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AIR MINISTRY

METEOROLOGICAL OFFICE

Scientific Paper No. 1

Airborne Measurements of the Latitudinal Variation of Frost-Point, Temperature and Wind

by N. C. HELLIWELL, B.Sc.

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SUMMARY

The results of six flights in July and August 1956 and three flights in March 1957 between 40°N and 68°N are presented together with diagrams showing the variation of frost-point, temperature and wind. Little latitudinal variation of frost-point at 46,000 feet (140 millibars) was found, and generally frost-points in the lower stratosphere showed little variation except in the region of upper fronts or jet streams. Some of the flights showed evidence of frontal zones in the lower stratosphere. Some aspects of the clear-air turbulence associated with jet streams are discussed and the location of turbulence with respect to the jet-stream maximum and the tropopause is presented in a diagram using the data obtained on these flights.

INTRODUCTION

Until the beginning of 1956 the only comprehensive measurements of frost-point in the lower stratosphere were those made over southern England by the Meteorological Research Flight.[1,2,3] * Three isolated flights made from Khartoum in 1953,[4] a few from Norway in 1955[5] and about a dozen in 1956 from Idris, Tripolitania,[6] were the only airborne measurements of frost-point at altitude known to exist for other latitudes, although in 1947, Barrett[7] and co-workers, using a radio-sonde, were able to make three soundings to 30 kilometres in the United States. Barrett's results showed higher frost-points than those found over southern England at heights where comparison was possible. Because of the inadequacy of these data, it was decided to use the Canberra aircraft to obtain more measurements of frost-point, together with winds and temperatures, at different latitudes. A summer programme of six flights was completed between 18 July and 9 August 1956. A similar winter programme was planned but owing to unserviceability of the aircraft it was possible to make only three limited flights—all in March 1957.

The programme required considerable organization. A subsidiary base was established at Royal Air Force, Kinloss, where the aircraft was refuelled and a supply of liquid nitrogen provided for use with the frost-point hygrometer. Also at this base the cameras in the bomb bay of the aircraft and in the tail cone were reloaded with film, since a cassette of film lasts only about two hours when readings are taken every 50 seconds or so. Because of the complexity of the organization, flights could be made only when administratively convenient and no regard was taken of the synoptic situation in planning the dates of the flights.

FLIGHT PLAN

All outbound legs were flown at an altitude (L) approximately equal to that of the tropopause, while inbound legs (with one exception) were flown at a pressure of 140 millibars, which corresponds to a height (H) of approximately 46,000 feet and was generally well above the tropopause. During summertime, when the aircraft does not require de-icing before flight and the hours of daylight are long, the journey from Farnborough to 40°N and then to about 68°N can be accomplished in one day, but in winter two consecutive days would be needed.

* The index numbers refer to the bibliography on p.10

In a full flight the aircraft left Farnborough at about 0500 G.M.T. and climbed to L on course for Minorca (40°N). At Minorca the aircraft climbed to H and returned to Farnborough at this level. After refuelling and a change of crew, the aircraft flew at L to about 100 miles north of Kinloss and returned there to be refuelled again. From Kinloss to midway between Iceland and northern Norway (67°N or 68°N) the aircraft flew at L and returned to Kinloss at H. The final leg was Kinloss to Farnborough at H, although the aircraft flew northwards initially to climb to H.

Four such complete flights were possible in the summer of 1956 and the remaining five flights were over one or two legs only. Table I shows full details.

TABLE I. Details of flights

Flight no.	Date	Time G.M.T. from	to	Lower altitude L *millibars*	Higher altitude H *millibars*	Extreme point reached *degrees*
1	18.7.56	0805	1220	187	—	64N, 3W
2	19.7.56	1230	1500	187	140	42N, 4E
3 (i)	24.7.56	0510	0814	227	140	40N, 5E
3 (ii)	24.7.56	0925	1744	227	140	67N, 3W
4 (i)	26.7.56	0455	0746	250	140	41N, 4E
4 (ii)	26.7.56	0920	1752	250	140	66N, 4W
5 (i)	31.7.56	0501	0800	187	140	40N, 4E
5 (ii)	31.7.56	0906	1614	187	140	66N, 4W
6 (i)	9.8.56	0510	0755	187	140	40N, 4E
6 (ii)	9.8.56	0912	1720	187	140	67N, 3W
7	4.3.57	1216	1500	187	140	41N, 5E
8	14.3.57	1245	1524	187	140	42N, 5E
9	22.3.57	0852	1638	187	140	67N, 4W

Farnborough: 51° 17′N, 00° 45′W; Kinloss: 57° 39′N, 03° 34′W.

INSTRUMENTATION

The instruments used were the standard flat-plate thermometer and Meteorological Office balanced bridge for temperature, the Dobson–Brewer pressurized frost-point hygrometer, and the standard navigational instruments for pressure, height and airspeed. Temperature was corrected for all known errors using standard techniques and has a standard error of about 2°C at these altitudes. Wind was measured using a Marconi Doppler navigator.[8] The standard vector error of the wind measurement is about five knots. An automatic observer, in which a camera took photographs of the meters every 50 seconds or so, was used to obtain readings of wind similar to those taken by the observer in the pressure cabin. The automatic observer was mounted in the bomb bay of the aircraft.

ANALYSIS

Surface conditions at 0600 G.M.T. and 200-millibar contours at 1500 G.M.T. are shown in Figures 1 (*a*) to 9 (*a*). The details of Flights 1 to 9 are shown in Figures 1 (*b*) to 9 (*b*), which were obtained by using known aircraft positions and interpolating where necessary to find the latitudinal position of the meteorological observations. On each of the diagrams times and heights are given against latitudes; temperature and frost-point (dashed lines) are plotted on the same diagrams; wind speed and wind direction are plotted separately on the diagram: regions in which clear-air turbulence was found are indicated.

Using radio-sonde ascents for either 0300 G.M.T. or 1500 G.M.T. or both, where necessary, a tropopause analysis was constructed along the line of flight. It was assumed that the tropopause was a uniformly sloping surface between any two radio-sonde ascents and linear interpolations were made for any point along the track. The tropopause was obtained from tephigrams by inspection, the use of potential temperatures and the official definition. No discontinuities in the tropopause surface were assumed even though they may have existed in the region of upper frontal zones (Flight 3 and Flight 4) because it was impossible to decide exactly where these discontinuities were. However, where a double tropopause was suggested on several ascents near together, the two tropopause sheets were drawn on the graph. (Flight 3: at 0300 G.M.T. at Lerwick and at 1500 G.M.T. at Stornoway double tropopauses were suggested and it was convenient to make the surface discontinuous at 60°N and 58°N respectively at 0300 G.M.T. and 1500 G.M.T.) Surface frontal zones at 0600 G.M.T. and upper frontal zones are also indicated on Figures 1 (*b*) to 9 (*b*) where they existed. Figures 1 (*b*) to 9 (*b*) are useful in that they present new data on the variation of winds and humidities near fronts in the upper troposphere and lower stratosphere. They are, however, too few to be used for any general synoptic discussion although this may be possible when further data have been obtained. Several interesting features can be pointed out at this stage; in particular the latitudinal variation of frost-point, the profiles of jet streams, the occurrence of clear-air turbulence, and the relationship of the measurements to frontal phenomena are discussed below. On some occasions it was possible to compare values of temperature obtained from the aircraft measurements with the radio-sonde values at 1500 G.M.T. over northern Scotland: differences never exceeded 2°C.

FROST-POINT

General

The poor resolution of the frost-point hygrometer makes any detailed discussion of these results rather difficult especially at 140 millibars where the instrument is used near its lower limit, and conclusions which are drawn should be treated with reserve.

One very important point brought out by these flights is the homogeneity of the stratospheric air. The variations at 140 millibars in the value of the frost-point were less frequent and of less amplitude than those at 187 millibars and below: the amplitude of the over-all variation between 40°N and 70°N was also less. Except for well marked trends, where a change of air mass may have been involved (as on Flight 4) the observed frost-point at 140 millibars was remarkably uniform in each air mass, but the apparent uniformity may have been partly due to the fact that the instrument was being used very near to its limit. At 187 millibars observations are easier to make, and even the smaller variations recorded are probably real, being due either to genuine heterogeneities in the atmosphere or, in some cases, to accidental variations in the height of the aircraft.

Mean values of frost-point

Table II shows the mean values of the frost-points arranged in flight legs as follows:— leg 1 is roughly 40°N to 50°N, leg 2, 50°N to 60°N and leg 3, 60°N to 70°N. The three flights in March are called winter flights for this purpose and those in July and August are called summer flights. No deviations from the mean values are given in this table because the variations can be seen clearly from the diagrams (Figures 1 (*b*) to 9 (*b*)). Observations of frost-point over the British Isles[1,2] are also included for reference under the heading 'mean B.I.';

the summer 'mean B.I.' is taken using the observations made between April and September through June; the winter 'mean B.I.' is taken using the observations made between October through December to March. The total number of observations on which these means are based is between 60 and 80 depending on the height and this is roughly divided in the ratio five to eight for summer to winter. A mean of the observations from the current flights under discussion is also taken over legs 2 and 3 (north mean).

TABLE II. Mean frost-point (°C) for the flights and averages for the British Isles 1954, 1955

		140 mb			187 mb		
Flight (leg)	Season	Mean frost-point	Mean B.I.	No. of readings	Mean frost-point	Mean B.I.	No. of readings
1(2)	summer	—		—	-79·8		12
1(3)	summer	—		—	-78·0		5
2(1)	summer	-82·9		15	-77·6		7
3(1)	summer	-81·8		19	-70·6*		17
3(2)	summer	-77·5		10	-59·2*		10
3(3)	summer	-80·6		15	-74·0*		11
4(1)	summer	-78·6		12	-64·4†		10
4(2)	summer	-80·7		9	-63·4†		12
4(3)	summer	-82·1		14	-76·0†		13
5(1)	summer	-81·2		19	-76·8		16
5(2)	summer	-81·6		8	-77·7		11
5(3)	summer	-82·6		12	-77·5		10
6(1)	summer	-79·9		17	-72·9		16
6(2)	summer	-79·5		10	-76·5		11
6(3)	summer	-80·8		16	-78·9		13
7(1)	winter	-82·0		16	-72·3		16
8(1)	winter	-84·5		16	-73·7		16
9(2)	winter	-80·6		11	-80·5		11
9(3)	winter	-82·1		14	-80·1		12
1(1) to 6(1)	summer	-81·0	-81·0	82	-75·0‡	-74·2	39
1(2) to 6(2)	summer	-79·7	-81·0	37	-77·8‡	-74·2	34
1(3) to 6(3)	summer	-81·4	-81·0	57	-78·5‡	-74·2	28
7(1)+8(1)	winter	-83·4	-81·8	32	-73·0	-75·9	32
9(2)+9(3)	winter	-81·5	-81·8	25	-80·2	-75·9	23
north mean	summer	-80·8	-81·0	94	-78·0‡	-74·2	62
north mean	summer + winter	-80·9	-81·4	119	-78·6‡	-75·4	85
1(1) to 9(1)	summer + winter	-81·7	-81·4	114	-74·3‡	-75·4	71
1(2) to 9(2)	summer + winter	-79·9	-81·4	48	-78·8‡	-75·4	40
1(3) to 9(3)	summer + winter	-81·6	-81·4	71	-78·5‡	-75·4	45
All	summer	-80·9	-81·0	176	-77·0‡	-74·2	101
All	winter	-82·5	-81·8	57	-76·0‡	-75·9	55
All	summer + winter	-81·3	-81·4	233	-76·6‡	-75·4	156

* Readings apply to height 227 mb

† Readings apply to height 250 mb

‡ Means apply only to readings at height 187 mb

At 250 mb, mean B.I. = -64·6°C; at 227 mb, mean B.I. = -67·6°C. Mean 3(2)+3(3) = -67·0°C (21 readings); Mean 4(2)+4(3) = -70·0°C (25 readings); Mean 3(1)+3(2)+3(3) = -68·6°C (38 readings); Mean 4(1)+4(2)+4(3) = -68·4°C (35 readings).

1(1) to 6(1) is the mean of these 6 flights on leg 1 (40°N to 50°N), etc.

(*a*) *140 millibars.*—The average frost-point on eight days between 40°N and 70°N was −81·3°C (233 readings) and this differed by only 0·1°C from the mean B.I. The mean for summer differed by 0·1°C from the mean B.I. but the mean for winter differed by 0·7°C.

It has been suggested by Brewer[9] that there is a circulation of air from the equator towards the poles in the stratosphere. The air would have been dried by ascent to the tropical tropopause at about 90 millibars, and would have a frost-point of about −85°C assuming saturation at the tropopause. If this were so and there was only a small amount of diffusion through the tropopause surface at higher latitudes, as is suggested by earlier observations of frost-point in the region of the tropopause (and by various diffusion experiments in the lower troposphere when inversions were present), then the frost-point in the stratosphere might be expected to be nearly constant at any given height, but to show a slight increase towards the poles. This was tested by comparing the summer mean values in the latitude ranges 40°N to 50°N, 50°N to 60°N and 60°N to 68°N in Table II. Although there were only slight differences from the mean B.I. the data indicated that there was on average no steady gradient from south to north, but that there was moister air between 50°N and 60°N than in the other two latitude ranges. However, bias may have caused this and it is desirable to look at the individual flights. Only on Flight 3 did any significantly higher frost-points appear in the middle latitude range. On Flights 4 and 5 there was a slight gradient of decreasing frost-point from south to north; while on Flight 6 the frost-point was nearly the same in the two bands 40°N to 50°N and 50°N to 60°N, but decreased north of 60°N. These results are consistent with Brewer's hypothesis, but indicate that on some occasions the distribution of humidity in the lower stratosphere of middle latitudes is dependent on the current synoptic situation.

(*b*) *187 millibars.*—There were six occasions on which frost-points could be meaned in the three latitude ranges and almost the whole of the 156 observations were in the stratosphere; those not in the stratosphere were in the intertropopause region. The over-all average frost-point was −76·6°C, about 1·2°C colder than the mean B.I. In the latitude range 50°N to 60°N, the most nearly comparable latitudes, the average frost-point was −78·8°C, 3·4°C colder than the corresponding mean B.I. In the summer flights the over-all mean decreased northwards, values being −75°C, −77·8°C and −78·5°C for the three latitude belts; in winter the corresponding values were −73°C, −80·2°C and −78·0°C. In the individual flights there was again no uniform trend.

On Flights 5 and 9 nearly the same mean values were found in the ranges 50°N to 60°N and 60°N to 68°N and there was more water vapour from 40°N to 50°N on Flight 5. On Flight 6 there was evidence of a general northward advection of moister air in the increase of frost-point at this level at 45°N.

(*c*) *Lower levels.*—On Flights 3 and 4 the high mean frost-points in the range 50°N to 60°N are associated with frontal zones as can be seen from the cloud data. Although the flights were made at a constant height, the aircraft was in the troposphere while flying in the zone 40°N to 50°N and in the stratosphere when north of 60°N; the zone from 50°N to 60°N was one of transition. The lowest frost-points were encountered in the northern zone, where the aircraft was in the stratosphere, but it is striking that the frost-point was higher in the transition zone than in the troposphere to the south.

Results

(*a*) An increase of frost-point usually occurred when the aircraft passed from the stratosphere into the troposphere and in the upper troposphere there were almost constant values even at 250 millibars where patchy cloud was encountered.

(*b*) On some of these flights the transition from tropospheric air to stratospheric air in the southern leg cannot be detected by the frost-point measurements and it seems that the frost-point of air below the tropical tropopause but above the polar tropopause is almost indistinguishable from that of the stratospheric air to the north. This can be seen on Flight 3 between 42°N and 48°N and on Flight 5 between 40°N and 50°N.

WIND FIELDS

On all these flights the wind field found shows similar features to those found by the radiosonde network and the profiles of wind speed and direction agree well with similar profiles deduced from synoptic charts. Two good traverses, one at 250 millibars (Flight 3) and the other at 227 millibars (Flight 4) were obtained through a jet stream near the level of the jet core, which lay between 55°N and 65°N. There were also two good flights into jet streams at 187 millibars (Flight 5 and Flight 6) when the core was between 40°N and 45°N and perhaps a little below the height of the measurements. On Flight 6, in particular, there is a possibility that the jet stream was a northern extension of the subtropical jet stream. The two traverses at 250 millibars and 227 millibars showed greater horizontal wind shear to the north of the maximum speed than to the south; for example, on Flight 3 the mean shear over five degrees of latitude to the north was 20 knots per degree ($9{\cdot}2 \times 10^{-5}$ sec^{-1}) and to the south it was 14 knots per degree of latitude ($6{\cdot}5 \times 10^{-5}$ sec^{-1}), and even over about nine degrees of latitude the shear to the north was 13·5 knots per degree of latitude, about one knot per degree latitude greater than to the south. At 140 millibars similar profiles were found to those at lower altitudes on all four flights but the maximum values and variations were less. Despite the fact that readings were taken at short intervals (about five minutes or 35 miles of flight) the profiles of wind speed are reasonably smooth. Variations in wind direction are also smooth for winds greater than about 20 knots. At speeds less than 20 knots the wind direction becomes more variable possibly because of instrumental errors.

CLEAR-AIR TURBULENCE

The jet stream and orographic influences

Figure 10 (*a*) presents the information obtained on the position of clear-air turbulence relative to the jet-stream maximum and the tropopause. It is evident that although most of the turbulent regions were in the vicinity of the jet stream others were far removed from it. The data available were not well suited for examining possible physical connexions with lapse rate, vertical wind shear and Richardson number but the connexion with horizontal wind shear can be examined in some cases. The values found in turbulent zones vary between $4{\cdot}5 \times 10^{-5}$ sec^{-1} and 24×10^{-5} sec^{-1}. Values in non-turbulent zones, however, up to about 8×10^{-5} sec^{-1} were measured on occasion and it appears likely therefore that horizontal shear is only a contributory factor although its effect may be of importance above 8×10^{-5} sec^{-1} to 10×10^{-5} sec^{-1}.

Table III summarizes the observations of turbulence for these flights. Leg 1*b* is over the Mediterranean (40°N to 44°N), leg 1*a* is over France (44°N to 50°N), leg 2 is over Britain (50°N to 60°N) and leg 3 is between 60°N and 68°N. The number 3(1)*a* refers to Flight 3, leg 1, over the land. The table compares the occurrence of turbulence with orographic influences and the jet stream. It was assumed that if the turbulence occurred more than 500 miles from a jet-stream core then no jet stream was present.

TABLE III. Turbulence, the jet stream and land/sea influence

	Jet (*flight data*)	No jet (*flight data*)	Jet (*number of occasions*)	No jet (*number of occasions*)	Jet (*number of occasions*)	No jet (*number of occasions*)	Total
(i) Turbulence							
Land	4(2) 6(1)*a*; 6(2)	7(1)*a*; 8(1)*a*	3	2	5	5	10
Sea	2(1)*b*; 3(3)	3(1)*b*; 5(3) 6(3)	2	3			
(ii) No turbulence							
Land	2(1)*a*; 3(2) 5(1)*a*	1(2) 3(1)*a* 4(1)*a*; 5(2) 9(2)	3	5	5	11	16
Sea	5(1)*b*; 6(1)*b*	1(3) 4(1)*b* 4(3); 9(3) 7(1) 8(1)*b*	2	6			
Total			10	16	10	16	26

This simple analysis of only a few cases shows that neither the contrast between land and sea nor jet-stream influences were predominant in their association with turbulence. Before going into greater detail, however, it is perhaps relevant to point out that Flights 2(1)*b*, 3(1)*b* and 7(1)*a* were to the lee of the Pyrenees. An attempt will be made to explain the turbulence of Flight 6(3) but on Flight 5(3) the turbulence was of short duration in a col area and no real explanation can be offered.

If the data in Table III are representative then on any day in a flight of about 600 miles in the stratosphere, the chance that turbulence is encountered is about two in five; if there is a jet stream present, this chance is about one in two and if no jet stream is present the chance is about one in three.

Particular example of interest

The turbulence found on Flight 6, that is, the heavy turbulence near the maximum wind speed and the slight to moderate intermittent turbulence found in the stratosphere from 6 to 17 degrees north of the maximum are of particular interest. Figure 10(*b*) shows the vertical accelerometer traces from 07 hr 42 min 23 sec to 07 hr 43 min 15 sec when the aircraft was travelling at 140 millibars from 48° 24′N to about 48° 31′N (about seven miles) in the first of these regions. There were two types of recording: the continuous trace recorder giving negative and positive accelerations in g units and the stepped trace recorder which shows positive accelerations in $0{\cdot}1g$ steps on one trace and negative accelerations in $0{\cdot}1g$ steps on another trace (positive g acts downwards). The accelerometers began to record after a severe bump in which the navigator's equipment left his table and which was estimated to have been an incremental acceleration of about $1g$. The maximum increment recorded was $-0{\cdot}5g$ at 07 hr 43 min 8 sec and can best be seen on the stepped trace record. The accelerations changed sign with a frequency which varied from about once per second to once in five seconds but in addition there were high frequency fluctuations. There were six occasions on which $+0{\cdot}3g$ was recorded and four occasions on which $-0{\cdot}3g$ was recorded, in the 50 seconds or so of trace. Accompanying these accelerations were rapid fluctuations in the indicated temperature often reaching amplitudes of 4°C about the mean. The indicated airspeed was 192 knots but rapid unrecorded fluctuations occurred. No satisfactory examination of the causes of this turbulence is possible since the Richardson number cannot be determined, but the following are possible contributory factors: (i) the variation of horizontal wind shear, which rose quickly during this part of the flight from $4{\cdot}5 \times 10^{-5}$ sec^{-1} to $9{\cdot}0 \times 10^{-5}$ sec^{-1}; (ii) the proximity of the tropopause; (iii) the fact that the flow was accelerating: at Trappes, at 140 millibars the wind speed increased from 90 knots at 0300 G.M.T. to 150 knots at 1500 G.M.T.

Turbulence of a different kind was found between 53°N and 64°N at 187 millibars on the same day. This was intermittent and varied between slight and moderate. It is not possible to give horizontal wind shear nor is an accelerometer record available but some attempt can be made to analyse this turbulence which occurred in the region of the tropopause in the south but was about three kilometres above it in the north. The radio-sonde ascents over the British Isles show an isothermal region from the tropopause to about one kilometre above it (that is, at the level of the flight) and then an increase in the temperature. The 200-millibar wind field suggests a region of confluent flow with moderate winds in the north and strong winds in the south and it is possible that some instability of motion was set up in the south which was transferred north.

TEMPERATURE AND FRONTS

Temperature fluctuations were found on all the flights and the small irregularities may have been due partly to changes in the height of the aircraft by 100 feet or so and partly to the random errors of observation. On all the flights when the height of the aircraft above the tropopause decreased, the temperature also decreased. When the aircraft flew from the troposphere into the stratosphere the air temperature at the fixed height increased. The temperature, at a given altitude near the level of the jet-stream core increased from a minimum on the high-pressure side of the core and reached a steady value 300 to 500 miles to the low-pressure side. The wind maximum was 100 miles or so to the low-pressure side of the lowest temperatures.

When a frontal zone was shown on the surface chart, it was also indicated by temperature changes in the upper troposphere on the cold-air side of the surface frontal zone at different levels. In the stratosphere there were also changes of a similar sign as that in the upper troposphere and these began to occur nearer the surface front than those at a lower altitude in the stratosphere or in the upper troposphere, the amplitude of the change being less at the greater altitudes.

On Flight 3 at 227 millibars the temperature rose about 2°C per degree of latitude over about 500 miles of flight northwards and on Flight 4 the same rate of rise was maintained at 250 millibars for about 350 miles both in the region of jet streams. At 140 millibars the temperature increased northwards at about 1°C per degree of latitude over about 1,000 miles of flight on both days. If the hypothesis that a frontal zone can exist in the stratosphere is accepted then these data suggest that a diffuse frontal zone was possibly traversed at 140 millibars. The extent of these zones is suggested on Figures 1(*b*) to 9(*b*) where relevant. On

Flights 2, 5 and 6 there were decreases in temperature of the same order as those on Flights 3 and 4 towards the south but these were in the extreme south. There is no evidence on the synoptic charts at the appropriate time that fronts existed in the region for Flights 2 and 5 but there is a warm front to the north of the temperature change region found on Flight 6. However, on the charts drawn 12 hours previous to the time of the Flights 2 and 5, weak cold fronts are traceable and it is possible that the decreases of temperature are associated with upper frontal phenomena remaining. On two occasions in the stratosphere immediately above a cold front there were some higher frost-points than in the surrounding air. This bulge of moister air extended to 140 millibars probably along the line of the front and suggests that upward motion in this region had been stronger than in the surrounding atmosphere. The bulge was not found in Flight 3 over a warm front but on Flight 6 there was an increase in frost-point over the cold air, about 350 miles from the surface warm front at 140 millibars and 400 miles from it at 187 millibars. The increase at 140 millibars here occurred in the region of the tropopause surface and this may have been a contributing factor. If the air at 187 millibars constituted a bulge in the same sense as that used above for the cold front, then the frontal zone suggested would have had a slope of one in sixty. Another possibility in this case is that moister air—involving a change of air mass—was being advected from the south at both 187 millibars and 140 millibars, and that an upper warm front had been created by this advection. There is no evidence of a wind change near the frontal zone at either 187 or 140 millibars.

CONCLUSIONS

This series of flights between 40°N and 70°N may be summarized as follows:

(i) At heights well above the tropopause there were no major latitudinal variations of frost-point in any given air mass although there were some minor heterogeneities.

(ii) When the tropopause was crossed in horizontal flight there was no noticeable change of frost-point.

(iii) Except on traverses into and through jet streams no rapid changes of importance were found in the wind field. The horizontal wind shear on the low-pressure side was greater than that on the high-pressure side of the wind maximum.

(iv) Although several good examples of clear-air turbulence were found in association with the jet stream, there were also some cases of turbulence in the stratosphere for which no explanation can be offered from the data available. Horizontal wind shear in the turbulent areas varied between $4 \times 10^{-5}\,\text{sec}^{-1}$ and $24 \times 10^{-5}\,\text{sec}^{-1}$ but values up to $8 \times 10^{-5}\,\text{sec}^{-1}$ were found in non-turbulent regions.

(v) The temperature at 140 millibars decreased by about 10°C in 600 miles on two flights in the stratosphere above cold frontal zones in such a way as to suggest that the frontal region existed in the stratosphere. These effects also occurred at lower altitudes in the region of the tropopause.

(vi) In the stratosphere on the high-pressure side of a cold front on two occasions there was evidence of a bulge of moister air which, it is suggested, was caused by upward motion in this region and the frost-point increased at 140 millibars from the low-pressure side to the high-pressure side.

In order to investigate the frost-point structure near the equatorial tropopause and hence more fully test theories of general circulation in the stratosphere, it is very desirable to obtain an aircraft which can fly to 60 millibars. For this work a fully automatic frost-point hygrometer is desirable especially since measurements of ozone concentration may soon be possible.

ACKNOWLEDGEMENTS

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KEY TO CHARTS

surface isobars at 0600 G.M.T. at 4 mb intervals

200 mb contours at 1500 G.M.T. at 60 m intervals

flight track

KEY TO GRAPHS

readings at height H

readings at height L

frost-point at height H

frost-point at height L

tropopause at 0300 G.M.T.

tropopause at 1500 G.M.T.

flight track at height H, time G.M.T.

flight track at height L, time G.M.T.

clear-air turbulence

surface cold front

surface warm front

direction of motion of front

wind observations omitted: lack of reliable data

heights of cloud are given in thousands of feet

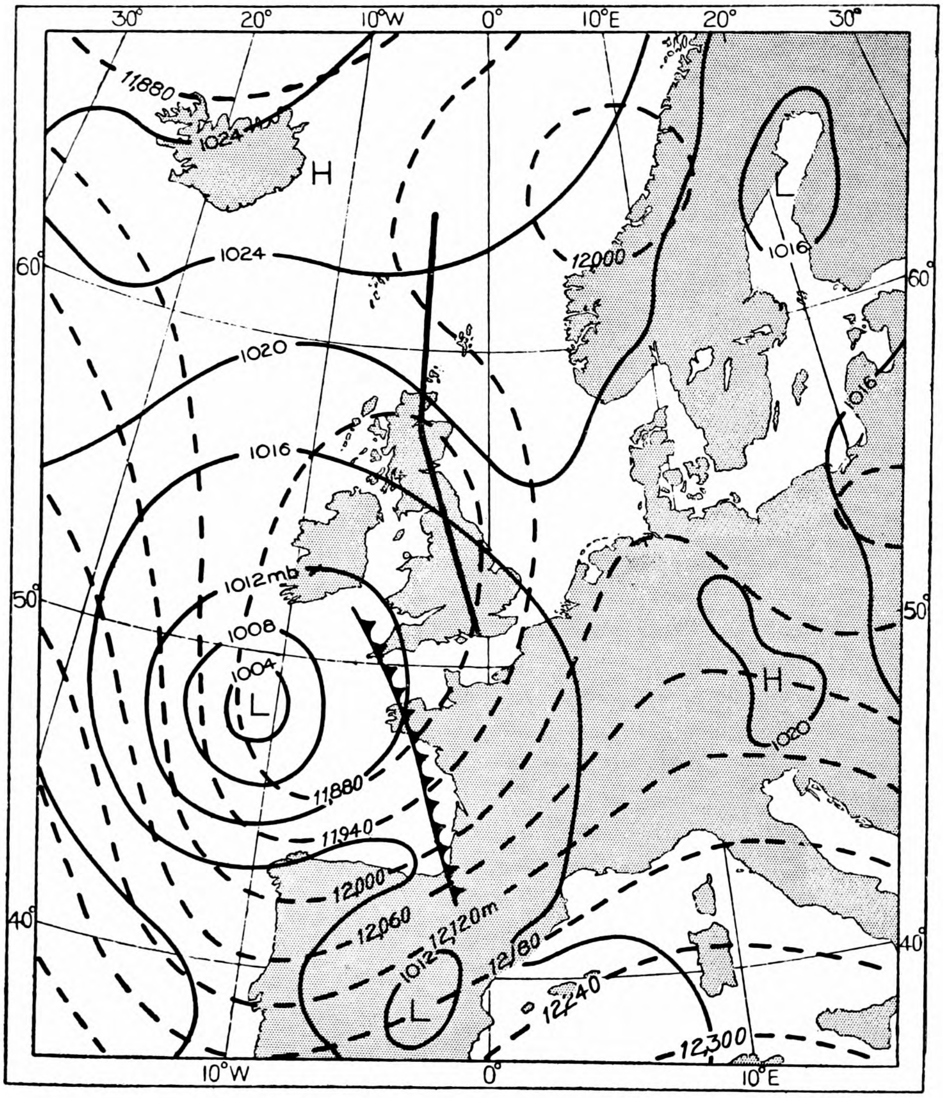


FIGURE 1(*a*). Surface and 200-millibar contour chart for Flight 1, 18 July 1956

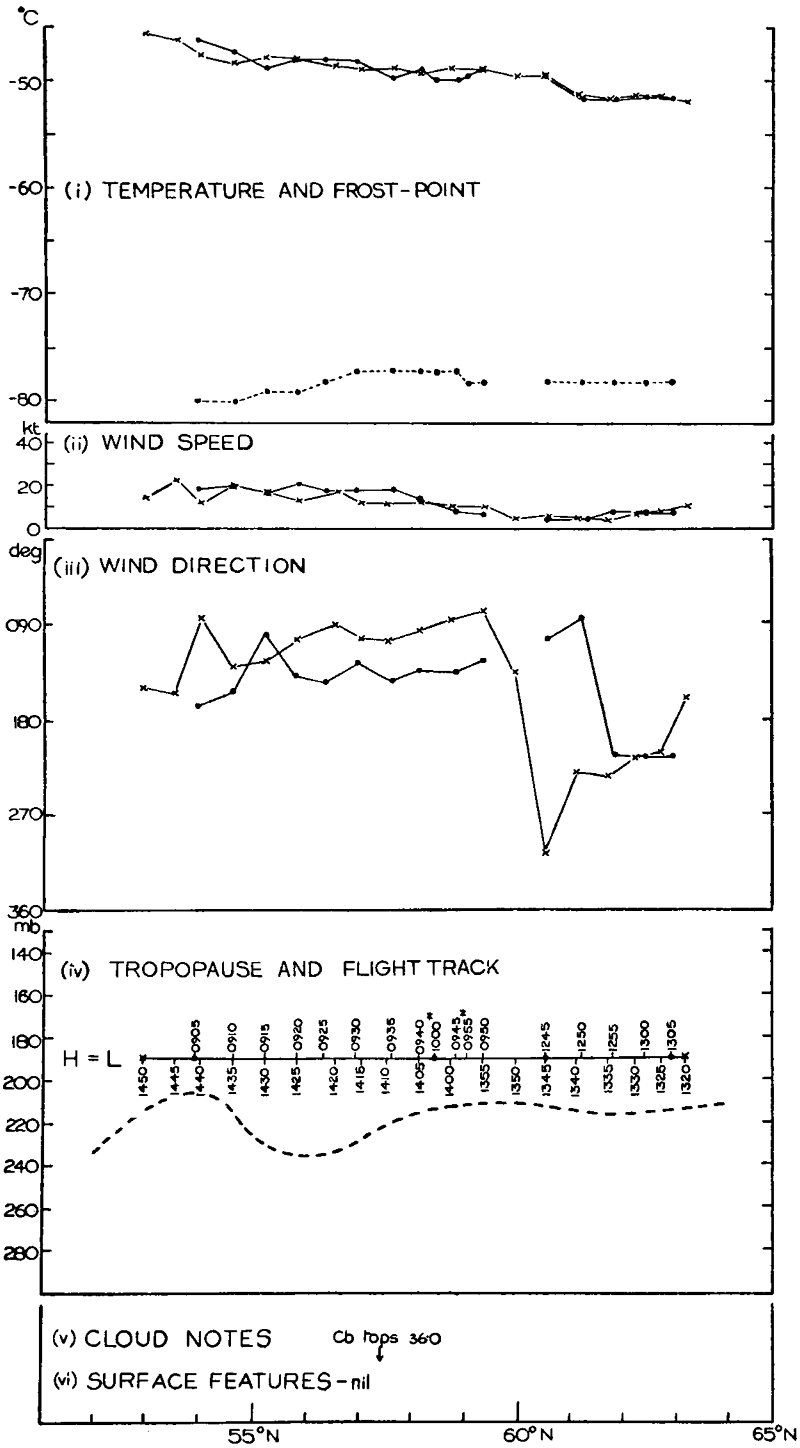


FIGURE 1(*b*). Variation of frost-point, temperature and wind on Flight 1, 18 July 1956

* Aircraft returning towards Kinloss in level flight.

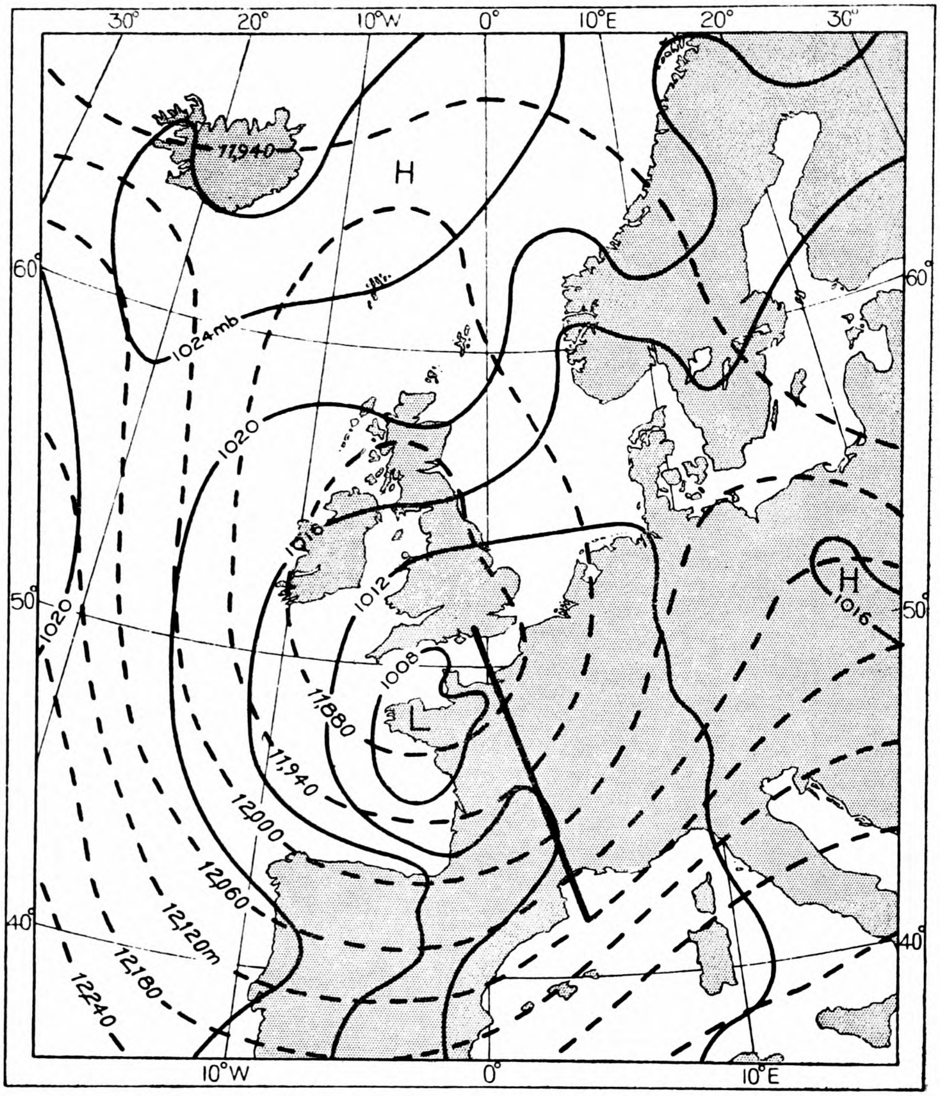


FIGURE 2(*a*). Surface and 200-millibar contour chart for Flight 2, 19 July 1956

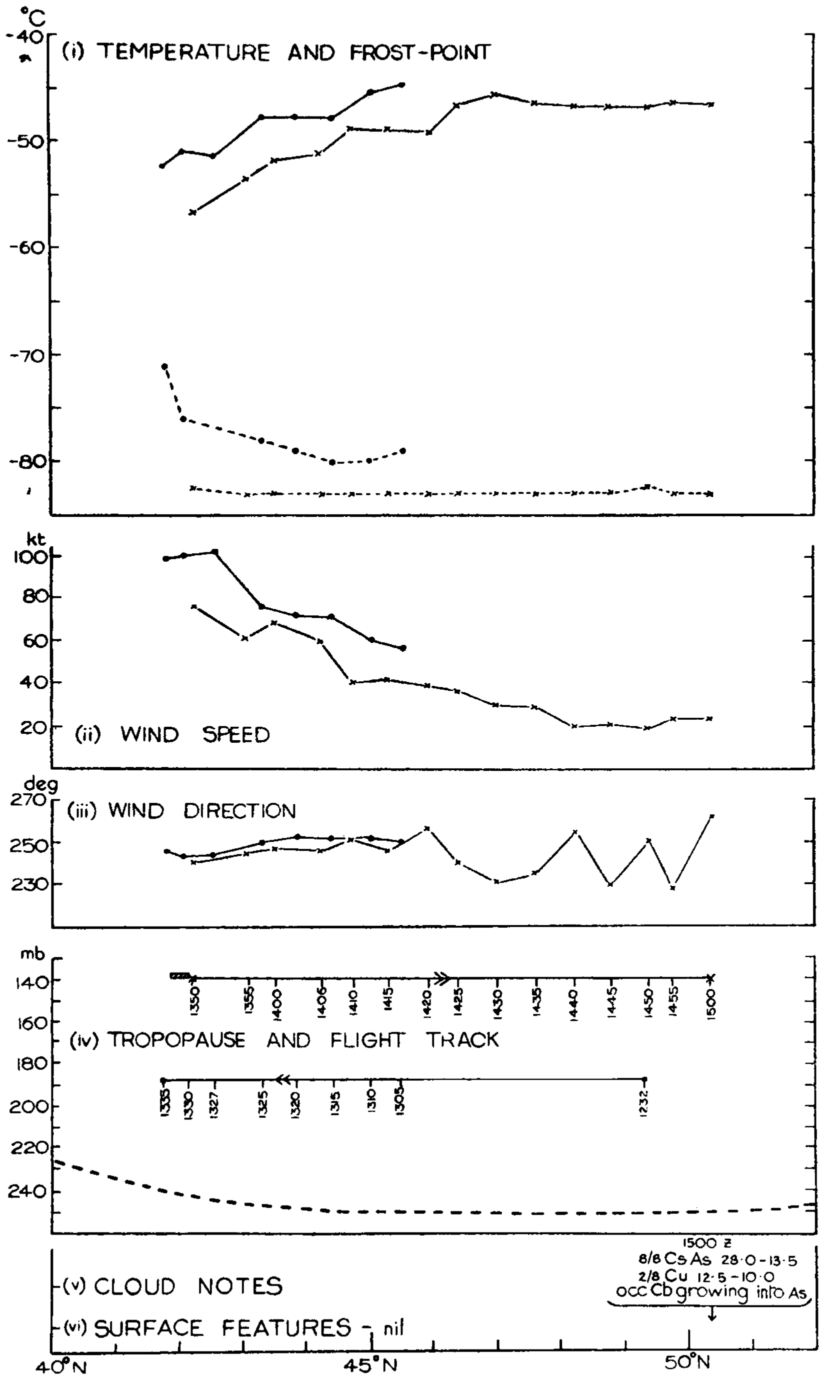


FIGURE 2(*b*). Variation of frost-point, temperature and wind on Flight 2, 19 July 1956

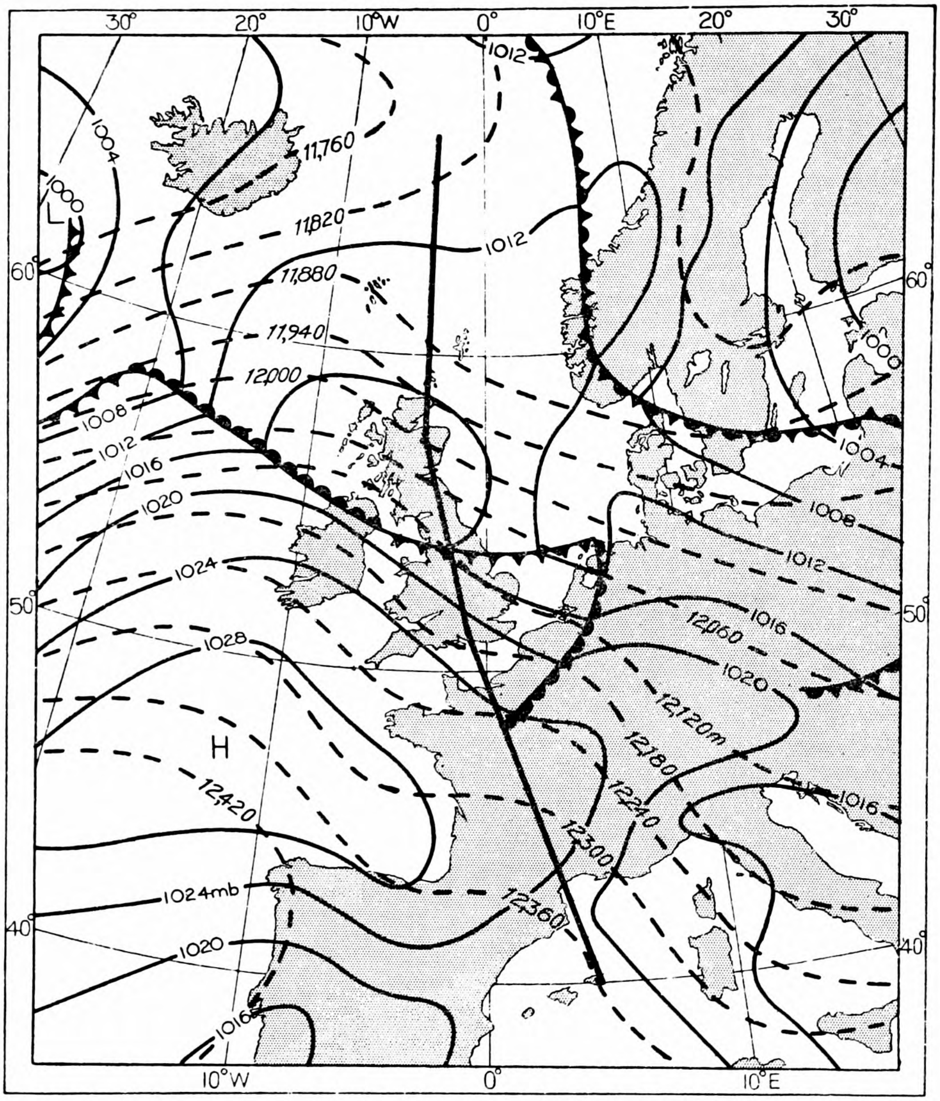


Figure 3(*a*). Surface and 200-millibar contour chart for Flight 3, 24 July 1956

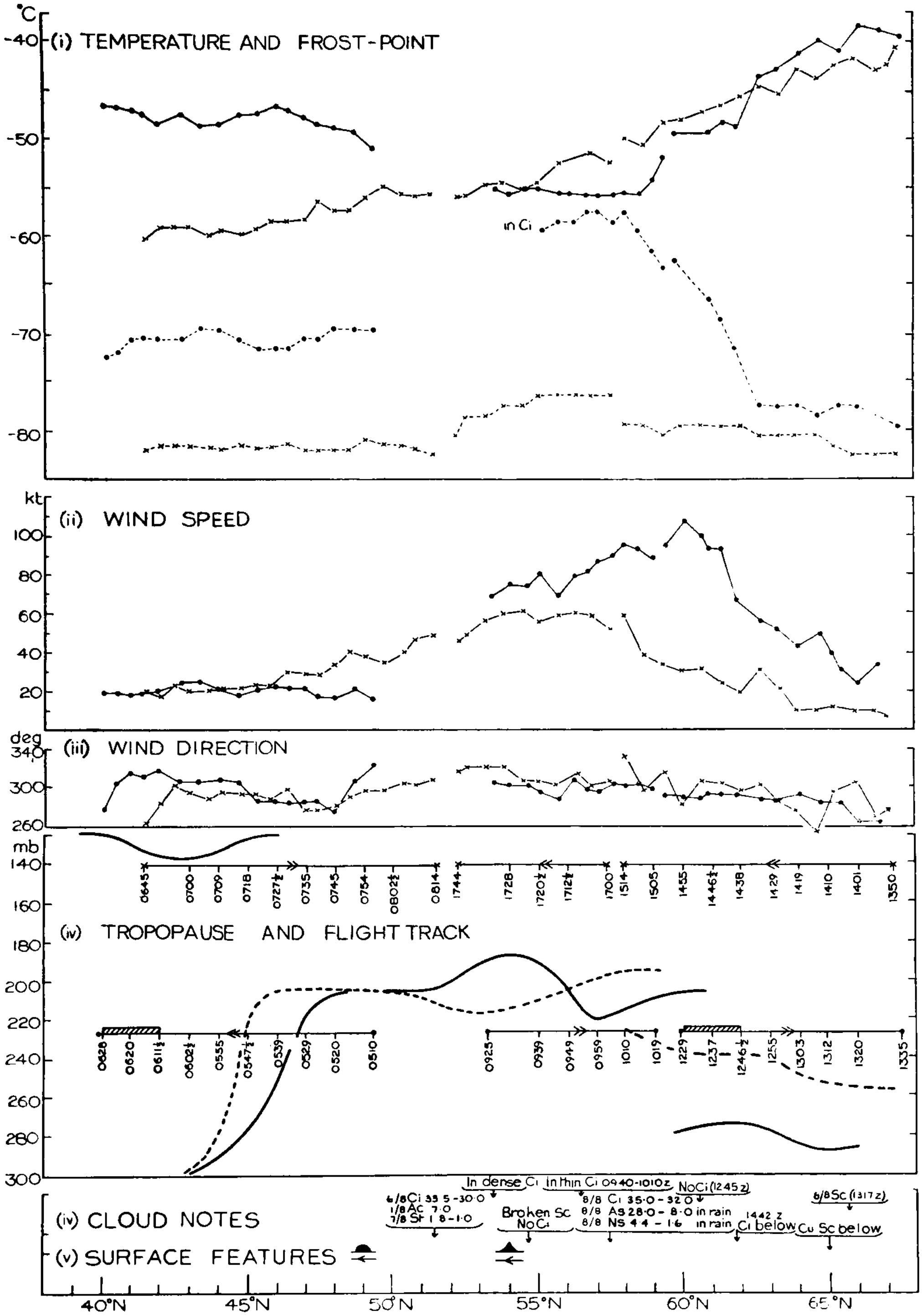


FIGURE 3(*b*). Variation of frost-point, temperature and wind on Flight 3, 24 July 1956

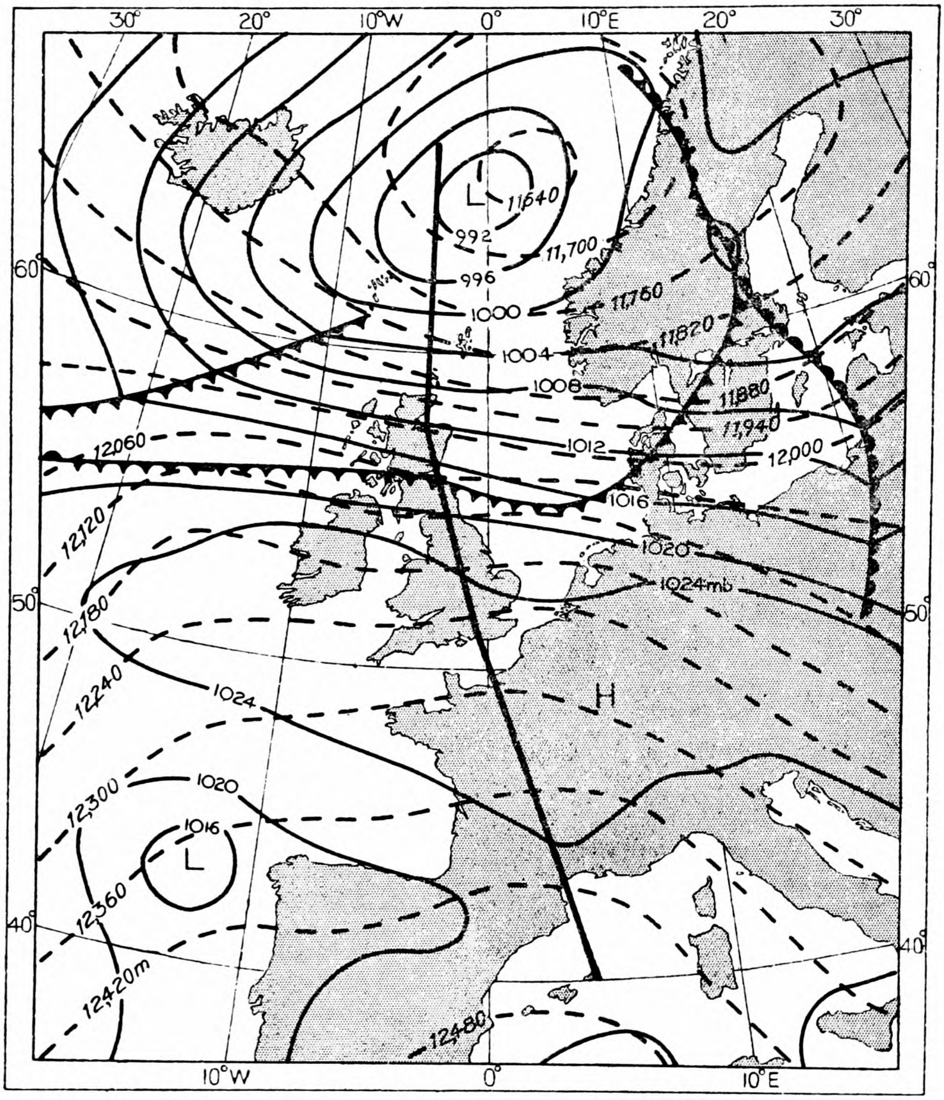


FIGURE 4(*a*). Surface and 200-millibar contour chart for Flight 4, 26 July 1956

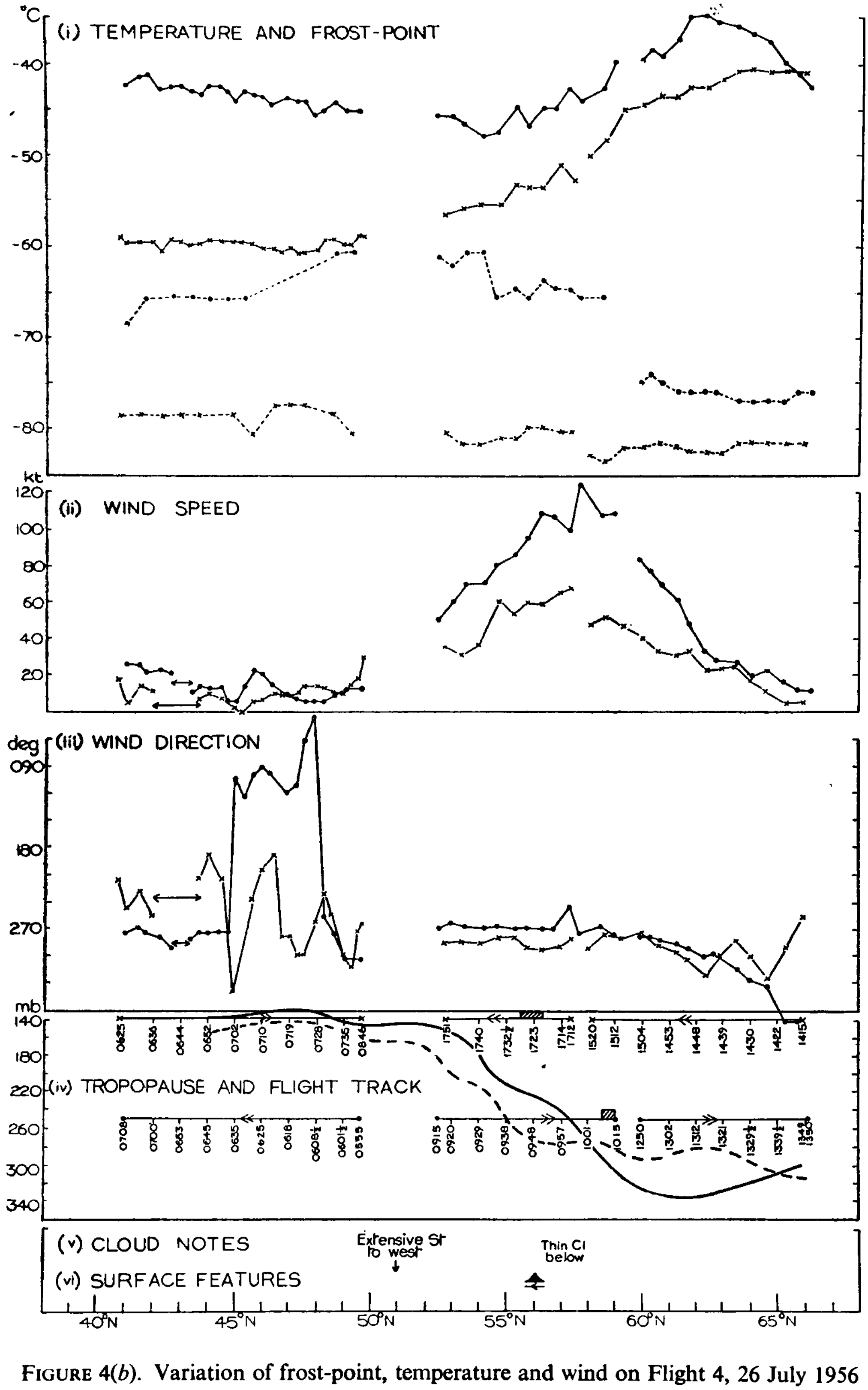


FIGURE 4(*b*). Variation of frost-point, temperature and wind on Flight 4, 26 July 1956

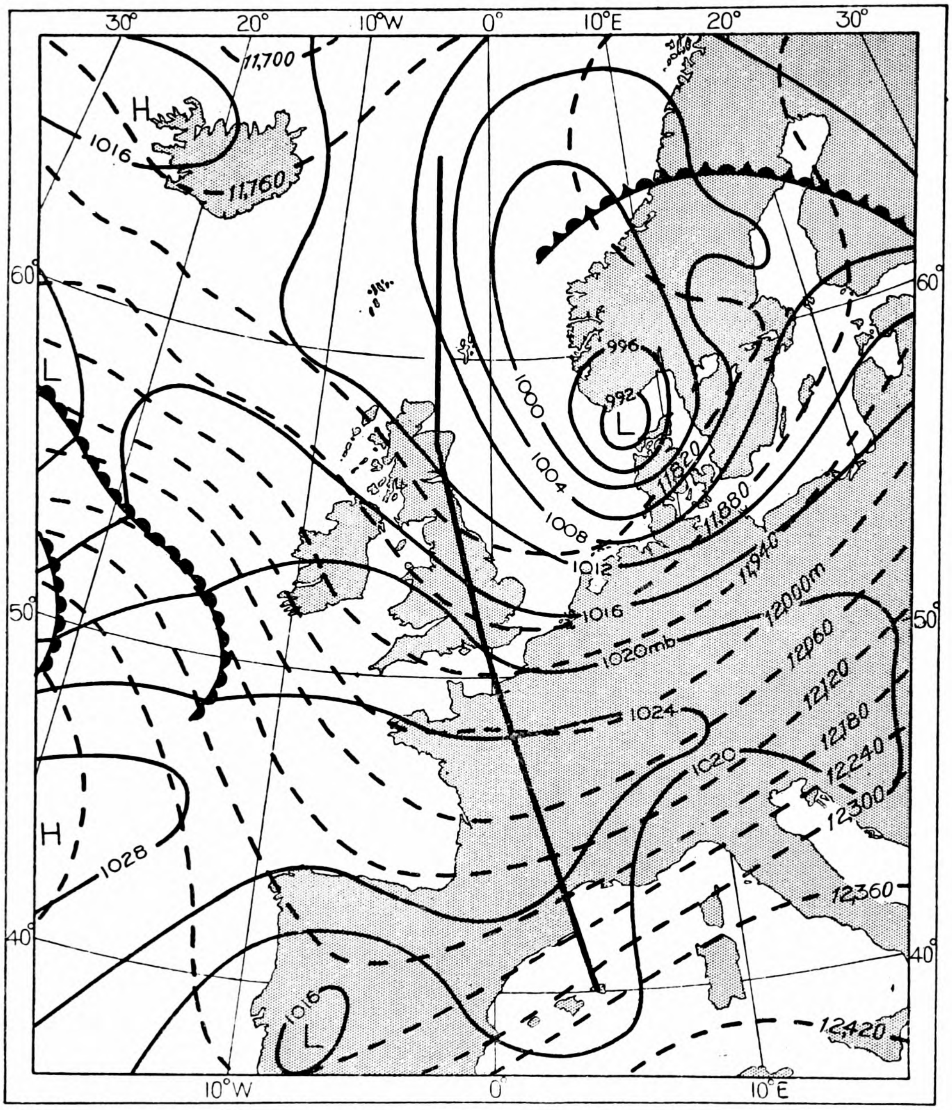


FIGURE 5(*a*). Surface and 200-millibar contour chart for Flight 5, 31 July 1956

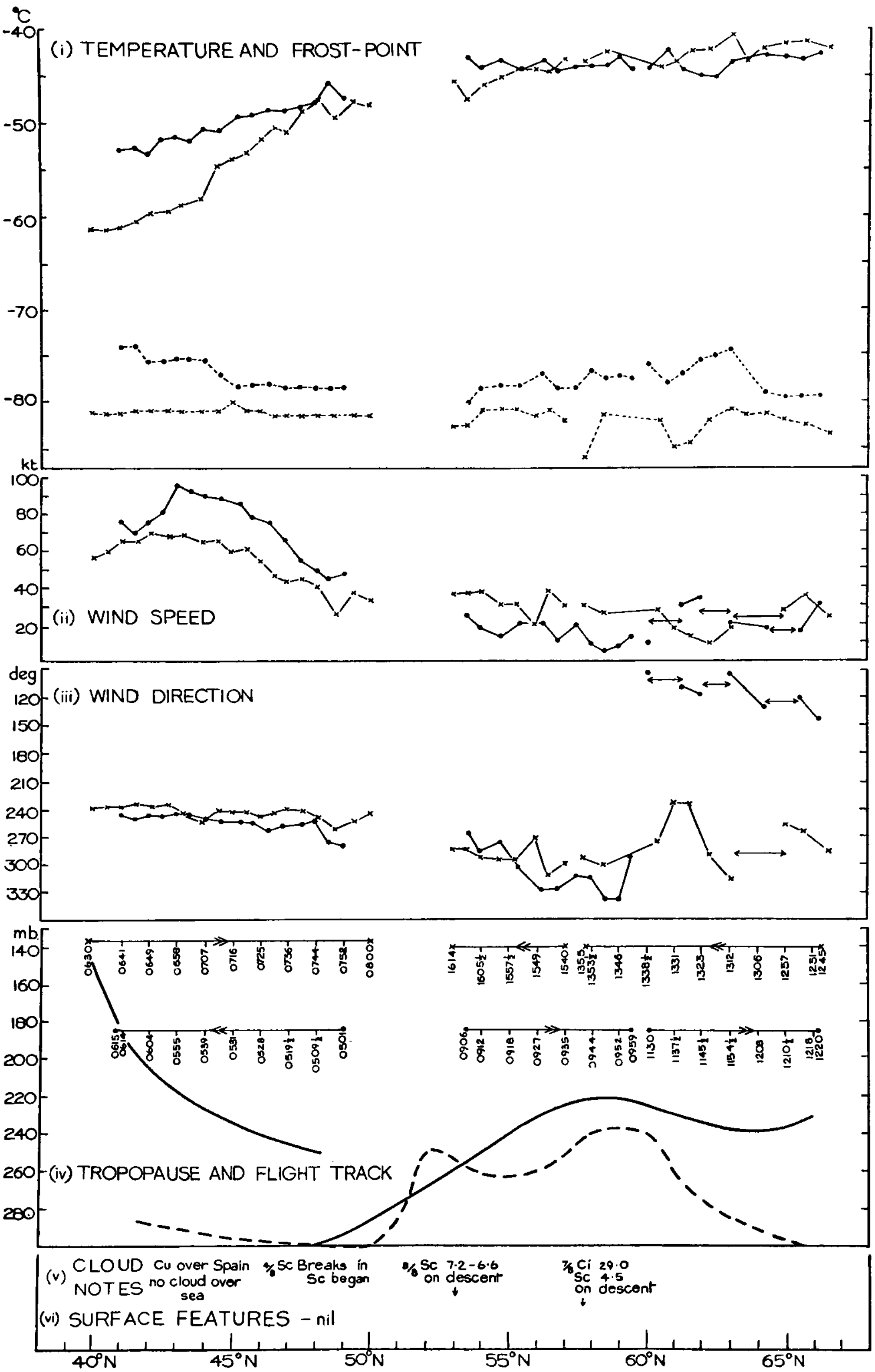


Figure 5(*b*). Variation of frost-point, temperature and wind on Flight 5, 31 July 1956

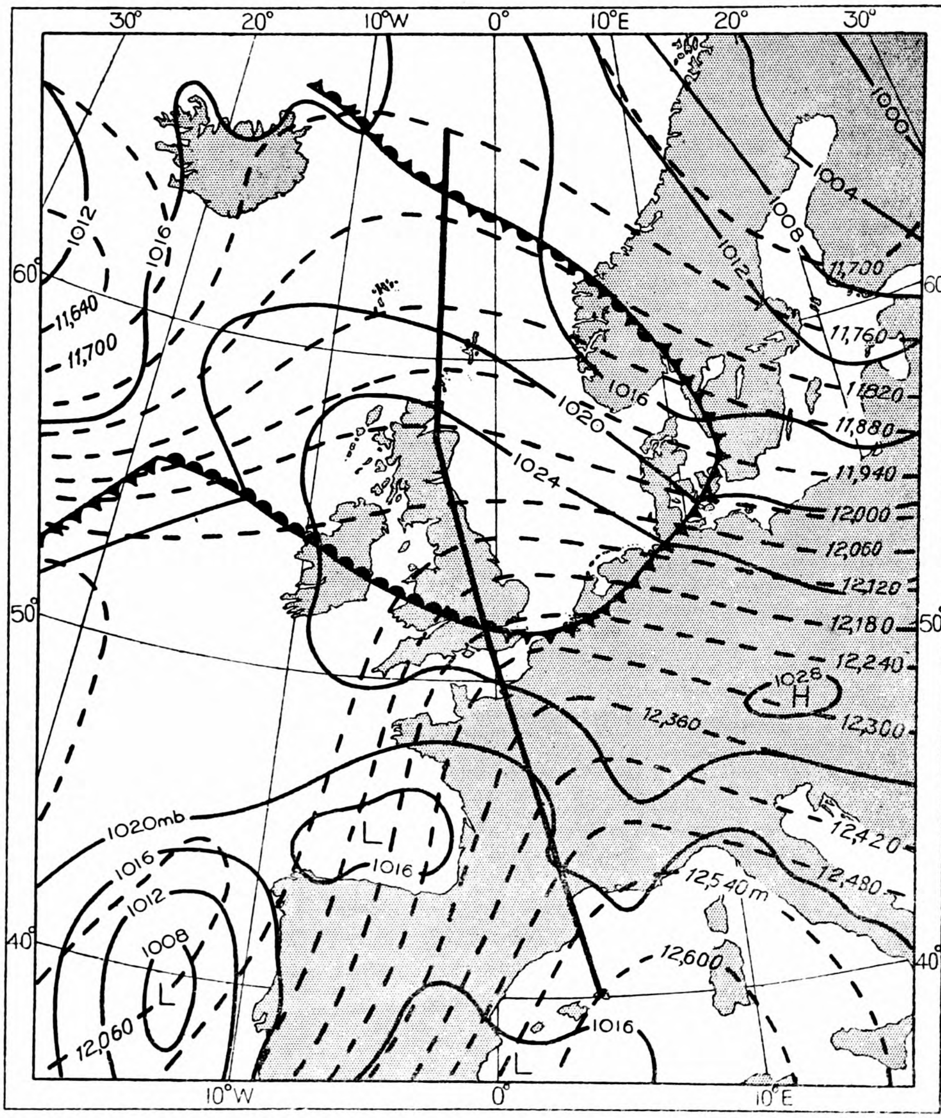


FIGURE 6(*a*). Surface and 200-millibar contour chart for Flight 6, 9 August 1956

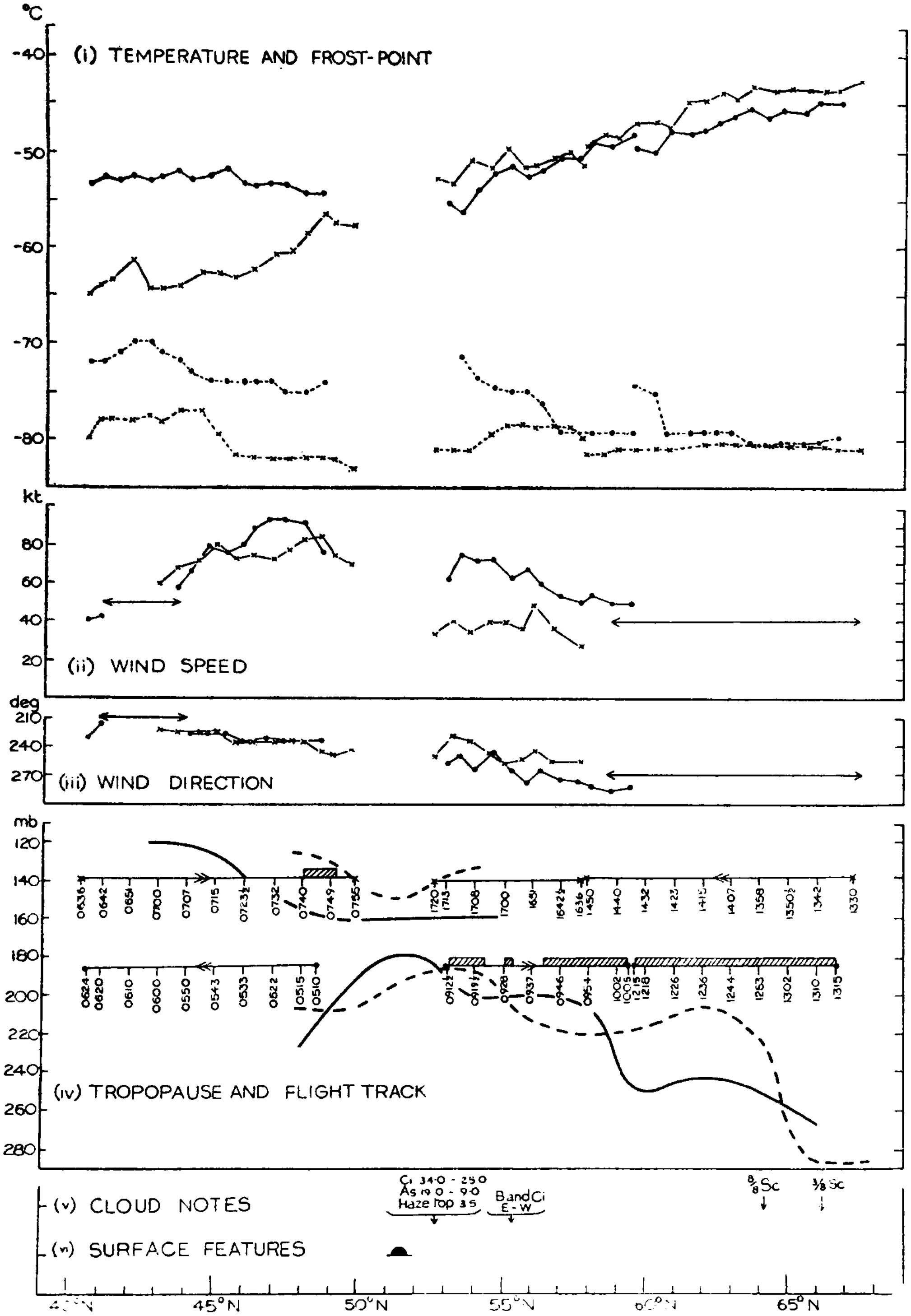


FIGURE 6(*b*). Variation of frost-point, temperature and wind on Flight 6, 9 August 1956

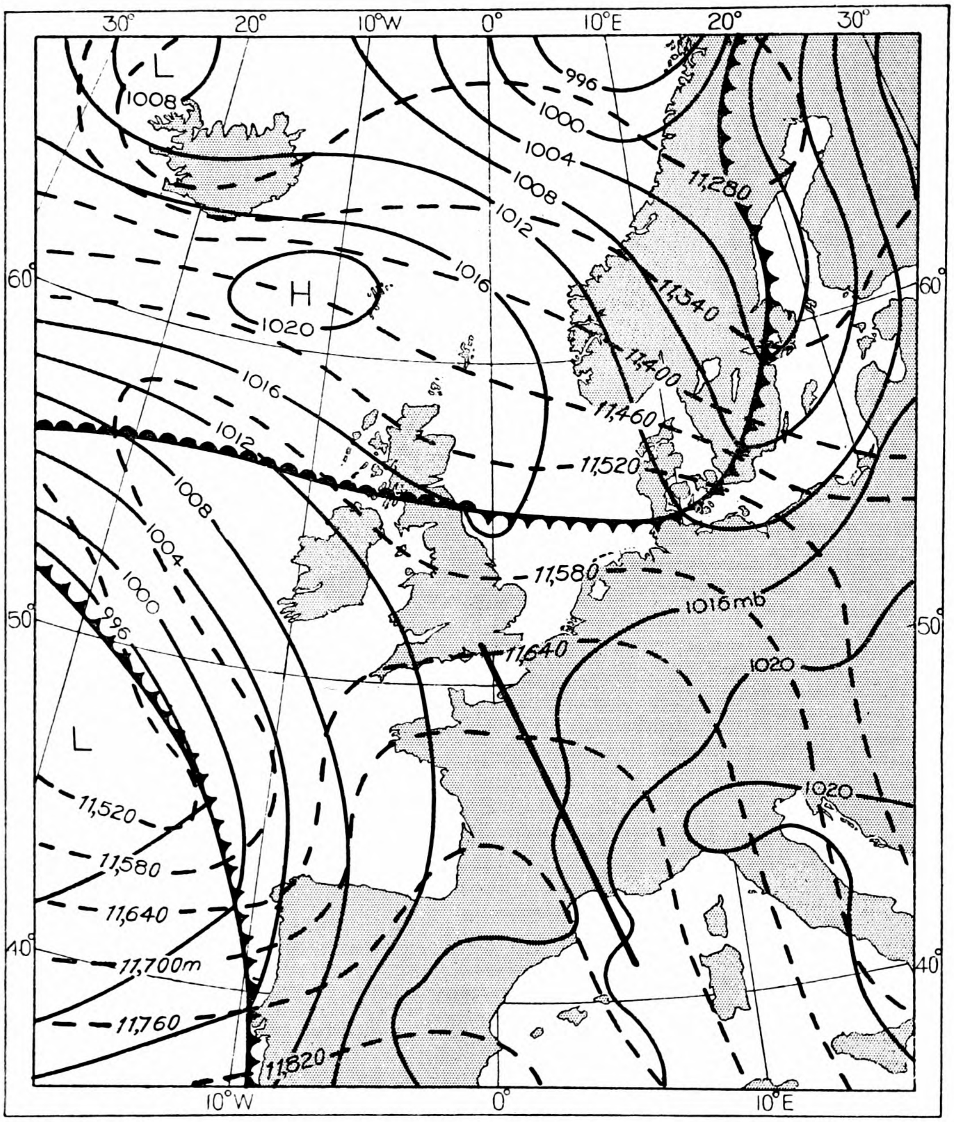


FIGURE 7(*a*). Surface and 200-millibar contour chart for Flight 7, 4 March 1957

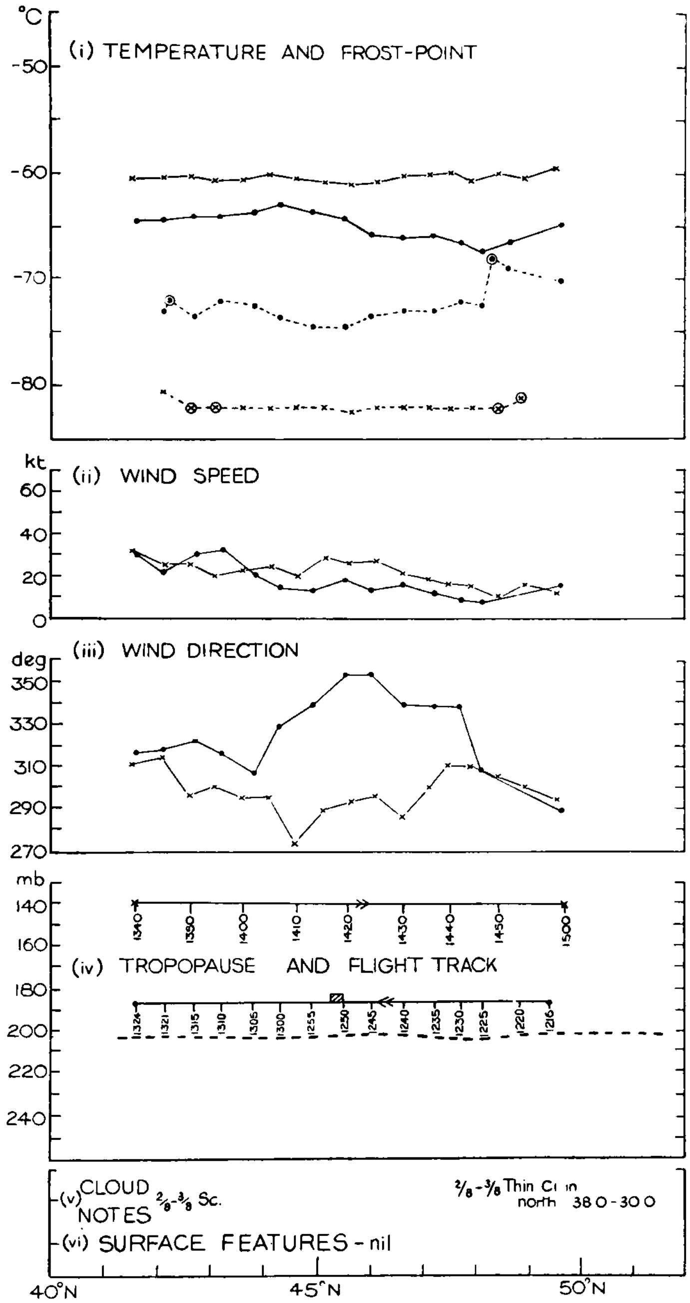


FIGURE 7(*b*). Variation of frost-point, temperature and wind on Flight 7, 4 March 1957 (compressor frost-points have been encircled)

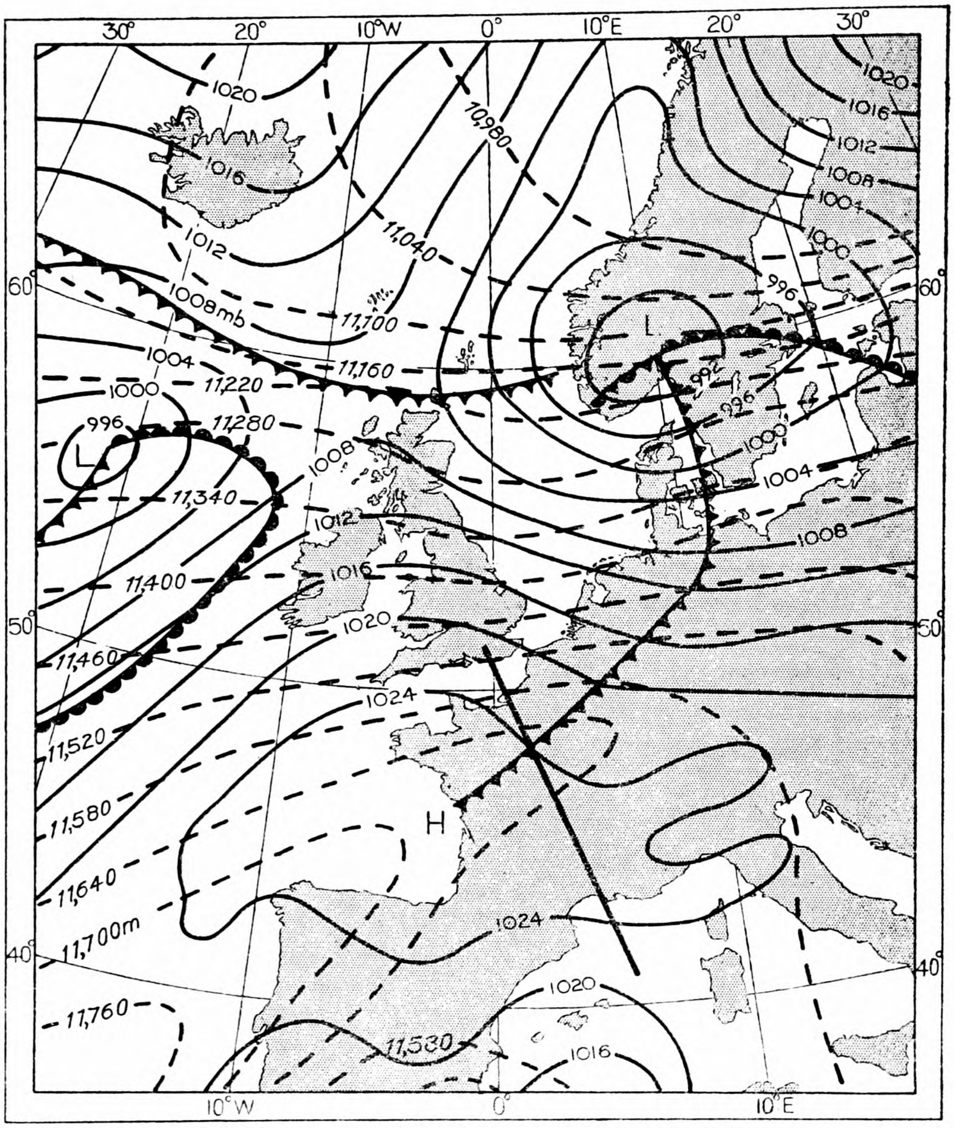


FIGURE 8(*a*). Surface and 200-millibar contour chart for Flight 8, 14 March 1957

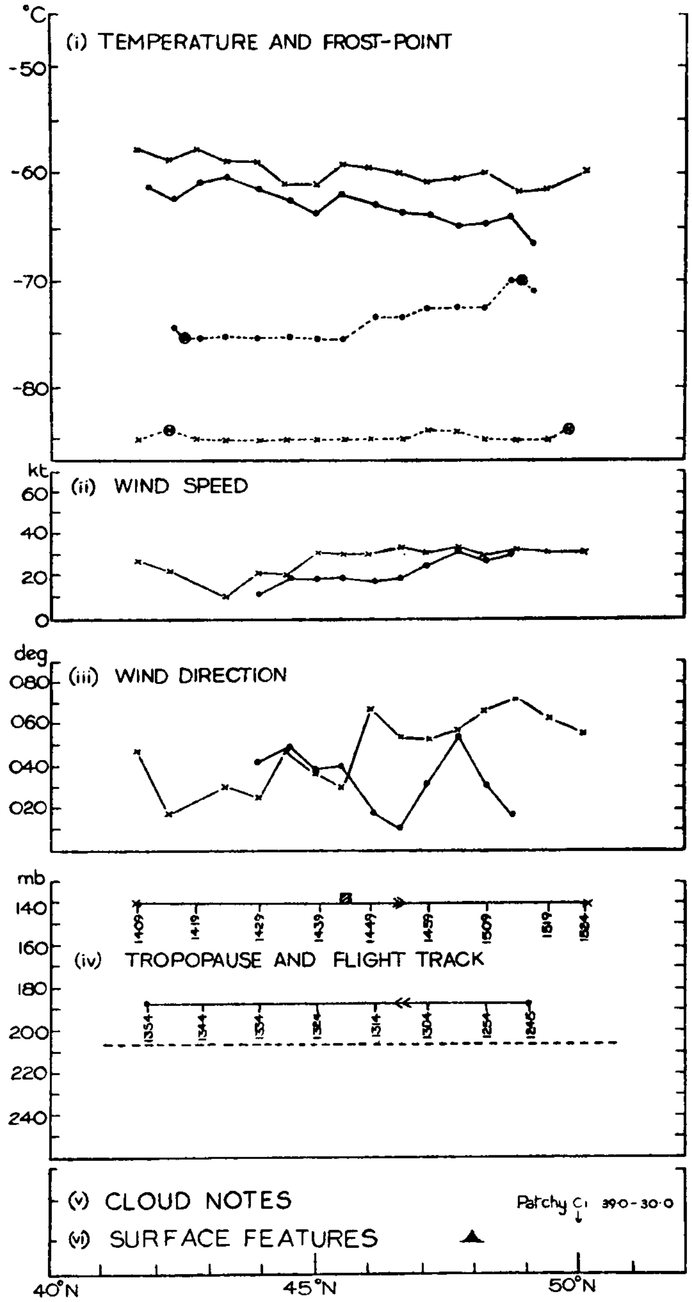


FIGURE 8(*b*). Variation of frost-point, temperature and wind on Flight 8, 14 March 1957 (compressor frost-points have been encircled)

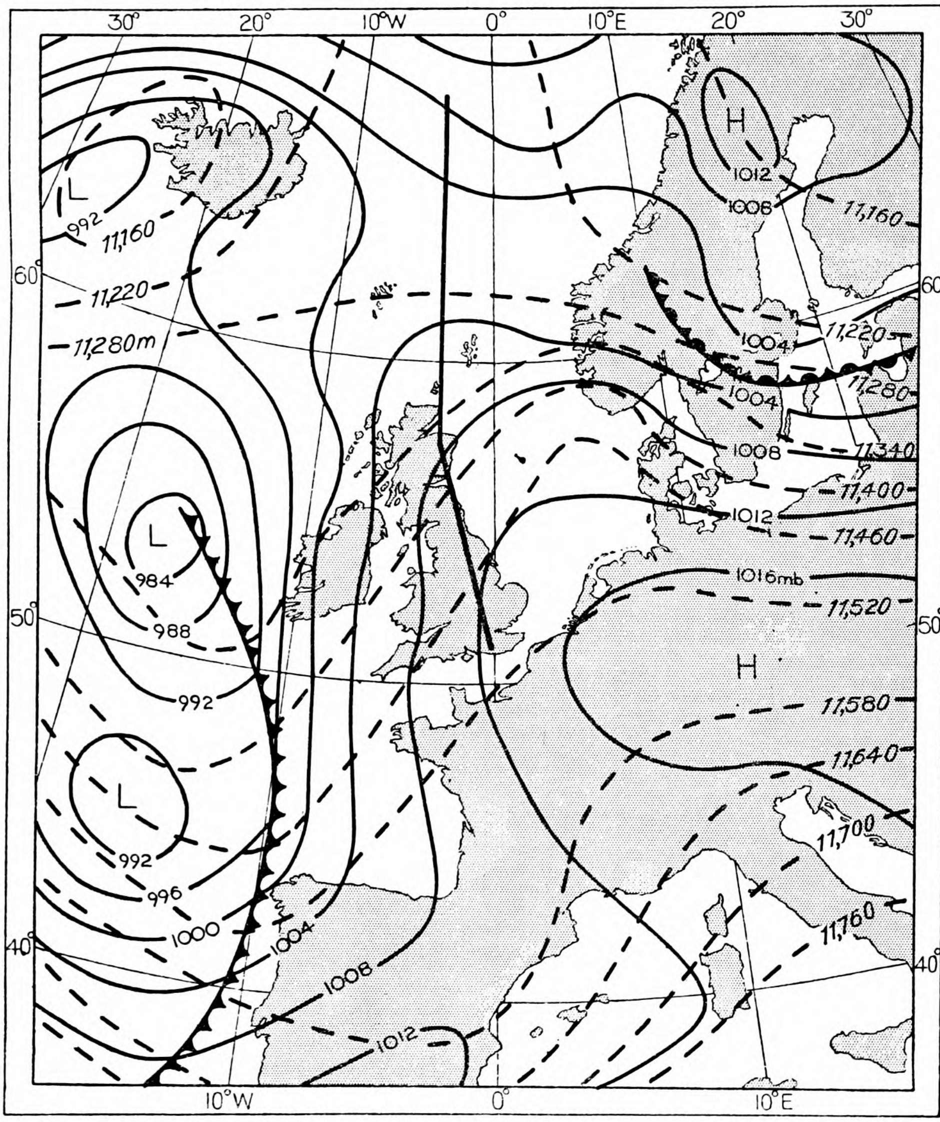


FIGURE 9(*a*). Surface and 200-millibar contour chart for Flight 9, 22 March 1957

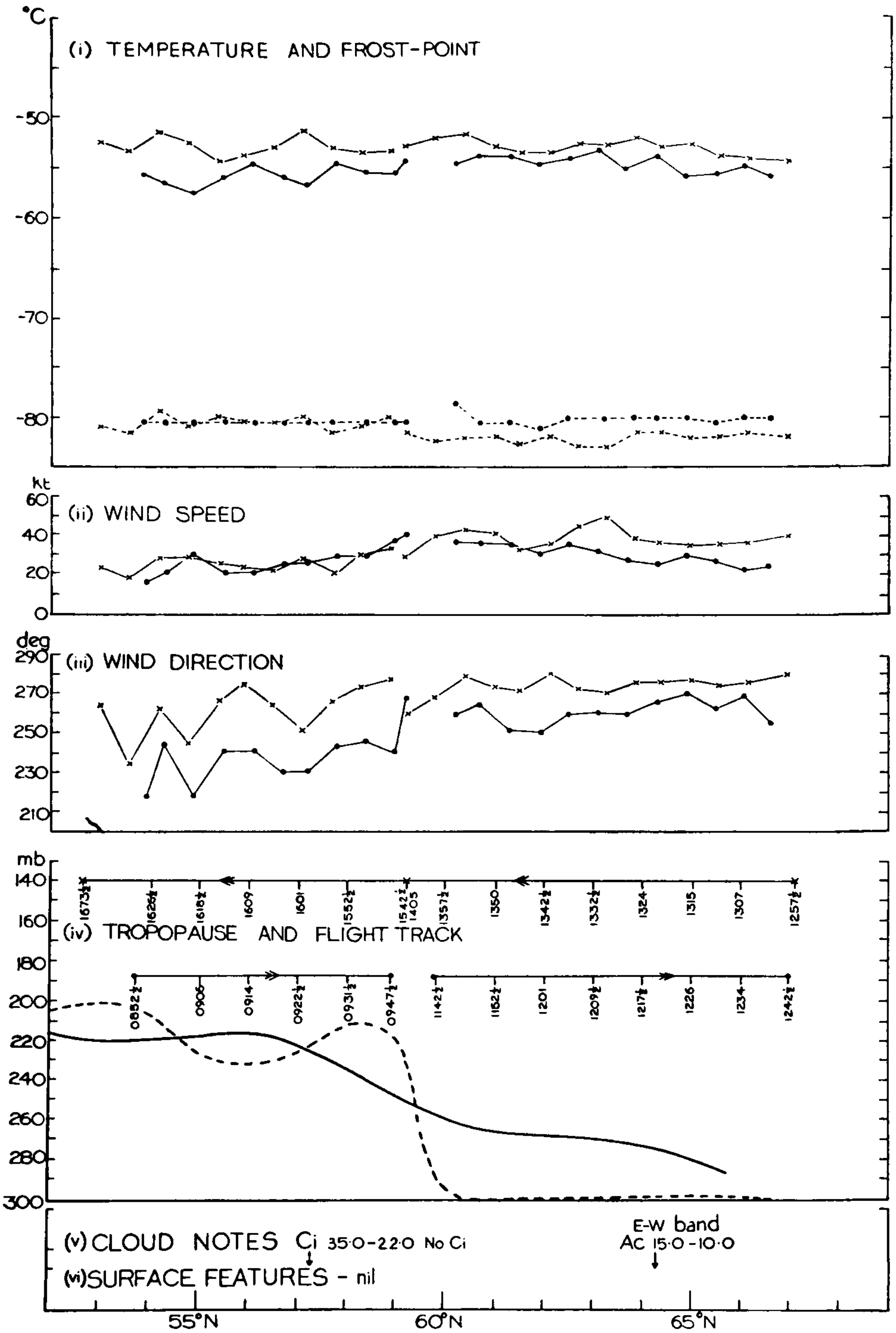
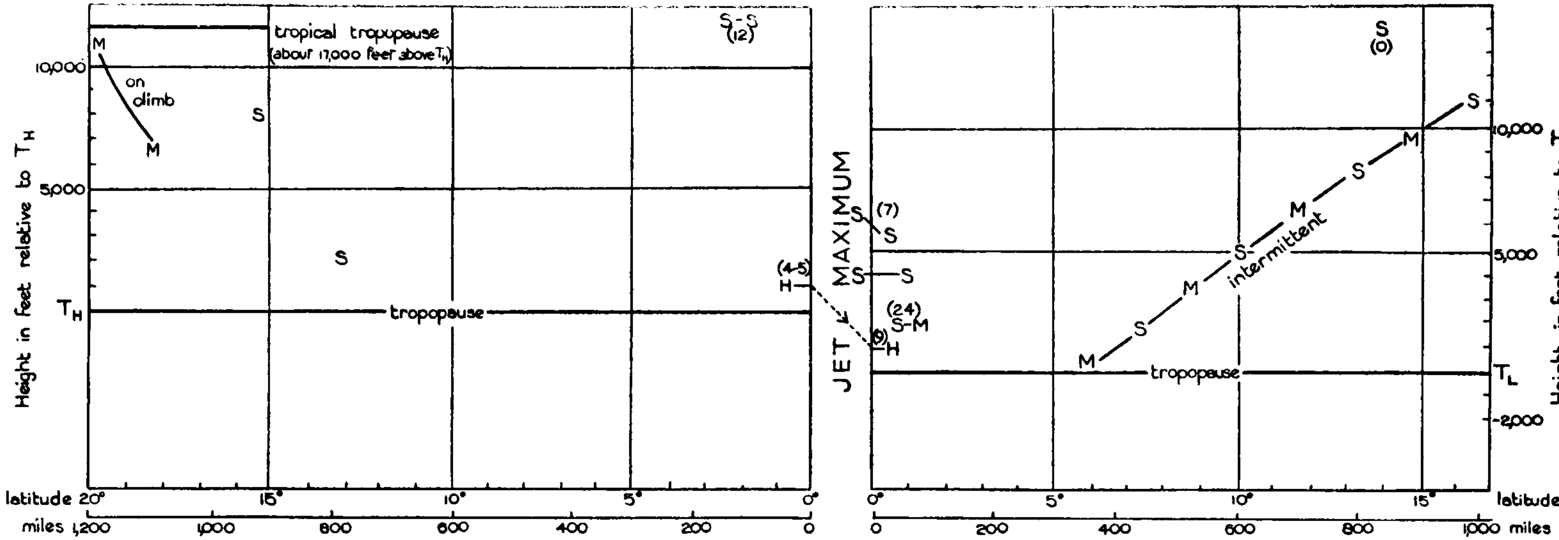


FIGURE 9(*b*). Variation of frost-point, temperature and wind on Flight 9, 22 March 1957



Warm-air side of jet maximum

Cold-air side of jet maximum

FIGURE 10(*a*). Position of clear-air turbulence relative to jet stream and tropopause

T_H: level of tropopause in warm air T_L: level of tropopause in cold air

S–S: slight turbulence along line M–M: moderate turbulence along line

H–H: heavy turbulence along line

The figures in brackets are the shear in units 10^{-5} sec^{-1}

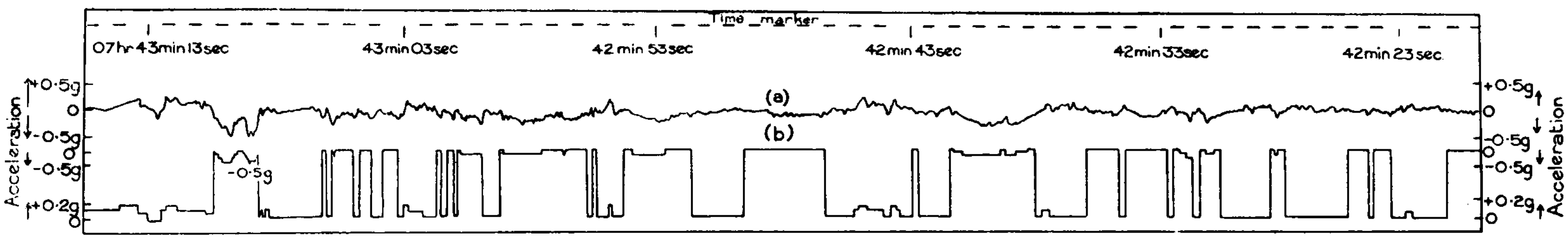


FIGURE 10(*b*). Copy of accelerometer trace made on 9 August 1956 between 48°N and 49°N at 46,000 feet

(*a*) Continuous trace accelerometer; (*b*) Stepped trace accelerometer

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