer to photograph Mount Olympus weather conditions from the air.

TABLE II—COMPARISON OF MOUNT OLYMPUS AND NICOSIA TEMPERATURE AND RAINFALL STATISTICS

	TEMPERATURE						RAINFALL					
	Average daily maximum			Average daily minimum			Monthly average			Wet days* per month		
	Mount Olympus	Nicosia	Difference	Mount Olympus	Nicosia	Difference	Mount Olympus	Nicosia	Difference	Mount Olympus	Nicosia	Difference
			degrees Celsius					*millimetres*				
Jan.	1·7	14·6	12·9	−2·9	5·8	8·7	—	64·6	—	11	9	−2
Feb.	2·2	15·3	13·1	−3·0	5·6	8·6	—	42·9	—	8	7	−1
Mar.	5·2	17·8	12·6	−1·0	6·9	7·9	—	30·5	—	7	6	−1
Apr.	9·7	23·1	13·4	2·3	10·1	7·8	42·7†	17·3	−25·4	5	3	−2
May	14·1	28·2	14·1	6·4	14·2	7·8	50·7	17·9	−32·8	5	2	−3
June	19·6	32·6	13·0	10·7	18·1	7·4	4·3	9·6	5·3	<1	1	<1
July	22·6	35·6	13·0	13·6	20·7	7·1	11·6	0·9	−10·7	1	<1	−<1
Aug.	22·7	35·8	13·1	13·9	21·0	7·1	4·0	1·7	−2·3	<1	<1	0
Sept.	18·9	32·1	13·2	10·3	18·3	8·0	25·2	4·7	−20·5	1	1	0
Oct.	13·1	27·2	14·1	6·0	14·8	8·8	65·0	31·0	−34·0	6	3	−3
Nov.	9·5	22·0	12·5	3·3	11·2	7·9	70·9	29·4	−41·5	6	4	−2
Dec.	3·7	16·7	13·0	−0·9	7·8	8·7	—	76·3	—	13	8	−5
Mean values			13·2			8·0						

* Wet day ⩾ 1·0 mm/24 hours
† Includes 8 days when precipitation was reported but not recorded.

Mount Olympus statistics : April 1961 to March 1971 = 10 years.
Nicosia statistics : January 1943 to December 1968 = 25 years.

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THE DIURNAL VARIATION OF GLOBAL RADIATION ON A HORIZONTAL SURFACE — WITH SPECIAL REFERENCE TO ABERDEEN

By R. W. GLOYNE

Summary. The broad features of the mean diurnal course of global radiation on a horizontal surface — when meaned over a sufficient number of days (say 10 at least) — may be reproduced either by a sine curve or by a (sine)^2 curve.

If S = mean daily integral of global radiation, T = day-length, t = time from sunrise, and $\alpha = \pi\, t/T$, the intensity $G(t)$ at time t is given by

$G(t) = (\pi S/2T)\sin\alpha$ (Monteith) or $G(t) = (2S/T)\sin^2\alpha$ (Gloyne).

The accuracy of the methods were examined (a) by comparing actual and computed monthly values of mean daily peak intensities at Aberdeen for June 1966 to May 1967, (b) by comparing the durations above three threshold levels, and (c) by their success in reproducing the detail of the mean diurnal course for July 1970. (In almost all comparisons a simple arithmetic mean of the estimates by the two methods was superior to either estimate separately.)

Introduction. Information is required by a range of interests on the variation during the day of the intensity of global radiation (and of illumination) on a horizontal surface. Some inquirers require estimates of the length of period when the intensity was above or below or between stated levels.

Centres providing direct data on an hourly basis are relatively few, although there are more which record the daily integral; furthermore, much of the readily available published data is in the form of daily integrals, meaned over varying periods and generally for calendar months. In addition one can — with varying degrees of accuracy — estimate the mean daily integral from data on the duration of bright sunshine.

The present contribution draws attention to certain useful empirical methods of representing the diurnal variation of mean daily global radiation, and tests the accuracy of some derived estimates against 12 months of data obtained from a recently installed solarimeter at the University of Aberdeen. It was the lack of data from regions such as north-east Scotland and the hazard of interpolating from, for example, data from long-period stations, such as the Observatories at Lerwick and Eskdalemuir, which led to the case study from which this paper has been compiled.

In passing it should be noted that it is not necessarily useful if acceptable statistical relationships are obtainable only for mean values over long periods; in many practical cases relationships are needed which can be used for periods of individual months or even shorter duration.

Analysis. For a given latitude and solar declination, global radiation on a horizontal surface is broadly a function of solar altitude which in turn is a function of cos H, where H is the local hour angle.

Trial plots of the diurnal march of global radiation, when meaned over a sufficient number of days (say 7 to 10 at least, and more generally for a month), suggest that the course is approximately sinusoidal. Monteith* has stated that there is a useful relationship with that portion of a sine wave comprised within the argument $\pm\,\pi/2$ from the maximum point, i.e. that at local apparent noon (LAN). The writer, whose immediate interest was in the circumstances at the ends of the day, i.e. at times of relatively low

* MONTEITH, J. L.; Light distribution and photosynthesis in field crops. *Ann Bot, London*, **29**, 1965, pp. 17–37.

intensities, suggests that for certain purposes the relevant portions of the diurnal curve may possibly be better reproduced by a (sine)^2 curve. (See Figure 1 (a) and (b).)

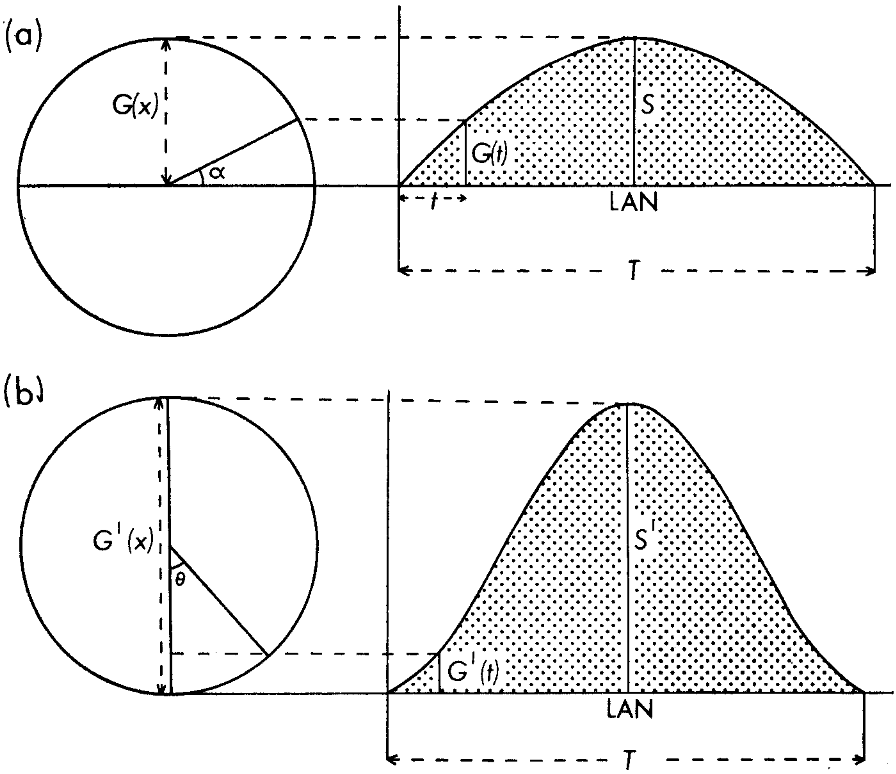

FIGURE 1—CO-ORDINATE SYSTEMS FOR ESTIMATION OF DIURNAL COURSE OF GLOBAL RADIATION ON A HORIZONTAL SURFACE

(a) After Monteith (b) After Gloyne

(a) *Monteith's method.* In Figure 1 (a) let

$G(t)$ = intensity of global radiation on a horizontal surface at time t (measured from sunrise)

$G(x)$ = intensity at LAN and assumed to be the maximum for the day

T = day-length

S = daily integral and equal to the area under the curve

$\alpha = \pi t/T \; (0 \leqslant t \leqslant T)$.

Then, with origin at sunrise

$$G(t) = G(x) \sin \alpha. \qquad \ldots (1)$$

It is easy to show that

$$S = G(x)\, 2T/\pi$$

and hence

$$G(t) = \frac{S}{T} \frac{\pi}{2} \sin \frac{\pi t}{T}. \qquad \ldots (2)$$

Also for a given threshold intensity G,

$\tau = (T/\pi) \sin^{-1} (G/G(x))$,

where 2τ = total period when $G(t) < G$

and $T - 2\tau$ = the duration of global radiation of an intensity above the threshold values.

(b) *Gloyne's method.* Using dashed symbols $G'(t)$, $G'(x)$ and S' and $\theta = 2\pi t/T$ $(0 \leqslant t \leqslant T)$ the alternative expressions are (Figure 1 (b)) :

$$G'(t) = \tfrac{1}{2}G'(x)\,(1-\cos\theta), \qquad \ldots (3)$$
$$S' = \tfrac{1}{2}G'(x)\,T,$$

therefore

$$G'(t) = (S'/T)\,(1-\cos\theta), \qquad \ldots (4)$$

$$1 - G'(t)\frac{T}{S'} = \cos\theta = \cos\left(\frac{2t}{T} \cdot \pi\right);$$

and for a given threshold G,

$\tau = (T/2\pi) \cos^{-1} (1-(G/S')T) = (T/2\pi)\cos^{-1} (1-2G/G'(x))$,

where 2τ is the total period when $G(t) < G$ and $T - 2\tau$ is the period with global radiation above the threshold intensity.

Since $\theta = 2\alpha$, equation (4) may be written

$$G'(t) = (S'/T)\,2\sin^2\alpha. \qquad \ldots (5)$$

A preliminary comparison of estimates is informative. Consider the value of the expressions $G(t)/(S/T)$ and $G'(t)/(S'/T)$ at various values of t:

t	0	$T/6$	$T/4$	$T/3$	$T/2$
Method (a)	0	0·79	1·11	1·36	1·57
Method (b)	0	0·50	1·00	1·50	2·00

The difference in the shape of the curves is evident. From $t = 0$ to beyond $T/4$ Method (a) gives the higher value; equality is reached at $\sin^{-1}\pi/4$ (about $51\frac{1}{2}°$ or $T/3{\cdot}5$) after which Method (b) gives the higher estimate and an indicated maximum at LAN approaching 1·3 times that for Method (a). Of necessity the bounding curve for Method (b) is narrower than for Method (a). The important point is, of course, which of the two is the better approximation to the observed values. The second representation, i.e. that by a $(\text{sine})^2$ curve, corresponds to a complete sine wave from trough to trough with an oscillation occurring around a base-line equal to half the maximum radiation.

(c) For future reference, if S is assumed equal to S', note the approximate expression relating to the arithmetic mean of the two estimates, namely

$$\tfrac{1}{2}(G(t) + G'(t)) = (S/2T)\sin\alpha\,((\pi/2) + 2\sin\alpha). \qquad \ldots (6)$$

(d) In Figure 2 the basic features of the results are illustrated using data for a month (July 1970) not included in the original data.

Results. Hour-by-hour actual values and estimates by both methods of the mean intensities for each month in the period June 1966 to May 1967 (inclusive) were plotted on convenient scale (specifically: abscissa $\frac{1}{2}$ in = 1 hour, and ordinate 1 in = 10 mW/cm², for all except winter months of November to February when a large scale, usually 4 in = 10 mW/cm², was used).

A check on the accuracy of free-hand drawing of the diurnal curves was made by measuring the area under the curves and comparing the results with mean daily integral as recorded; the errors were less than ±1 per cent for all months except October (+ 1·2 per cent) and January (+ 2·8 per cent).

Examination of graphs — such as Figure 2 — shows that in general the observed daily march of global radiation assumes a course intermediate between the two empirical representations. Method (a) tends to overestimate, while Method (b) tends to underestimate duration above a threshold intensity except for approximately the middle third of the day; accordingly a simple arithmetic mean of the separate estimates might be expected to give a better representation than either of the individual estimates.

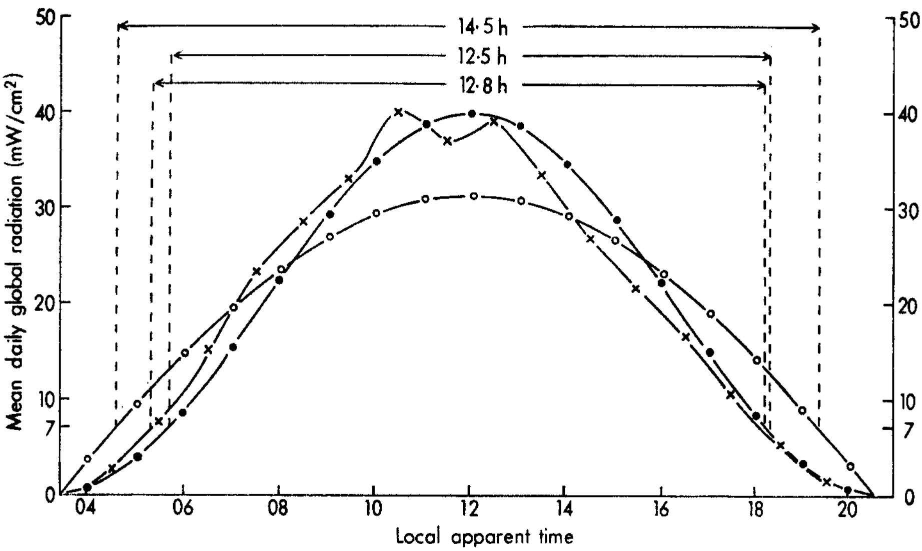

FIGURE 2—DIURNAL COURSE OF MEAN DAILY GLOBAL RADIATION FOR ABERDEEN, JULY 1970

x———x Observed values
o———o Estimated (Monteith)
•———• Estimated (Gloyne)

The adequacy of the empirical representations was examined in three ways.

(a) *Table I.* This compares the peak intensity as recorded (mean value over 60 minutes) with the computed maxima at LAN *(G(x), G′(x))*.

TABLE I—COMPARISON OF MONTHLY MEAN VALUES OF THE MEASURED MEAN DAILY MAXIMUM INTENSITIES WITH EMPIRICAL ESTIMATES AT LOCAL APPARENT NOON (ABERDEEN)

	1967				1966							
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					milliwatts per square centimetre							
Measured	9·6	18·7	33·1	42·6	47·3	40·4	45·6	34·2	30·2	17·8	10·7	5·8
Method (a)	8·3	16·3	31·1	38·3	41·4	30·4	40·1	28·9	28·4	16·1	9·7	5·8
Method (b)	9·6	20·7	39·6	48·8	52·7	38·6	51·0	36·8	35·3	20·5	12·4	7·4
Mean of (a) + (b)	9·0	18·5	35·3	43·5	47·1	34·5	45·6	32·9	31·9	18·3	11·1	6·6
Deviation of mean from measured	−0·6	−0·2	+2·2	+0·9	−0·2	−5·9	0·0	−1·3	+1·7	+0·5	+0·4	0·8

(b) *Table II.* This compares the estimated and measured periods above selected threshold intensities, namely :
  (1) 7 mW/cm² (equivalent to 800 foot-candles — the requirement which led to the current investigation).
  (2) An intensity equal to 50 per cent of the observed maximum. For the estimated periods the threshold used was 50 per cent of the empirical maximum.
  (3) As for (2) but at the 75 per cent level.

(c) *Table III.* This shows the complete daily march of global radiation for July 1970 (i.e. a particular month outside the period June 1966–May 1967).

The underestimate by Method (a) reaches a maximum of about 10 mW/cm² in June but otherwise is numerically less than 5 mW/cm²; the largest overestimate by Method (b) is 6·5 mW/cm² in March; otherwise the errors are numerically less than 3 mW/cm² in 7 of the 12 months; using a simple arithmetic mean the largest error is in June, otherwise it is less than about 2 mW/cm².

On duration above stated levels (Table II), the arithmetic mean of the two estimates leads in most months to an error in duration of one-half hour or less for intensities $\geqslant$7 mW/cm², usually less than one hour (June excepted) associated with the 50 per cent peak intensity, and for the 75 per cent level, 1·0 mW/cm² or less for 10 of the 12 months. It should perhaps be emphasized that the actual value of the peak intensity and the estimated values all differ and hence necessarily the 50 and 75 per cent levels; by hypothesis the estimates are to be derived *solely* from a knowledge of the mean daily integral and the day-length.

Since values for short periods are required, 10-day means were also formed (1–10, 11–20, 21–(30, 31 or 28)), and the actual data and the estimates from Method (b) plotted; the intercepts at 7 mW/cm² were measured from the 'actual' and the estimated curves. The errors incurred were almost all underestimates with an absolute value of one hour or less. Accordingly from this particular sample it might be concluded that the method is capable of giving results for means over 10 days as reliably as over a calendar month.

The results illustrated in Figure 2 and set out in Table III merit some attention. In general terms Gloyne's method gives the closer fit for this particular sample, although the use of a simple arithmetic mean between the two estimates gives a close general fit except during the middle of the day. It is perhaps a matter for comment that a rather closer fit in this instance arises if Gloyne's curve is displaced to the left by 30 minutes (i.e. his value for hh + 30 being associated with the actual values for hh). It is perhaps worthy of note that June 1966 — the month giving rise to the largest deviations — was very dull (Aberdeen 55 per cent of possible sunshine) and hence perhaps atypical.

Conclusions.

(a) From a limited sample, it has been found that many features of the diurnal course of mean daily total radiation on a horizontal surface (meaned over periods of at least 10 days) can be reproduced, given mean daily total and day length, either by a sine curve with maximum at LAN (Monteith) or by a (sine)² curve (Gloyne).

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Photograph by M. G. Phillips

PLATE I—TORNADO OVER NICOSIA, 3 AUGUST 1966

See page 53

Photograph by K. M. Jones

PLATE II—HOUSE DAMAGED BY TORNADO

See page 55

Photograph by K. M. Jones

PLATE III—TREE UPROOTED BY TORNADO

See page 55

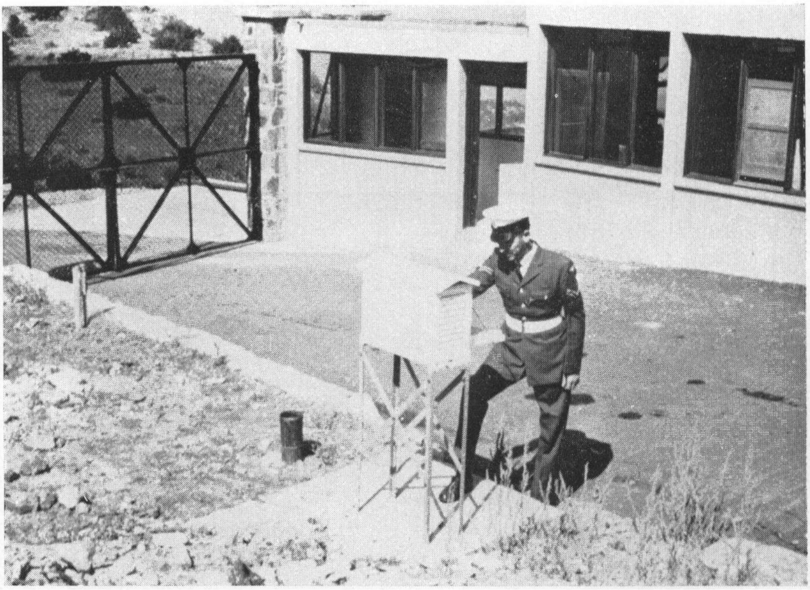

PLATE IV—MOUNT OLYMPUS OBSERVING STATION, CYPRUS, IN SUMMER 1970

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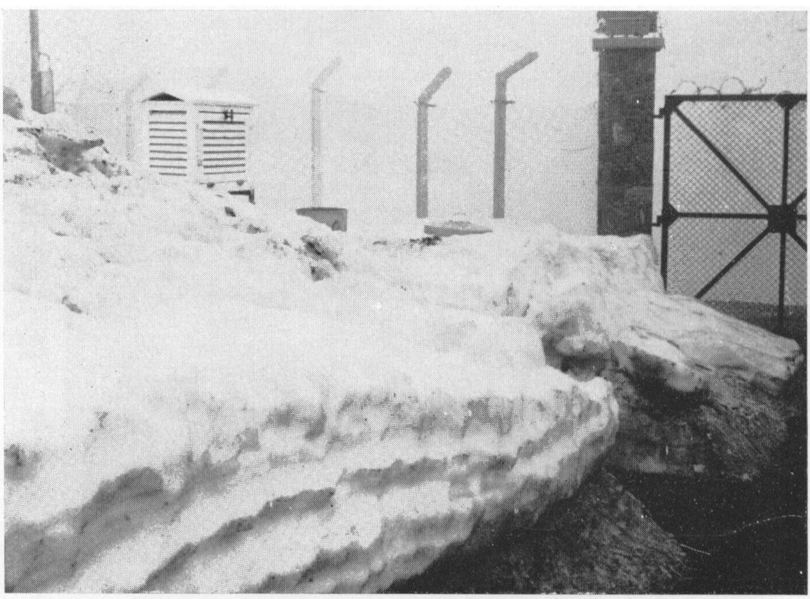

PLATE V—MOUNT OLYMPUS OBSERVING STATION, CYPRUS, 26 MARCH 1971

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PLATE VI—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES AND AIR VICE-MARSHAL D. G. EVANS

Left to right : Mr H. H. Lamb, Corporal R. Cotton, Major K. G. Groves, Air Vice-Marshal D. G. Evans, Mrs K. G. Groves, Squadron Leader G. F. Holbrook and Flight Lieutenant T. J. Kenny (see page 62).

TABLE II—COMPARISON OF MEAN MONTHLY VALUES OF DAILY DURATIONS OF INTENSITIES AS MEASURED AND AS ESTIMATED

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(1) For intensities ⩾ 7 mW/cm²						*hours*						
Measured	2·4	6·4	9·4	11·9	13·5	13·0	13·7	11·9	9·9	6·7	3·8	0·0
Method (a)	2·7	6·9	10·1	12·6	14·7	15·0	15·4	12·9	10·8	7·2	4·0	0·0
Method (b)	2·6	5·7	8·6	10·8	12·6	12·9	13·1	10·9	9·2	6·3	3·8	0·9
Mean of (a) and (b)	2·7	6·3	9·4	11·7	13·7	13·9	14·3	11·9	10·0	6·7	3·9	0·5
Deviation of mean from measured	0·3	−0·1	0·0	−0·2	0·2	0·9	0·6	0·0	0·1	0·0	0·1	0·5
(2) For intensities ⩾ 50 per cent peak intensity, either measured or estimated												
Measured	3·7	5·4	7·3	8·3	9·4	8·7	10·1	8·6	7·7	6·0	4·7	4·7
Method (a)	4·9	6·3	7·9	9·5	11·0	11·9	11·5	10·2	8·5	6·9	5·4	4·3
Method (b)	3·7	4·8	5·9	7·1	8·3	8·9	8·6	7·6	6·4	5·2	4·1	3·2
Mean of (a) and (b)	4·3	5·6	6·9	8·3	9·7	10·4	10·1	8·9	7·5	6·1	4·7	3·8
Deviation of mean from measured	0·6	0·2	−0·4	0·0	0·3	1·7	0·0	0·3	−0·2	0·1	0·0	−0·9
(3) For intensities ⩾ 75 per cent peak intensity, either measured or estimated												
Measured	2·2	3·3	5·0	5·7	5·3	5·2	6·5	5·0	5·6	4·4	3·2	3·3
Method (a)	3·4	4·4	5·4	6·6	7·6	8·2	8·0	7·0	5·9	4·8	3·7	3·0
Method (b)	2·5	3·1	3·9	4·7	5·5	5·9	5·7	5·0	4·2	3·4	2·7	2·1
Mean of (a) and (b)	2·9	3·8	4·7	5·6	6·5	7·1	6·8	6·0	5·1	4·1	3·2	2·6
Deviation of mean from measured	0·7	0·5	−0·3	−0·1	1·2	1·9	0·3	1·0	−0·5	−0·3	0·0	−0·7

TABLE III—INTENSITY OF GLOBAL RADIATION THROUGHOUT THE DAY (MEAN VALUES FOR ABERDEEN, JULY 1970) AT THE HALF HOUR AS MEASURED AND AS COMPUTED; TOGETHER WITH ERRORS OF ESTIMATE

Method	Time (GMT) 0430	0530	0630	0730	0830	0930	1030	1130	1230	1330	1430	1530	1630	1730	1830	1930
	milliwatts per square centimetre															
Measured	2·4	7·4	14·9	23·0	28·2	32·8	39·8	36·8	39·0	33·5	26·9	21·6	16·7	10·7	5·5	1·8
Method (a)	6·4	11·8	16·8	21·3	25·0	27·9	29·9	31·0	31·0	29·9	27·9	25·0	21·3	16·8	11·8	6·4
Deviation of (a) from measured	4·0	4·4	1·9	−1·7	−3·2	−4·9	−9·9	−5·8	−8·0	−3·6	1·0	3·4	4·6	6·1	6·3	4·6
Method (b)	1·7	5·7	11·6	18·6	25·5	31·9	36·7	39·3	39·3	36·7	31·9	25·5	18·6	11·6	5·7	1·7
Deviation of (b) from measured	−0·7	−1·7	−3·3	−4·4	−2·7	−0·9	−3·1	2·5	0·3	3·2	5·0	3·9	1·9	0·9	0·2	−0·1
Mean of (a) and (b)	4·1	8·7	14·2	20·0	25·3	29·9	33·3	35·1	35·1	33·3	29·9	25·3	20·0	14·2	8·7	4·1
Deviation of mean from measured	1·7	1·3	−0·7	−3·0	−2·9	−2·9	−6·5	−1·7	−3·9	−0·2	3·0	3·7	3·3	3·5	3·2	2·3

(b) For estimates of the LAN (peak) intensity and of the duration above, below or between stated levels of intensity, the value obtained by meaning the two estimates appears the most successful (the error in the duration usually being but a fraction of an hour).

(c) Except perhaps in the winter months, there are indications that the (sine)^2 curve gives a somewhat better representation of the daily course — at any rate in higher latitudes.

(d) Obviously the above findings should be subjected to extensive tests before a firm recommendation on the best procedures is possible.

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A REPORT OF CLEAR-AIR TURBULENCE ASSOCIATED WITH A LARGE TEMPERATURE CHANGE

By J. D. PERRY

Details of a report of severe clear-air turbulence over the southern Mediterranean, associated with a rapid temperature rise of 8 degC, were given recently by McGinnigle.[1]

A further occurrence of clear-air turbulence also associated with a large temperature change is of interest, in that the upper winds were by no means similar to those previously reported. On this occasion at 0141 GMT on 4 August 1970 a Boeing 707 encountered light to moderate clear-air turbulence at 18 000 ft (5·5 km) during descent into Bahrain Airport with a simultaneous temperature change of 11 degC, while at about 0215 GMT a second aircraft reported moderate to severe turbulence at the same height with a temperature change of 7 degC.

The synoptic situation showed a seasonal pressure pattern with a complex low-pressure area covering West Pakistan, central south Arabia and much of Persia. The reports, which were made within a few hours of the midnight Bahrain radiosonde ascent, Figure 1, were found to have occurred in the transitional zone between low-level north-westerly winds and upper easterly winds (see Table I). A marked inversion had been a feature of this zone for several days and the midnight ascent showed an inversion of 7 degC in 10 mb at about 500 mb.

TABLE I—BAHRAIN UPPER WINDS, 4 AUGUST 1970

mb	00 GMT	06 GMT *degrees knots*	12 GMT
850	335 23	350 21	350 21
800	340 19		335 20
780		335 14	
700	335 08	320 12	315 18
655	345 07		
650		320 13	
600	010 04		320 11
575		320 09	310 06
531	065 05		
500	095 07	155 08	195 10
486			130 14
470		125 18	
450		105 18	
440	100 18		
430			105 19
400	085 18	105 19	100 22
358	080 19		
300	090 20	090 21	110 17

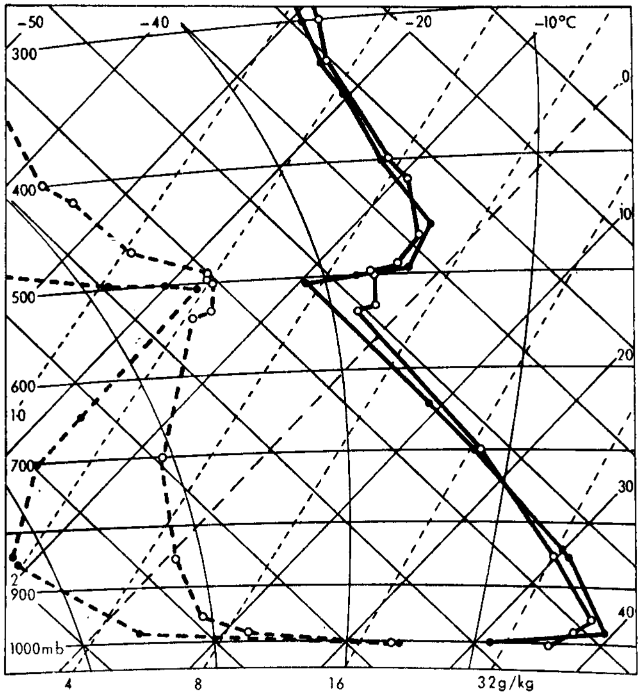


FIGURE 1—BAHRAIN ASCENTS, 4 AUGUST 1970

00 GMT		12 GMT	
.———.	Temperature	o———o	Temperature
. - - - - .	Dew-point	o - - - o	Dew-point

Discussion. A study of the upper air charts shows the air at 700 mb to have originated over the desert and this flow is representative of the virtually dry adiabatic layer which extends from 850 mb to 500 mb, whereas the subsided air above 500 mb is tropical in character.

The wind shear of 30 knots (1 kt $\approx$ 0·5 m/s) in the dry adiabatic layer between 850 mb and 500 mb is sufficient to produce turbulence (the Richardson number for this layer being about 0·8), and evidence that vertical motion was present on this occasion is given by the working sheets of the midnight Bahrain radiosonde ascent which show a significant increase in the rate of ascent in the layer between 640 mb and 505 mb. The actual rates of ascent were :

Surface to 640 mb	5·9 m/s
640 mb to 505 mb	6·5 m/s
505 mb to 400 mb	6·1 m/s

Dry convection is typical of desert air. However, the turbulence reported occurred in the shallow layer of the inversion in which the aircraft experienced the large changes of temperature. The ascent in the layer below the inversion and the shallow layer of turbulence associated with the marked inversion are indicative of the turbulent motion suggested by Townsend,[2] who used a laboratory model (in which a stably-stratified fluid overlay an unstable layer) to study the disturbance of a stable layer by convective columns. The results of this study showed that convection in the unstable layer is sufficient to produce internal waves within the interface between the two fluids. Townsend further suggested that the energy of these waves would be dissipated in shallow patches of turbulence.

Evidence that mixing was occurring on the occasion on which turbulence was observed is given by the Bahrain radiosonde ascents, Figure 1, which show that considerable mixing had taken place between 540 mb and 460 mb between midnight and midday, resulting in erosion of the previously marked inversion. It is therefore suggested that the main mechanism of the turbulence, which was confined to the shallow inversion layer and was associated with a large temperature change, was the dissipation of convectionally induced internal waves.

Acknowledgement. The author would like to thank Dr W. T. Roach for his constructive comments.

REFERENCES

1. MCGINNIGLE, J. B.; An occurrence of highly localized clear-air turbulence over the southern Mediterranean. *Met Mag, London*, **99**, 1970, pp. 208–211.
2. TOWNSEND, A. A.; Natural convection in water over an ice surface. *Q J R Met Soc, London*, **90**, 1964, pp. 248–259.

551.515.3

TORNADO AT NICOSIA, CYPRUS, 3 AUGUST 1966

By K. M. JONES and R. F. WILLIAMS

Summary. Just before 12 GMT (2 p.m. local time) on 3 August 1966 a tornado developed to the west of the Strovolos district of Nicosia and caused substantial damage to property and vegetation as it subsequently tracked northwards across the western part of the city. Although dust devils are quite common over inland districts of Cyprus during the summer months, tornadoes, which have a similar mechanism, are comparatively rare. The tornado is described in relation to its environment and the synoptic situation prevailing at the time.

Observations and effects of the tornado. One of the Nicosia Meteorological Office staff, Mr M. G. Phillips, was travelling between the airfield and Nicosia city (see the map of the area — Figure 1). He was fortunately able to photograph the tornado and give an eye-witness account of its progress (the tornado could not be seen from the Meteorological Office because of intervening high ground and generally hazy conditions).

The photograph (Plate I) was taken at 1155 GMT from the position shown in Figure 1 with the tornado about 2 miles* away to the east. Although it is not clear from the photograph, Mr Phillips recorded the normal snake-like tornado column rising to the base of the cloud from the low-level umbrella-shaped mass of rising dust and debris. The rotation appeared to be anti-clockwise or cyclonic. The tornado was associated with a thunderstorm which had developed over Nicosia.

Mr Phillips continued his journey towards Nicosia and then northwards out of the city. He recalled that the tornado was still visible to the south-east (approximately in the position shown in Figure 1) when he was passing

* 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.

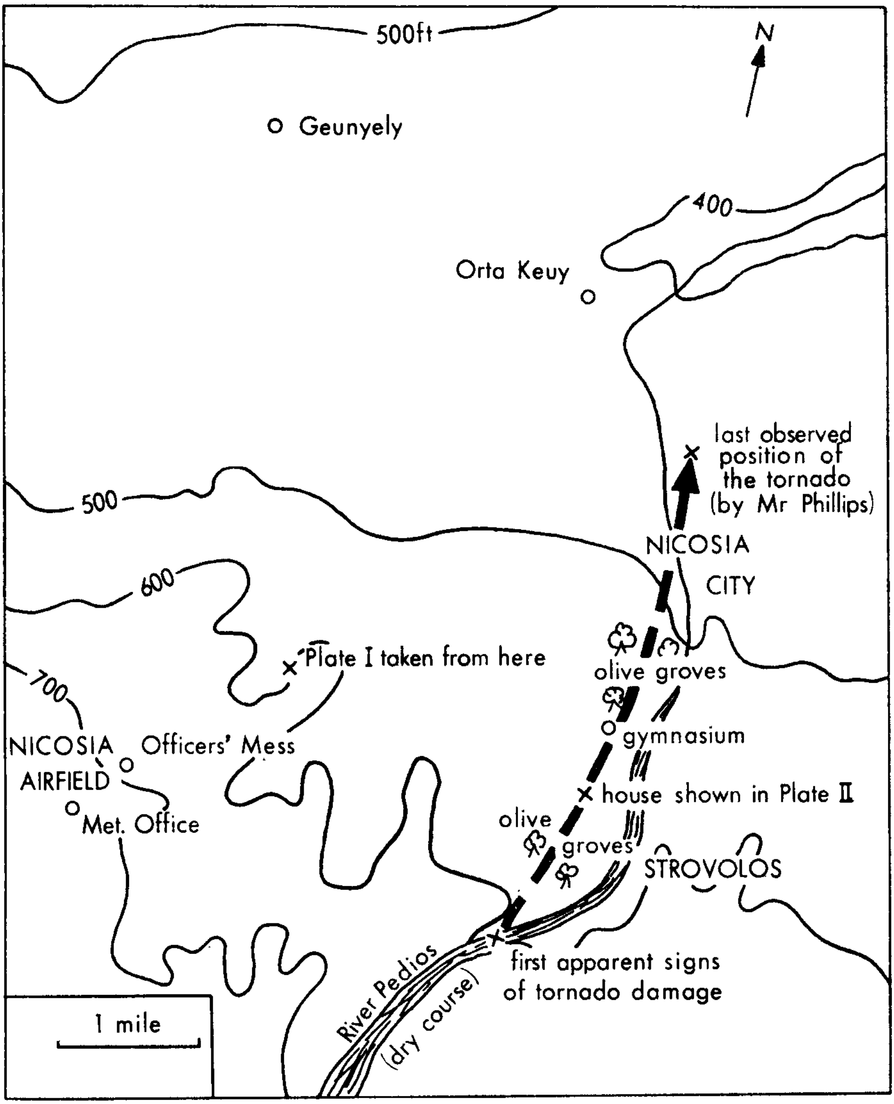


FIGURE 1—MAP OF NICOSIA AREA SHOWING THE TORNADO TRACK

through the village of Orta Keuy at 1220 GMT. Subsequently he drove north-westwards towards Geunyely but could not see any further signs of the tornado itself owing to the large amount of dust haze and general atmospheric obscurity in the direction of Nicosia city. However, he did observe a well-developed dust devil rising from ground-level to about 2000 ft in a position about 5 miles north-east of Geunyely at 1235 GMT. Although this was obviously not the remains of the tornado itself (it was too far north and was divorced from the main cloud system with which the tornado had been associated) its occurrence is relevant to the discussion which follows later.

An attempt to trace the path of the tornado by inspection of the damage inflicted was made the following day. The first signs of damage appeared in the position indicated in Figure 1 amongst the vegetation on the periphery of the dry flat bed of the river Pedios. The trail of damage then led north-north-eastwards into the western part of the Strovolos area through an extensive area of olive groves. Trees in the direct path of the tornado sustained considerable damage with branches as thick as 6 to 12 inches being torn away from the main trunk. The most spectacular area of damage was found about one mile north of the area where the initial damage began and a house in the track of the tornado at this point suffered extensive damage (Plate II). The tiles of the roof were blown outwards, as were the windows of an adjoining house, thus exhibiting the usual signs of explosive damage associated with the rapid reduction of air pressure outside the buildings, as is common with tornadoes. About 25 yards further on from the house a large tree was uprooted (Plate III). As the tornado proceeded north from this position it passed over the buildings of the Kykko gymnasium where structural damage in the form of loss of roofing and blown-out windows was again observed. Further damage to trees was evident where the tornado had passed through another olive grove some 300 yards north of the gymnasium but from eye-witness reports and lack of any further evidence of damage on the northern side of this grove it appears that the tornado had begun to diminish in intensity at this point. Judging from the observations recorded by Mr Phillips it appears that the tornado maintained its identity as a revolving disturbance for at least another mile north of the second olive grove, i.e. 3 miles north of the original area of damage, although the actual length of the trail of damage was about 2 miles. Based on the length of time (40 minutes) between the time that Mr Phillips took his photograph and his final sighting of the disturbance, it appears from the distance the tornado travelled that it was moving quite slowly (about 3 miles per hour), at least in its latter stages of life.

Discussion. Figure 2 shows the surface chart for the eastern Mediterranean at 12 GMT on the day in question. The usual surface pattern at this time of year is a shallow trough of low pressure extending westwards from the seasonal low over Iraq to the vicinity of Cyprus. As can be seen from Figure 2

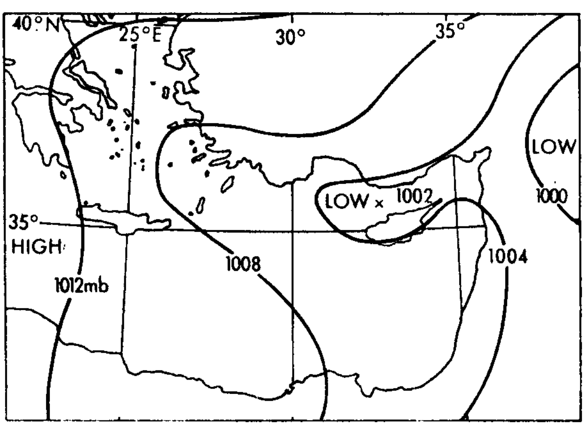


FIGURE 2—SURFACE ANALYSIS, 12 GMT ON 3 AUGUST 1966

this trough was well defined on the day in question with a suggestion of a separate cell of low pressure to the north-west of Cyprus. There was a trough adjacent to the island at all levels up to and including 300 mb and this was well marked at 700 mb. By 00 GMT on 4 August the axis of the 700-mb trough had moved to the south-east of Cyprus and winds at this level over the island had veered from south-west to north-east.

Wallington[1] lists four favourable criteria for the development of a tornado :

(a) The presence of a cold front.

(b) Moist unstable air from the surface to several thousand feet.

(c) A stable layer above the moist air.

(d) A deep layer of unstable and relatively dry air above the stable layer.

The 12 GMT upper air sounding for Nicosia on 3 August 1966 (Figure 3) appeared to satisfy the last three of Wallington's criteria, as detailed above, fairly well. Conditions up to 14 000 ft were very moist and unstable and a stable layer between 14 000 ft and 19 000 ft capped the moist lower levels and in turn was beneath a deep layer of dry unstable air.

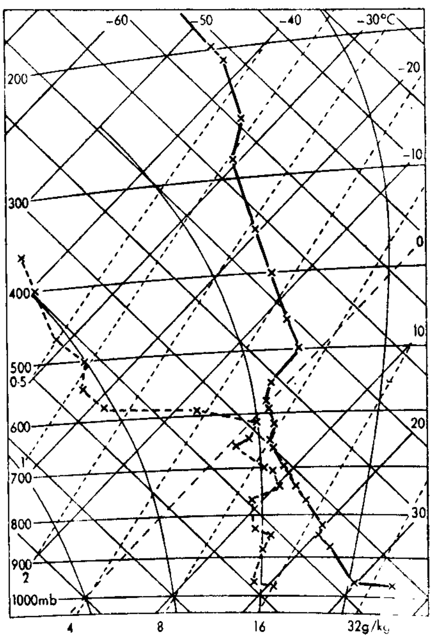


FIGURE 3—NICOSIA ASCENT, 12 GMT ON 3 AUGUST 1966

x———x Temperature   x – – – – x Dew-point

Although no surface cold front was evident on the 12 GMT surface chart on the day in question an important factor which must be taken into consideration is the onset of the west-north-westerly sea-breeze in the vicinity of Nicosia. The sea-breeze front appears almost certainly to have been the 'trigger' for the thunderstorm and associated tornado that afternoon. This sea-breeze front appears to have satisfied the first of Wallington's criteria in the manner detailed below.

Conditions prior to the arrival of the sea-breeze at Nicosia were quite moist. The island had been surrounded by very moist stagnating surface air for several days prior to 3 August and dew-points around the coasts of Cyprus were around 24°C. Even well inland at Nicosia the morning dew-point was around 20°C. This was well above normal even for August. Light easterly winds prevailed at Nicosia Airfield during the morning and the approach of the westerly sea-breeze was heralded by a line of cumulus cloud observed just to the west of the airfield at 1045 GMT. The sea-breeze front arrived at the airfield at 1120 GMT with a rapid reversal of the surface wind direction to west-north-westerly and an increase in mean speed from around 7 kt to a mean of 18 kt with gusts to 28 kt. Figure 4 shows the anemograph trace at Nicosia Airfield around this time. At the time of the passage of the sea-breeze front across the airfield the cumulus cloud appeared to be developing with base estimated at 6000 ft and tops 12 000 to 14 000 ft. No precipitation was observed at the Meteorological Office but there was apparently a shower at the Officers' Mess on the camp. As well as halting the morning rise in temperature at 35°C, the sea-breeze front also brought in a supply of moist maritime air and thus further increased the moisture content of the surface layers. In the next half hour the line of cumulus continued its slow eastward progress away from the airfield and towards Nicosia city and rapidly built

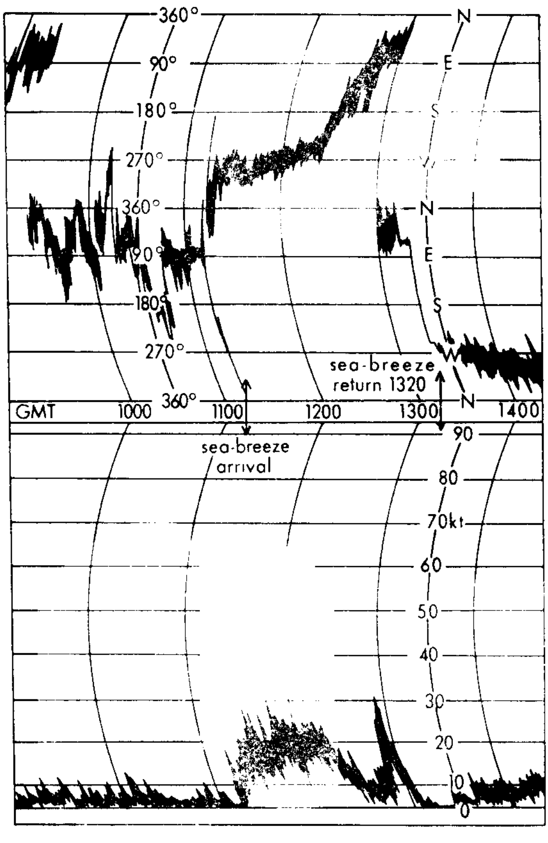


FIGURE 4—DIAGRAMMATIC REPRESENTATION OF ANEMOGRAPH CHART FOR NICOSIA AIRFIELD FOR 3 AUGUST 1966

into cumulonimbus proportions with one estimated top reaching at least 30 000 ft. The 12 GMT tephigram for Nicosia (Figure 3) clearly shows this to be possible. It is feasible that a sea-breeze from the south and east coasts of Cyprus had opposed the westerly sea-breeze and added to the general convergence taking place over Nicosia, but apart from the light easterly wind during the morning at the airfield there is insufficient observational evidence to confirm this.

Unfortunately there were no radar reports of the storm area but the fairly short duration of the thunderstorm (which from accounts lasted for less than one hour in Nicosia itself) and light upper winds with little vertical shear suggest that the tornado was not associated with the formation of a severe storm as described by Browning.[2] On this particular occasion it seems evident that the thunderstorm was entirely due to the normal convergence on the sea-breeze front combined with the abnormally high moisture content of the lower layers of the atmosphere, high temperatures and generally unstable conditions. The sighting of a well-developed dust devil by Mr Phillips in a position almost due north of Nicosia adds to the evidence that local vortices were developing on the sea-breeze front that day. Figure 5 shows

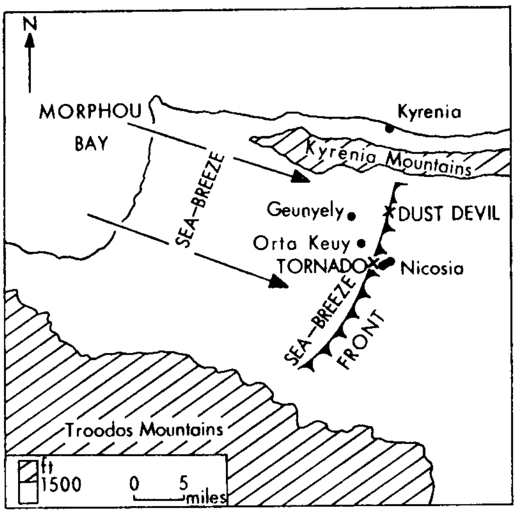


FIGURE 5—ESTIMATED POSITION OF SEA-BREEZE FRONT OVER NORTH-WEST CYPRUS AT ABOUT 12 GMT ON 3 AUGUST 1966

the estimated position of the sea-breeze front over the western plain area of Cyprus at about 12 GMT on 3 August with the positions of the tornado and observed dust devil marked. The trigger action for these revolving disturbances was probably a local unusually large superadiabatic lapse rate in the air close to the ground combined with some local microscale configuration of topography that might be conducive to rotation of the air. These conditions could well be produced in a small hollow or gulley. The appearance of the first signs of damage on the edges of the fairly wide (about 30 yards) dried-up bed of the Pedios river with rising ground on each side (see Figure 1) fits in with this fairly well.

As can be seen from the anemograph trace (Figure 4) the surface wind at Nicosia Airfield changed from the westerly sea-breeze direction to north-east with a gust of 31 knots at 1253 GMT. This was probably a downdraught effect from the thunderstorm to the east. The wind reverted to a westerly direction at 1320 GMT as the thunderstorm decayed and ceased to influence the local winds in the area around it.

Conclusions. On the day in question it would seem that the combination of marked instability, an environment curve fulfilling fairly well those conditions listed by Wallington,[1] high temperatures of both the surface layers of air and the ground, convergence associated with both the upper trough and the sea-breeze front and, finally, sufficiently moist air in the lower layers to allow condensation, produced the necessary conditions for the quite common phenomenon of a dust devil to develop into the comparatively rare phenomenon of a tornado.

Acknowledgement. The authors are grateful to Mr Phillips for his account of the tornado and his photograph.

REFERENCES

1. WALLINGTON, C. E.; Meteorology for glider pilots. London, John Murray, 1961.
2. BROWNING, K. A.; The organization of severe local storms. *Weather, London*, **23**, 1968, pp. 429–434.

REVIEWS

Meteorology: a historical survey, by A.Kh. Khrgian. 245 × 173 mm, pp. iv + 387, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem). Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1970. Price: £10.

The only substantial volume on the history of meteorology known to the reviewer is Volume 1 of Napier Shaw's *Manual of meteorology*,* so that there is ample room for Professor Khrgian's new book, which takes the historical survey up to 1920. It is a much longer book than is Shaw's and must be the result of very careful research and reading in the literature of textbooks, papers and reports of international meetings of meteorologists. It also has the advantage of seeing the later period with the hindsight of another 35 years and so of being able to put emphasis in the right place.

The author rightly deals briefly with the first phase of speculation and the introduction of instrumental observation, and gives most space to the phase divided from the first by the acquisition of the ability to communicate observations which led to meteorological institutes, national services, synoptic meteorology and the professional meteorologist. We can see clearly in the narrative the forces which made meteorology important about the mid 19th century: different needs for different nations, illustrated by the state department in which the service found its greatest support — in Russia, the Naval Department and the Department of Mines; in the U.S.A., the Signal Service;

* SHAW, Sir N.; Manual of meteorology. Volume 1 — Meteorology in history. London, Cambridge University Press, 1932.

in the U.K., the Board of Trade — and then the need for international co-operation, so clearly seen and so well founded that today we regard it as natural.

The author also reviews the meteorological thought of the 19th century when synoptic charts were beginning to yield up the typical mid-latitude weather patterns and the problems of explaining the mechanisms became of prime importance. Some remarkably successful ideas, considering the total lack of upper air observations, and some otherwise, were put forward and argued about, and if now some of the controversies seem as irrelevant as the Morphy–Anderssen match, they were nevertheless very real. Cyclones, anticyclones, fronts (though not so named) and the general circulation are some of the subjects that claimed a great deal of attention. Towards the end of the period under survey came the exploration of the upper air, which simplified some old problems but inevitably raised new ones. Throughout the period meteorologists were laying not only the foundations of synoptic meteorology but also of climatology both by the taking and recording of observations and by theorizing about them.

Professor Khrgian gives the history of his period in a lot of detail and it cannot fail to fascinate and educate the meteorologist of today. If he errs occasionally on the side of parochialism by over-emphasizing the contributions of his countrymen, then let it be so, for Shaw was also parochial and the author is simply redressing the balance. The translation reads well with just the odd infelicity of phrase and of retranslating names which have been transcribed into Russian.

E. KNIGHTING

World survey of climatology, Volume 13 Climates of Australia and New Zealand, edited by J. Gentilli. 300 mm × 215 mm, pp. x + 405, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Barking, Essex, 1971. Price: £17.

The editor of this volume, Dr J. Gentilli, Reader in Geography at the University of Western Australia, has been carrying out research in climatology in Australia since 1940. Consequently he is well qualified to contribute the vast majority of the description of Australian climate himself.

He has chosen deliberately to write a dynamic account of the spatial relationships of climate, rather than a static description. However, it is claimed that the inclusion of numerous maps still makes it possible to obtain a large amount of detailed factual knowledge by interpolation. This approach leads the reader from a description of the position of Australia in the General Circulation of the Southern Hemisphere (contributed by Dr U. Radok, Department of Meteorology, University of Melbourne), through a discussion of climatic factors such as duration and intensity of sunshine, albedo of the surface and ocean temperatures, to an account of the dynamics of the Australian troposphere. Then follows quite naturally the key chapter on the main climatological elements and a shorter chapter on climatic fluctuations.

The last three chapters of the book deal with the climate of New Zealand and are written by W. J. Maunder of the Department of Geography, University of Otago, Dunedin, New Zealand. A similar treatment is used here, a chapter on the causes of the main types of airflow in New Zealand being followed by a description of the elements of New Zealand's climate and the climatic areas of New Zealand. At the end are over 100 pages of detailed climatological tables for Australia and New Zealand, which some readers would undoubtedly consider the most valuable part of the whole book.

This is a beautifully printed and bound volume, and the style of writing makes it easy to read and to assimilate the information. The maps are very clear but a statement such as 'more than 80 Campbell-Stokes sunshine recorders are now in use' (in the whole of Australia) makes one wonder how accurate are some of the isopleths. In places the underlying physical ideas are woolly, e.g. page 123 'the source of heat is the cloudless interior'. What a pity, too, that a really good topographical map is not included near the beginning of the book.

There is no evidence that the book is aimed at one particular class of reader, but appears rather to be a broad survey which will be of value to a wide spectrum of people interested in the climatology of Australia and New Zealand. To an industrialist considering the location of a new factory, the book could well provide all the information required. To a hydrologist or research climatologist it is an excellent 'launching pad' and the copious references to original sources at the end of each chapter will suggest many profitable avenues of investigation. As a general work of reference it fulfils its role admirably and many librarians will be very anxious to have a copy on their shelves.

P. D. BORRETT

World survey of climatology, Volume 14 Climates of the polar regions, edited by S. Orvig. 300 mm × 215 mm, pp. x + 370, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Barking, Essex. Price: £14·75.

Established meteorological observing stations are sparse in the polar regions and a considerable part of the available data come from discontinuous and short-lived series provided by expeditions and drifting ice stations. Observational backing is insufficient for the climatological statistics normally compiled by the meteorological services; on the other hand there is at present little requirement for applied climatology as in the developing countries. So it is to be expected that this volume will differ to some extent, in its approach, from the more conventional and factual texts and climatological handbooks. A substantial part of the book is in fact devoted to climatic tables for a number of stations, but in using them the limitations of the data must be borne in mind.

The volume is in three sections dealing respectively with Greenland, the North Polar Basin and Antarctica. Because of the regions' differing topography, particularly in regard to their effects on the atmospheric circulation, there is a good deal of emphasis on synoptic and dynamic climatology. Synoptic charts are not detailed enough, and upper air observations are too sparse for the study of the structure of individual depressions and anticyclones. The activity of these systems has often to be inferred from derived data, for example 24-hour pressure and temperature changes at fixed stations, zonal and meridional indices, and changes with time of thickness and lapse rate. The section on Greenland provides the clearest example of these methods. Greenland is an elevated ice-sheet extending through more than 20° of latitude, its southern extremity lying on the fringe of the mid-latitude westerlies. Its role as a barrier to the westerlies and to depressions approaching from west or south-west (problems of great interest to European forecasters) is thoroughly discussed from several of the indirect viewpoints mentioned above. Geographical factors, and their climatic effects, are emphasized in the sections on the other two regions. The North Polar Basin is a level, mostly ice-covered, surface, with no topographical complications, so that a single observing station is usually representative of a large area. Antarctica, on the other hand is an elevated ice-cap more or less symmetrical about the pole.

Because a large proportion of the observing stations have been established for scientific rather than purely utilitarian purposes in the reporting network, they are equipped for the more sophisticated as well as the standard observations. So the book deals climatologically with such factors as radiation and the heat balance, and phenomena special to the polar regions such as whiteout, ice crystals in the air, ageostrophic flow caused by rugged topography and sharp temperature differences at the water–ice boundaries.

All this results in a mine of information on a very large number of topics — difficult reading if too much is attempted at once, so essentially a reference book. It is an exhaustive contribution to meteorological knowledge of the polar regions. It is copiously and well illustrated with charts and diagrams, and my only criticism is that a few maps showing the names and locations of places mentioned in the text would have helped the reader.

A. G. FORSDYKE

AWARDS

L. G. Groves Memorial Prizes and Awards

The 25th award of prizes was made on Friday, 26 November 1971, at the Ministry of Defence, Whitehall, by Major and Mrs K. G. Groves. The Assistant Chief of Air Staff (Operations), Air Vice-Marshal D. G. Evans, C.B.E., presided and the ceremony was attended by the Director-General of the Meteorological Office. (See Plate VI.)

The 1971 Aircraft Safety Prize has been awarded to Flight Lieutenant D. R. Clark, RAF Regiment, formerly of Royal Air Force Coningsby. Flight Lieutenant Clark is at present serving overseas and was unable to attend this ceremony, but arrangements have been made for him to receive his prize at his present station. The citation for this award is as follows :

'Under existing arrangements, if an aircraft has used the Rotary Hydraulic Arrester Gear (RHAG) on landing, the hookwire is re-tensioned by an 84 lb lever pulley hoist affixed to an ACRT crash vehicle. Flight Lieutenant Clark has devised a lightweight pulley which is not only 63 lb lighter than the present hoist but which also enables the re-cycling process to be effected in about 7 minutes as compared with the present average of 12 minutes. The quicker restoration of runway availability could be vital if other aircraft were simultaneously in difficulty.

He has also successfully tackled another aspect of RHAG operations in devising an Aircrew Indicator Board for conveying signals to pilots. The device consists of a rotatable illuminated sign, for attachment to an

ACRT crash vehicle, to replace the existing arrangement which requires RHAG operators to communicate with pilots by the less satisfactory medium of hand signals.

The lightweight pulley is to be adopted for all RHAG installations in the Royal Air Force and the Indicator Board is also being considered for wide application.

In devising practical improvements to 2 separate aspects of RHAG operations which materially enhance their effectiveness, Flight Lieutenant Clark has made an important contribution to flight safety in the Royal Air Force.'

The 1971 Meteorology Prize has been awarded to Mr H. H. Lamb, Senior Principal Scientific Officer, Meteorological Office, with the following citation :

'Mr Lamb has over many years carried out important studies of past climates and of the causes of climatic change. During the past year his unique and comprehensive study of the effects of volcanic dust on weather and climate was published by the Royal Society. This is of great importance at the present time since it provides an indication of the climatic effects of natural dust against which the significance of man-made dust as a climatic factor can be assessed. Mr Lamb's work is likely to be the standard reference on the subject for many years to come.'

The 1971 Meteorological Observers Award has been awarded to Squadron Leader G. F. Holbrook, D.F.C., formerly of Royal Air Force Farnborough, with the following citation :

'Squadron Leader Holbrook was OC Meteorological Research Flight from July 1966 to August 1970. Throughout this period he spared no effort to understand the scientists' requirements so that he could always give valuable advice on the flying aspects and organize aircrew support in order that these requirements were met as far as aircraft and safety considerations allowed. As a pilot his flying on research projects was always carried out with care and the highest possible accuracy and contributed both directly and by example to the success of the meteorological research flights carried out during his four years with the Flight.'

The second Memorial Award for 1971 has been awarded jointly to Flight Lieutenant T. J. Kenny and Corporal R. Cotton, Royal Air Force Akrotiri, with the following citation :

'In the Lightning flight simulator, the practice of emergencies which involve ejection presently terminates with a token pulling of the ejection handle. In reality however seat ejection does not occur until the canopy has jettisoned, and if because of some malfunction the latter does not happen the pilot is compelled to adopt an alternative drill. Although a thorough knowledge of such procedures is an integral part of pilots' continuation training the simulator makes no provision for a realistic portrayal of this particular situation.

Flight Lieutenant Kenny devoted much effort to resolving this problem and, with the assistance of Corporal Cotton, certain modifications were devised which permit the whole ejection sequence to be realistically simulated and the various emergencies properly rehearsed. In applying themselves to this problem and achieving a workable solution Flight Lieutenant Kenny and Corporal Cotton have made a valuable practical contribution to flight safety.'

NOTES AND NEWS

Retirement of Mr H. H. Lamb

On 31 December 1971 Mr H. H. Lamb retired from the Meteorological Office after more than 30 years' service.

In the earlier years of his career Mr Lamb was largely engaged in aviation forecasting, and in particular with the early stages of transatlantic aviation. He worked as a forecaster at Foynes, then one of the principal transatlantic terminals, from 1939 to 1945. However, from the earliest stage of his meteorological career Mr Lamb has contributed to research; his work on North Sea stratus in particular sprang from his experience as a forecaster at Montrose.

In 1946 Mr Lamb was asked by the Director of the Meteorological Office, Sir Nelson Johnson, to sail on the whaling ship *Balaena* to the Antarctic waters in order to study the requirements of whaling activities for meteorological services. Despite the very limited synoptic data Mr Lamb was able to develop a number of important studies on the weather and climate of the Antarctic seas from his experience of eight months in these waters and has continued to maintain a keen interest in southern-hemisphere meteorology ever since. He is a member of the international working group on Antarctic meteorology of SCAR (the Scientific Committee on Antarctic Research).

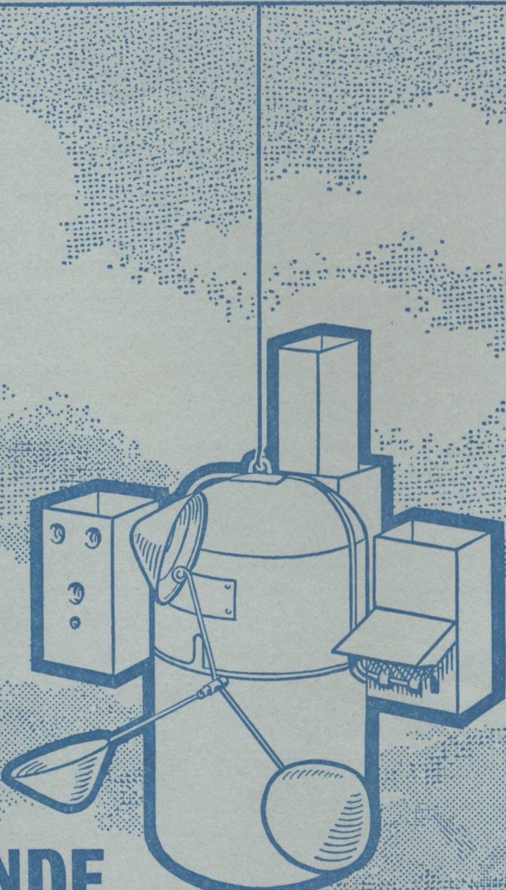
However, it is the study of variations in the general circulation of the atmosphere and of climatic changes in particular to which Mr Lamb has devoted most of his efforts during recent years. He has collected evidence on climatic change on all time scales from a wide variety of sources and by a variety of methods. His catalogues of daily weather types are widely used and his monthly mean pressure charts back to the year 1750 provide a unique means of studying the changes in general circulation. Moreover, his ability to seek out relevant historical and other evidence of climatic change, and to provide a meteorological interpretation has been particularly fruitful in building up a coherent picture of the climate of the past.

Mr Lamb was granted a special merit promotion to Senior Principal Scientific Officer in 1963 in recognition of his research work and in order that he could continue his climatic-change studies without administrative responsiblity. Mr Lamb has now accepted an Honorary Professorship at the University of East Anglia and has left the Office to take up his new post as Director of the Climate Research Unit in the School of Environmental Sciences at the University. His colleagues in the Meteorological Office take this opportunity of expressing their wishes for the fruitful continuation of his studies of climatic change in his new environment.

J. S. SAWYER

OBITUARY

It is with regret that we record the death on 23 October 1971, of Mr R. Jenner, Senior Scientific Officer, Met. O. 8.



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