167

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METEOROLOGICAL OFFICE

Scientific Paper No. 19

Some Further Observations from Aircraft of Temperatures and Humidities near Stratocumulus Cloud

by J. G. MOORE, B.Sc.

LONDON: HER MAJESTY'S STATIONERY OFFICE

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Contents

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INTRODUCTION

Observations made in 1955 by the Meteorological Research Flight near anticyclonic stratocumulus cloud were analysed by James.[1]* All showed sharp temperature inversions and hydrolapses above the cloud top, while significant turbulence was encountered up to 300 feet above the cloud top.

From an analysis of the heat and water-vapour budgets of the cloud and air below, James suggested that a balance could be maintained only by large-scale subsidence in the inversion layer above cloud. His analysis also suggested that the coefficient of turbulent diffusion in the inversion layer, *K*, was greater by night than by day, being of the order of 10^4 cm^2 sec^{-1} by night and 3×10^3 cm^2 sec^{-1} by day. Subsidence rates of 3 mb hr^{-1} and 1 mb hr^{-1} respectively would be required to balance the transport of heat and water vapour associated with these values of *K*.

As all flights were made in day-time, when there seemed little systematic change in cloud height during the flights, James thought it reasonable to assume that a rate of subsidence of the order of 1 mb hr^{-1} occurred in the inversion layer by day. Further, he considered that a three-fold increase in the rate of subsidence in the inversion layer at night-time seemed unlikely in a slowly changing synoptic situation. The assumption of a subsidence rate of 1 mb hr^{-1} at night also, would lead to a tendency for the cloud top to rise at night, although the loss of water vapour by cloud might also lead to its dissipation.

FLIGHTS BY METEOROLOGICAL RESEARCH FLIGHT AIRCRAFT

In connexion with the investigation into stratocumulus cloud another series of 11 flights was carried out in the Farnborough area by the Meteorological Research Flight during the period March 1958 to March 1960. Seven of the flights were made between October and November 1958. Eight of the flights were made in day-time, two at night and one around the sunset period. All flights were carried out when conditions were anticyclonic and extensive sheets of stratocumulus cloud covered southern England.

Table I gives details of dates and times when flights were made, heights of cloud bases and tops and probable times of dissipation, together with details of the synoptic situation and flight notes. The presence of higher cloud during the flights of 22 October 1958 and 25 March 1960 should be noted. The cloud of 9 February 1959 is perhaps more properly classed as stratus, its base being at only 500 feet.

The flight plan to be followed necessitated that the aircraft should ascend to 2000 feet above the cloud top and make horizontal runs of five minutes duration at successively lower levels down to 2000 feet below cloud base. (In practice this last figure varied between 1000 and 2000 feet depending on the height of the cloud base and flight safety considerations.) Apart from the 500-foot layer above the cloud top where runs were to be made every 100

*The superscript figures refer to the bibliography on page 15.

feet, runs were to be carried out at intervals of 250 feet. Unfortunately, on several occasions, the runs at 100-foot intervals missed their target by several hundred feet, owing to variations in cloud height.

On the flights of 18 and 19 March 1958 on level runs, aircraft heights, airspeed, temperature and frost-point were observed every 30 seconds. On all other flights a single assessment of aircraft height was made for each run, and measurements of airspeed, temperature and frost-point were made every 15 seconds. Readings of frost-point were not as complete as those of temperature owing to the difficulty of maintaining a series of frost-point observations at only 15-second intervals.

A photographically-recording accelerometer was used on four of the flights, but no attempt was made to measure the water content in cloud.

The selection of occasions when flights were carried out was made in the Synoptic Research division of the Meteorological Office.

RESULTS OF OBSERVATIONS

Temperature

Apart from the flight on 21 November 1958 when the usual temperature element was unserviceable and a Sangamo–Weston temperature element was substituted, all temperature measurements were made using the standard Meteorological Office flat-plate thermometer. This thermometer has a lag of about eight seconds, thus the variations in temperature readings made on a five-minute level run should provide a good indication of actual temperature fluctuations.

The vertical profiles of the mean corrected temperatures of level runs for each of the flights are shown in Figure 1. Figure 2 shows the Crawley radiosonde ascents for the dates and times nearest those of the flights. Table II gives values of temperature inversion rate from the cloud top to specified heights above while Table III gives values of temperature lapse rate from the cloud base to specified heights below.

These data support James's findings in that:

(i) All but one of the flights showed a marked inversion above the cloud top which was steeper than that shown on the corresponding Crawley radiosonde ascent. The exception was the case of 25 March 1960 when there was 7/8 altocumulus above, which presumably reduced the outgoing radiation considerably.

(ii) The temperature inversion rate within 200 feet of the cloud top was of the order of 2°C per 100 feet.

(iii) The inversion, on average, extended about 600 feet above cloud though values ranged between 300 and 1000 feet.

(iv) In general, on occasions of persistent cloud, the inversions were more intense than when cloud was broken or was later seen to disperse. The cloud on 9 February 1959 provided an exception.

(v) The lapse rate below cloud was nearly dry adiabatic.

The impression created by Table III, that there is a tendency for a superadiabatic lapse rate immediately below the cloud base, may possibly be due to a systematic underestimation of the temperature owing to the uncertainty in applying corrections for airspeed when flying in, or in and out of cloud. Any underestimation due to this cause would only need to be about 0·25°C to make the average lapse rate dry adiabatic.

Figure 3 shows the variation with height of the standard deviations of temperature observed on level runs. These again exhibit the same features noted by James, namely, a marked increase of standard deviation of temperature near the cloud top with values reducing to the average level, 300–400 feet above the cloud top. This may, as James concluded, be an indication of turbulence near the cloud top. On the other hand it may be accounted for, in part at least, by the aircraft flying in and out of cloud, but the flight notes were not sufficiently detailed to enable this point to be settled. It may be worthy of note, however, that on the one occasion when the flight notes did make it clear that the aircraft was flying in and out of cloud the standard deviation was large.

Frost-point

Frost-points were measured using the manually operated Dobson–Brewer frost-point hygrometer. As has already been remarked the difficulty of recording a series of readings at 15-second intervals resulted in a less complete set of observations of frost-point than of temperature. The error of the instrument for the range of values encountered on the flight was about 0·5°C.

Vertical profiles of dew-point are shown in Figure 1 and all show, as James found with the earlier flights, a sharp decrease in humidity mixing ratio above cloud top. On several of the flights the dew-point profile indicated constant water content with height below cloud. Values of change of humidity mixing ratio with height ($\Delta r/\Delta z$) below cloud all lay between $\pm$ 0·1 gm kgm^{-1} per 100 feet. There was a sudden change above cloud, however, when values of −0·4 to −0·9 gm kgm^{-1} per 100 feet occurred.

The standard deviations of frost-point on level runs are shown in Figure 4. They display similar characteristics to those of standard deviations of temperature with a tendency for a maximum value near the cloud top. As the frost-point observations were less complete than those of temperature this effect is less marked than in Figure 3.

Accelerometer observations

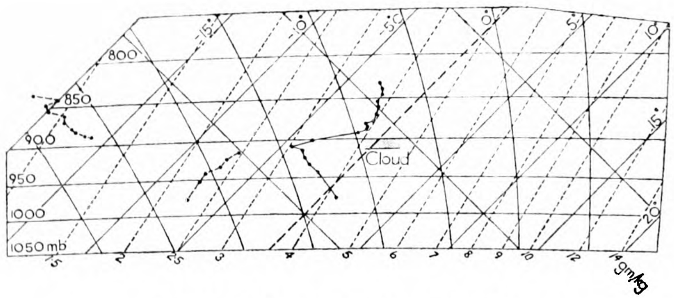
A photographically-recording accelerometer was used on the flights made on 3, 4, 21 and 26 November 1958. The traces show the same features noted by James on the earlier flights, i.e. significant turbulence in cloud and above the cloud top, decreasing with height above cloud. The accelerometer records of 3 November 1958 (Figure 5) form the best example of the decrease of turbulence with height above the cloud top as this was the only date on which accelerometer records were made above the top of the inversion (6200 feet). In the upper part of the inversion layer the trace is very smooth and completely free of the high-frequency variations apparent in cloud and at the cloud top, but occasional bumps occur which are of comparable magnitude with those which occur nearer the cloud top. On the other three occasions the highest runs were made 200–400 feet below the inversion top where significant turbulence was still experienced. A general decrease of turbulence with height above the cloud top was noted.

No attempt was made to integrate the traces since no record of the variation of aircraft height was made. The speed of the film in the camera appeared to increase with time, probably because one of the spools in the camera was being driven at a constant speed.

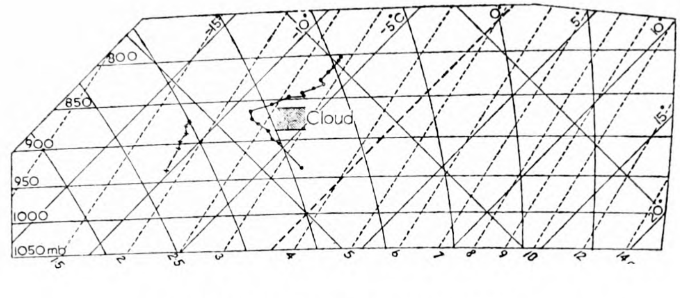
ANALYSIS

General

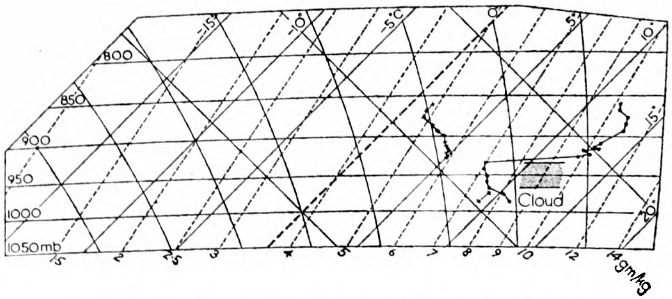
All four flights where accelerometer records were taken showed considerable turbulence in cloud and for several hundred feet above. The standard deviations of temperature and frost-point show a maximum near the cloud top which may be another indication of turbulence although this is by no means certain, as the fluctuations may also be due to gravity waves.



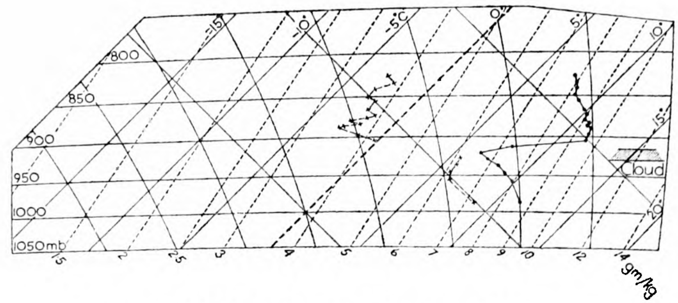
(*a*) 1520–1730 GMT, 18 March 1958



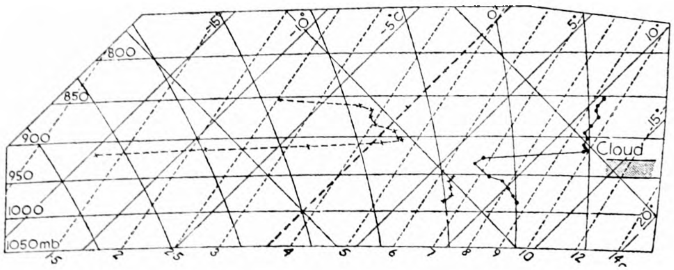
(*b*) 1010–1250 GMT, 19 March 1958



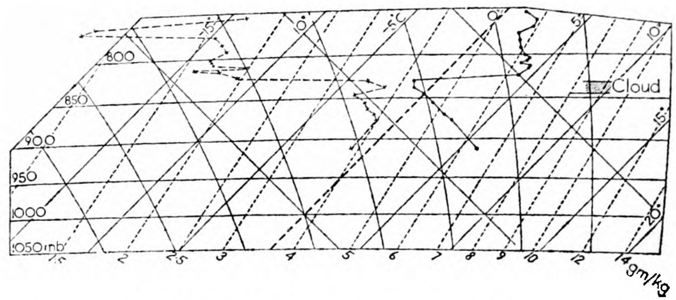
(*c*) 1430–1630 GMT, 22 October 1958



(*d*) 1800–2030 GMT, 23 October 1958



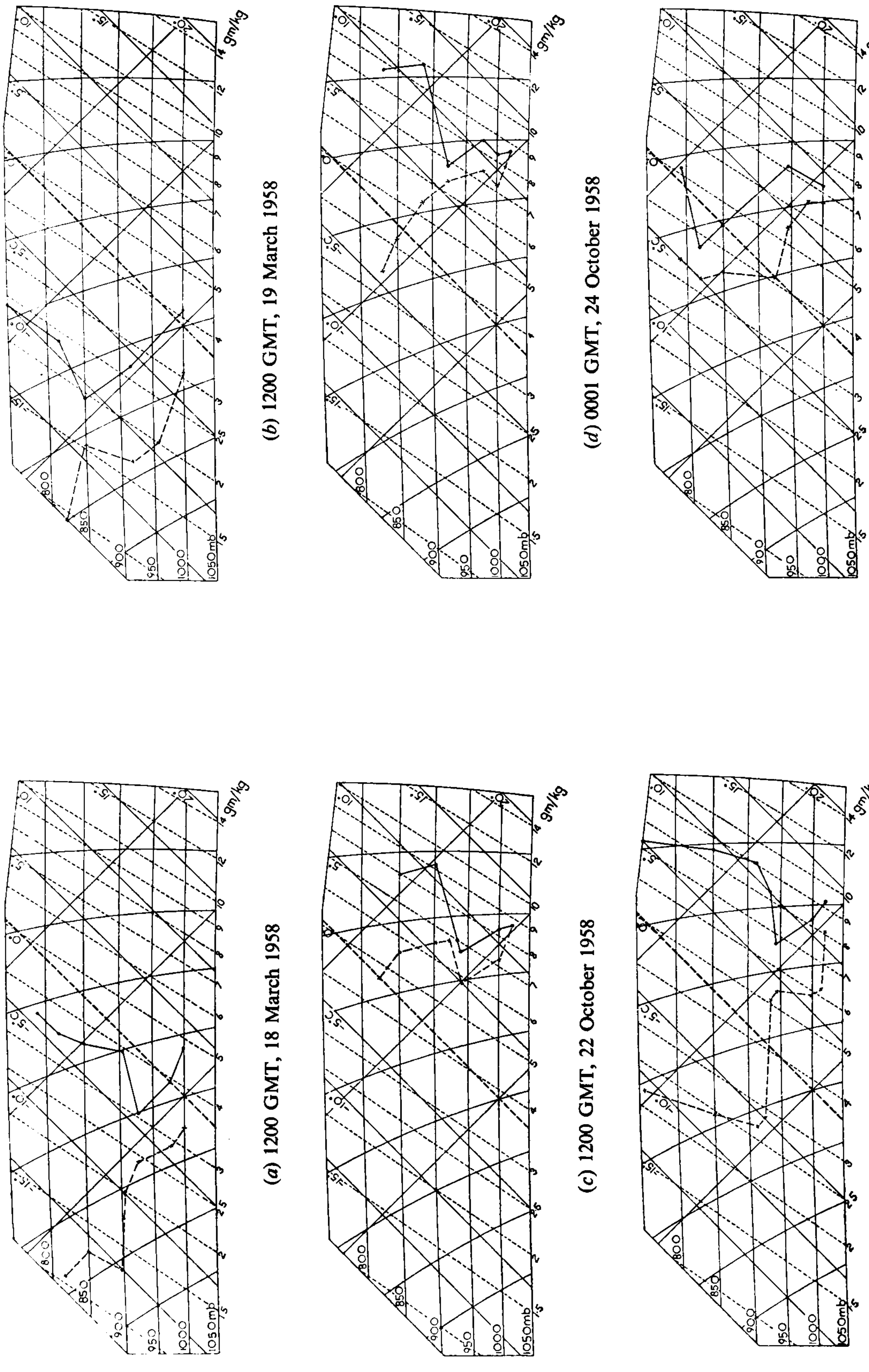
(*e*) 1000–1300 GMT, 24 October 1958



(*f*) 1800–2030 GMT, 3 November 1958

FIGURE 1. Aircraft measurements—means of level runs. (*Continued on p. 6.*)

—— dry-bulb temperature - - - - dew-point temperature



(*a*) 1200 GMT, 18 March 1958

(*b*) 1200 GMT, 19 March 1958

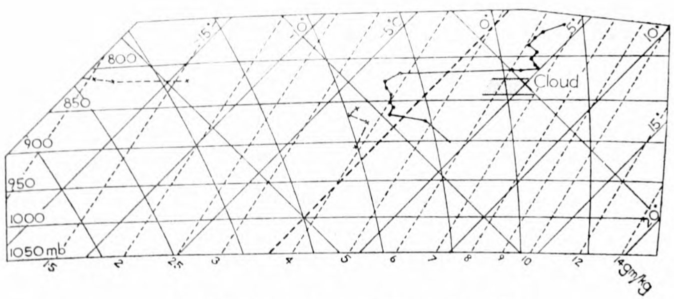
(*c*) 1200 GMT, 22 October 1958

(*d*) 0001 GMT, 24 October 1958

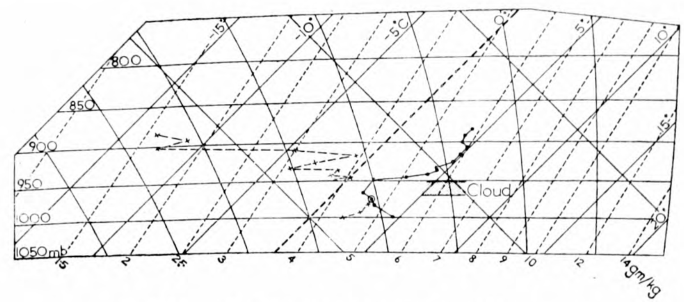
(*e*) 1200 GMT, 24 October 1958

(*f*) 0001 GMT, 4 November 1958

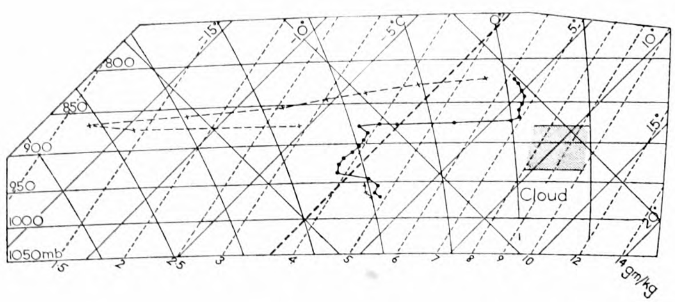
FIGURE 2. Crawley radiosonde ascents. (*Continued on p. 7.*)
——dry-bulb temperature - - - - dew-point temperature



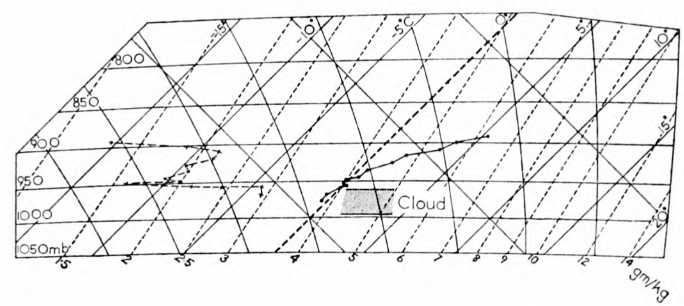
(*g*) 1340–1540 GMT, 4 November 1958



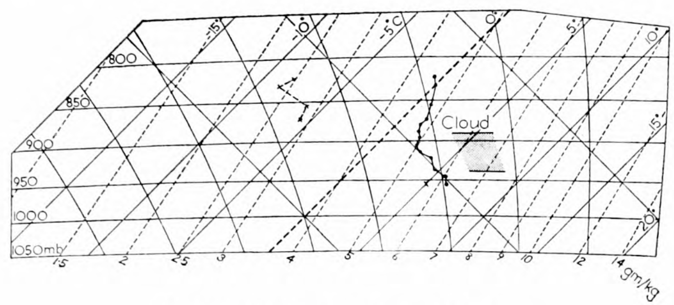
(*h*) 1200–1430 GMT, 21 November 1958



(*j*) 1430–1700 GMT, 26 November 1958

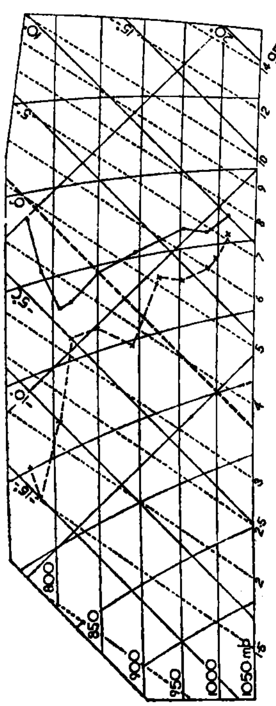


(*k*) 1100–1300 GMT, 9 February 1959

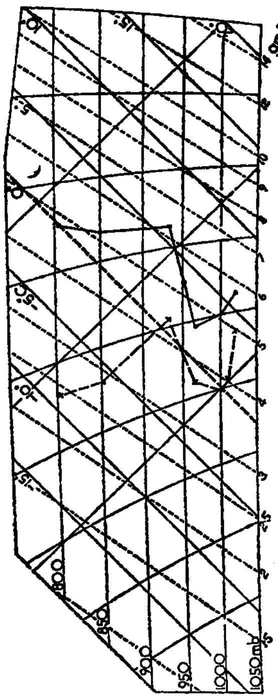


(*l*) 1030–1230 GMT, 25 March 1960

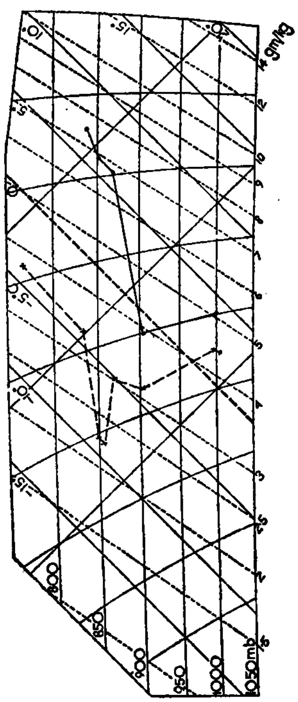
FIGURE 1. (*contd*) Aircraft measurements—means of level runs.
—— dry-bulb temperature - - - - dew-point temperature



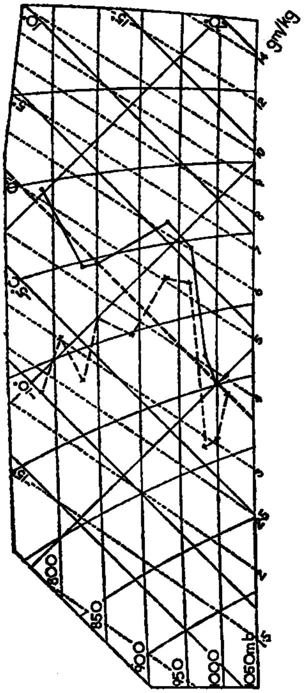
(*g*) 1200 GMT, 4 November 1958



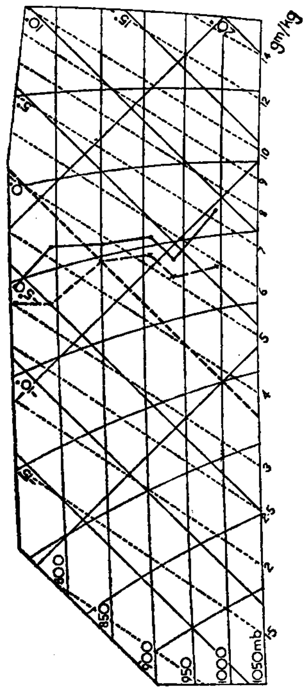
(*h*) 1200 GMT, 21 November 1958



(*j*) 1200 GMT, 26 November 1958



(*k*) 1200 GMT, 9 February 1959



(*l*) 1200 GMT, 25 March 1960

FIGURE 2. (*contd*) Crawley radiosonde ascents.

—— dry-bulb temperature   - - - - dew-point temperature

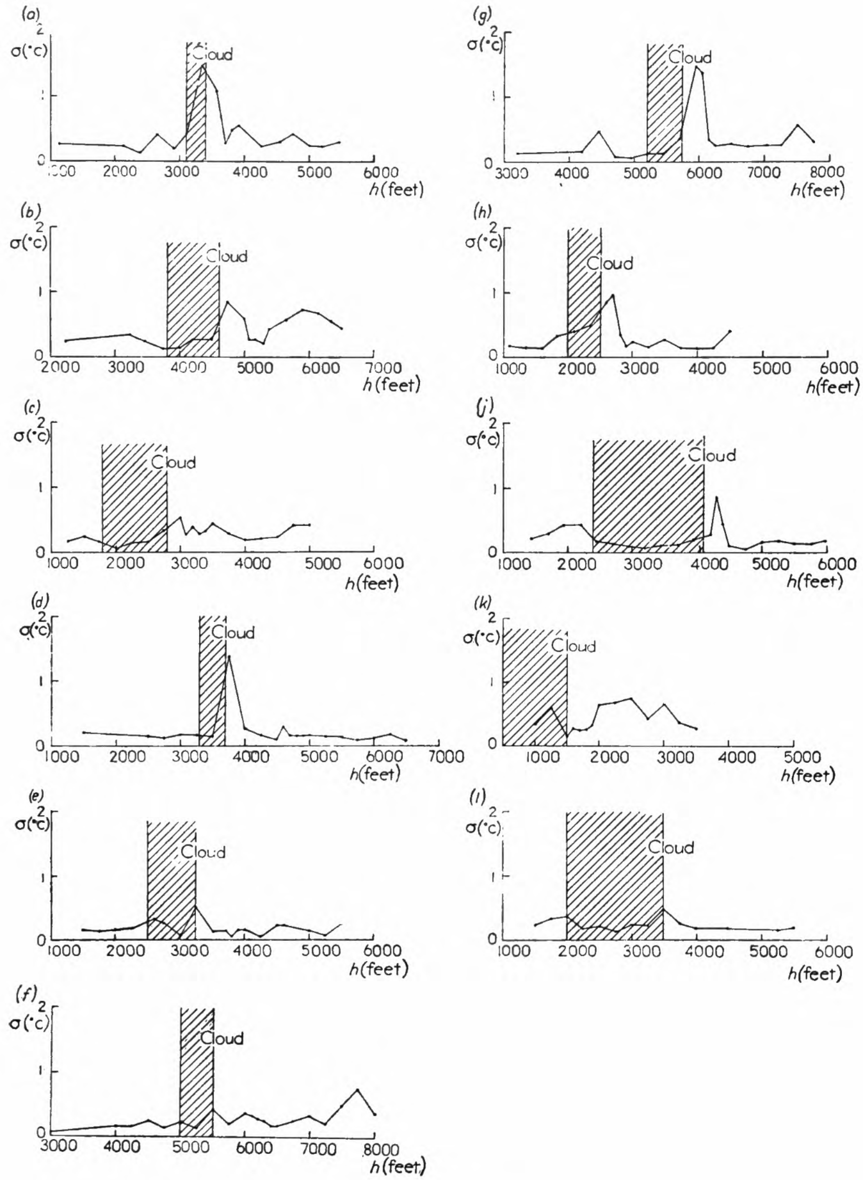


FIGURE 3. Standard deviation (σ) of temperature on level runs at height *h*.

(*a*) 18 March 1958
(*b*) 19 March 1958
(*c*) 22 October 1958
(*d*) 23 October 1958
(*e*) 24 October 1958
(*f*) 3 November 1958
(*g*) 4 November 1958
(*h*) 21 November 1958
(*j*) 26 November 1958
(*k*) 9 February 1959
(*l*) 25 March 1960

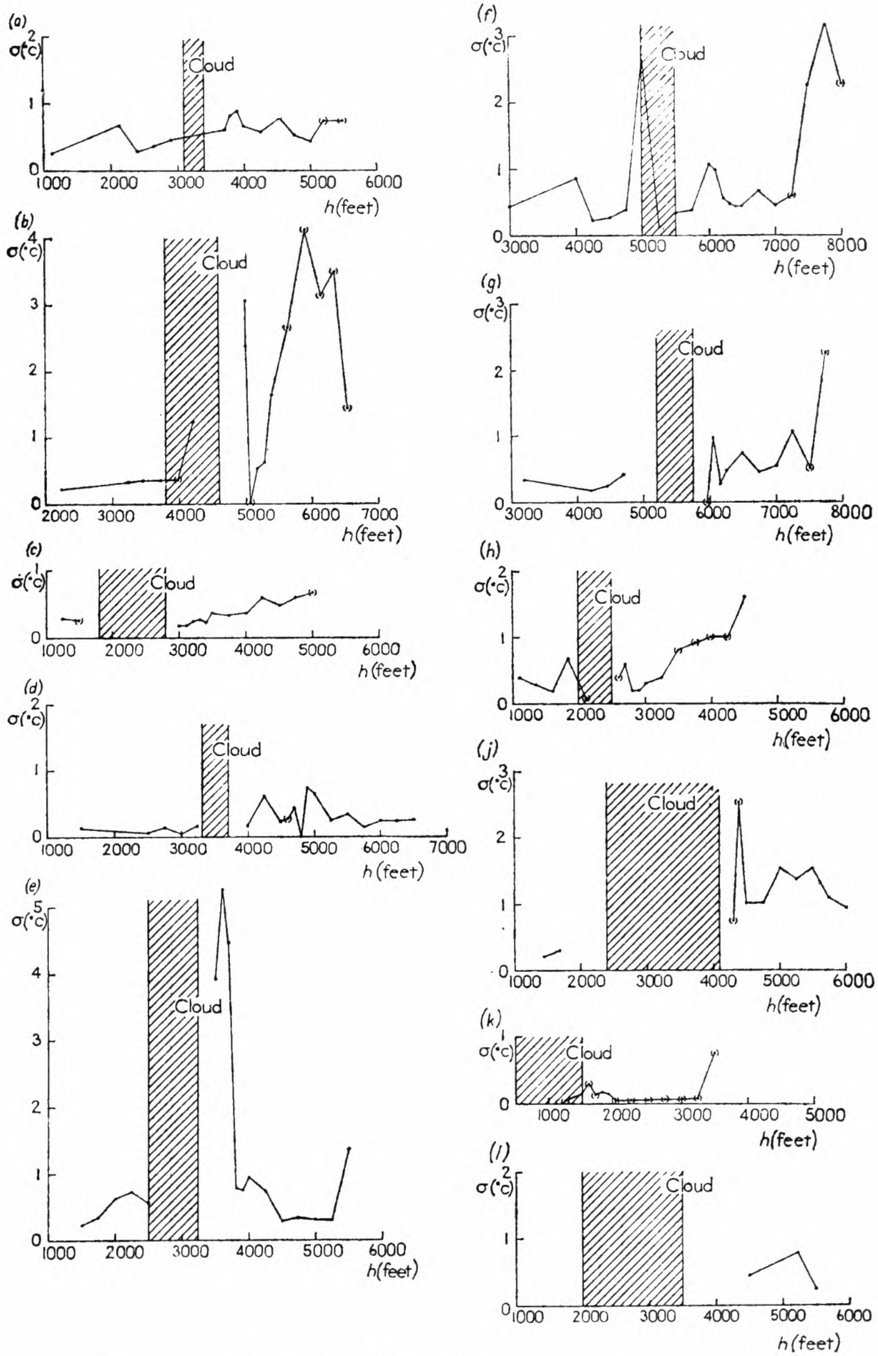


FIGURE 4. Standard deviation (σ) of frost-point temperature on level runs at height *h*. Values where points are bracketed were computed from 10 or fewer readings.

(*a*) 18 March 1958
(*b*) 19 March 1958
(*c*) 22 October 1958
(*d*) 23 October 1958
(*e*) 24 October 1958
(*f*) 3 November 1958
(*g*) 4 November 1958
(*h*) 21 November 1958
(*j*) 26 November 1958
(*k*) 9 February 1959
(*l*) 25 March 1960

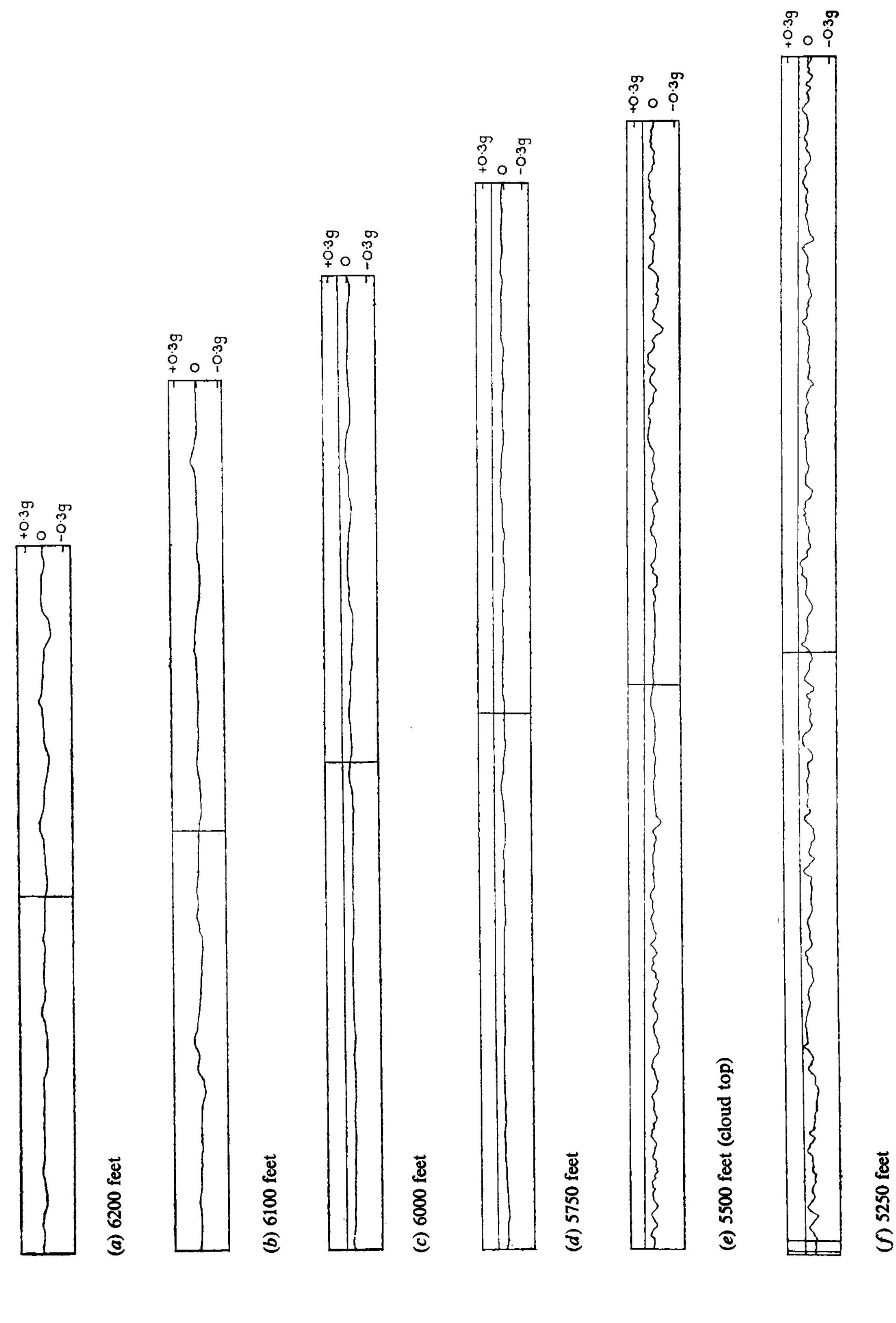


FIGURE 5. Sections of accelerometer readings (2 minutes duration), 3 November 1958.

Firstly, some attention must be paid to the heat and water-vapour budget of the air below the cloud top, deriving first the amount of heat which must be transferred downwards through the cloud top by turbulence to maintain the heat balance in the cloud and air below. In determining this budget, it is necessary amongst other things to consider the heat transfer across the upper and lower boundaries of the air, i.e. the cloud top and the earth's surface.

Heat transfer across the earth's surface

From measurements made daily at Kew of:

(i) soil temperature,
(ii) solar radiation received at the earth's surface,
(iii) long-wave radiation emitted by the earth's surface and
(iv) evaporation from tanks of water (using an American Class 'A' evaporation pan)

an estimate was made of the amount of heat conducted from air to ground (or vice versa) during the 24 hours on the dates of the flights. In calculating the amount of solar radiation entering the earth, the earth's albedo was assumed to be 0·1 (Berry, Bollay and Beers[2]).

Rohwer[3] found by experiment that the evaporation from lakes averaged about 0·7 of that from the American Class 'A' pan, and Linsley, Kohler and Paulhus[4] suggest that the annual rates of lake evaporation and potential evapotranspiration are approximately equal. Thus when evaluating the heat required to evaporate water at the earth's surface a factor of 0·7 was applied to the Kew evaporation figures in an attempt to make them more representative of conditions at the ground.

Table IV shows the values of the above quantities and the amount of heat that must be taken per day from the air to effect a balance.

On the dates of each flight, surface air temperatures over the area showed only small variations throughout the day and the earth temperatures measured at depths of 4 inches to 4 feet appeared slow to change with time. It seems reasonable to assume then that heat was conducted from air to earth and water was evaporated from the surface at a uniform rate throughout the 24 hours, i.e. the net amount of heat required for conduction to the earth and to effect evaporation will be that shown in the column headed 'Balance required from air' in Table IV. Making the above assumptions it can be asserted that this net transfer of heat takes place uniformly throughout the day. Bearing in mind the essential roughness of the calculations, Table IV shows a reasonable consistency from case to case and appears to confirm that in general the air below the cloud loses heat to the ground.

Heat balance

Heat budget of cloud and air below.—In considering the heat balance of the cloud and air below, the following factors were taken into account:

(i) solar radiation,
(ii) heat lost by long-wave radiation from the cloud top,
(iii) heat gained by long-wave radiation by the ground,
(iv) evaporation from the earth's surface,
(v) heat lost by the earth,
(vi) heat lost by the air and
(vii) advection.

The amount of solar radiation passing through the cloud top was taken as the solar radiation received at the ground plus the amount of solar radiation absorbed by cloud. Hewson[5] theoretically computed that the amount of incident solar radiation absorbed by clouds varied from 1 to 7 per cent depending on the cloud thickness. Murgatroyd,[6] however, reports the absorption of incident solar radiation by water cloud to be 10–20 per cent. These last figures are confirmed by Fritz[7] who has reported aircraft measurements of up to 20 per cent absorption. Here, the proportion of incident solar radiation absorbed by cloud is assumed to be 15 per cent.

Amounts of solar radiation incident on the cloud top were taken from figures given by Stagg[8] of the average solar radiation received at the ground at Kew on days of high radiation for different months. The earth's albedo was again assumed to be 0·1. The net amount of heat required for conduction to the earth and to effect evaporation at the surface was taken from Table IV. The amount of heat lost at the cloud top by long-wave radiation was found using an Elsasser radiation diagram. From the solar radiation figures used above an estimate of the albedo of cloud was made, allowing for variations in cloud amount during the day. These figures are shown in Table V.

In all but three of the cases, horizontal temperature gradients over the area of the flight were negligible and no allowance for advection was necessary. In those three cases an estimate of the advective effect was made by considering the effect of advection on the 1000–500-millibar thickness over the flight area and applying the implied change in temperature to the cloud and air below.

The change in temperature of the cloud and air below was obtained from the relevant Crawley radiosonde ascents made 12 hours apart, the change 0001–1200 GMT being regarded as applicable to day-time and the change 1200–0001 GMT as applicable to night-time.

Table V shows all the various heat quantities for both day-time and night-time in cal cm^{-2} per 3 hours. In the column headed 'Balance' is the amount of heat which would have to be supplied to the cloud and air below for a heat balance to be maintained.

Turbulence.—One of the effects of turbulence near the cloud top will be to transfer heat downwards through the cloud top from the inversion layer. It seems reasonable to assume that the balance below the cloud top is maintained by such a downward transfer by turbulent diffusion.

The flow of heat (F) downwards due to turbulence is given by

$$F = \rho c_p K \frac{T}{\theta}\frac{\partial\theta}{\partial z}$$

where ρ is the air density at the heights considered, c_p is the specific heat of air at constant pressure, K is the coefficient of turbulent diffusion, T is the absolute temperature, θ is the potential temperature and z is the height.

If $K = K' \times 10^3$ cm^2 sec^{-1}, the flow of heat downwards may be written

$$F = 10{\cdot}8\rho c_p K' \frac{T}{\theta}\frac{\partial\theta}{\partial z} \times 10^6 \text{ cal cm}^{-2} \text{ per 3 hours.}$$

Assuming a saturated-adiabatic lapse rate in cloud, this assumption being necessary to determine the cloud-top temperature, values of

$$F' = 10{\cdot}8\rho c_p \frac{T}{\theta}\frac{\partial\theta}{\partial z} \times 10^6$$

were computed for the inversion layer above the cloud top for each flight, a layer usually 300–600 feet thick. These values are shown in Table V.

Assuming the heat required by the cloud and air below is supplied by downward turbulent diffusion we obtain the values of K, for both day and night, necessary to achieve the balance. These are also shown in Table V.

Values of K are generally smaller by day than by night. The mean day-time and night-time values of $4{\cdot}4 \times 10^3$ and $13{\cdot}2 \times 10^3$ cm^2 sec^{-1} respectively agree remarkably well with those assumed by James, i.e. 3×10^3 and 10×10^3 cm^2 sec^{-1} respectively. Confidence in these estimates of K is increased by the degree of consistency from case to case as regards the sign and magnitude of the heat-balance figures, both within the day-time and the night-time sets.

On two occasions (22 October 1958 and 25 March 1960) a layer of altocumulus was reported above the stratocumulus. The presence of such a sheet is likely to affect drastically the heat budget as computed. However, the mean values of K for the other nine cases do not materially differ from those shown in Table V.

Heat balance in the inversion layer.—It is now necessary to consider, as did James, the rate of subsidence required in the inversion layer to restore the heat lost by turbulence and thus maintain the cloud top at the same height, assuming that the heat transported downwards is taken entirely from the inversion layer.

When air subsides through a given layer the temperature rise in the layer is proportional both to the rate of subsidence and to the difference in potential temperature between the top and base of the layer. Values of the rates of subsidence required in the inversion layer to balance the losses by turbulent diffusion are shown in Table V. The average rates of subsidence required for all cases are of the order of 1 mb hr^{-1} by day and 4 mb hr^{-1} by night.

Water-vapour balance

Turbulent diffusion, apart from transferring heat downwards, will also transport water vapour upwards from cloud into the inversion layer. The flux of water vapour (F'') transferred upwards by turbulence is given by

$$F'' = \rho K \frac{\partial r}{\partial z}$$

where ρ is the air density at the heights considered, K is the coefficient of turbulent diffusion, r is the humidity mixing ratio and z is the height.

On no flight was complete saturation observed in cloud. The humidity measurements in cloud were accordingly regarded as suspect. It was therefore assumed that the dry-bulb temperatures below cloud were correct and that the temperature at cloud base (obtained if necessary by extending the temperature profile along a dry adiabatic) defined the humidity mixing ratio at cloud base. Similarly the humidity mixing ratio at the cloud top was assumed to be determined by a saturated-adiabatic lapse rate through cloud.

Taking $K = 3 \times 10^3$ cm^2 sec^{-1} by day and 10^4 cm^2 sec^{-1} by night and making the above assumptions, values of the upward flux of water vapour from cloud top were computed. These are shown in Table VI. Values are also given in Table VI of the mean value of the water content of the inversion layer. From these two sets of figures are derived the rates of subsidence in the inversion layer necessary to balance the upward transfer of water vapour by turbulent diffusion. The figures for mean subsidence rates are of the same order as those shown in Table V for the heat budget, i.e. about 1 mb hr^{-1} by day and 3–4 mb hr^{-1} by night.

DISCUSSION

The analysis of the preceeding section broadly followed that carried out by James. In the flights that he analysed he noted no systematic variations in height of the cloud top and his deduction that subsidence played a part in maintaining a sheet of stratocumulus arose from this.

In the flights analysed here there were significant variations in cloud height on several occasions (see flight notes in Table I) while the relevant Crawley radiosonde ascents show marked variations in the height of the inversion base during the days concerned.

Table VII shows the loss of heat (computed from consecutive Crawley ascents) of the layer between the initial level of the base of the inversion and the higher of the initial and final levels of the top of the inversion. This represented an attempt to determine the change of heat content of the inversion layer.

During 22–24 October, and on 26 November, 1958, centres of high pressure lay over southern England. The air over the flight area at these times appeared to be subsiding since the inversion level descended during the period of the flight. On 25 March 1960, the inversion on the radiosonde ascents was not sufficiently well defined for estimates of heat loss to be made.

Comparison of the figures of heat lost in the inversion layer for the remaining dates, with those in the column headed 'Balance' in Table V, shows that for the most part the heat lost by the inversion layer is of the same order as that required to be transferred downwards through the cloud top by turbulent diffusion. This suggests that subsidence may not be an essential part of the process by which a sheet of stratocumulus is maintained. It is therefore necessary to consider the behaviour of the cloud in the absence of subsidence.

Owing to the great thermal stability of the inversion layer it seems probable that the mixing length of air particles will be small and that the effects of turbulence in the inversion layer will be localized. If this is so it seems likely that water vapour transferred upwards from cloud will remain in a shallow layer at the base of the inversion. When the air in this layer becomes saturated cloud will form. Long-wave radiational losses from the new cloud will probably ensure that the lapse rate through the new cloud is continuous with that below and that an inversion is maintained at the cloud top. There will thus be a steady raising of the cloud top.

Table VIII shows the amount of water vapour transferred upwards across the cloud top by day and by night (assuming $K = 3 \times 10^3$ cm^2 sec^{-1} by day and 10^4 cm^2 sec^{-1} by night). The depths of the layers immediately above the cloud top that these quantities would saturate were derived from the appropriate humidity mixing ratio at the cloud top. These figures are also shown in Table VIII, together with the actual changes in pressure of the base of the inversion by day and by night.

Excluding the cases where the air was thought to be subsiding, there appears to be some measure of agreement between the figures for the actual change and the computed pressure depth expected to be saturated by water vapour removed from cloud.

Table IX shows the expected behaviour of the cloud in the absence of subsidence during the 12 hours following flight time. Assuming a value of $K = 3 \times 10^3$ cm^2 sec^{-1} by day and 10^4 cm^2 sec^{-1} by night the pressure interval expected to be saturated by water vapour transferred upwards through the cloud top by turbulence was computed in the same way as for Table VIII. Assuming that the final level of the cloud top was at the top of this interval and that water evaporated at the surface was distributed uniformly throughout the layer the expected value of the humidity mixing ratio of the cloud and air below 12 hours later was computed.

This, with observed temperature changes, was used to derive the expected pressure at the cloud base after 12 hours. Excluding those occasions when the air was thought to be subsiding there appeared to be some measure of agreement between the expected and observed behaviour of the cloud. The dispersal of cloud on 19 March 1958 was expected but not that on 24 October 1958 which was thought to have been associated with subsidence.

CONCLUSIONS

(i) The temperature gradient in the inversion layer above the cloud top is generally of the order of 2°C per 100 feet and the hydrolapse is of the order of 1 gm kgm^{-1} per 100 feet. Average values of temperature gradient measured immediately above the cloud top appear to be greater for the cases measured over intervals of 100 feet (3·5°C per 100 feet) than for those measured over intervals of 250 feet (1·6°C per 100 feet). Temperature gradients are also larger than suggested by the corresponding Crawley radiosonde ascent. This implies that observations made at least at intervals of 100 feet are necessary for accurate profiles above cloud.

(ii) The inversion usually extends 300–600 feet above the cloud top.

(iii) The accelerometer records show considerable turbulence in cloud and within the first 300 feet above. The standard deviations of temperature and frost-point observed on level runs show an increase near the cloud top which may also indicate turbulence in the inversion layer.

(iv) The heat balance suggests that heat must be transferred downwards through the cloud top by turbulent diffusion to maintain the heat budget of the cloud and air below. The absence of solar radiation by night requires a greater degree of turbulence by night than by day. The coefficient of turbulent diffusion is probably of the order of 3×10^3 cm^2 sec^{-1} by day and 10^4 cm^2 sec^{-1} by night.

(v) The previous points in this section are in accordance with the findings of James. This later set of flights, however, does not altogether support James's theory that subsidence is an essential part of the process by which a sheet of stratocumulus is maintained. It seems probable that water vapour transferred upwards by turbulent diffusion will remain in the lower part of the layer and lead to a gradual upward extension of cloud. The sharp temperature inversion would be maintained by long-wave radiational heat losses from the cloud top.

Although some attempt has been made to allow for the effects of advection in particular cases it is difficult to determine precisely the state of the air. Findlater[9] in a study of the thermal structure of anticyclones noted that shallow warm and cold centres (the remnants of differing air masses) circulate in the lower layer of anticyclones near the inversion level. These warm and cold centres appear to be associated respectively with dips and peaks in the inversion level. The expected variations in temperature and inversion height may well be masked by effects such as these.

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Tables

TABLE I. *Details of flights made by*

All times

Date	Flight time	Accelerometer used	Cloud Amount	Cloud Base (feet)	Cloud Top (feet)	Flight notes
18 March 1958	1520–1730	No	7/8–8/8	3100	3400	Cloud became 4/8–5/8 during run, no cloud above.
19 March 1958	1010–1250	No	7/8	3800	4600	Cloud became 4/8–5/8, base and top rose by about 250 feet during run.
22 October 1958	1430–1630	No	8/8	1800	2800	3/8–4/8 altocumulus at 12,000 feet.
23 October 1958	1800–2030	No	8/8	3300	3700	No cloud above, base uniform throughout flight. Top lowered 700 feet during flight and a further 200 feet by 1000 on the 24th.
24 October 1958	1000–1300	No	8/8	2500	3250	Cloud top about 3600 feet at take-off. Cloud broke to 5/8–7/8 and top lowered 200 feet during flight.
3 November 1958	1800–2030	Yes	4/8	5000	5500	Cloud 7/8–8/8 all day but broke around sunset. Top rose slightly during flight.
4 November 1958	1340–1540	Yes	8/8	5200	5750	Occasional patches of fractostratus below. Cloud top rose about 200 feet during flight.
21 November 1958	1200–1430	Yes	8/8	2000	2500	Cloud broke temporarily to 5/8 during flight.
26 November 1958	1430–1700	Yes	8/8	2400	4100	Cloud top rose about 100 feet during flight.
9 February 1959	1100–1300	No	8/8	500	1500	No cloud above.
25 March 1960	1030–1230	No	8/8	2000	4000	7/8 altocumulus at 9000 feet.

the Meteorological Research Flight

are GMT.

Remarks	Probable time of dissipation	Synoptic situation
Cloud re-formed to 8/8 about 1800.	Not before 0600 on the 19th	Anticyclone centred over Norwegian Sea. Ridge extending south over the British Isles. Light easterly winds over the flight area.
	2000 on the 19th	Anticyclone over Scandinavia. Ridge extending southwards over the British Isles. Light easterly winds over the flight area.
	Not before 0600 on the 23rd	Anticyclone south of Ireland. Light notherly winds over the flight area.
	Not before 0600 on the 24th	Anticyclone intensifying over Wales. Light north-westerly winds over the flight area.
	1600 on the 24th	Anticyclone declining over Wales. Light northerly winds over the flight area.
Cloud re-formed to 7/8 after 2100.	Not before 0600 on the 4th	Ridge over Ireland moving slowly eastwards. Light north-westerly winds over the flight area.
Small 'low' developed over south-west England by 0001 on the 5th and moved along the English Channel. The cloud over the flight area on the morning of the 5th was probably associated with this.	Not before 0600 on the 5th	Ridge over the British Isles, trough over Ireland. Light northerly winds over the flight area.
	Not before 0600 on the 22nd	Anticyclone over eastern Europe with ridge extending west over the British Isles. Light easterly winds over the flight area.
	Not before 0600 on the 27th	Area of high pressure over central and southern England. Light and variable winds over the flight area.
Small 'low' formed over the English Channel by 0600 on the 10th. The cloud over the flight area on the morning of the 10th was probably associated with this.	Not before 0600 on the 10th	Anticyclone over Europe, trough west of Ireland. Light southerly winds over the flight area.
Cloud broke temporarily around sunset but re-formed to 8/8 around 2200.	Not before 0600 on the 26th	Anticyclone over eastern Europe and the Baltic. Ridge extending from Scandinavia south-west over the British Isles. Light north-easterly winds over the flight area.

TABLE II. *Mean inversion rate from cloud top to specified heights above*

Date	Flight time GMT	Cloud cover during flight	Height above cloud top (*feet*) 100	200	300	400	500	750	1000	1250	1500
			Mean inversion rate (°*C per 100 feet*)								
18 March 1958	1520–1730	7/8–8/8 becoming 4/8–5/8	–	0·94	0·73	0·56	0·31	0·37	0·15	0·11	0·08
19 March 1958	1010–1250	7/8 becoming 4/8–5/8	–	0·35	–	–	0·30	0·29	0·19	0·16	0·12
22 October 1958	1430–1630	8/8	–	1·95	1·47	0·97	0·92	0·63	0·52	0·42	0·33
23 October 1958	1800–2030	8/8	–	1·52	–	–	0·72	0·40	0·32	0·19	0·13
24 October 1958	1000–1300	8/8 becoming 4/8–5/8	–	2·12	1·54	1·13	0·87	0·64	0·43	0·33	0·27
3 November 1958	1800–2030	4/8	–	2·12	–	–	1·12	0·70	0·49	0·32	0·24
4 November 1958	1340–1540	8/8	5·10	3·15	2·33	–	1·16	0·80	0·53	0·42	0·36
21 November 1958	1200–1430	8/8 becoming 5/8 temporarily	1·60	1·40	1·00	0·75	–	0·52	0·38	–	0·21
26 November 1958	1430–1700	8/8	7·1	3·75	–	–	1·55	0·99	0·70	0·51	0·38
9 February 1959	1100–1300	8/8	0·1	0·0	0·0	−0·05	0·08	0·07	0·16	0·15	0·23
25 March 1960	1030–1230	8/8	–	–	–	–	−0·12	–	–	−0·11	−0·13

TABLE III. *Mean lapse rate between cloud base and specified heights below*

Date	Flight time GMT	Cloud cover during flight	Height below cloud base (*feet*) 250	500	750	1000
			Mean lapse rate (°*C per 100 feet*)			
18 March 1958	1520–1730	7/8–8/8 becoming 4/8–5/8	0·35	0·29	0·27	0·28
19 March 1958	1010–1250	7/8 becoming 4/8–5/8	0·29	0·32	0·30	0·29
22 October 1958	1430–1630	8/8	0·48	0·38	–	–
23 October 1958	1800–2030	8/8	0·40	0·36	0·35	–
24 October 1958	1000–1300	8/8 becoming 4/8–5/8	0·40	0·32	0·31	0·29
3 November 1958	1800–2030	4/8	0·40	0·32	0·31	0·30
4 November 1958	1340–1540	8/8	0·16	0·14	0·40	–
21 November 1958	1200–1430	8/8 becoming 5/8 temporarily	0·28	0·26	0·31	0·31
26 November 1958	1430–1700	8/8	0·88	0·62	0·43	0·38
9 February 1959	1100–1300	8/8	–	–	–	–
25 March 1960	1030–1230	8/8	0·40	0·28	–	–

Dry-adiabatic lapse rate = 0·30°C per 100 feet.

TABLE IV. *Heat budget at earth's surface*

Date	Solar radiation received at ground at Kew	Radiation entering earth (assuming albedo = 0·1)	Loss of heat by earth's surface by long-wave radiation	Heat required for evaporation	Loss of heat by earth at Kew during 24 hours	Balance required from air
	cal cm^{-2} day^{-1}					
18 March 1958	89	80	45	96	1	60
19 March 1958	295	266	187	75	15	−19
22 October 1958	35	32	24	41	−18	51
23 October 1958	71	64	45	17	− 6	4
24 October 1958	83	75	57	41	20	3
3 November 1958	95	86	66	34	12	2
4 November 1958	48	43	43	0	13	−13
21 November 1958	26	23	18	41	3	33
26 November 1958	2	2	2	0	− 3	3
9 February 1959	36	32	82	8	−29	87
25 March 1960	108	97	66	87	− 5	61

TABLE V. *Heat budget of cloud and air below*

Day-time (*cal cm*$^{-2}$ *per 3 hours*)

	18 March 1958	19 March 1958	22 October 1958	23 October 1958	24 October 1958	3 November 1958	4 November 1958	21 November 1958	26 November 1958	9 February 1959	25 March 1960	Mean
Solar radiation received at ground at Kew	22	74	11	21	25	32	16	10	1	12	27	
Solar radiation absorbed by cloud	16	10	17	16	14	13	14	22	14	14	18	
Cloud albedo	0·74	0·47	0·76	0·76	0·77	0·78	0·83	0·80	0·84	0·71	0·64	
Heat lost at cloud top by long-wave radiation	25	26	22	26	30	30	33	26	22	29	25	
Heat lost by earth's surface by long-wave radiation	6	23	3	6	7	8	5	3	0	10	8	
Heat lost due to advection	0	20	0	0	0	16	0	0	0	−15	0	
Net heat conducted to earth and used for evaporation	7	−2	6	1	0	0	−2	4	0	11	8	

Night-time (*cal cm*$^{-2}$ *per 3 hours*)

	18 March 1958	19 March 1958	22 October 1958	23 October 1958	24 October 1958	3 November 1958	4 November 1958	21 November 1958	26 November 1958	9 February 1959	25 March 1960	Mean
Solar radiation received at ground at Kew												
Solar radiation absorbed by cloud												
Cloud albedo	0·74	0·47	0·76	0·76	0·77	0·78	0·83	0·80	0·84	0·71	0·64	
Heat lost at cloud top by long-wave radiation	25	26	22	26	30	30	33	26	22	29	25	
Heat lost by earth's surface by long-wave radiation	6	23	3	6	7	8	5	3	0	10	8	
Heat lost due to advection	0	0	0	0	0	0	0	0	0	−15	0	
Net heat conducted to earth and used for evaporation	7	−2	6	1	0	0	−2	4	0	11	8	

TABLE V. *Heat budget of cloud and air below—contd*

Heat lost by air	2	0	4	−1	1	20	6	1	−1	−1	0		11	−15	0	−2	6	12	11	−2	5	−2	7	
Balance	8	11	4	6	8	5	6	4	9	2	7		15	16	25	23	17	10	15	29	17	17	18	
Flow of heat downwards due to turbulence (F')	1·3	0·7	2·1	2·3	2·5	1·7	1·9	1·5	3·2	0·8	0·8		1·3	0·7	2·1	2·3	2·5	1·7	1·9	1·5	3·2	0·8	0·8	
Coefficient of turbulent diffusion (K) ($cm^2\ sec^{-1} \times 10^3$)	2·2	15·7	1·9	2·7	3·2	3·0	3·2	2·6	3·2	2·5	8·7	4·4	11·5	22·9	11·9	10·0	6·8	5·9	7·9	19·3	5·3	21·3	22·5	13·2
Subsidence rate required in inversion layer to balance loss of heat by turbulence ($mb\ hr^{-1}$)	1·9	2·5	0·5	1·3	1·8	1·3	1·2	0·7	1·3	0·6	2·5	1·4	3·5	3·7	3·5	5·3	3·6	2·3	2·8	4·3	2·4	4·7	6·3	3·9

TABLE VI. *Water-vapour budget of inversion layer*

Date	Day-time: Flux of water vapour upwards (assuming $K = 3 \times 10^3$ cm² sec⁻¹)	Day-time: Water content of inversion layer	Day-time: Subsidence rate required to balance loss by turbulence	Night-time: Flux of water vapour upwards (assuming $K = 10^4$ cm² sec⁻¹)	Night-time: Water content of inversion layer	Night-time: Subsidence rate required to balance loss by turbulence
	$\frac{gm\ cm^{-2}\ per\ 3\ hours}{\times 10^{-2}}$	$gm\ kgm^{-1}$	$mb\ hr^{-1}$	$\frac{gm\ cm^{-2}\ per\ 3\ hours}{\times 10^{-2}}$	$gm\ kgm^{-1}$	$mb\ hr^{-1}$
18 March 1958	0·9	4·0	0·7	3·0	4·0	2·5
19 March 1958	1·2	1·8	2·2	4·0	1·8	7·2
22 October 1958	0·3	6·0	0·2	1·0	6·0	0·6
23 October 1958	0·3	4·0	0·3	1·0	4·0	0·8
24 October 1958	0·9	3·5	0·9	3·0	3·5	2·9
3 November 1958	0·9	3·0	1·0	3·0	3·0	3·3
4 November 1958	1·2	2·5	1·6	4·0	2·5	0·5
21 November 1958	0·3	3·5	0·3	1·0	3·5	2·9
26 November 1958	0·3	2·5	0·4	1·0	2·5	4·0
9 February 1959	0·3	2·7	0·4	1·0	2·7	3·7
25 March 1960	0·9	3·0	1·0	3·0	3·0	3·3
			Mean 0·8			Mean 2·9

TABLE VII. *Loss of heat of inversion layer*

	Day-time			Night-time		
	Loss of heat of inversion layer	Loss due to advection	Loss due to non-advectional processes	Loss of heat of inversion layer	Loss due to advection	Loss due to non-advectional processes
		cal cm^{-2} per 3 hours			*cal cm^{-2} per 3 hours*	
18 March 1958	1	0	1	13	0	13
19 March 1958	16	8	8	14	0	14
22 October 1958	2	0	2	8	0	8
23 October 1958	2	0	2	−14	0	−14
24 October 1958	− 2	0	− 2	− 8	0	− 8
3 November 1958	16	7	9	10	0	10
4 November 1958	5	0	5	9	0	9
21 November 1958	4	0	4	18	0	18
26 November 1958	−22	0	−22	−14	0	−14
9 February 1959	− 4	−10	6	–	–	–
25 March 1960	–	–	–	–	–	–

TABLE VIII. *Expected change in level of cloud top in absence of subsidence*

Date	Day-time				Night-time			
	Flux of water vapour upwards* (assuming $K = 3 \times 10^3$ $cm^2\ sec^{-1}$)	Humidity mixing ratio at cloud top	Pressure interval saturated by flux of water vapour at this value of the humidity mixing ratio	Fall in pressure at inversion base (from Crawley radiosonde ascent)	Flux of water vapour upwards* (assuming $K = 10^4$ $cm^2\ sec^{-1}$)	Humidity mixing ratio at cloud top	Pressure interval saturated by flux of water vapour at this value of the humidity mixing ratio	Fall in pressure at inversion base (from Crawley radiosonde ascent)
	$gm\ cm^{-2} \times 10^{-2}$	$gm\ kgm^{-1}$	*millibars*	*millibars*	$gm\ cm^{-2} \times 10^{-2}$	$gm\ kgm^{-1}$	*millibars*	*millibars*
18 March 1958	3·6	2·9	12	10	12·0	2·9	41	50
19 March 1958	4·8	2·2	22	30	16·0	2·2	75	120
22 October 1958	1·0	6·8	1	-	4·7	6·8	7	40
23 October 1958	1·0	6·5	1	−15	4·7	6·5	7	−15
24 October 1958	3·0	6·5	4	−25	14·0	6·5	22	−20
3 November 1958	2·7	4·0	7	30	15·0	4·0	37	40
4 November 1958	3·6	3·9	9	15	20·0	3·9	51	30
21 November 1958	0·8	4·3	2	15	5·3	4·3	12	30
26 November 1958	0·8	3·8	2	−15	5·3	3·8	14	−15
9 February 1959	0·9	3·8	2	0	5·0	3·8	13	-
25 March 1960	3·6	4·8	7	-	12·0	4·8	25	-

*These figures were calculated from those given in Table VI for the flux of water vapour upwards per 3 hours, assuming 12 hours of daylight in March, 10 in October, 9 in February and early November and 8 in late November.

TABLE IX. *Expected behaviour of cloud in 12 hours following flight time*

Date	Flight time	Cloud thickness	Expected fall of pressure at cloud top	Expected fall of pressure at cloud base	Expected fall in thickness of cloud	Notes
	GMT	*millibars*	*millibars*	*millibars*	*millibars*	
18 March 1958	1520–1730	11	40	15	−25	Cloud had thickened by 17 millibars by midday on the 19th.
19 March 1958	1010–1250	28	50	85	35	Cloud base and top rose by about 250 feet during flight. Cloud dispersed about 2000 GMT.
22 October 1958	1430–1630	32	5	−12	−17	Cloud thinned between flight time and 1800 GMT on the 23rd. Air appeared to be subsiding.
23 October 1958	1800–2030	15	6	5	−1	Cloud base uniform throughout flight. Top lowered 700 feet during flight time, and a further 200 feet by 1000 GMT on the 24th.
24 October 1958	1000–1300	21	12	10	−2	Cloud base uniform throughout flight. Top lowered 200 feet during flight. Air still appeared to be subsiding, cloud dispersed about 1600 GMT presumably owing to subsidence.
3 November 1958	1800–2030	15	30	−5	−35	Cloud thickened slightly between flight time and 1340 GMT on the 4th.
4 November 1958	1340–1540	18	42	25	−17	Cloud top rose about 200 feet during flight.
21 November 1958	1200–1430	20	8	20	12	Cloud broke temporarily to 5/8 during flight.
26 November 1958	1430–1700	55	11	10	−1	Cloud top rose about 100 feet during flight. Air appeared to be subsiding.
9 February 1959	1100–1300	35	9	30	21	Cloud persisted till at least 0600 GMT on the 10th.
25 March 1960	1030–1230	50	16	0	−16	Cloud became broken at sunset and re-formed to 8/8 at 2200 GMT.

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