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by

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RESULTS OF A SERIES OF FLIGHTS IN THE STRATOSPHERE OVER MOUNTAINOUS TERRAIN IN THE WESTERN U.S.A. DURING FEBRUARY, 1967

by
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SUMMARY

In a number of flights in the stratosphere over mountainous terrain in the western U.S.A., much valuable data was collected. Flights were planned on the basis of tropospheric lee wave forecasts and were usually made along wind at heights from the tropopause to about 50000 ft over California and Nevada. Mountain waves, deduced from an analysis of the temperature along the flight track, were moderate or strong on four flights. Moderate or severe turbulence and marked temperature changes were encountered on three flights. The results give an insight into the severity of the stratospheric environment and the meteorological conditions in which the severe disturbances occur.

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* Replaces RAE Technical Report 70034 - ARC 32579

** On loan to Royal Aircraft Establishment, Bedford

CONTENTS

1 INTRODUCTION

Mountain waves are one possible source of high altitude disturbances* sufficient to affect the operation of an aircraft (the other chief source is, of course, thunderstorms). Clear air turbulence (CAT) encounters are common at and below the tropopause in conjunction with lee wave activity over mountainous terrain. It is also known, from experience in gliders and from 'mother of pearl' clouds, that mountain waves propagate through the tropopause well into the stratosphere. Information on the wavelengths, amplitudes and associated turbulence of stratospheric waves is, however, rather sparse and, in view of the growing interest in the stratosphere with the advent of the supersonic transport aircraft, it is important to gain a greater understanding of the nature and magnitude of disturbances in the stratosphere. The stratosphere is, in general, a stable layer in which, prior to the tests described here, it was anticipated that disturbances transmitted through the tropopause in general would be damped out. It was known, however, that in some conditions, disturbances could propagate into and be amplified in the stratosphere but it was not clear under what conditions or how frequently this occurred[1,2].

While the primary purpose of the present tests was to investigate the nature and magnitude of disturbances in the stratosphere, it was also considered important to assess their predictability. Tropospheric mountain waves can be predicted with some confidence from meteorological considerations[3] and it was hoped that this exercise would provide data from which the propagation of tropospheric waves into the stratosphere could be forecast with similar success. In addition it was hoped to improve our understanding of the circumstances in which marked turbulence and changes in outside air temperature were associated with mountain waves.

The Canberra PR 7/9 aircraft (shown in Fig.1) operated by Aero Flight, R.A.E. Bedford, was based at the NASA Ames Research Center, California from late January until the end of February, 1967 on Project WAVERIDER, a part of the general R.A.E. programme of research on high altitude atmospheric disturbances. Thirteen flights were made over mountainous terrain, mainly in California and Nevada, but on one occasion in Utah (see Fig.2). The Canberra flew at and above the tropopause up to 50000 ft (once to 54000 ft).

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*'Disturbances' is used throughout this paper to indicate any atmospheric phenomenon, such as gusts or changes in outside air temperature, which might affect the operation of an aircraft.

Each flight was planned on the basis of a tropospheric mountain wave forecast (see Appendix A) made by a member of the trials team, based on information provided by the Weather Bureau Office at San Francisco International Airport. Mountain waves are likely to be found when there is a fairly strong wind component at right angles to a mountain ridge (20 kt or more at mountain top height, increasing at greater heights) and the temperature profile shows stability near mountain top height. Upper air reports from civil airlines and hourly cloud reports from the surface were also taken into account.

Whenever possible the aircraft flew over an area where strong tropospheric lee wave activity was forecast. On some occasions, however, strong wave activity was out of range and on these days flights were made in the area nearest to base where any wave activity was expected. Several horizontal legs displaced at height intervals of from one to five thousand feet from one another were normally flown from about 20 naut miles upwind of the mountain to 80 naut miles downwind. On a few occasions the track was across-wind, parallel to the ridge and some 20 naut miles on the downwind side. The flight levels were chosen in early flights on the basis of the height of the tropopause but in later flights, in the light of experience gained, the aircraft flew at the height of discontinuities in the wind or temperature profile in the stratosphere. Most of the runs were in the lowest 18000 ft of the stratosphere.

Nine of the 13 flights yielded valuable data and these are discussed in this Report. Section 3 contains a detailed description of each flight and the general reader may omit it since the relevant material is reiterated in the discussion in section 4.

A T33 aircraft operated by the Canadian National Aeronautical Establishment (NAE) was also based at Ames during February 1967 and, on many occasions, it flew with the Canberra. When the T33 did accompany the Canberra it patrolled the region around the tropopause along the same ground track and at the same time. The results obtained by the T33, which is fully instrumented, are published separately[5].

A shortened version of this present paper was given at an AGARD Specialists Meeting on Atmospheric Shear Flows in Munich in September 1969 and was published in Ref.8.

2 THE TEST AIRCRAFT AND INSTRUMENTATION

Canberra WH 793 is the PR 9 prototype developed from the PR 7 by increasing the wing area, fitting more powerful engines and fitting power controlled ailerons and rudder. The aircraft is fitted with wing-tip tanks one of which contains a weather radar antenna and the other a forward looking 16 mm camera. There is also a nose pole carrying a pitot head, supplying pitot and static pressure to the pilot's instruments but pitot pressure only to the recorders (see below), and an incidence vane. Navigation aids include TACAN and Green Satin Doppler.

Recordings were made on two oscillograph recorders running 'slow' and 'fast' respectively, and a downward looking camera with a 4 in lens. The slow recorder records airspeed, barometric height, normal acceleration, outside air temperature, elevator angle and pitch attitude. In addition this recorder was used to give time synchronisation by means of 'event' marks by the pilot or navigator, and by synchronous pulses from the fast recorder and camera. The fast recorder duplicates measurements of outside air temperature, elevator angle and pitch attitude in addition to recording incidence, pitch rate and a more sensitive normal acceleration.

The slow recorder, which ran throughout the flight, was used to calculate the long wavelength components of the waves, to edit the fast recorder records, and to provide temperature information at varying heights to supplement the conventional meteorological radiosonde measurements. The fast recorder has limited duration and was only switched on when the pilot considered that a significant event was occurring or was about to occur. The fast recorder records were used to measure fine detail and true gust velocities in the more turbulent regions.

The transducers used for the recordings are conventional instruments with inductive pick-offs, except for the pitch attitude information which is obtained from a standard aircraft horizon gyro unit with a potentiometer fitted. Outside air temperature is measured by a Rosemount 102E rapid response open platinum element total temperature sensor[6]. All instruments were calibrated before and after the exercise.

During these tests a consistent difference was noted between the indicated airspeed reported by the crew and measured by the recorders. Calibration of the instruments indicated that both were correct under static conditions but a difference was discovered which depended on the speed of the aircraft. The differences in pilot's indicated and recorded airspeed and height are to be expected from differences in position error of the nose pole static source and the fuselage static vent. Since the conclusion of the project the static pressure input to the recorder has been moved from the side of the fuselage to the nose pole.

3 RESULTS OF FLIGHTS OVER MOUNTAINOUS TERRAIN

Canberra WH 793 was based at the NASA Ames Research Center, Moffett Field NAS, California from 30 January to 24 February 1967. In that time 13 experimental and 2 other flights were made in 39½ hours flying time. Significant disturbances were found on 3, 9, 13 and 14 February and these flights are discussed in section 3.1. Lesser disturbances were noted on about half of the remaining flights which are discussed in section 3.2.

For each flight a considerable amount of meteorological detail is given before the results are discussed. This should be read in conjunction with Appendix A which details the method of forecasting tropospheric waves used to identify a suitable area for the flight. The pre-flight forecast is summarised to give an indication of the accuracies which might be achieved in forecasts made some 4 to 6 hours before flight. Comments by the pilot, made 2 or 3 hours after completion of the flight, are included to give an impression of the effect of the disturbances on the aircrew. Both the meteorological forecast and pilot comments may be omitted by the general reader since the relevant parts are reiterated in the following discussions.

The Canberra is well instrumented for gust research studies and true air motion is established by well tried methods from measurements in turbulence[4]. New methods had to be developed to deduce the longer wavelengths associated with mountain waves (see Appendix B). The first of these is based on the assumption that the vertical profile of temperature is the same in disturbed flow over mountains as it is upwind of the ridge. This method of potential temperature streamline analysis is summarised in Fig.3. A composite stratospheric temperature profile is assembled (left side of Fig.3) which is usually based on two or more radiosonde ascents and the aircraft measured temperature upwind of the mountain range. From this profile a potential temperature profile is deduced by assigning to each height the temperature the air at that height would achieve if it descended adiabatically to the 1000 mb level (approximately to sea level). The aircraft-measured temperature along a run is converted to true outside air temperature by including the effect of kinetic heating and further converted to potential temperature (right side of Fig.3). From these measurements and the potential temperature profile, isentropes can be drawn which in many cases approximate to streamlines of air motion (see Appendix B).

The second method makes use of the principle of conservation of energy. If the aircraft is trimmed and the throttle setting is not changed then waves will cause changes in height and airspeed. True airspeed is calculated from the recorded ias (corrected for static source errors) and variations from a standard true airspeed are converted to equivalent height changes (i.e. kinetic energy is transformed into potential energy). As shown in Appendix B, these height changes are added to the actual height changes measured to give the effective wave motion. The two methods show reasonable agreement.

3.1 Flights with significant disturbances

3.1.1 3 February

Pre-flight forecast: The wind direction at 700 mb (10000 ft) indicated that the favourable wave areas would be west of the Coastal Range and south-east of the ranges north of Los Angeles. Due to marked mid-tropospheric stability it was thought that wave intensity would be moderate to strong in the Los Angeles area.

Flight area (Fig.4): The flight was in two parts: (1) from Los Angeles (Ventura VORTAC) to Palm Springs and return, roughly across wind in the lee of the San Bernardino Mountains; (2) across the Southern Sierras from Fresno on the west to Coaldale on the east and back to Stockton on the west: this latter part is not shown on Fig.4.

Run 1	Ventura to Palm Springs	FL 370	1958-2030 GMT*	
2	Palm Springs to Ventura	370	2030-2050	
3	Fresno to Coaldale	430	2119-2130	no disturbances
4	Coaldale to Stockton	430	2133-2148	

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*GMT (Greenwich Mean Time) is used throughout this paper. Local time is GMT - 8 hours. FL (flight level) is defined as "one of a series of levels of equal atmospheric pressure separated by notified intervals and each expressed as the number of hundreds of feet which would be indicated at the level on a pressure altimeter calibrated in accordance with the International Standard Atmosphere and set to 1013.2 mb". The General Aviation Flight Guide (B.O.T.).

Meteorological summary: Fig.5 shows the flow patterns at 700 mb (10000 ft) and 200 mb (39000 ft). The circulation at both levels was almost normal to the ridge-lines of the mountains of Southern California which were chosen as the main area of investigation. Vertical sections normal to the flow showed the flight area to be in a zone of transition between wind fields with one maximum to the north and two maxima to the south. Successive 6-hourly charts showed that only minor variations in the wind and temperature fields were occurring between 1200 and 2400 GMT.

Fig.6 shows the upwind vertical wind and temperature profiles appropriate to these mountains. The temperature profile is a mean of the Edwards (2101) and Las Vegas (2400) soundings at all heights, and of the aircraft measured temperature between 37000 ft and 43000 ft. The three were very similar over their common height ranges. There is a thin isothermal layer between 7000 and 9000 ft. The wind profile is also a mean of the Edwards and Las Vegas soundings and shows the wind increasing from 040°/25 kt at mountain top height to 020°/65 kt at 34000 ft. Under these conditions tropospheric lee waves of moderate intensity, with calculated wavelength about 4.3 naut miles (see Appendix A) were probable. The slight difference between the forecast intensity (moderate to strong) and this value is mainly due to the forecast 'large inversion' turning out to be a less deep isothermal layer.

The stratospheric part of the temperature profile is interesting, with a 2500 ft deep semi-adiabatic* layer embedded in the lower stratospheric stable layers; the position of this layer is coincident with the part of the negative shear zone in which -6 kt per 1000 ft was measured.

Pilot's comments: "The aircraft encountered moderate clear air turbulence (CAT) at FL 370 on Run 1 at $33^{\circ}58'$ N $118^{\circ}32'$ W. At $33^{\circ}44'$ N $116^{\circ}35'$ W south-east of Mount Jaquinto (10831 ft) severe CAT was encountered. After approximately one minute the autopilot was disengaged. Prior to disengagement the autopilot had maintained level fore-and-aft attitude (within reason) but the bank consistently varied through $\pm 3^{\circ}$. The stick was vibrating fore-and-aft, but not laterally,

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*A 'semi-adiabatic' layer is a layer in which the lapse rate is defined to be half the adiabatic lapse rate.

> in sympathy with the 'bumps' under autopilot control. Manually the aircraft's fore-and-aft attitude was reasonably easy to maintain but no effort was made to damp the ±3° oscillation with aileron. The rudder was clamped neutral throughout. The g meter readings were 0 to 1.89. The whole experience was uncomfortable and a little frightening. My head was constantly rattled against the canopy and the instrument panel vibrated out of frequency with my head. During the turn to fly onto a westerly heading down the valley between the San Bernardino and Jaquinto Mountains (N.W. of Palm Springs) it was very difficult to maintain a 20° bank turn. The turbulence over the valley was severe and the transition to light CAT was made about 15 naut miles N.W. of Mount Jaquinto.
>
> In the severe CAT the ias fell from 235 kt and fluctuated rapidly around 210-225 kt. No attempt was made to regain or hold the trimmed speed, merely to hold a reasonably constant attitude on the horizon gyro unit. The power setting was 84% throughout."

On this day the aircraft flew at 37000 ft just above the tropopause and in the zone of large negative wind shear, but the aircraft frequently flew through air which appeared to have been brought down from the upper semi-adiabatic and stable layers by the action of the waves. Two runs were made about 10 naut miles apart more or less across wind in the lee of and roughly parallel to the San Bernardino Mountains in Southern California (see Fig.4). The pilot reported moderate to severe turbulence during the second half of Run 1, in the turn and during the first half of Run 2. The flight records (Fig.7 shows copies of the records just before and just after the turn) support the pilot's opinion: turbulence was almost continuous from 2023 to 2033, becoming moderate or severe in three places. Fig.8 shows true vertical gust velocity for the part of the run indicated on Fig.7. Several temperature changes of about 10°C in 5½ naut miles occurred and the largest gradient was of 5.7°C in 0.3 naut mile.

Fig.9 shows a line of constant potential temperature (see Appendix B for a full description of the method of analysis) at 37000 ft. The large scale features of the isentropes probably represent a section through a stream surface since they remained stationary with respect to the underlying terrain; they are not, however, streamlines since they do not lie along the wind direction. Two large disturbances of amplitude about 3500 ft were found to the lee of the two main mountain blocks and these disturbances were smooth and free of turbulence. The most interesting part of the isentrope (i.e. the line of constant potential temperature) is that part just to the lee of the Little San Bernardino range at B' where disturbances of some kind are evident with maximum amplitude about 1500 ft. The apparent wavelength of the largest disturbances is about 1.4 naut miles, but since the flight was at about 60° to the wind direction the true wavelength would be nearer half this value, i.e. about 0.7 naut mile. These disturbances broke down downstream to eddies of smaller amplitude and true wavelength about 0.3 naut mile (from a more detailed isentropic analysis not shown here). Similar disturbances are also evident in the trough of the line further to the north over the same valley. Moderate or severe turbulence extended through these disturbances (Fig.9), which were probably mobile and may have been large turbulent eddies formed in the downdraught to the lee of the Little San Bernardino Mountains, and which broke down downstream into eddies of smaller dimensions. The potential temperature of the turbulent air indicated that it came from the semi-adiabatic layer and the stable layer in the undisturbed flow.

This is a good example of nearly continuous turbulence containing patches of moderate or severe disturbance. The area in which turbulence was found extended about 70 naut miles across wind and at least 10 naut miles along wind. It should be noted that this flight was made just above the tropopause, a height limitation imposed by Air Traffic Control Centre as the upper air was being intensively used.

3.1.2 9 February

Pre-flight forecast: The afternoon wind direction was likely to be northwest near Salt Lake City. It was thus thought favourable to fly in the lee of both the Uinta and Wasatch Mountains in Utah. The wind and temperature profiles indicated that wave conditions in the Southern Idaho/Utah area would be very good. Turbulence and cloud reports substantiated this forecast.

Flight area (Fig.2): This flight was in the area of the Uinta Mountains south east of Salt Lake City. The first run extended from just south of Salt Lake City (Malad City VORTAC) to Fort Bridger VORTAC which is just to the north of the Uinta range. Hanksville VORTAC is some 175 naut miles south of Fort Bridger.

Run 1	Malad City to Fort Bridger	FL 370	2105-2116 GMT
2	Fort Bridger to Hanksville	370	2116-2133½
3	Hanksville to Fort Bridger	450	2142-2206

Meteorological summary: Fig.10 shows the flow patterns at 700 mb and 200 mb. Winds at both levels were light over California, with the axis of maximum windspeed lying south-eastwards through Wyoming. The flight was over Utah just ahead of the cold front, which was almost stationary, and on the equatorial side of the jet stream. Successive 6-hourly charts showed negligible changes in the large scale wind and temperature fields in the flight area between 1200 and 2400 GMT.

Fig.11 shows a composite upwind wind and temperature profile. The temperature profile is based on the Salt Lake City (2400) sounding but is a mean of this and the aircraft measured temperature between 37000 and 45000 ft, which is very similar. The Salt Lake City sounding up to 40000 ft was upwind of the wave producing mountains, while the aircraft sounding, although downwind of the range, was made in an area of negligible wave activity. There is a deep isothermal layer between 10000 and 15000 ft. The wind profile is a mean of the Salt Lake City and Grand Junction (2400) soundings. The two are similar but with a difference of 2000 ft between the levels of maximum wind. The wind increased from 310°/25 kt at 10000 ft to 330°/105 kt at 36000 ft. Since these winds were within 20° of normal to the Uinta range, strong tropospheric lee waves were probable in the lee of that range with a calculated wavelength of 9 naut miles. This is in good agreement with the pre-flight forecast.

The stratospheric lapse rate is fairly constant, but wind shears between 36000 and 40000 ft were about -8.5 kt per 1000 ft with smaller negative shear above.

Pilot's comments: "The CAT at FL 450 was moderately unpleasant, due to the reduction in lateral control available with increase in height. The attendant speed fluctuations were minor and were not worrying. Moderate CAT of this nature above FL 500 would, however, probably be very worrying." (A Canberra at FL 500 would be close to its ceiling.)

There was very little activity during Run 1. Run 2 was flown at 37000 ft, the level of the tropopause, and it was in the downwind direction (see Fig.11). Two small patches of turbulence (Fig.12) were found. Run 3 was flown at 45000 ft in the upwind direction along almost the same track as Run 2 (Fig.11). On Run 3 there was continuous turbulence from 2200 to 2206 with three small patches of marked turbulence (Fig.12). The most marked turbulence occurred upwind of the Uinta Mountains (Fig.11). The largest changes in temperature, which occurred on Run 2 at the tropopause, were frequently of about 5°C in 1.9 naut miles and 4°C in 0.9 naut mile.

Fig.13 shows the potential temperature analysis for Runs 2 and 3. The isentropes at both levels were probably stationary (see Appendix B) and since they lie approximately along the wind direction they may be thought of as streamlines of airflow. The lower streamline (at 37000 ft) shows a large disturbance to the lee of the Uinta Mountains of amplitude 1250 ft and what appears to be a train of lee waves downwind of this with amplitude 500 ft and wavelength 9.5 naut miles. This run was just at the tropopause and the measured wavelength agrees well with the calculated wavelength (Appendix A) of 9 naut miles for the troposphere. The upper streamline (at 45000 ft) shows that the waves at this height have a longer wavelength of probably 12 naut miles. Both the disturbance to the lee of the mountains and the following waves have greater amplitude than the waves at 37000 ft: about 1750 and 1000 ft respectively. Turbulence was encountered at 45000 ft upwind of the mountains. The turbulent air had a potential temperature which indicated that it had descended from 48000 ft where there was a shear of about -4 kt per 1000 ft and temperature was decreasing with increasing height.

The most interesting feature of this flight is that both the wave motion and the turbulence were more marked at 45000 than at 37000 ft. This is exactly the opposite result to that which was anticipated before the start of the present exercise. It was expected that disturbances would be most marked at the tropopause (37000 ft on 9 February) and below, and would tend to die out in the stratosphere.

3.1.3 13 February

Pre-flight forecast: The wind shear and strength indicated that the Tahoe area would be more favourable than the Bishop area for flying. Since the temperature soundings showed no marked stability in mid-troposphere the intensity of the waves in the Tahoe area was forecast to be light to moderate in the troposphere.

Flight area (Fig.14): The direction of flight was about S.W.-N.E. from some 20 naut miles west of Lake Tahoe (Mather VORTAC) to 80 naut miles east of the lake (Hazen VORTAC).

Run	1	Mather to Hazen	FL 450	1948-1958 GMT
	2	Hazen to Mather	460	2005-2024
	3	Mather to Hazen	470	2030-2042
	4	Hazen to Mather	480	2051-2111
	5	Mather to Hazen	490	2118½-2133
	6	Hazen to Mather	500	2138-2159

Meteorological summary: Fig.15 shows the airflow patterns at 700 mb and 150 mb (45000 ft). The cold front at the surface lay just to the north of the flight area at 2400 GMT and was moving south-eastwards. The upper flow pattern shows two axes of maximum windspeed one lying over the flight area and the other well to the south. Also shown is the axis of the polar jet core which was at 27000 ft.

Fig.16 shows a cross-section of winds above 20000 ft from Boise to Las Vegas, and it can be seen that the aircraft was flying close to a discontinuity in the level of the maximum wind. A rapid temperature rise of 3°C measured by the aircraft at all heights between the eastern edge of Lake Tahoe and Carson Sink (points C and D respectively of Fig.17) may have been connected with the discontinuity. Fig.17 also shows the temperature profiles upwind of the Sierras (point A) and over the foothills (point B) as deduced from aircraft measurements. Since the isotherms lie in a 250°-070° orientation at the flight levels (Fig.15) it is possible that the temperature change occurred in about 5 naut miles normal to the isotherms. Successive 6-hourly charts showed that the temperature and wind fields were moving south at the speed of the cold front (about 22 kt).

Fig.17 also shows the temperature profile which is representative of the vertical temperature variation upwind of the mountains. It is based on the Oakland (2400 GMT) sounding up to 43000 ft, on the aircraft measured temperature upwind of the mountains between 43000 and 50000 ft, and on the Las Vegas sounding above 50000 ft. The last two were in good agreement between 43000 and 50000 ft indicating that the stratospheric part of the Las Vegas sounding is probably representative of the upwind profile although the station is downwind of the Sierras. The stratospheric temperatures on the Oakland sounding differed from those measured by the aircraft possibly due to the time difference (2 to 4 hours) between the measurements. The composite profile shows an isothermal layer between 10000 and 12000 ft. The upwind wind profile shown in Fig.17 is based on a somewhat smoothed Oakland sounding and on mean winds deduced from the aircraft air and ground speeds measured along each leg, the two 'soundings' being in good agreement between 45000 and 50000 ft. Smoothing of the Oakland sounding was necessary in the troposphere due to minor variations of the wind profile in the vertical probably induced by waves originating at the Coastal Range. Winds increased from 250°/35 kt at 10000 ft to a maximum of 250°/80 kt at 45000 ft. Thus at the south-western (upwind) end of the runs tropospheric waves of moderate to strong intensity and with a wavelength of about 5½ naut miles were probable.

Aircraft and synoptic scale evidence both indicate that there is a substantial difference between the upwind and downwind wind and temperature fields in the stratosphere. A sounding at Winnemucca (north of Carson Sink) also indicated that the tropospheric winds were much stronger and the temperature inversion much broader than those represented in Fig.17. Thus at the downwind end of the runs (the Carson Sink area) strong waves were probable with wavelength about 7½ naut miles. The whole situation was much more complex than it appeared in prospect and thus the pre-flight forecast of light to moderate wave intensity was rather inaccurate.

The stratospheric part of the temperature profile shows marked variations in lapse rate at all locations, with a layer of semi-adiabatic lapse rate between 45000 and 48000 ft embedded in more stable layers.

Pilot's comments: "Moderate CAT and waves were encountered at all test heights. The aircraft was difficult and tiring to fly as the ias/imn and height fluctuations required constant monitoring and adjustment. The aircraft became dramatically easier to fly west of the centre of Lake Tahoe on every run. This change was most marked and was the only time the aircraft could be flown 'hands off'.

> A strong wave was encountered on Run 5 when the aircraft, from a trimmed state of 0.75 M/178 kt, increased speed to 0.79 M/188 kt and then entered a 2000 ft min^{-1} climb following corrective action on the stick. The aircraft levelled out at 0.75 M at 50000 ft for a few seconds and then returned to 49000 ft at 0.75 iMn.
>
> The worst turbulence was encountered between FL 485 and 500. On Run 6 at FL 500 the aircraft entered a strong draught and descended to 49700 ft at 0.80 iMn as the power was reduced to 85%. The power was then increased to 92% to climb the aircraft back. On arrival at FL 500 the aircraft again encountered a strong draught and as power was reduced to flight idle the aircraft accelerated to 0.82 iMn (0.02 above M_{NE}) in a 1000 ft min^{-1} rate of descent (Note: power idle!). An estimated 40 lb one-handed pull on the stick produced little or no response to elevator. Both hands were then used and an 80 lb pull reduced speed to 0.80 imn. The aircraft was finally levelled at 47000 ft. The aircraft, after a breather by the crew, was then reclimbed to 50000 ft in moderate CAT and returned to base."

On this flight near Lake Tahoe (Fig.14) turbulence increased in severity and extent with height. Comparison of Figs.18, 19 and 20 shows how the turbulence increases in duration and magnitude from Run 4 to Run 6 (nominally 48000 to 50000 ft). The turbulence on Runs 1 to 3 was very slight in comparison. Figs.21 and 22 show true vertical gust velocity for the sections marked on Fig.19 and 20. Marked temperature changes occurred in association with the wave motion (Fig.23) with the largest changes (7.3°C in 1.1 naut miles and 10.6°C in 2 naut miles) occurring on Run 6.

Fig.24 shows the potential temperature streamline analysis for this flight. The isentropes on the right of the cross-section on Runs 3 and 4, and on the whole of Runs 1 and 2 appear to be stationary and in these locations are probably trajectories of airflow. Values of potential temperature shown on the streamlines confirm that the less stable layer (between 45000 and 48000 on Fig.17) lay within the height band flown. The changes in potential temperature that occur along the runs are due to the changes in airmass characteristics discussed above. The gap in the uppermost streamline occurs where the pilot temporarily lost control when the aircraft encountered a severe draught and turbulence.

The streamlines show several important points about the airflow. There is a possible nodal surface between the Points A and B of Fig.24. On the right of the profile the waves show an amplification either with height above the nodal surface, or with time. The amplitude of the waves at 46000 ft at about 2006 GMT is 500 ft and at 50000 ft at 2141 is 2250 ft. The isentropes at 47000 and 46000 ft appear to intersect in this part of the flow and this could mean that vertical cramping or amplification with time was occurring. In the latter case the isentropes would still be a good guide to the airflow. The wavelength of this right hand part of the flow decreases from 7½ naut miles at 47000 ft to 5½ naut miles at 49000 ft. The first value is within ½ naut mile of the natural wavelength (see Appendix A) at that level calculated from representative airmass characteristics. The natural wavelength of the more stable air above 49000 ft is about 2½ naut miles.

The change in wave structure along the runs was probably related to the gross changes in atmospheric structure which existed between Lake Tahoe and Carson Sink. The change in wave structure at the western end of the runs between Runs 2 and 6 was perhaps related to the southward movement of the wind and temperature fields, although the results could have been affected by slight variations in the flight tracks.

On Runs 3 and 4 the turbulence was most marked in the troughs of the waves but on the last two runs it was altogether more extensive and there is no clear distinction between the severity of the disturbances in crests and troughs. The potential temperature of the turbulent air indicates that it lay almost completely in the base of the stable layer.

This flight contained several very interesting features. The wave motion was much more marked at 50000 ft at 2141 GMT than at 46000 ft at 2006. The turbulence tended to occur in the troughs and there were marked changes in outside air temperature associated with the turbulence and waves. There was a marked layer of relatively low stability between 45000 and 48000 ft bounded above by a stable layer, and the marked disturbances were found above a relatively gentle ground profile (Fig.17).

3.1.4 14 February

Pre-flight forecast: Although the surface analysis showed a pattern normally taken as not favourable for wave activity, the upper air charts indicated the upper trough to be well behind the surface cold front. The trough was expected over Bishop at 2400 GMT and the 1200 soundings showed the pre-trough conditions (strong mid-tropospheric inversion and marked vertical wind speed shear) to be favourable for moderate to strong wave activity in the troposphere. Due to the forecast trough position it was thought that the flight should be made over the central portion of the Sierras.

Flight area (Fig.25): The flight direction was roughtly E-W over the central Sierras from about 20 naut miles west of the main ridge (Lamoore VORTAC) to some 80 naut miles east (Beatty VORTAC).

Run 1	Lamoore to Beatty	FL 450	1937-1950½ GMT
2	Beatty to Lamoore	460	1954-2007
	sortie abandoned		

Meteorological summary: Fig.26 shows the airflow pattern at 700 mb and 150 mb. The pressure trough at 700 mb lay well behind the surface cold front and was over the flight area at 2400 GMT. The variation of the Tonopah winds, shown in the table, over the period 1702 to 2010 show that the trough was moving through the area just to the north of the flight track at the time of the flight with a velocity of about 340°/32 kt.

Tonopah radiosonde winds on 14 February 1967

(Tonopah is marked 'T' on Fig.26)

Height (× 1000 ft)	Winds		
	1702 GMT	2010 GMT	
6	311°/15 kt	322°/48 kt	
10	231°/33 kt	311°/38 kt	700 mb level
15	234°/35 kt	271°/28 kt	
20	230°/84 kt	275°/38 kt	
25	229°/103 kt	252°/65 kt	
30	227°/93 kt	247°/84 kt	
35	241°/92 kt	264°/104 kt	
40	250°/90 kt	245°/70 kt	
45	253°/94 kt	263°/77 kt	150 mb level
50	217°/30 kt	242°/48 kt	
55	223°/23 kt	205°/27 kt	
60	270°/15 kt	273°/25 kt	
65	253°/12 kt		

Large directional changes occurred in this period from 8000 ft to 20000 ft and the level of maximum wind also increased by 10000 ft. These changes may well have been occurring in the flight area at least towards the end of the flight period (1930 to 2000). By 2400 the winds at 30000 ft in the flight area had veered to 300°/75 kt. From the 150 mb chart it can be seen that the jet core lay very close to the flight track and one axis of maximum wind at 150 mb lay just north of the track.

The temperature profile shown on Fig.27 is representative of the upwind vertical distribution of temperature at the beginning of the flight (1930 GMT). The profile is based on the Fresno (2030) sounding up to 51000 ft, but between 40000 and 45000 ft it is a mean of this sounding and the aircraft measured temperature upwind of the mountains. The two profiles were in good agreement. Above 40000 ft Las Vegas, Vandenburg and China Lake soundings showed good agreement with the Fresno readings, although the China Lake temperature gradients were more marked. Above 51000 ft the profile of Fig.27 is based on the Las Vegas sounding. The profile shows marked stability between 14000 and 17000 ft. The wind profile in Fig.27 is based on the Fresno sounding but wind directions in the lower troposphere were backed by about 20° to take account of the differences between the time of the sounding and the flight (about one hour) and the fact that the flight track was slightly south of the sonde station. No winds were available from Fresno or Las Vegas between 51000 and 60500 ft, so winds shown at these levels on Fig.27 were averaged from the Vandenburg (1800) and Tonopah (2010) winds. Winds increased from about 290°/25 kt at 5000 ft to a maximum of 260°/110 kt at 28000 ft. In these wind and temperature conditions, strong tropospheric lee waves were likely at the beginning of the flight, especially in the lee of the main Sierra crest to the south of Bishop, of calculated wavelength about 8.3 naut miles. This retrospective assessment is in good agreement with the pre-flight forecast.

The stratospheric part of the profile shows marked variations in lapse rate with vertically alternating stable and semi-adiabatic layers, the most marked of which is between 44000 and 46000 ft. This was also a zone of marked negative wind shear of about -8 kt per 1000 ft.

> Pilot's comments: "On the turn onto Run 2 CAT was encountered that made accurate bank holding difficult. The start of Run 2 at FL 460 was very smooth. Further along this run it was noticed that an increase in imn at constant height and power usually heralded a patch of moderate CAT.
>
> Approaching the eastern ridge a moderate patch of CAT was encountered and then the aircraft was eased slightly nose-up to check the rise in imn (0.77). The aircraft entered a climb at 2000 ft min^{-1} with 87% rev/min with the imn increasing from 0.775 to about 0.79! Suddenly, and without any warning at all, the ias dropped in under one second from about 198 kt to 150 kt at 47300 ft. The airflow could be heard breaking away from the canopy and I was conscious of the aircraft continuing upward even as I applied about ½ forward stick (this could easily be the effect of -ve g). The aircraft bunted over at about 150 kt. No pre-stall buffet was felt although the airflow was distinctly heard as it broke away over the canopy. After the aircraft was diving satisfactorily the speed increased slowly and then jumped suddenly to 200 kt (0.81 imn). I held the aircraft at 0.8 and descended to 42000 ft to gather my wits. The power was held at 87% throughout the manoeuvre. The airbrakes were not used. A check on the g meter showed -1 g. The aircraft was descended to 24000 ft and a slow speed check in the approach configuration was made at 108 kt. The aircraft was returned to base.
>
> The violence and suddeness of the drop in ias following what appeared to be a moderately strong but smooth upward wave was literally staggering. I failed to operate the fast recorder or even speak into the tape recorder."

Six runs were planned at heights from 45000 to 50000 ft over the Bishop Valley but the sortie was abandoned towards the end of Run 2 after the incident described by the pilot. Run 1 contained practically no turbulence and only smooth waves. On Run 2 the wave motion was much more marked (Fig.28) and it contained two patches of severe disturbance which occurred with almost no warning as shown in Fig.29, a copy of the original record. The first of these was not directly commented on by the pilot although it may have occasioned his comment that "it was noticed that an increase in imn at constant power usually heralded a patch of moderate CAT". Both patches were characterised by marked changes in airspeed (100 kt change in true airspeed in the second incident over a period of some 15 to 20 sec: the most rapid changes were of 68 kt in 1½ sec, 33 kt in 2 sec and 45 kt in 4 sec) and in outside air temperature (certainly 7.5°C in 0.27 naut mile, 7°C in 0.55 naut mile 12.5°C in 0.22 naut mile and 20.5°C in 1.1 naut miles and probably 9.5°C in 0.6 naut mile and 15.5°C in 0.8 naut mile) as shown in Figs.29 and 30.

Fig.28 shows the potential temperature analysis. The obvious differences between the isentropic disturbances at the two levels is probably due to temporal changes in meteorological parameters governing wave structure. It is unlikely that the 10-15 naut mile separation of ground tracks (Fig.25) was in itself the cause since the underlying terrain in the neighbourhood of the major disturbances is very similar on each run. The more northerly track (Run 2) was, however, nearer to the zone of changing meteorological parameters. Nor is it likely that the differences were due solely to the 1000 ft height difference since the cramping of the flow should have caused turbulence and marked wind and airspeed fluctuations on the lower run (Run 1), which did not occur.

The isentropes at 45000 ft are probably streamlines of airflow. The flow pattern at this height shows mountain waves with no following trains of lee waves. The maximum amplitude of the disturbance is about 2500 ft and some small amplitude disturbances of wavelength 1.8 naut miles were encountered towards the eastern end of the run. The isentropes at 46000 ft are probably not streamlines of airflow since there is evidence that meteorological conditions were changing at this time. However it is still possible to make some important deductions about the airflow. The two major isentropic disturbances at X and Z (Fig.28) were immediately to the lee of the Sierra Nevada and White Mountains respectively. This suggests that the major isentropic disturbances were stationary although their amplitudes were probably varying with time. In support of this, the aircraft encountered severe horizontal gusts at X, Y and Z which suggests that the velocity of the isentropic disturbances at these points was less than 'u' (see Appendix B). The potential temperature of the air at Z (124°C) indicates that it had descended 7000 ft from its upstream equilibrium level (and possibly 9000 ft in all) and later returned towards that level. The distance between the troughs at Y and Z is 2.2 naut miles and the natural wavelength of the air encountered at X and Z is about 3 naut miles. It seems likely that the periodic disturbances in the

$98^{\circ}C$ and $106^{\circ}C$ isentropes (Fig.28) originated at the major disturbances and were therefore moving with a velocity less than 'u'. These periodic disturbances had approximate wavelengths of 3.5 naut miles and 1.8 naut miles respectively with maximum amplitudes at the time of 1500 and 300 ft respectively. $98^{\circ}C$ was the potential temperature at the lapse rate discontinuity at 46000 ft and a natural wavelength cannot be calculated for this air. However the natural wavelength of the air in the layer of low stability below this is 8 naut miles and in the stable layer above is 2.7 naut miles (this last value is applicable to the air at $106^{\circ}C$).

The moderate to severe turbulence which occurred is shown in Fig.28 and it can be seen that the disturbances occurred mainly in the troughs. On passing through the troughs at Y and Z, four static pressure peaks of about 1 mb above normal were measured in association with turbulence and these may be indicative of rotors in the troughs of the waves. Associated with each peak was air of constant potential temperature and the distance between the peaks was about 650 ft. The partial loss of control by the pilot occurred at Y. This violent incident occurred with very little warning and was over in a very short time. However temporary and local it may have been, it serves as a measure of the violence of which the stratosphere is capable.

3.2 The remaining flights

The results of the remaining 9 flights over mountainous terrain are summarised in two groups in the table:-

Date	Run No.	Flight level	Time (GMT) Start	End	Turbulence (estimated from flight record)	% time with 'constant energy' analysis indicated vertical velocities greater than: 20 ft sec^{-1}	30 ft sec^{-1}	40 ft sec^{-1}
30 Jan	1	330	2050	2105	100 s light	2.7	0	0
	2	330	2109	2125	20 s light			
	3	350	2128	2138	20 s light	5.6	2.1	0
	4	350	2142	2158	nil			
	5	390	2202	2211	nil	17.8	5.2	1.5
	6	390	2214	2229	nil			
	7	430	2233	2242	10 s light	5.3	3.0	1.5
	8	430	2243	2300	nil			
7 Feb	1	350	2030	2056	100 s light	15.1	7.1	2.4
	2	350	2059	2114	40 s light	36.1	11.1	0
	3	350	2119	2130	nil	12.4	1.4	0
	4	450	2140	2144	nil	8 3	0	0
	5	450	2145	2150	nil	3.3	0	0
	6	350	2156	2222	nil	10.4	3.5	1.4
10 Feb	1	370-450	2012	2043	nil	12.9	4 3	0
	2	450	2046	2110	nil	7.2	1.4	0
	3	510	2119	2148	nil	11.4	2.4	0.6
	4	530	2153	2207	nil	3.7	0	0
15 Feb	1	410	1951½	2008½	nil	11.5	5.1	2.6
	2	410	2015	2029½	nil	13.1	3.6	0
	3	430	2034½	2048	nil	21.8	6.4	3 8
	4	430	2054½	2108½	nil	6.2	0	0
	5	330	2114	2127½	20 s light	4.5	1.5	1.5
	6	350	2133	2152	70 s light	18.5	8.3	3.7
24 Feb	1	450	1955	2011	nil	7 3	1.0	0
	2	410	2017½	2036	30 s light	1.9	0	0
	3	390	2041½	2055½	nil	15.2	10.1	3.8
	4	390	2108	2122	nil	-	-	-
		lowest	highest					
31 Jan	4 runs	FL 330	FL 430	-	nil	-	-	-
6 Feb	5 runs	410	450	-	nil	5.0	0	0
16 Feb	4 runs	230	350	-	35 s light	0	0	0
20 Feb	2 runs	370	410	-	nil	-	-	-

The second group - 31 January, 6, 16 and 20 February - contained few disturbances and they will be briefly discussed in 3.2.6. There was a little turbulence on Run 4 of 16 February but it occurred at 23000 ft well into the troposphere. The first group are discussed in 3.2.1 to 3.2.5, below.

3.2.1 30 January

Pre-flight forecast: With the morning data available it could be seen that the wind profile would produce strong tropospheric activity if the stability factors were satisfied. The stability profile was not perfect for waves in the Bishop area, but since some stability was evident and since Bishop was expected to lie ahead of a cold front during the flight period, moderate to strong tropospheric waves were forecast.

Flight area (Fig.31): The flights were in a roughly E-W direction over the North and Central Sierras from some 20 naut miles west of the ridge (Fresno VORTAC) to about 80 naut miles east (Beatty VORTAC).

Meteorological summary: Fig.32 shows the 700 mb (10000 ft) and 200 mb (39000 ft) flow patterns. A cold front associated with a wave depression off the coast of Northern California was moving eastwards and its surface position at 2400 GMT (1 to 3 hours after the flight tests) is shown on the 700 mb chart. The maximum windspeed axis on the 200 mb chart was over Central California just north of the flight area at 2400. Successive 6-hourly charts showed minor atmospheric changes in the flight area at the time of flight. Windspeeds were slowly increasing and at the end of the period tropospheric cooling was evident in the west.

The temperature profile (Fig.33) is based on the Vandenburg (2400) sounding up to 55000 ft. Both Ely and Las Vegas soundings showed good agreement with the Vandenburg ascent at all heights, even though they are downwind of the mountains. The aircraft temperature measurements were not used since the whole flight was in disturbed flow. The increase in stability between 8000 and 14000 ft is not so marked as it may seem, since the air at these levels was saturated. The wind profile (Fig.33) is also based on the Vandenburg sounding. The speeds were, however, weighted a little by the Ely sounding which was closer to the jet core (Fig.32). There was a uniform increase in windspeed up to the tropopause but between 38000 and 44000 ft the radiosonde indicated marked negative shear.

The tropospheric wave activity was probably light to moderate, rather than moderate to strong as in the pre-flight forecast, because the mid-tropospheric stability was less marked than expected. Since the height of the stable layer was not changing and wind directions remained constant it is unlikely that wave dimensions varied during the period of the flight.

Stratospheric features of interest include the variable lapse rate and the marked wind shears. In the flight area the wind was $250^{\circ}/35$ kt at 10000 ft and $250^{\circ}/95$ kt at 38000 ft, with marked vertical shear above this to 44000 ft of about -5 kt per 1000 ft.

Pilot's comments: "On Run 3 (FL 350) at 37°02' N 117°30' W at time 2136 the aircraft entered slight CAT followed by a strong downdraught. The imn rose rapidly from 0.75 to 0.775 as the aircraft entered a dive at about 500 ft min^{-1}. The aircraft was returned to level flight by an estimated 10 lb pull on the stick. The stick was loosely held in the trim position and the aircraft climbed at 1800 ft min^{-1} to 35800 ft leaving the CAT at 35600 ft, and then returned slowly to the trimmed state. We (the crew) felt that this was an isolated but comparatively major disturbance."

The potential temperature analysis for Runs 3, 5 and 7 is shown in Fig.34. The isentropes are probably trajectories of airflow since the disturbances near the mountains appear to be stationary. Small amplitude waves were apparent on all runs but were most marked on Runs 3 and 4 which were flown at the height of the tropopause. The waves occurred, in the main, over the mountains and there is little evidence of following trains of lee waves. The downdraught mentioned by the pilot is on Run 3 at point A. Slight turbulence was encountered on most runs and the maximum changes in outside air temperature were 5°C in 2.5 naut miles and 3°C in 1.3 naut miles.

It is interesting to speculate whether the pilot would have described the flight as containing "an isolated but comparatively major disturbance" if he had experienced it after the flights of 13 and 14 February.

3.2.2 7 February

Pre-flight forecast: There was a wind component of about 20 kt perpendicular to the southern Californian ranges at all heights in the troposphere and it was thought that due to the inversions near 6000 ft the chance of waves in that area would be slightly better than on 6 February. At the time the forecasts were given there were already reports of severe turbulence at 10000 ft.

Flight area (Fig.4): Runs 1 and 6 were flown across wind from Los Angeles to Palm Springs in the lee of the San Bernardino Mountains. The remaining runs were in a roughly N-S direction and along wind, again in the lee of the San Bernardino Mountains. Runs 4 and 5 were about 25 naut miles further east than Runs 2 and 3.

Meteorological summary: Fig.35 shows the 700 mb and 200 mb flow patterns at 2400 GMT. The winds in the Southern California area were moderate and at about 40° to the mountain crest line with the axis of maximum wind well to the east. Successive 6-hourly charts showed that little or no change in atmospheric wind and temperature fields was occurring at the time of the flight.

Fig.36 shows composite wind and temperature profiles. The temperature profile is based on the Fresno (2000) sounding, with aircraft temperature measurements between 35000 and 45000 ft. There is a good agreement between the radiosonde and aircraft values over their common height ranges. Some correction was made to the Fresno sounding below 4000 ft to allow for greater surface heating in the flight area. Subsidence had produced inversions between the surface and 7000 ft. The wind profile (Fig.36) is a mean of the Fresno and San Diego soundings, the measurements at the two stations being very similar. Since the winds were oblique to the mountains it is likely that tropospheric waves would only be slight in intensity, with calculated wavelength about 2.2 naut miles.

The stratospheric part of the temperature profile does not show any internal 'fine structure'*, and the wind shears above the maximum wind level were small (about -2.5 kt per 1000 ft).

Pilot's comments: No pertinent comments.

There was evidence from the isentropes of small waves on all runs (Fig.37) reaching 500 ft amplitude at 2050 GMT on Run 1 and 2114 on Run 2. The activity was much more marked at 35000 than at 45000 ft, but the runs at 45000 ft were not over mountainous terrain. There was light, randomly distributed turbulence on Run 1 from 2052 to 2056 and three patches on Run 2 between 2113 and 2116. There were several reports of severe turbulence at 10000 ft from civil aircraft flying in the same area throughout the day. The largest changes in outside air temperature were 2°C in 0.4 naut mile and 2.8°C in 2.3 naut miles.

The wave motion was less marked in the stratosphere (45000 ft) than in the vicinity of the tropopause (35000 ft) and below (reports at 10000 ft). On this day there was no 'fine structure' in the stratospheric temperature profile. These results should be treated with some caution, however, due to the differences in underlying terrain (see Fig.4).

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*'fine structure' is used to describe adjacent layers of contrasting lapse rate with depths from 1000 to 5000 ft.

3.2.3 10 February

Pre-flight forecast: Conditions looked very good from the 1200 GMT data (about 9 hours before flight) for waves of moderate to strong intensity over Utah. Conditions were considered to be less favourable in the Mount Shasta area but with fairly strong winds in this locality it was thought to be worth investigating.

Flight area (Fig.2): The flight was in a roughly N-S direction over Mount Shasta, an isolated conical peak in Northern California, from about 20 naut miles north to 80 naut miles south of the mountain.

Meteorological summary: Fig.38 shows the flow patterns at 700 mb and 100 mb (53000 ft). It can be seen that the axis of maximum wind at the 100 mb level lay over Southern Idaho with the jet core axis over the north and east of Utah. Successive 6-hourly charts showed no significant changes in the wind and temperature fields in the flight area between 1200 and 2400 GMT.

Fig.39 shows the upwind wind and temperature profiles. The temperature profile (Fig.39) is based on the Medford (2400) sounding up to 58000 ft with the aircraft measured temperature between 37000 and 54000 ft. There was very good agreement between the two sets of readings. The profile shows a narrow inversion between 10500 and 11500 ft. The wind profile is based on the Medford sounding, slightly smoothed in places to eliminate some minor fine structure. Moderate to strong intensity tropospheric lee waves of wavelength 6 naut miles were probable in these conditions of wind and temperature.

The stratospheric part of the temperature profile shows that the temperature decreases fairly steadily with height and the wind profile shows the most marked shear, of about -6 kt per 1000 ft, between 43000 and 47000 ft.

Pilot's comments: "Patches of light CAT were encountered at all levels. No real difficulty was experienced. I believe that a minor wave was encountered at FL 525. The aircraft was stabilised in a cruise climb with 100 ft min^{-1} rate of climb. Quite suddenly the aircraft started to increase speed from 160 to 162 kt. I eased the stick back and the aircraft stabilised again at 160 kt at 500 ft min^{-1} rate of climb. At this height this is a significant change in rate of climb. The aircraft climbed to FL 530 at which point the speed fell to 158 kt and the

> aircraft descended at 160 kt and 300 ft min^{-1} to 52700 ft, where it again stabilised at 100 ft min^{-1} rate of climb at 160 kt. The time in the wave was about 2 min, i.e. 14 naut miles."

As the cross-section (Fig.39) shows, Mount Shasta is an isolated conical peak over 14000 ft high and some 9000 ft above the general level of the surrounding terrain. The potential temperature analysis is shown in Fig.40. The isentropes are trajectories of airflow since the pattern is obviously stationary. There was a mountain wave and one lee wave at all heights (Fig.40) and the amplitude (750 to 1400 ft) does not appear to reduce at greater heights. The flow experienced by an aircraft to the lee of an isolated conical peak will depend critically on its exact location with respect to the peak. The difference in wave amplitude between Runs 2 and 3 is probably due to slightly different ground tracks having been flown. The wavelength remained constant with height at about 9 naut miles; the natural wavelength of the air at 40000 and 50000 ft (where there was little shear) was about 4 naut miles. There was a very small amount of slight turbulence and only small changes in outside air temperature.

3.2.4 15 February

Pre-flight forecast: Due to the possibility of a low level (700 mb) north-west wind at Bishop and a westerly at Tahoe, the Tahoe area was thought to be preferable for flying. With stability indicated at 8000 ft the wave activity was forecast to be moderate to strong.

Flight area (Fig.14): The flight was in a roughly N.W.-S.E. direction from about 20 naut miles west of Lake Tahoe to some 80 naut miles east of the lake.

> Meteorological summary: Fig.41 shows the flow patterns at 700 mb and 200 mb. A very weak cold front was moving southwards through Central California, with a northwesterly flow on both sides at 700 mb. Between 25000 and 45000 ft the axis of a sharp trough was moving through the flight area at 270°/25 kt during the flight time. At 30000 ft winds ahead of the trough were about 260°/65 kt and behind it a north-northwesterly jet was propagating through Northern and Central California with a core of about 340°/95 kt. This jet and the medium level stability (Fig.42) were both associated with the eastward moving warm front shown in Fig.41.

Fig.42 shows composite upwind wind and temperature profiles. The choice of representative soundings was complicated by the positions of the surface cold front and the trough. The temperature profile shown in Fig.42 is based on the Fresno (2000 GMT, 0 to 2 hours before the flight tests) ascent and on the aircraft measured temperatures between 33000 and 43000 ft, the two sets of readings were very similar. The profile shows some stability in the 4000 to 6000 ft and 17000 to 20000 ft height bands. The wind profile is the mean of the Fresno (2000) and Oakland (1800) soundings up to and including 25000 ft and is based on the Oakland sounding alone above this height. The winds increased from 300°/20 kt and 5000 ft to 340°/95 kt at 31000 ft. The intensity of the tropospheric lee waves ahead of the trough was probably slight, due to lack of marked tropospheric stability. Behind the trough the intensity was also probably slight due to the small normal component of the upper winds and the directional changes with height. This differs from the pre-flight forecast (moderate to strong) because of the rapid propagation of the north-northwesterly jet stream at 300 mb into Northern California. This propagation was not forecast. The calculated tropospheric wavelength ahead of the trough axis was 5.5 naut miles.

Some minor 'kinks' occur in the stratospheric temperature lapse rate, but they are much smaller than those of 13 and 14 February.

Pilot's comments: "No significant CAT and only weak waves were encountered. Minor speed fluctuations of ±5 kt were encountered in weak waves with associated outside air temperature changes. The only point which aroused my interest was the fact that, from trimmed datum conditions, the aircraft tended to increase speed on the eastbound runs into wind and decrease speed on westbound runs."

There was wave motion on every run (Fig.43) in places reaching 500 ft amplitude. The most interesting features are found in the isentropes on Runs 5 and 6. The velocity of the temperature discontinuity in the centre of the pattern is 25 kt. This suggests that the discontinuity is associated with the trough axis, adding to the synoptic scale evidence that the axis was moving through the area at the flight time. The wavelength of the disturbances on the eastern side of the discontinuity is 3.8 naut miles compared to 4.3 naut miles for Runs 1 to 3. There were small patches of light turbulence on Runs 5 and 6 flown in the region of the tropopause. The largest temperature changes were of 3.5°C in 1.3 naut miles and 4.5°C in 2.1 naut miles.

3.2.5 24 February

Pre-flight forecast: No record made at the time.

Flight area (Fig.44): The first three runs were in a roughly S.W.-N.E. direction over the Southern Sierras from about 20 naut miles west of the ridge (Friant VORTAC) to 80 naut miles east (Tonopah VORTAC).

Meteorological summary: Fig.45 shows the airflow patterns at 700 mb and 200 mb. The 700 mb chart shows a southwesterly flow over Central and Southern California ahead of a slow moving cold front. The upper level chart shows that the main jet-stream was over Southern California. Successive 6-hourly charts showed little change in the large scale wind and temperature fields in the twelve hour period 1200 to 2400 GMT. Flights were made over the mountains surrounding Bishop, including the White Mountains.

The temperature profile (Fig.46) is based on the Fresno (2000) sounding at all heights, with the aircraft measured temperature incorporated in the profile between 39000 and 45000 ft. There is good agreement between the Fresno and the aircraft measurements. The profile indicates a stable layer between 15000 and 18000 ft. The wind profile (Fig.46) is a mean of the Fresno (2000) and Las Vegas (2400) measured winds up to 25000 ft. This interpolation was necessary since the Fresno winds at some levels below this height were inconsistent with the overall flow pattern at these levels. Above 25000 ft the Fresno winds fitted the flow patterns over the Western States and were the basis of the composite profile. Since the winds were rather oblique to the mountains only light to moderate tropospheric waves were likely, of wavelength (component normal to the range) about 3.9 naut miles.

The stratospheric part of the profile shows little 'fine structure' the layer between 42500 and 44500 ft being slightly less stable than surrounding layers. Wind shear between 40000 and 45000 ft was approximately -9 kt per 1000 ft.

Pilot's comments: "Light smooth waves were found on Runs 1 through 3. They were most marked at FL 450. Marked OAT changes were noted on Run 3."

Fig.47 shows the small and irregular waves deduced from the constant energy analysis which were encountered on Runs 1 to 3. Little turbulence was found and temperature changes of 1.3°C in 1.3 naut miles and 1.6°C in 2.6 naut miles were the largest measured.

3.2.6 The flights on 31 January, 6, 16 and 20 February

These flights were made on days when little or no activity was forecast. The forecasts were based on criteria established in Appendix A, and it had been hoped to fly on days when just one of the several parameters made conditions unsuitable. 31 January and 6 February were not particularly interesting: no activity was found and none was expected because practically none of the wave criteria was satisfied.

The pre-flight forecast for 16 February was: "The temperature profile indicated maximum ℓ^2 (see Appendix A) at the ground. This profile was thought to be indicative of turbulent flow below mountain top level and although the winds were quite strong at Mount Shasta it was not thought likely that any wave motion would be taking place above the mountain top". No wave activity was found at the heights flown - 29000, 26000 and 23000 ft - but a small patch of slight turbulence was encountered at 23000 ft.

The flight of 20 February was the most interesting of this group of four. The pre-flight forecast was: "The 700 mb flow pattern showed about 360°/25 kt in Southern California. With the stronger winds aloft and stability at 8000 ft slight to moderate wave activity was forecast over the Tehachapi Mountains". The flight was made in this area at FL 370 and 410 and no wave activity was found. Yet during the day there were many reports of moderate to severe turbulence by civil pilots operating over the Tehachapi Mountains and in other mountainous areas near Los Angeles. Most of the reports were below FL 150 with a few at FL 270. It would appear that the wave motion, forecast and deduced to be present at the lower levels, was substantially damped, probably due to a marked change in wind direction with increasing height.

4 DISCUSSION OF RESULTS

Out of 13 flights over mountainous terrain in the western U.S.A., disturbances were encountered in the stratosphere or at the tropopause on nine. On two occasions the disturbances were so severe that the pilot partially lost control of the aircraft and did not regain full control until several thousand feet of height had been lost. It is clear that very marked disturbances can exist in the stratosphere but the frequency of occurrence of such events cannot be deduced directly from the results of an exercise such as this where comparatively few flights are made in areas selected because they are likely to contain disturbed air. Some general inferences can, however, be made on the meteorological conditions prevailing when the disturbances were found, and these and some general implications to the operation of aircraft are discussed in this section.

Forecasts of tropospheric lee wave activity and extension of this activity into the stratosphere were made, based on the theoretical aspects of waveflow outlined in Appendix A. Upper air reports from civil airlines and hourly cloud reports from the surface were also taken into account. Whenever possible the aircraft flew in an area where strong tropospheric lee wave activity was forecast. On some occasions, however, strong wave activity was out of range, and on these days flights were made in the area nearest to base where any wave activity was expected. Several horizontal legs displaced at height intervals of from one to five thousand feet from one another were normally flown from about 20 naut miles upwind of the mountain to 80 naut miles downwind. Most of the runs were in the lowest 18000 ft of the stratosphere, and levels of large wind shear and changes in lapse rate (i.e. rate of change of temperature with height) were preferentially investigated.

Tropospheric lee wave studies have previously been made but there have been few reports of flights above the tropopause in conditions suitable for tropospheric lee waves. Only two papers are known to have reported disturbances in the stratosphere in possible lee wave situations[1,7]. Of these, only one[1], describing two flights over the Sierra Nevada by the HICAT U2, contains the meteorological and positional information which allows the results to be incorporated in this discussion. The results of the U2 flights were published after the analysis of the present results and so provide independent corroboration of the conclusions. The present results add considerably to the fund of knowledge on stratospheric airflow in conditions suitable for tropospheric waves. The implications of these results are developed below but it must be stressed that more flights will be needed to establish the generality of the conclusions. In addition, work should be extended to greater heights to establish the vertical extent of disturbances, and to areas where there is a single tropopause in contra-distinction to the latitudes of the Sierra Nevada where a second tropopause at about 60000 ft was frequently evident.

4.1 Wave motion

Table 1 summarises the nature of the measured disturbances on the nine flights of interest, with the probable tropospheric wave intensity and wavelength. In general, on days when the tropospheric lee wave intensity was probably slight to moderate or less, the stratospheric disturbances were in the main irregular with amplitudes of 1000 ft or less (30 January, 15 and 24 February*). Amplitudes do, however, appear to vary little with height. Wavetrains appeared on only two of these days, 15 and 24 February, at one height on each day. The wave amplitudes were less than 300 ft and wavelengths were approximately equal to the natural wavelength and less than the calculated tropospheric wavelength (see Appendix A). It may be concluded that on the days of little tropospheric wave activity stratospheric vertical velocity gradients are negligible.

When the probable intensity of the tropospheric lee waves was moderate to strong or greater (9, 10, 13 and 14 February) well developed waves were present in the stratospheric isentropes. On 9 and 10 February there were negligible temporal variations in the atmospheric parameters governing wave structure. The isentropic patterns were stationary, wave amplitudes were about 1500 ft with no damping with height, and wavelengths were greater than the calculated tropospheric wavelength and much greater than the natural wavelength. On 13 and 14 February the aircraft encountered violent disturbances which caused the pilot temporarily to lose control. The disturbances on 14 February were particularly large; the aircraft encountered air which had been brought down from 7000 and perhaps 9000 ft above, and experienced a change of true airspeed of 100 kt. Both days were characterised by strong tropospheric lee wave conditions, by some change in the controlling meteorological parameters during the period of the flight and by adjacent layers of high and low stability in the stratosphere. The amplitude to wavelength ratios of the isentropes were the greatest of the flight series (with the exception of 3 February, which is discussed below). The wavelengths were close to the natural wavelength, and the vertical variation of wavelength on each day suggests that wavelengths in changing meteorological conditions were determined by the vertical variation of the wind and temperature fields; the data from 15 February supports this view. Frequently, in changing conditions

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*The data from 7 February is not included since the only part of that flight in the stratosphere was over non-mountainous terrain.

wave amplitudes appeared to increase with increasing height or time. If the increase is time dependent then it could be due to temporal changes in meteorological parameters over a particular mountain range.

3 February showed large amplitude (second to those of 14 February) short wavelength disturbances at the tropopause. Although no temporal changes were occurring during the flight period in the meteorological parameters governing tropospheric lee wave intensity, the stratospheric lapse rate was again characterised on this day by adjacent layers of high and low stability.

It is impossible on the evidence of these few flights to assess how far stratospheric wave parameters are dependent on topography. All the flights were made over mountainous terrain, but it should be noted that the large amplitude waves of 13 February occurred to the lee of mountains whose crests were only 3000 or 4000 ft above the general terrain (Fig.17).

To summarise, it appears from the results of this exercise that in unchanging meteorological conditions, and when stratospheric lapse rates show no fine structure, stratospheric waves are characterised by long wavelengths, little variation of amplitude with height, and smoothness. Their presence is primarily due to the underlying topography and their intensity primarily dependent on the tropospheric mountain and lee wave intensity.

When meteorological conditions are changing with time in a specific location, or when stratospheric lapse rates show marked fine structure, short wavelength large amplitude waves of some sort are present, frequently superimposed on the longer wavelength topographically induced mountain and lee waves. These short wavelength features are frequently mobile and turbulent (see next section), and it is probable that their presence is dependent both on the presence of the longer wavelength waves and on the meteorological conditions found to be associated with them. They also appear to be centred at the level of lapse rate change, but in changing conditions they could possibly exist at all levels.

Two U2 flights[1] were made in unchanging meteorological conditions over the Sierra Nevada up to 65000 ft. On both flights tropospheric lee waves were probably moderate and wavetrains were found in the stratosphere with wavelength 17 naut miles (much larger than the tropospheric or natural wavelength). The data used in constructing the isentropes was averaged over one minute with consequent lack of resolution of short wavelengths and with reduction in amplitude. However, more detailed data on a run at 60000 ft on the first flight indicated a disturbance of amplitude 2500 ft in the lee of the main Sierra crest. The report also indicates that the wave crests and troughs tilted upwind with increasing height with the gradient of each axis given by z:x::1:5. Lack of wind data and accurate information on aircraft position made such calculations impossible from the results reported here.

4.2 Turbulence and horizontal temperature changes

In mountain wave conditions encountered during WAVERIDER there appeared to be a relationship between horizontal temperature change and turbulence. The air in the troughs of mountain waves is at a higher temperature than the surrounding air since the wave has caused the air to descend from a greater height and during this descent its temperature increases adiabatically. As shown below, turbulence tended to occur in the troughs so that there was a relationship between turbulence and temperature increase in mountain wave conditions on these flights. Not all troughs contained patches of turbulence and in some cases the turbulence extended over neighbouring crests, but an increase in temperature indicated that most likely location of turbulence. This result may not be generally applicable since the Canberra was always at its greatest height when the most marked turbulence was encountered. If the aircraft had flown higher a relationship between turbulence and wave crests might have been observed. The most marked and rapid temperature changes were associated with the areas of marked turbulence.

4.2.1 Turbulence

The Canberra encountered moderate or severe turbulence on 3, 13 and 14 February; the T33 flew at the same time on 13 and 14 February and in the same area but at lower heights encountering marked turbulence on 14 February but not on 13 February[5]. In many cases when turbulence was encountered it occurred with no warning - this can be seen from the indicated airspeed trace of Figs.19, 20 and 29. This sudden entry into turbulence was most common on runs along the direction of the wind. On 3 February the turbulence increased slowly from slight to severe (see the indicated airspeed on Fig.7) when the aircraft was flying more or less across wind.

In most cases, particularly where the turbulence occurred in patches, the disturbance was found in the trough of a wave. This is indicated in Figs.9, 24 and 28, though it will be noted that some of the most marked troughs were completely smooth. The sudden onset of turbulence in along-wind flights suggests that, in the horizontal plane, the turbulence patches have considerable length across wind and small width along wind. There is little evidence on which to base a suggested vertical extension of this picture* (Fig.24) and none at all to indicate the nature of the temporal dimension.

Considering the three flights with marked turbulence, it is not possible to construct a 'climatology' of turbulence from so little data but there are some common features in the meteorological environment on these days which can be compared with the results of previous studies[2,7]. Tropospheric lee wave activity was moderate or strong on the days of severe turbulence, but this was also the case on 9 and 10 February when little turbulence was found. As shown in Fig.48, 13 and 14 February were characterised by marked vertical lapse rate changes in the stratosphere (as was 3 February), whereas no such fine structure was present on 9 and 10 February. The temperature of the turbulent air on 3 and 13 February indicated that turbulence was occurring in the top of the semi-adiabatic and base of the stable layers. Spillane[2] also found a strong correlation over flat terrain between turbulence encounters and the presence and height of marked vertical variations in the stratospheric lapse rate. HICAT flights over the Australian Alps appear to indicate that the severity of the turbulence increases over mountainous terrain. During two U2 flights over the Sierra Nevada[1] moderate CAT was encountered on three occasions at 60000 ft with no more than a few patches of light turbulence at 38000, 44000, 52500 and 65000 ft, the other heights flown. There was evidence of marked variations in the stratospheric lapse rate centred at about 63000 ft which may have contributed to the turbulence at 60000 ft.

A possible cause of this fine structure is the onset of ageostrophic motion (i.e. motion caused by the component of the wind normal to the height contours or isobars), which is usually present between the 200 and 50 mb levels above a jet stream, and which results in destabilisation of certain stratospheric layers if macroscale horizontal temperature variations are present in the area of onset. The decrease in stability results in a reduction of Richardson's Number, Ri. No. (see Appendix A), and is a possible contributory cause of the turbulence. A further reduction of Ri. No. in the disturbed flow is possible due to cramping of the isentropes. In wave flow containing tilting

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*Some recent work by Nicholls using an RB57F aircraft over the Western Rockies suggests that turbulence may exist in layers some 1000 to 5000 ft deep. These layers will be distorted by the waveflow to give the turbulent areas a corrugated shape.

axes of crests an extra term is introduced into the denominator of the expression for Ri; this gives the minimum value of Ri just upstream of the wave troughs in normal stratospheric flow[1].

The severe turbulence encountered by the Canberra on 14 February at 46000 ft (whereas no turbulence was found 20 minutes earlier and 12 naut miles south at 45000 ft) was probably the result of rapid changes in the parameters governing tropospheric wave structure. However, it may also have been due to reduction of Ri. No. by ageostrophic motion or by streamline cramping in the disturbed flow or by some combination of these circumstances.

Thus, if ageostrophic motion is present in a stratospheric layer above a jet stream it may cause destabilisation of part of the layer with corresponding decrease in Ri. No. If tropospheric stability criteria are satisfied the jet will also cause strong tropospheric lee wave activity. If, as has been suggested, the waves tilt backward there will be a further decrease in Ri. No. in the wave troughs and just upstream of them[1]; any cramping of the isentropes will result in a reduction of Ri. No. in the locality of the cramping. The combination of ageostrophic motion and strong stratospheric wave activity appear to be conducive to severe turbulence near the level of the ageostrophic motion. The severity may well be increased by interference caused by changes in the meteorological parameters or geographical effects.

4.2.2 Horizontal temperature changes

The greatest horizontal temperature changes, strong stratospheric waves and severe turbulence occurred together. When the aircraft encountered strong stratospheric waves without turbulence, e.g. 9 and 13 February (Runs 3 and 4), the temperature changes were not more than 4°C in 0.9 naut mile (4.4°C per naut mile) and 6°C in 2 naut miles (3°C per naut mile). With the exception of 14 February, temperature changes at times of strong stratospheric waves and marked turbulence, e.g. 13 February (Run 6), were about 7.3°C in 1.1 naut miles (6.6°C per naut mile) and 10.6°C in 2 naut miles (5.3°C per naut mile). These are comparable with the largest changes found near thunderstorms. The greatest changes measured, on 14 February, were about 12.5°C in 0.22 naut mile (57°C per naut mile) and 20.5°C in 1.1 naut miles (19°C per naut mile). The U2[1] reported changes of 6°C in 0.1 naut mile (60°C per naut mile) and 13.5°C in 3 naut miles (4.5°C per naut mile) at 60000 ft over Bishop in moderate turbulence.

In view of the interest in the use of remote temperature sensing as an aid to avoiding turbulence, some remarks are appended on the relationship between horizontal temperature change and turbulence in mountain wave conditions. If the remote temperature detector had adequate performance it could identify the presence of waves but there are some serious objections to its use as a turbulence detector. In the first place, the shape of the turbulence patches has not been clearly defined. The results of the present exercise suggest a relationship between temperature increase and turbulence but the recent work by Nicholls referred to earlier, casts doubt upon the generality of this conclusion. Even if the relationship was general, an aircraft flying along wind would not be able to avoid the turbulence by horizontal manoeuvres (because of the elongated nature of the turbulence across wind). For an aircraft flying across wind, the turbulence could be avoided only if the temperature sensor was able to scan in the horizontal plane. Lack of knowledge of the vertical structure and extent of the turbulence makes climb or descent manoeuvres a matter of chance and lack of knowledge of the persistence of turbulence patches casts a mantle of uncertainty over the entire question.

5 CONCLUSIONS

The 13 flights over mountainous terrain reported in this paper have provided valuable information from which it has been possible to extend our understanding of stratospheric flow. However, more flights would be needed to give the greatest generality to the results. In particular flights at greater heights would be most valuable.

One particularly violent incident, on 14 February, serves to set the limit, within our present experimental knowledge, of the severity of the disturbances of which the stratosphere is capable. The aircraft flew through air which had been brought down from at least 7000 and possible 9000 ft above. In this air mass it experienced a 100 kt change in true airspeed and a temperature change of 12°C in 0.2 naut mile. The pilot partially lost control of the aircraft and during the incident -1 g was measured. While such an incident may be uncommon, or even rare, it can happen.

Significant long wavelength mountain waves were found in the stratosphere only when moderate to strong or greater waves were probable in the troposphere. Practically all the evidence suggests that there is no reduction in wave amplitude with height, a result opposite to that expected before the start of the exercise. The waves were most pronounced on days when meteorological parameters affecting wave production were changing in the flight area at the time of the flight. Disturbances which affected the handling of the aircraft were found in the stratosphere when moderate or strong mountain or lee waves were probably present in the troposphere and therefore also in the stratosphere and either (i) when rapid temporal changes in the wind and temperature fields were occurring over a specific location or (ii) when the stratospheric lapse rate showed marked fine structure. The disturbances took the form of either short wavelength, large amplitude and, possibly, travelling waves or moderate and severe CAT. They were normally centred at the level of change in lapse rate but, under changing conditions it is possible that disturbances could exist at all levels and be advected with the governing meteorological conditions. Large and rapid changes in outside air temperature were associated with these disturbances, some of the severest of which (on 13 February) were over comparatively gentle ground profiles.

It is probable that conventional techniques for forecasting tropospheric lee waves (Appendix A) can be used to give a good estimate of the severity of the stratospheric waves, at least over the Western U.S.A. The results of the WAVERIDER flights indicate that severe stratospheric disturbances should be forecast when strong tropospheric waves are present and either stratospheric lapse rates vary markedly with height with the disturbances centred at the level of lapse rate change, or when meteorological criteria governing wave intensity are changing rapidly over a specific location with the disturbances possibly occurring at all levels.

Appendix A

FORECASTING OF MOUNTAIN WAVES

A.1 General criteria

Predicting quantitative details such as amplitude and wavelength of lee waves, and their variations with height in the tropospheric airflow over and in the lee of individual mountain ranges is a lengthy task. It is however possible, in the time available in field trials such as WAVERIDER, to forecast with some confidence the presence of waves for the mountain ranges under consideration. The following criteria were used.

The theoretical requirement for the presence of tropospheric lee waves is that the parameter $\ell^2 = \frac{g\beta}{u^2}$ should have a maximum value in the lower or middle troposphere[3,9] (at or about mountain top height) with lower values in the upper troposphere. In the formula β, a stability factor, is given by $\frac{1}{\theta}\frac{d\theta}{dz}$ where θ is the potential temperature and z is height, u is the wind component normal to the range, and g is the acceleration due to gravity.

In terms of stability this means that the upstream vertical temperature profile should show marked static stability at levels where the airstream is disturbed by the mountain (i.e. $\frac{d\theta}{dz}$ large) with lower stability above. Synoptically this condition is frequently satisfied by the presence of a subsidence inversion, a frontal inversion or warm sector isothermal or near-isothermal layer near mountain top height*. Of course other synoptic situations exist in which the required profile would be produced.

Another necessary condition for the presence of tropospheric waves is that there must be a reasonable component of the wind current normal to the range. Also, for the necessary reduction in ℓ^2 with height, it is preferable for this component to increase with height. This too has synoptic implications since this increase is often found in or near jet streams. In practice it is found that marked wave activity is absent if the wind direction is not within about 30° of the normal to the range or if marked directional changes occur with height. The commonest situation in which both stability

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*The nearest standard level to mountain top height is 700 mb and a 700 mb chart is shown for each day. A second chart is also displayed showing conditions at the standard level closest to the flight level.

and wind criteria are satisfied is in the vicinity of fronts on the equatorial side of depressions.

When forecasting tropospheric waves any foreseeable changes in the synoptic situation must of course be taken into account, for example the movement of fronts will cause the height of the stable layer to vary at a fixed location. Observational evidence of waves in the form of wave clouds (which are by no means always present) and pilot reports are also important.

A few factors governing wave amplitude and wavelength are sometimes of help to the forecaster and will be mentioned here. The tropospheric lee wavelength (in km) is approximately equal to half the mean tropospheric windspeed (in msec^{-1}). If the lee wavelength is approximately equal to the horizontal 'scale' of the mountain range, the amplitude will be much larger than for broader or narrower mountains. The amplitude is approximately proportional to the mountain height and is also dependent on the symmetry of the range, asymmetric ridges producing greater disturbances. The natural wavelength, given by $\frac{2\pi}{\ell}$, is the wavelength at which the air would oscillate if it was being advected by the wind field at its equilibrium level unaffected by the air above and below.

All other factors being equal, amplitudes are largest when the wave forming criteria are only just satisfied. Thus, in this region, the amplitude depends critically on the airstream characteristics and large amplitude changes may result from small changes in the wind or temperature profiles. Also, larger amplitude waves are formed in airstreams containing a shallow layer of great stability than for a broad layer of slight stability, but in the first case the amplitudes of the tropospheric waves will fall off greatly with height.

No criteria had been evolved before this exercise from which stratospheric disturbances could be forecast. Here 'stratospheric disturbances' means mountain waves (a distortion of the flow just due to ground undulation with no following lee waves), lee waves, or turbulence in association with these waves. However, it was assumed that the magnitude of the stratospheric disturbances would be proportional to the magnitude of the tropospheric disturbance, and also that possible breakdown of the flow could be associated with large wind shears and possibly with marked changes in lapse rate.

A.2 Applications of these criteria to the Western Rockies

Several papers describe the formation of lee waves in the Sierra Nevada. An isothermal layer or inversion is needed in the upwind airstream for strong lee waves to be produced in the troposphere. The top of this inversion layer should be between 12000 and 19000 ft. The presence of a stable layer or inversion on strong wave days can often be seen in the form of a large horizontal temperature gradient in the vicinity of the mountains on the 500 mb or 700 mb contour charts. The windspeed normal to the range should be not less than about 30 kt at mountain crest height and about 70 kt at 300 mb.

Similar conditions for strong tropospheric lee waves should apply to other ranges of similar height in the western United States. However, the synoptic situations which produce these upwind conditions may vary, being dependent on the orientation of the mountain range.

Appendix B

METHODS OF ANALYSING MOUNTAIN WAVES

B.1 Isentropic analysis

An isentropic surface (in the meteorological context) is a surface on which air has the same potential temperature*. If the air has a velocity relative to that surface and if it can be shown that the gradients of the surface remain constant with time, then the air is flowing along the isentropic surface. In this case, if a vertical section is taken through the surface along the wind direction, the isentrope so produced is a trajectory of the airflow and vertical airspeeds can be directly deduced from the isentropic gradients and a knowledge of the windspeed in the undisturbed upstream flow. A mountain lee wave is indicated by a periodic disturbance in a stationary isentrope to the lee of a mountain range.

From aircraft and radiosonde measurements an isentrope can be drawn for each run as shown in Fig.3. Firstly, an upper air sounding is drawn which is, as far as possible, representative of the upwind temperature profile at the flight time. This is usually a composite of several radiosonde ascents and the aircraft readings taken on climbing upwind of the mountains, and obviously involves some interpolation in space and time. The vertical distribution of potential temperature is deduced from this estimate of the vertical temperature upwind of the mountains. Secondly, from the aircraft recorded temperature and airspeed the true outside air temperature is calculated along each run and, knowing the aircraft height, potential temperatures are calculated. By assuming that the vertical gradient of potential temperature is maintained in the disturbed flow an isentrope can be drawn for each run based on the mean potential temperatures calculated from the aircraft measured temperature for the run. It is, however, sometimes apparent from the mean temperatures at the downwind end of the runs that the vertical profile of temperature is not constant along a run. When the change was due to a change of airmass properties along the run, the isentropic displacements for a portion of the run were deduced from the vertical profile of potential temperature representative of that portion. The measurements of temperature from the aircraft

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*The 'potential temperature' of a parcel of air at height H is the temperature it would attain if brought dry adiabatically to the 1000 mb level (approximately to the surface) from H. In adiabatic motion it is therefore a conservative property of the parcel of air.

record were normally made at 10 second intervals but if rapid variations were occurring intervals down to $\frac{1}{2}$ second were used.

The representative potential temperature profile used in the calculations was compared with all the individual profiles. The greatest difference between any individual profile and the representative profile would have given rise to an error of about 30% in the calculated amplitude of the isentropes. Errors in the depicted amplitude along a run can also be caused by local changes of the vertical potential temperature gradients due to local vertical cramping or stretching of the flow. Cramping of the flow is obvious in the results for 13 February but it is possible to make a realistic estimate of the true amplitude on a run by 'fitting' the disturbances to those above and below.

As has been said, the isentropes will only be trajectories of airflow if they are stationary. Stationarity can strictly only be demonstrated by a reciprocal run along the same ground track at the same height. This was seldom done and on other days the criterion used was that there should be a reasonable alignment between the crests and troughs in the isentropes from one height to the next. If the height separation between the runs was too large to establish this or if the ground tracks were very different, the isentropes were considered to be stationary if the disturbances were distinctly non-turbulent, no temporal changes in the synoptic scale flow pattern were occurring, and the aircraft height variations had the correct phase relationship with the isentropic disturbances.

When the isentropes are not stationary the horizontal wavelength of the air vertical velocity W of the air is unchanged but the magnitude is reduced in a forward-travelling non-amplifying wave of velocity c, since

$$W = (u - c)\,\frac{\partial s}{\partial x}$$

where u is the horizontal component of the wind velocity and s is the isentrope vertical displacement. If mobility can be deduced from the flight measurements then an estimate of c can be made and the vertical velocity field constructed. Reliable estimates can only be made, however, when a reciprocal run is made soon after the original run at the same height and along the same ground track. So long as the disturbances are not amplifying or travelling with velocity u the wavelength and amplitude of the air oscillation is as depicted by an isentrope (assuming also that there is no vertical cramping of the streamlines and that the assumed upwind profile of potential temperature is representative).

It is particularly difficult to attach physical significance to the disturbances in an isentrope when the flight or atmospheric data do not indicate whether or not these disturbances are amplifying or stationary. In these cases all we can say is that the isentrope shows instantaneous air displacements at the time of measurement. If, however, wavelike disturbances occur in the isentropes on a day when meteorological changes are taking place in the area, then even if $u = c$, or the waves are amplifying, the disturbances must have been caused somewhere locally and their amplitude and period must be representative of the air oscillations somewhere in the flight area.

B.2 Constant energy analysis

The external energy of an aircraft will be $(mg\ H + \frac{1}{2}m\ V^2)$, where m is the mass, H the height and V the true airspeed. If changes in H or V occur slowly with no change of throttle setting, the aircraft will remain virtually in trim throughout so that the internal energy will remain sensibly constant. In these circumstances, if the speed is changed by a factor δV the height will change by δH in such a way that

$$mg\ H + \tfrac{1}{2}m\ V^2 = mg\ (H + \delta H) + \tfrac{1}{2}m\ (V + \delta V)^2 \quad ,$$

that is,

$$\delta H = -\frac{\delta V}{g}\,(V + \tfrac{1}{2}\ \delta V) \quad .$$

In mountain wave conditions it is assumed that any change of speed is caused by the transformation of potential into kinetic energy. Thus the total height h of a wave will be made up of a measured height change ΔH and a height change due to the change of speed, δH, that is

$$h = \Delta H - \frac{\delta V}{g}\,(V + \tfrac{1}{2}\ \delta V) \quad .$$

From the aircraft records, height and airspeed were measured at 10 second intervals along a run in mountain wave conditions and were corrected for position errors. From the measured airspeed, true air speed was calculated and a

δV was established by subtracting a suitable V_o*. δH was calculated and added to the measured height to give the air motion in the wave.

Because this method depends on slow changes in speed and height it becomes suspect in the most violent wave conditions. If the measuring interval is reduced to 1 second the results become inconsistent and the method cannot be applied with much confidence where significant changes in the air motion occur over periods of one or two seconds. For this reason the analysis by this method for 3, 13 and 14 February it not included; although in each of these cases the shape and wavelength calculated by the isentropic and energy methods are very similar, the amplitudes are very much smaller from the energy method.

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*The actual value of V_o is not important since an error in the magnitude of δV does not affect the shape of the wave but only changes the median height of the whole wave pattern.

Table 1

SUMMARY OF WAVE CHARACTERISTICS

Date	Tropopause (ft)	Tropospheric waves		Atmospheric variability	Run No.	Flight level	Nature of isentropic disturbance		Waves observed		
		Probable intensity	Probable wavelength				Type	Movement	Maximum amplitude (ft)	Wavelength	
										Observed	Calculated (natural)
			naut miles							naut miles	naut miles
30 Jan	37000	Slight to moderate	7.8	Minor changes.	3	350	Irregular	Stationary	1500	-	-
							Wavetrain	"	450	3.5	-
					5	390	Irregular	"	600	-	-
					7	430	Irregular	"	1000	-	-
3 Feb	37000	Moderate	4.3	Minor temporal changes. Some difference between vertical wind structures to north and south.	1	370	Irregular	Stationary	3000	-	-
							Wavetrain	Mobile^{I}	1500	≈0.3-0.7	-
					2	370	Irregular	Stationary	3500	-	-
							Wavetrain	Mobile^{I}	500	≈0.3-0.7	-
7 Feb	35000	Slight	2.2	Minor changes.	2	350	Irregular	Stationary	700	-	-
					3	350	Irregular	Stationary	700	-	-
					4 & 5	450	None (over	different terrain to Runs 2-3)			
9 Feb	37000	Strong	9.0	Minor changes.	2	370	Wavetrain	Stationary	1250	9.5	-
					3	450	Wavetrain	Stationary	1750	≈12.0	5.8
10 Feb	35000	Moderate to strong	6.0	Minor changes.	2	450	Wavetrain	Stationary	>750^{II}	9.0	-
					3	510	"	"	>1400^{II}	9.0	4.0
					4	525	"	"	>800^{II}	9.0	-
13 Feb	38500	West end of runs			West end of runs						
		Moderate to strong	5.5	Stratosphere (a) Marked temperature rises along runs.	1	450	Wavetrain	Stationary	1400	15.0	-
		East end of runs			2	460	Wavetrain	Stationary	1300	15.0	-
		Strong	7.5	(b) Possible difference in vertical wind shear between ends of runs.	3	470	None				
					4	480	Irregular	Uncertain	1100	-	-
				Troposphere (a) Wind and temperature field moving south at 22 knots.	5	490	Wavetrain	Uncertain	1250	6.0	-
					6	500	None				
					East end of runs						
				(b) Possible discontinuity in maximum wind level beneath flight track.	1	450	Wavetrain	Stationary	1000	7.5	-
					2	460	Irregular	Uncertain	500	-	-
				(c) Greater stability at mountain crest level, and stronger winds over N.E. of flight area.	3	470	Wavetrain	Stationary	1650	7.5	8.0
					4	480	"	Stationary	2550	7.5	-
					5	490	"	Uncertain	1500	5.5	-
					6	500	"	Uncertain	2200	-	III

Table 1 (Contd)

Date	Tropopause (ft)	Tropospheric waves		Atmospheric variability	Run No.	Flight level	Nature of isentropic disturbance		Waves observed		
		Probable intensity	Probable wavelength				Type	Movement	Maximum amplitude (ft)	Wavelength	
										Observed	Calculated (natural)
			naut miles							naut miles	naut miles
14 Feb	33000	Strong	8.3	Sharp trough between 8000 ft and 20000 ft moving through flight area.	1	450	Irregular	Stationary	2500	-	-
					2	460	Irregular IV	Uncertain	4500	IV	IV
							Wavetrain	"	1500	3.5	V
							Wavetrain	"	300	1.8	2.7
15 Feb	35000	Slight	5.5	Sharp trough between 25000 ft and 45000 ft moving through flight area.	1	410	Irregular	Stationary	700	-	-
							Wavetrain	"	200	4.3	4.8
					2	410	Irregular	"	350	-	-
							Wavetrain	"	250	4.3	4.8
					3	430	Irregular	Uncertain	650	-	-
					4	430	"	Mobile	700	-	-
					5	330	"	"	600	-	-
							Wavetrain	"	300	3.8	-
					6	350	Irregular	"	800	-	-
							Wavetrain	"	500	3.8	-
24 Feb	37000	Slight to moderate	3.9	Minor changes.	1	450	Irregular	Stationary	700	-	-
							Wavetrain	Uncertain	300	2.7	2.8
					2	410	Irregular	Stationary	200	-	-
					3	390	Irregular	Stationary	350	-	-

Key

(a) I Most likely turbulent eddies.

II Amplitude dependent on track relative to isolated peak.

III Natural wavelength of stable air above this level = 2.5 naut miles.

IV Possible wavelength of 2.2 naut miles compared to approximate natural wavelength of 3.0 naut miles.

V Natural wavelength of air below this level = 8.0 naut miles, and of air above this level = 2.7 naut miles.

(b) Disturbance amplitude is half the total streamline displacement in single perturbation.

(c) Of the remaining four flights, three were in the stratosphere and encountered no disturbances. On assessing retrospectively no tropospheric activity was likely on these four days.

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4	J.K. Zbrozek D.M. Ridland	A measured power spectrum of the vertical component of atmospheric turbulence. ARC CP 522 (1960
5	G.K. Mather	Some measurements of mountain waves and mountain wave turbulence made using the NAE T33 turbulence research aircraft. Quarterly Bulletin The Div. of Mech. Eng. and the NAE, DME/NAE 1967(2) April-June (p1)
6	A.A. Woodfield P.J. Haynes	Measurements of air temperature on an aircraft travelling at high subsonic and supersonic speeds. ARC CP 809 (1963)
7	T.L. Coleman R. Steiner	Atmospheric turbulence measurements obtained from airplane operations at altitudes between 20000 and 75000 ft for several areas in the northern hemisphere. NASA TN D-548 (1960)
8	A. McPherson J.M. Nicholls	Mountain waves in the stratosphere measured by an aircraft over the Western U.S.A. during February 1967. In AGARD CP 48, September 1969
9	M. A. Alaka (Editor)	The airflow over mountains. WMO Tech. Note No.34 (1960)

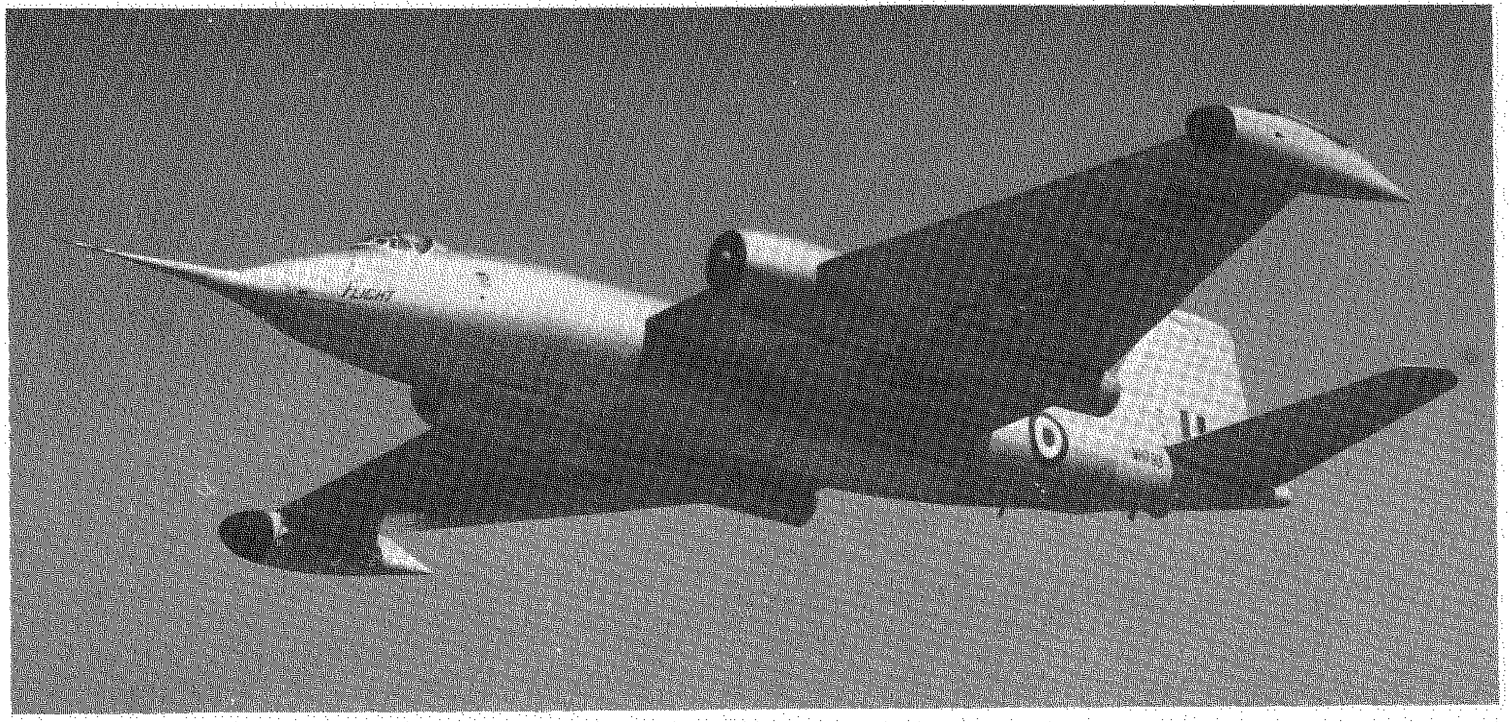


Fig.1. Canberra WH 793

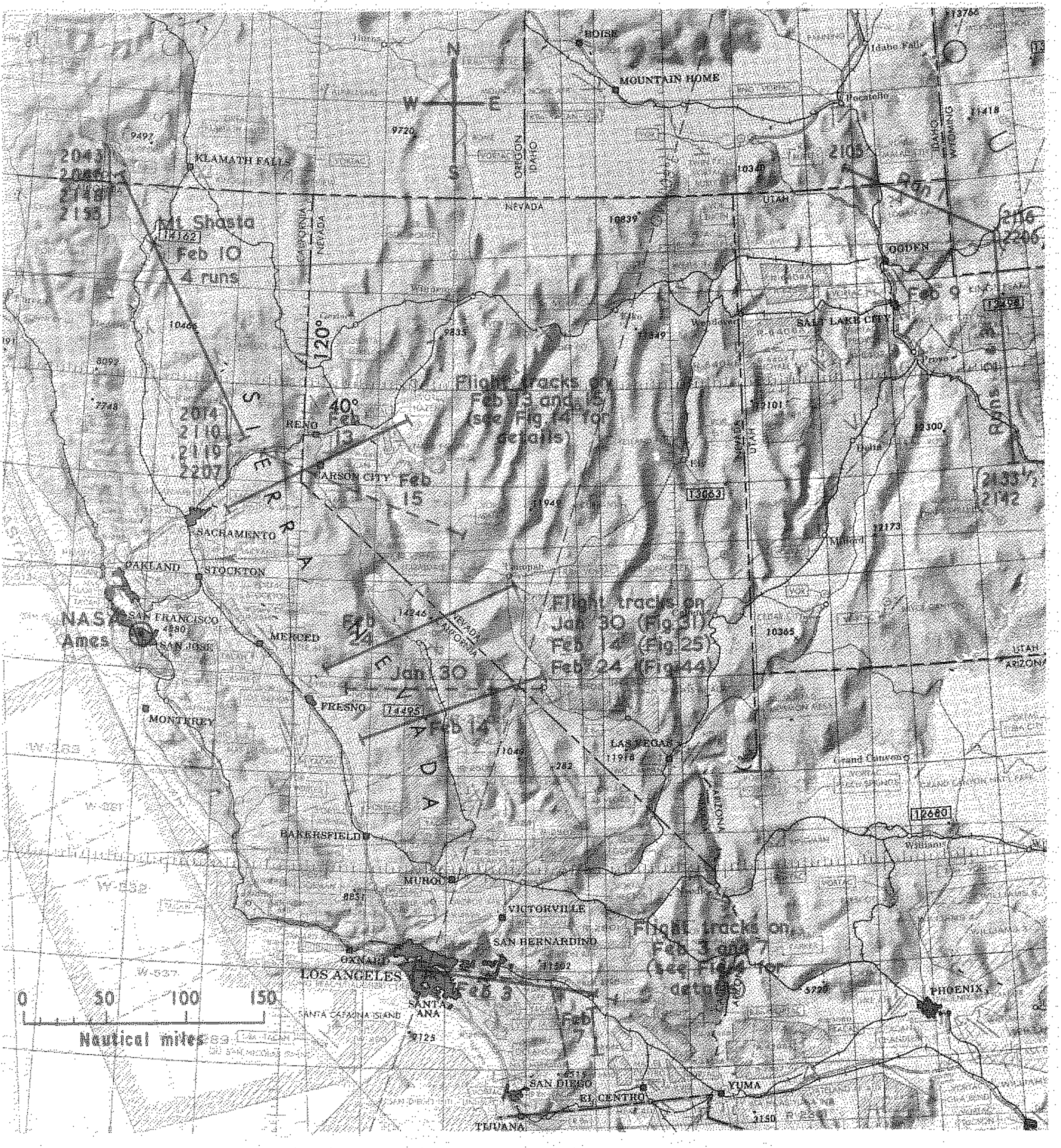


Fig.2. Map showing flight tracks for project waverider

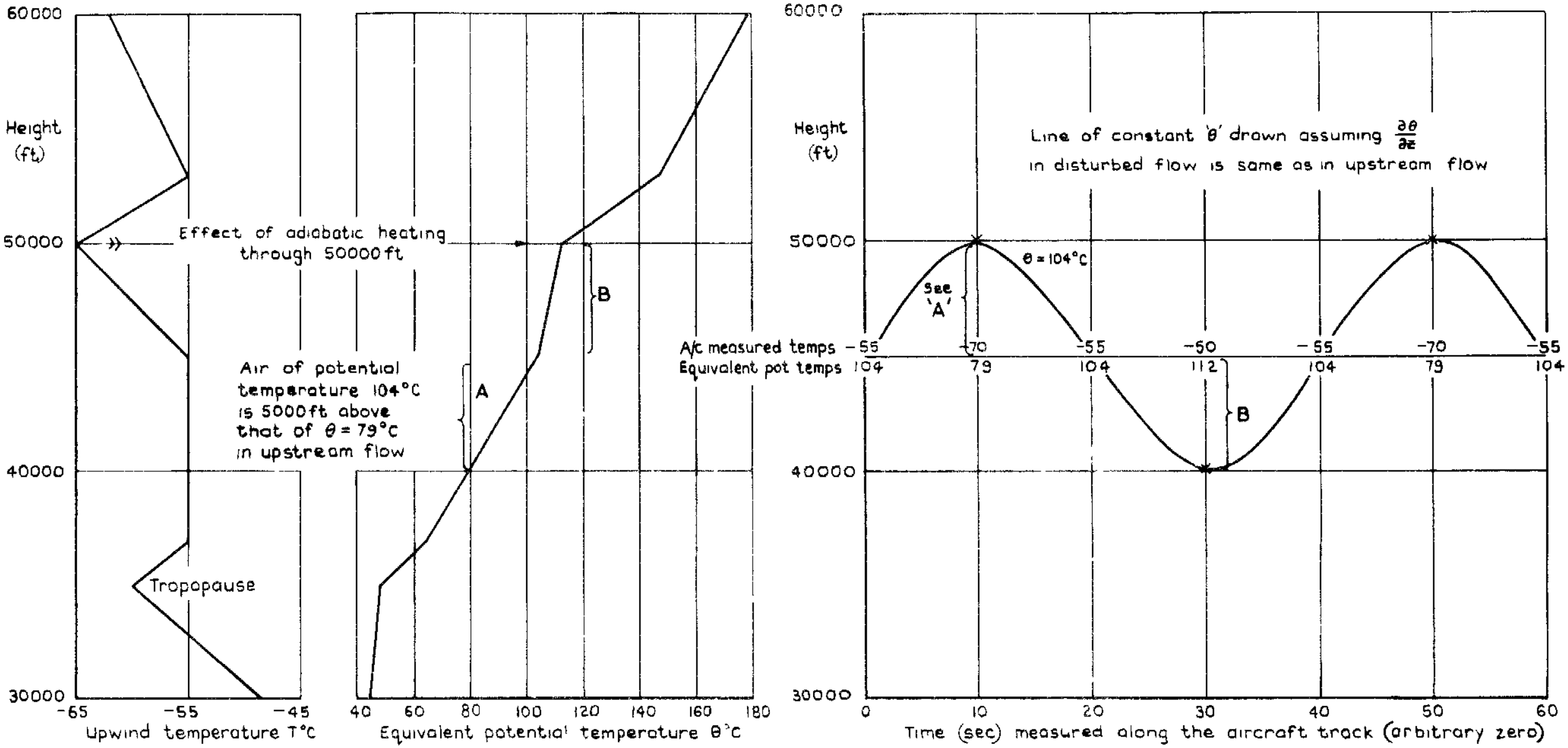


Fig. 3 Construction of line of constant potential temperature for a run at 45000 ft

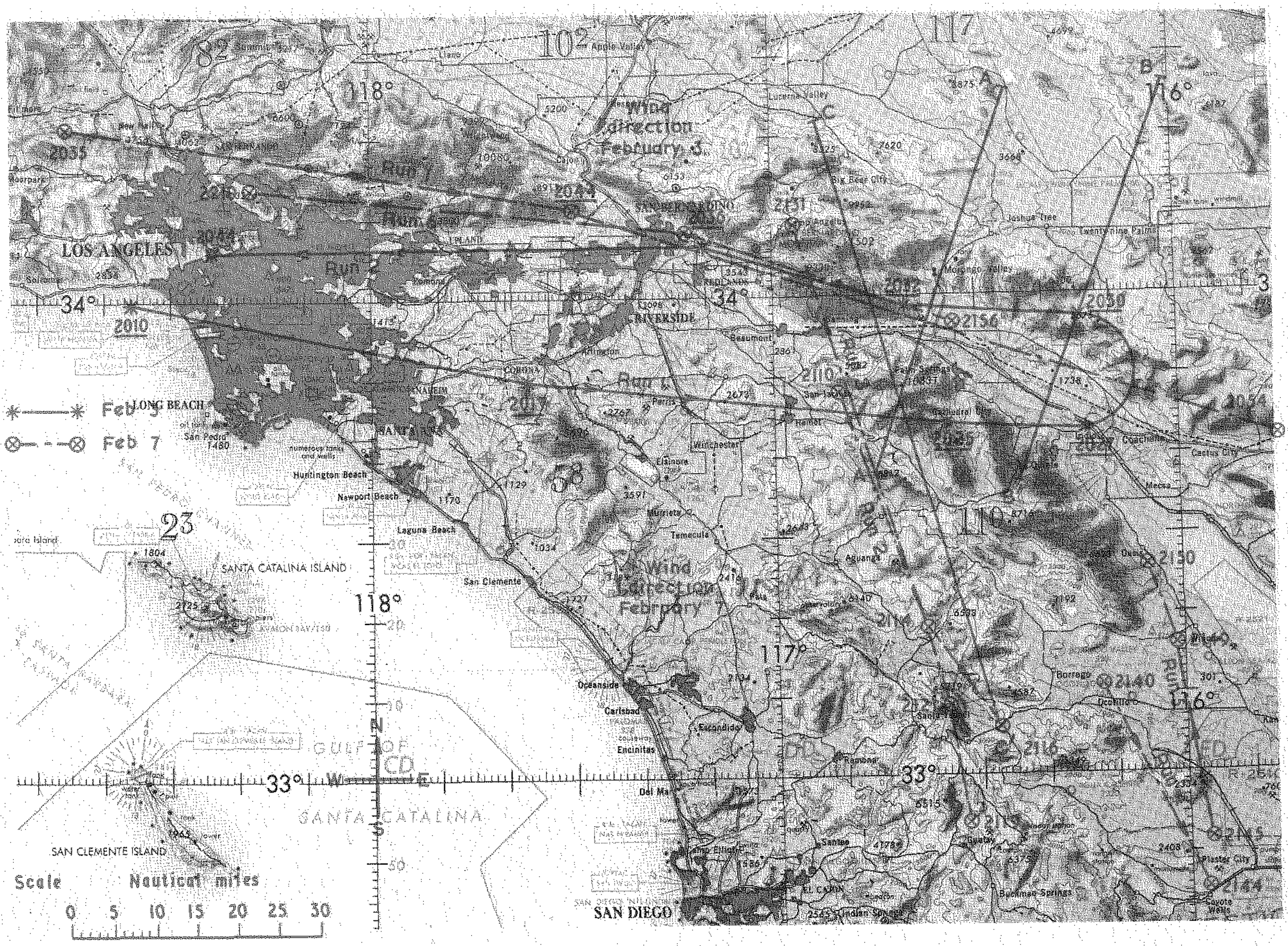
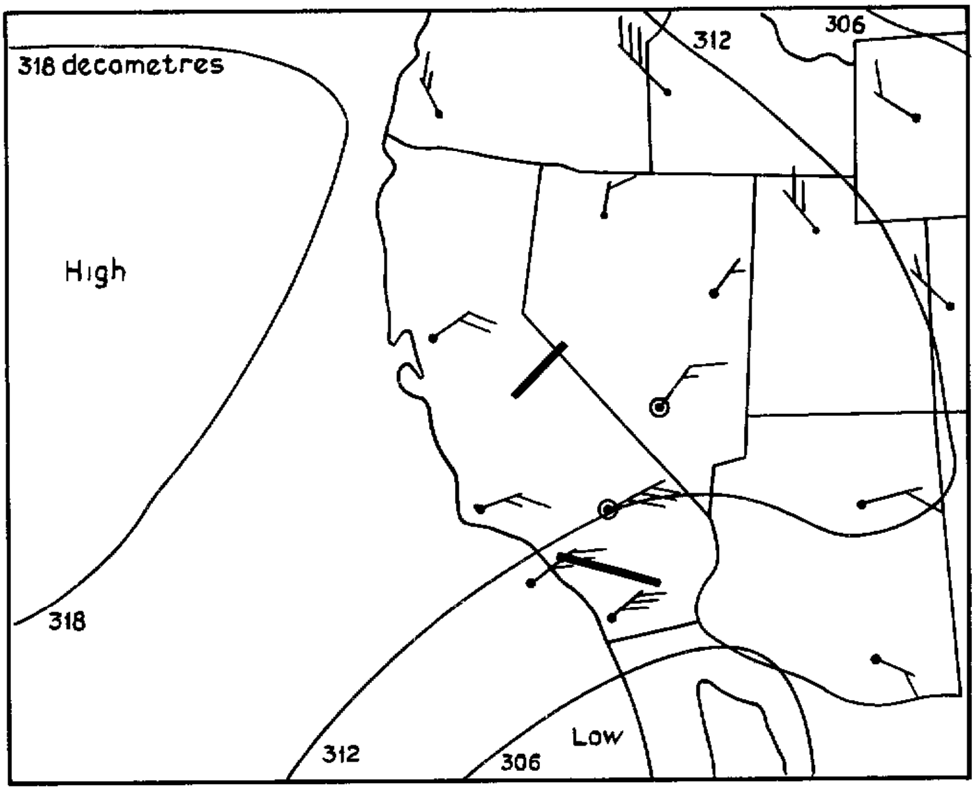


Fig.4 Ground tracks for the flights of February 3 and February 7

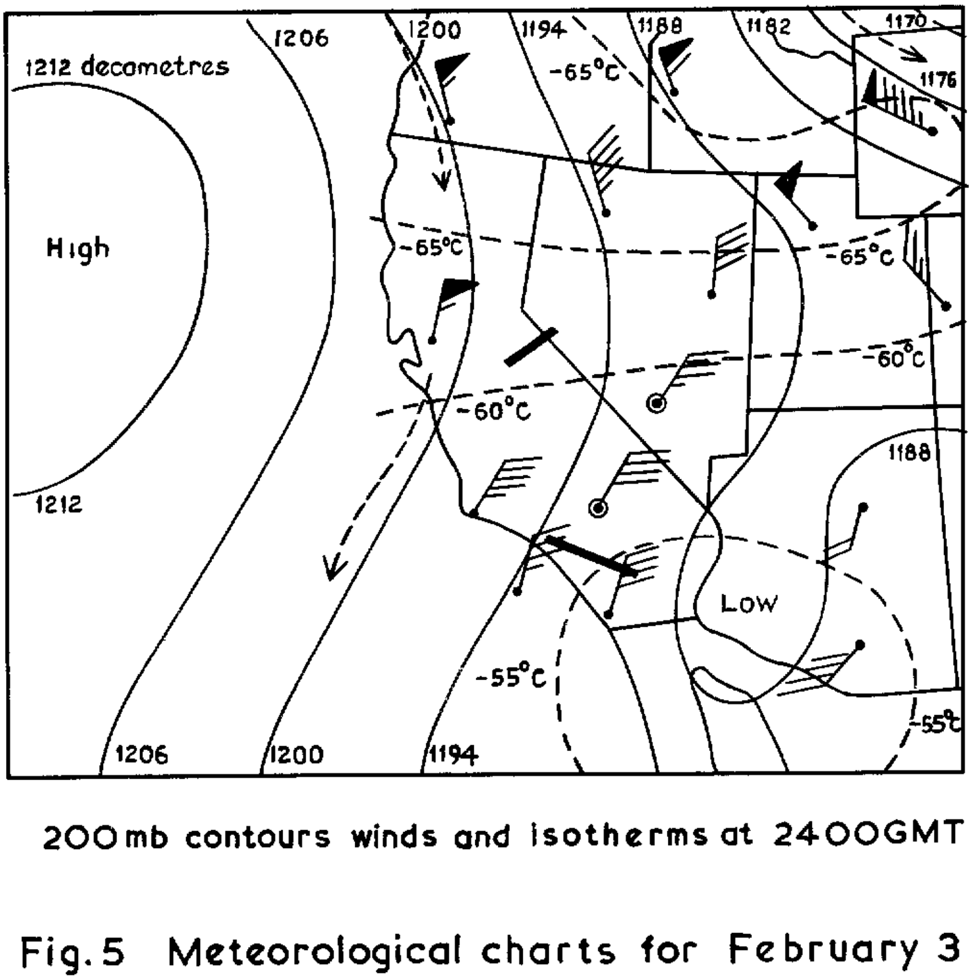


700mb contours (decametres) and winds at 2400GMT

⊙ Stations used for composite profiles

▬ Aircraft tracks

--- Maximum wind at 200mb



200mb contours winds and isotherms at 2400GMT

Fig. 5 Meteorological charts for February 3

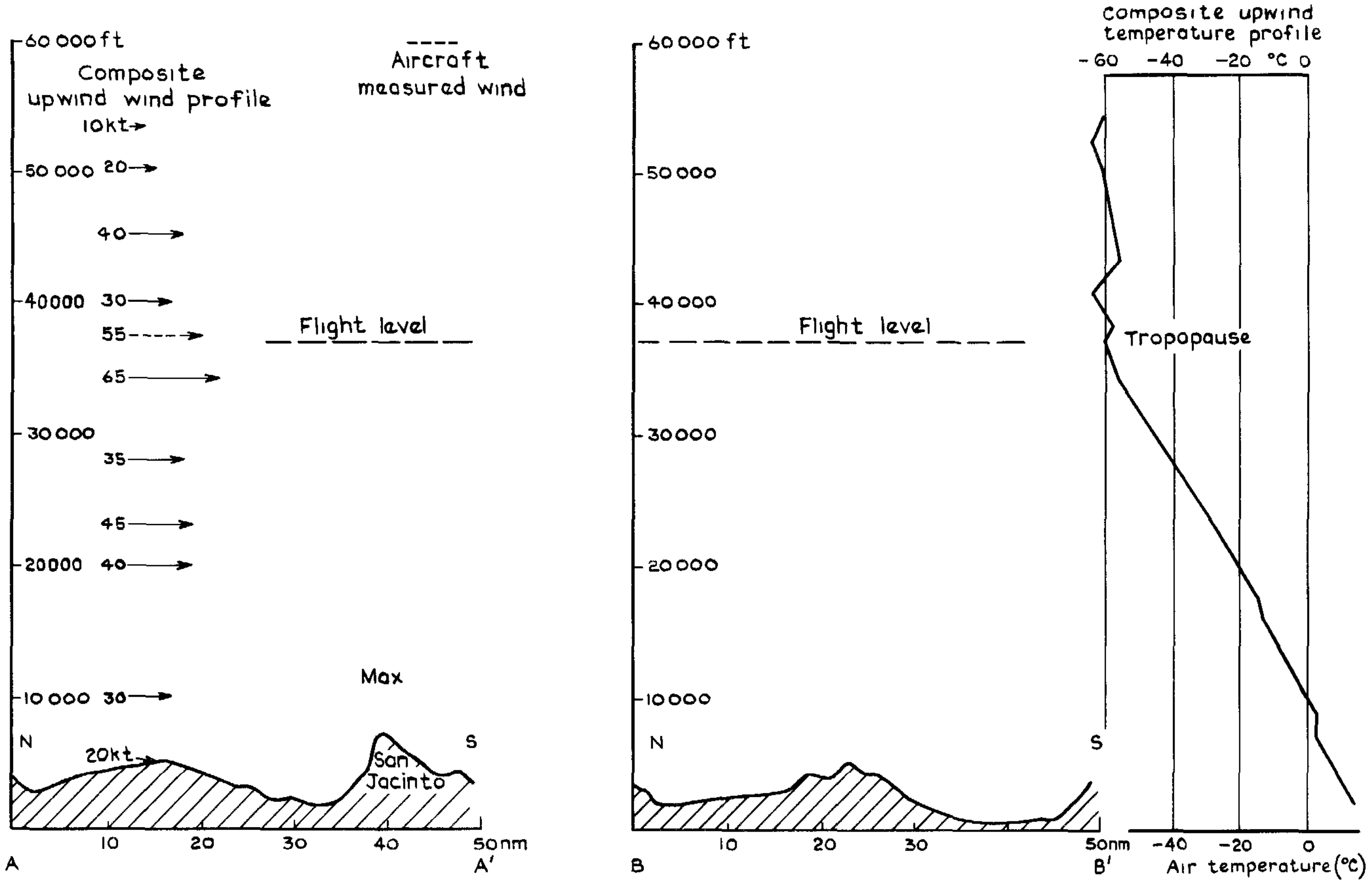
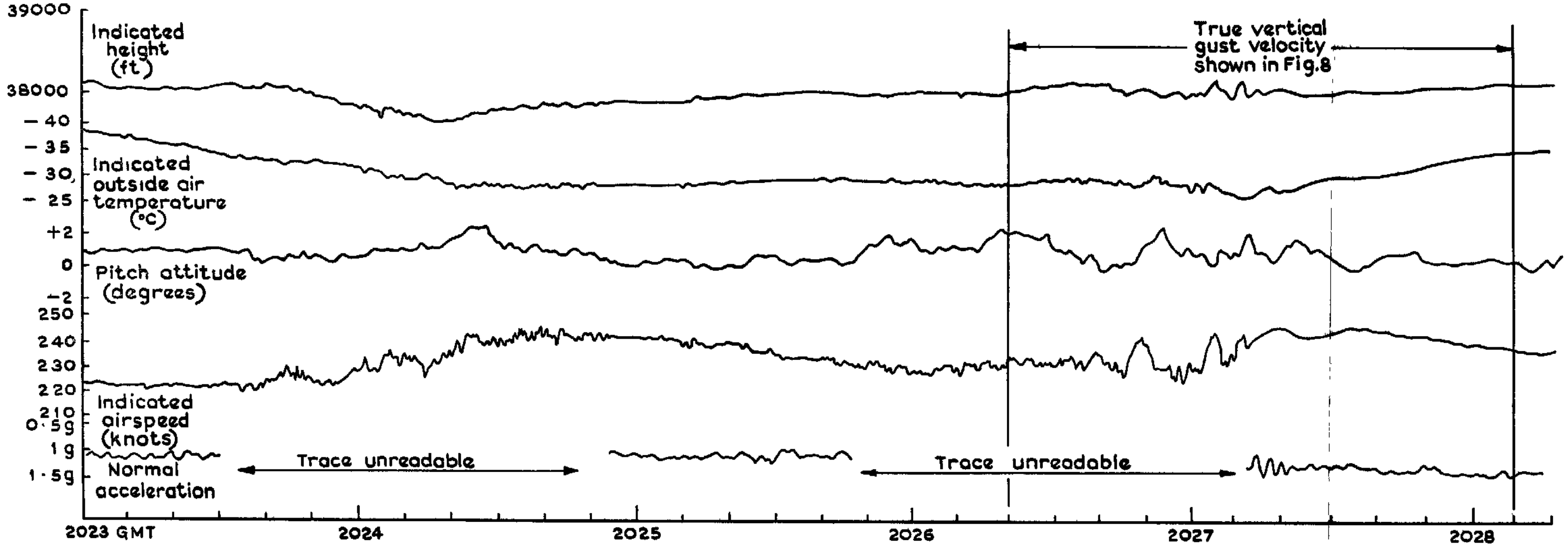
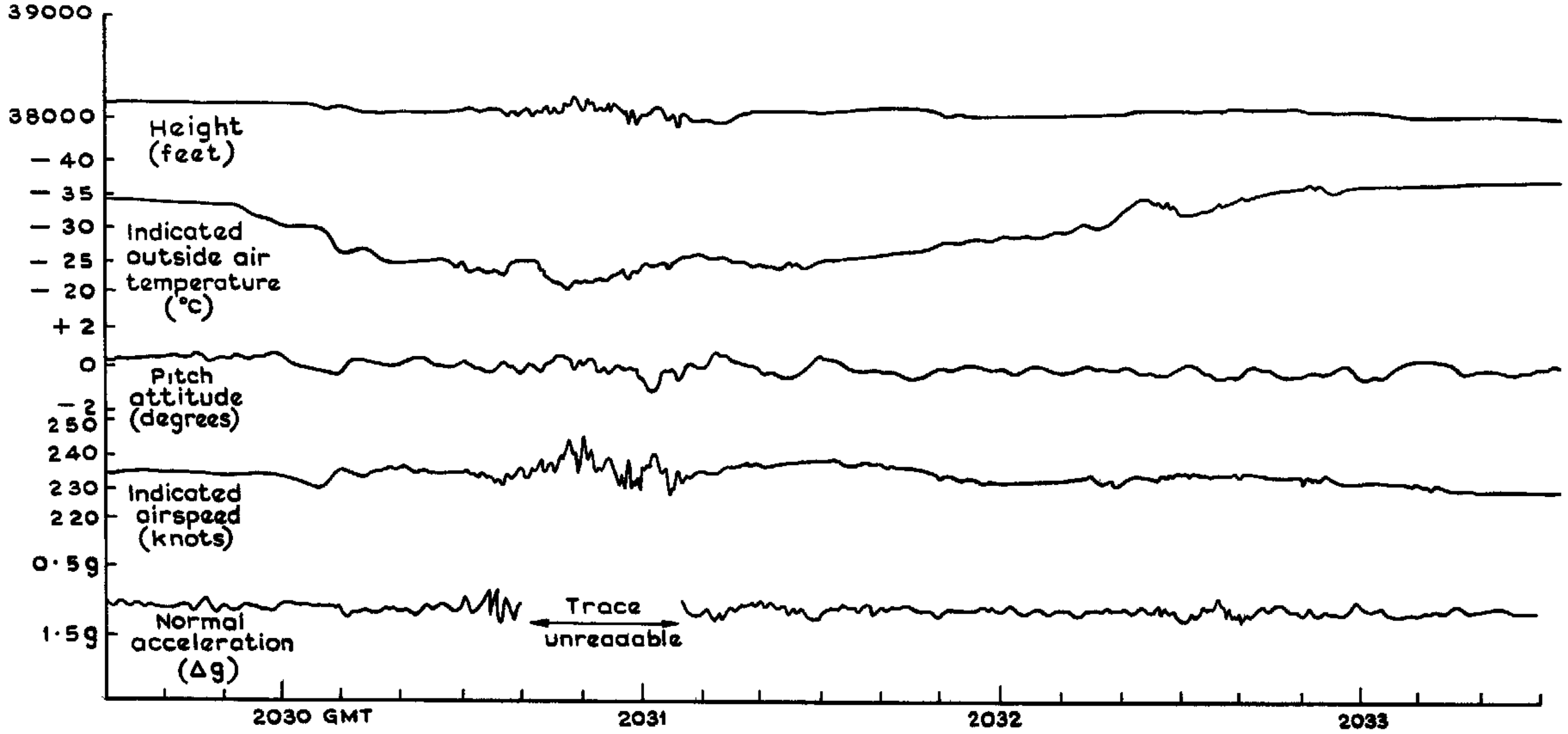


Fig. 6 Cross-sections of flights in Southern California on February 3



Run I East-bound



Run 2 West-bound

Fig.7 Copies of the original records for the flight of February 3rd

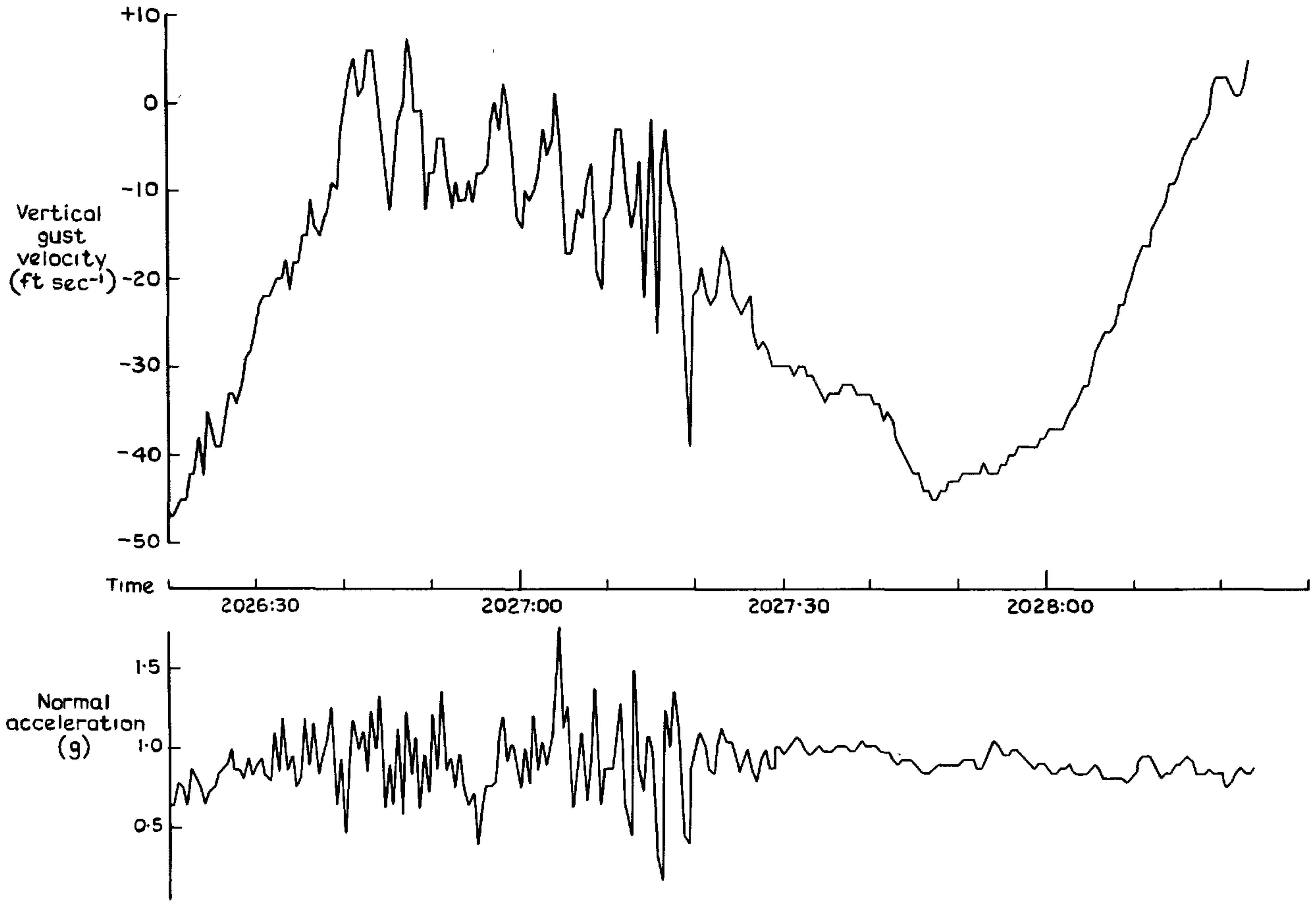


Fig.8 True vertical gust velocity on February 3

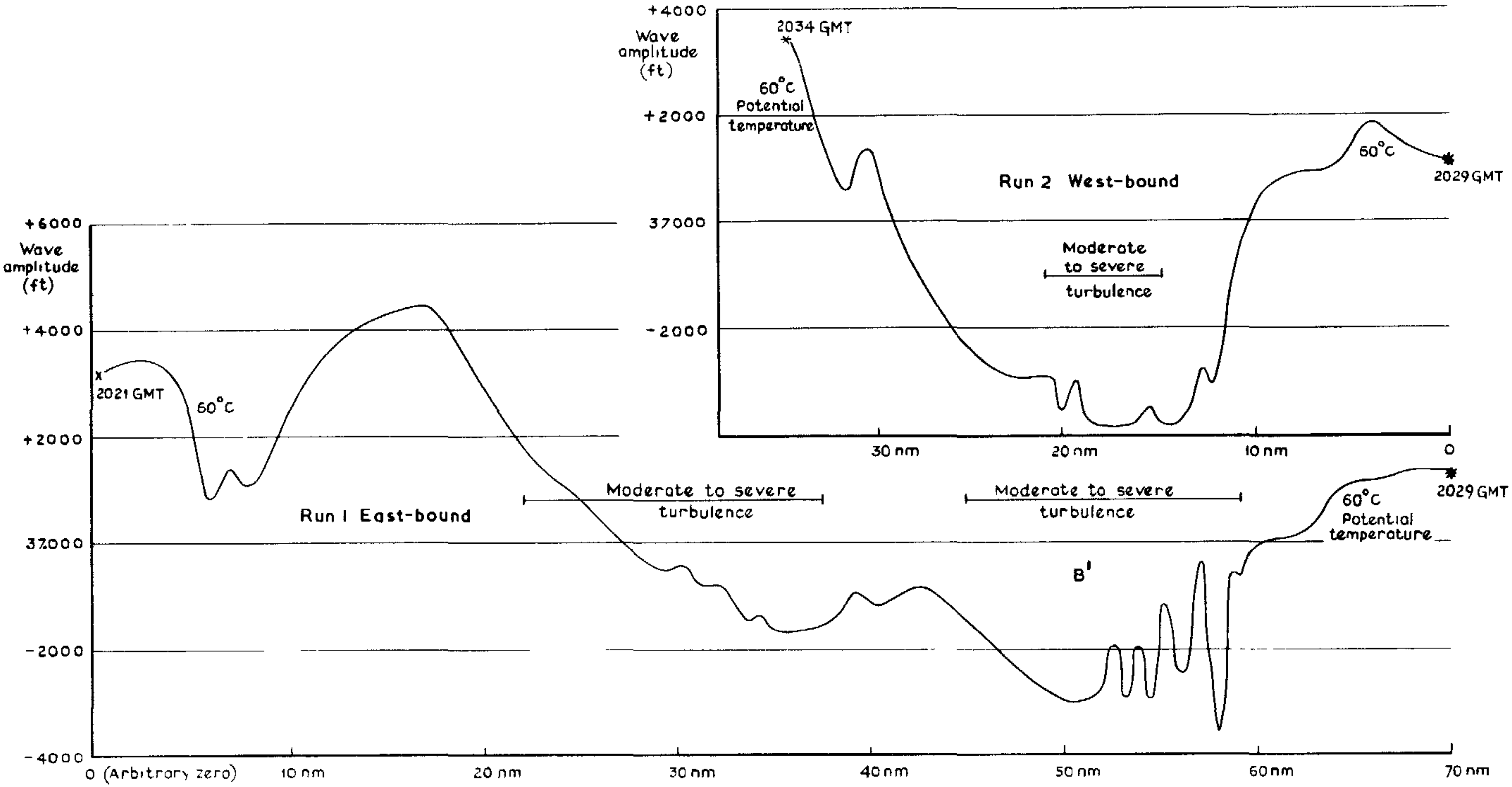
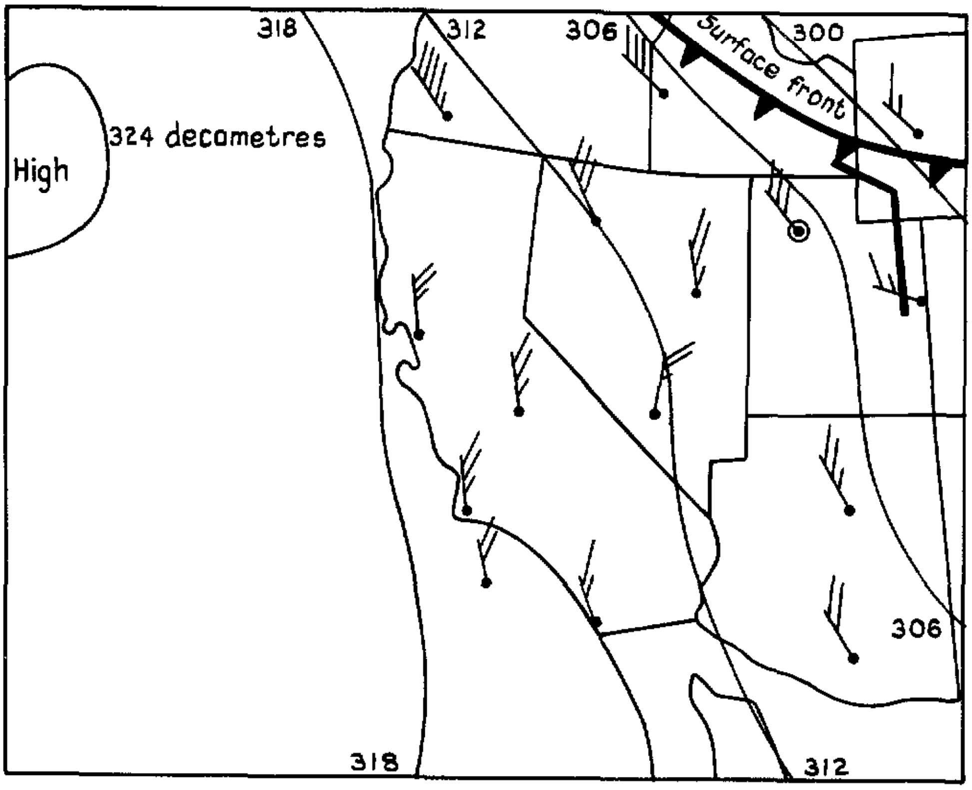


Fig.9 Wave motion on February 3

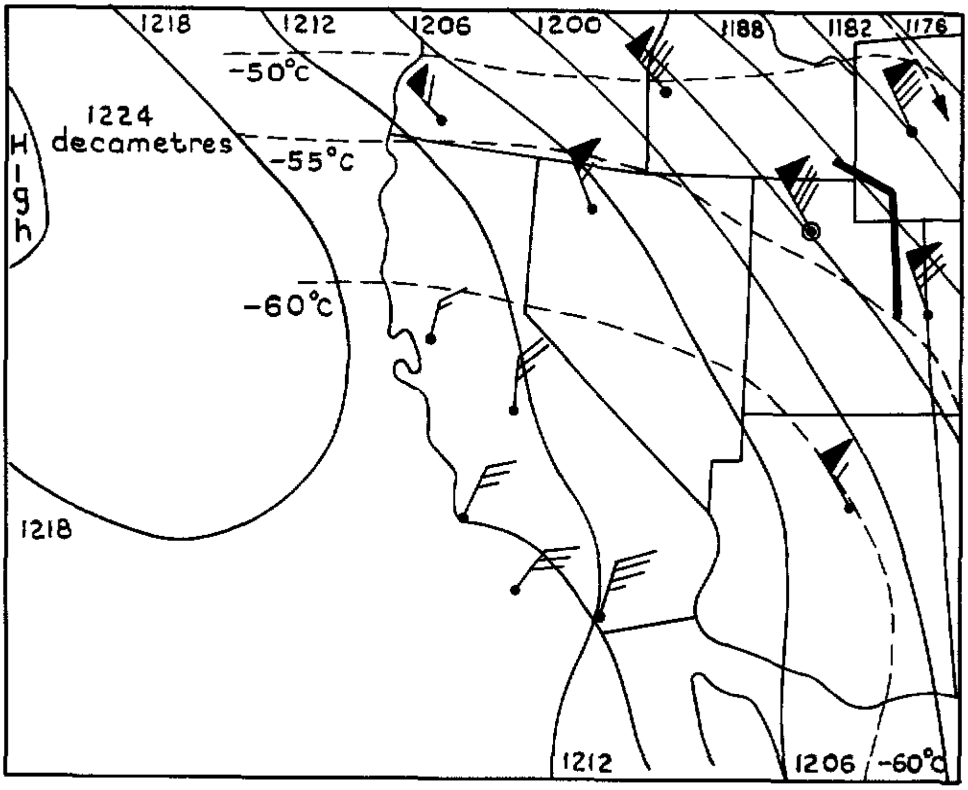


700 mb contours (decametres) and winds at 2400 GMT

⊙ Station used in composite profile

▬ Aircraft track

--- Maximum wind at 200 mb



200 mb contours, winds and isotherms at 2400 GMT

Fig. 10 Meteorological charts for February 9

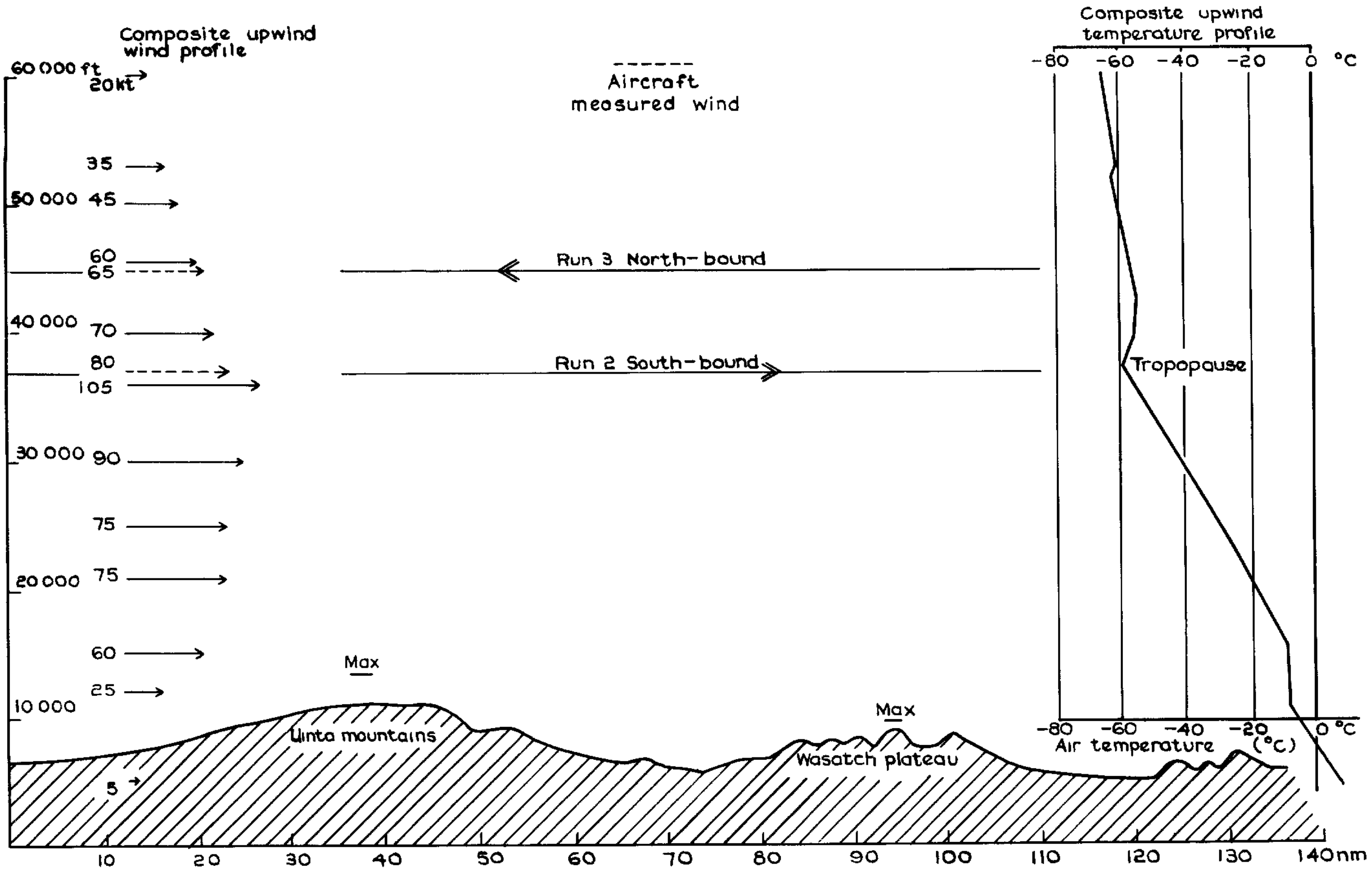
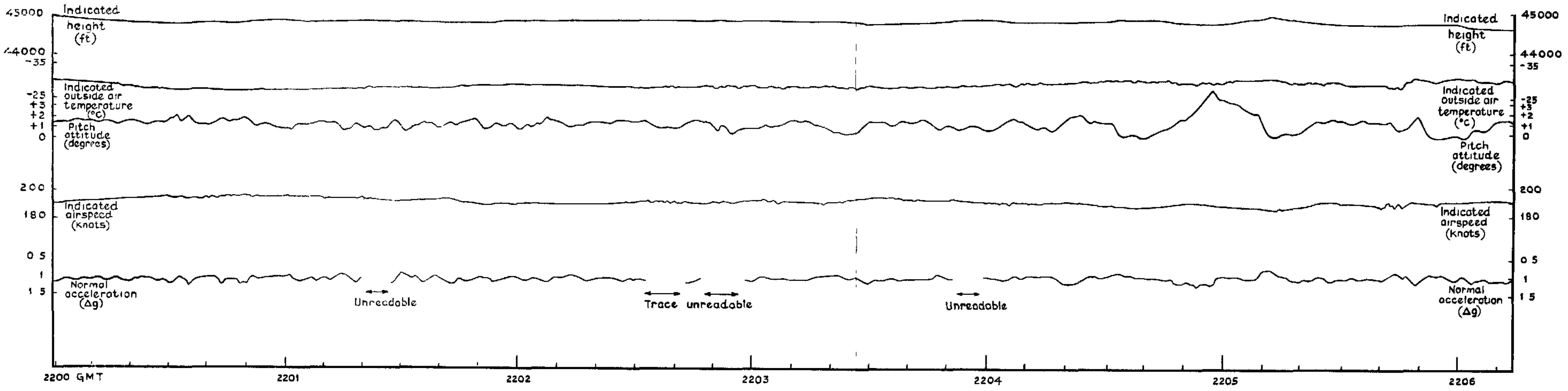
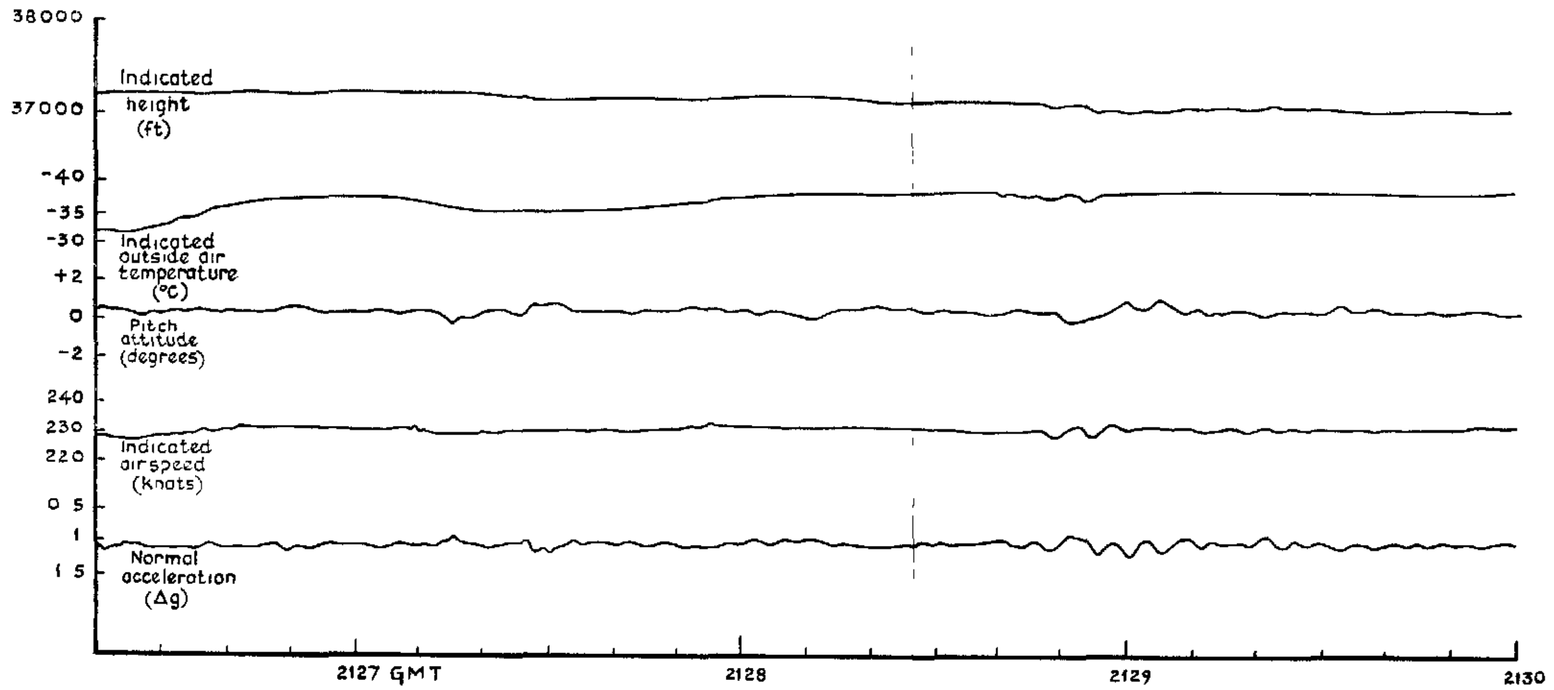


Fig. 11 Cross-section of flight near Salt Lake City on February 9



Run 3 North-bound



Run 2 South-bound

Fig. 12 Copies of the original records for the flight of February 9

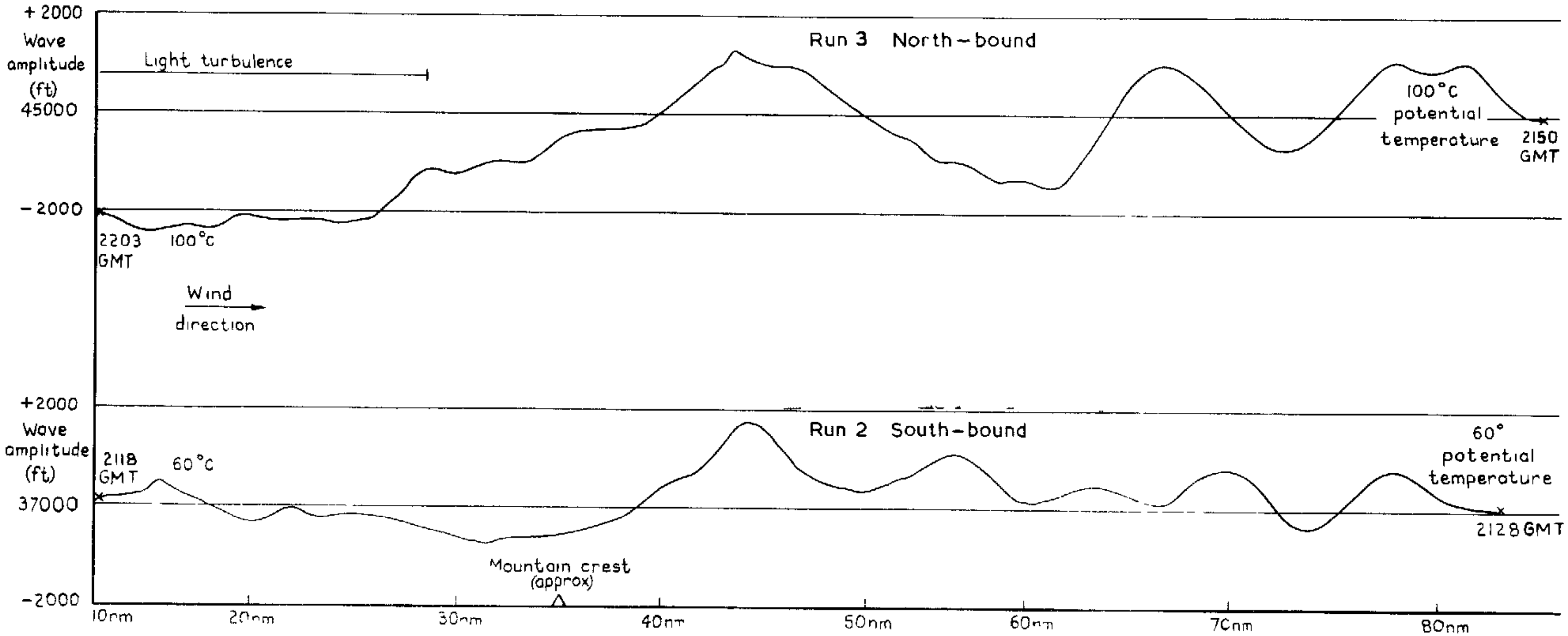


Fig 13 Wave motion on February 9

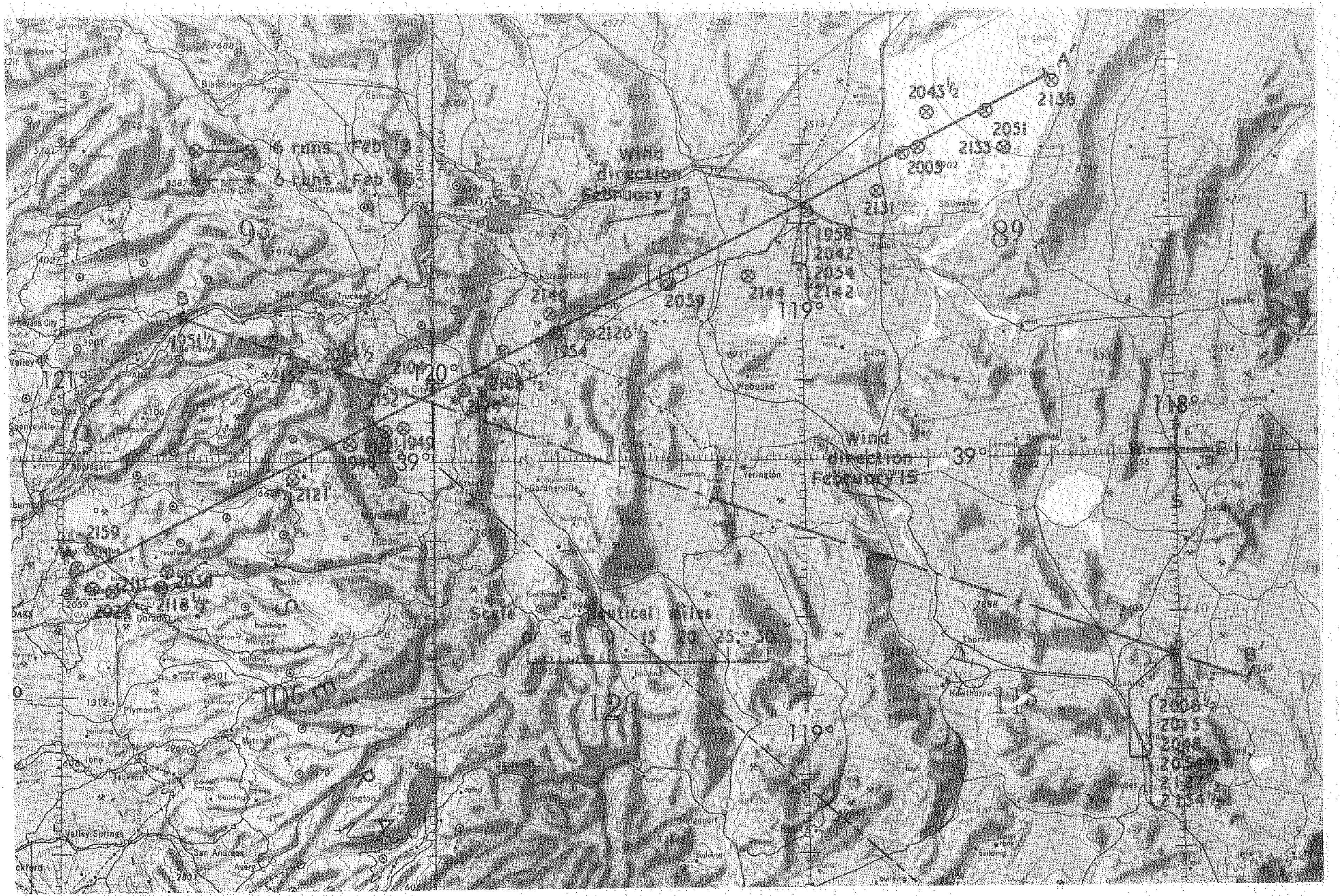
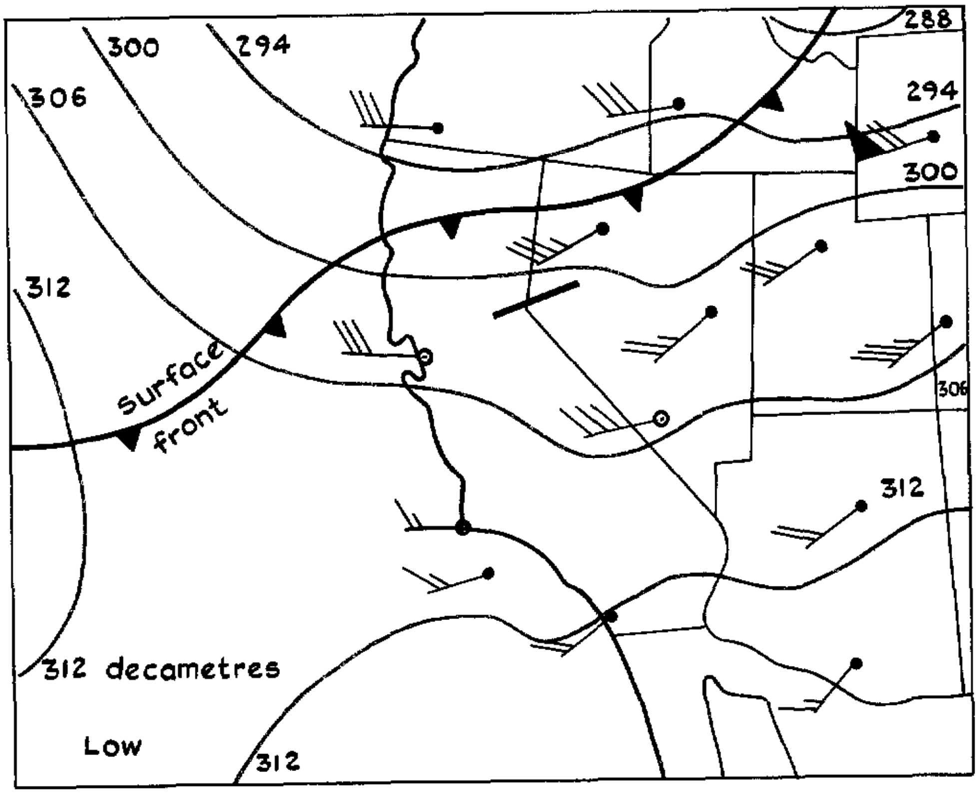


Fig.14. Ground tracks for the flights of February 13, and 15

NEG.NO.C6666 T.R.70034

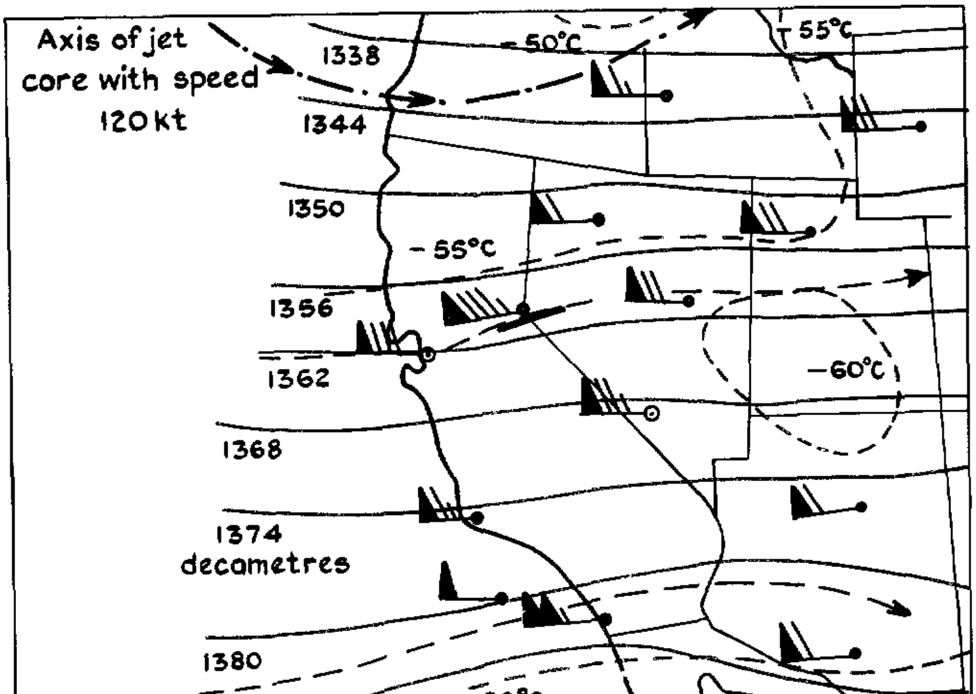


700 mb contours (decametres) and winds at 2400 GMT

⊙ Stations used for composite profiles

▬▬ Aircraft track

— — — Maximum wind at 150 mb



150 mb contours, winds and isotherms at 2400 GMT

Fig. 15 Meteorological charts for February 13

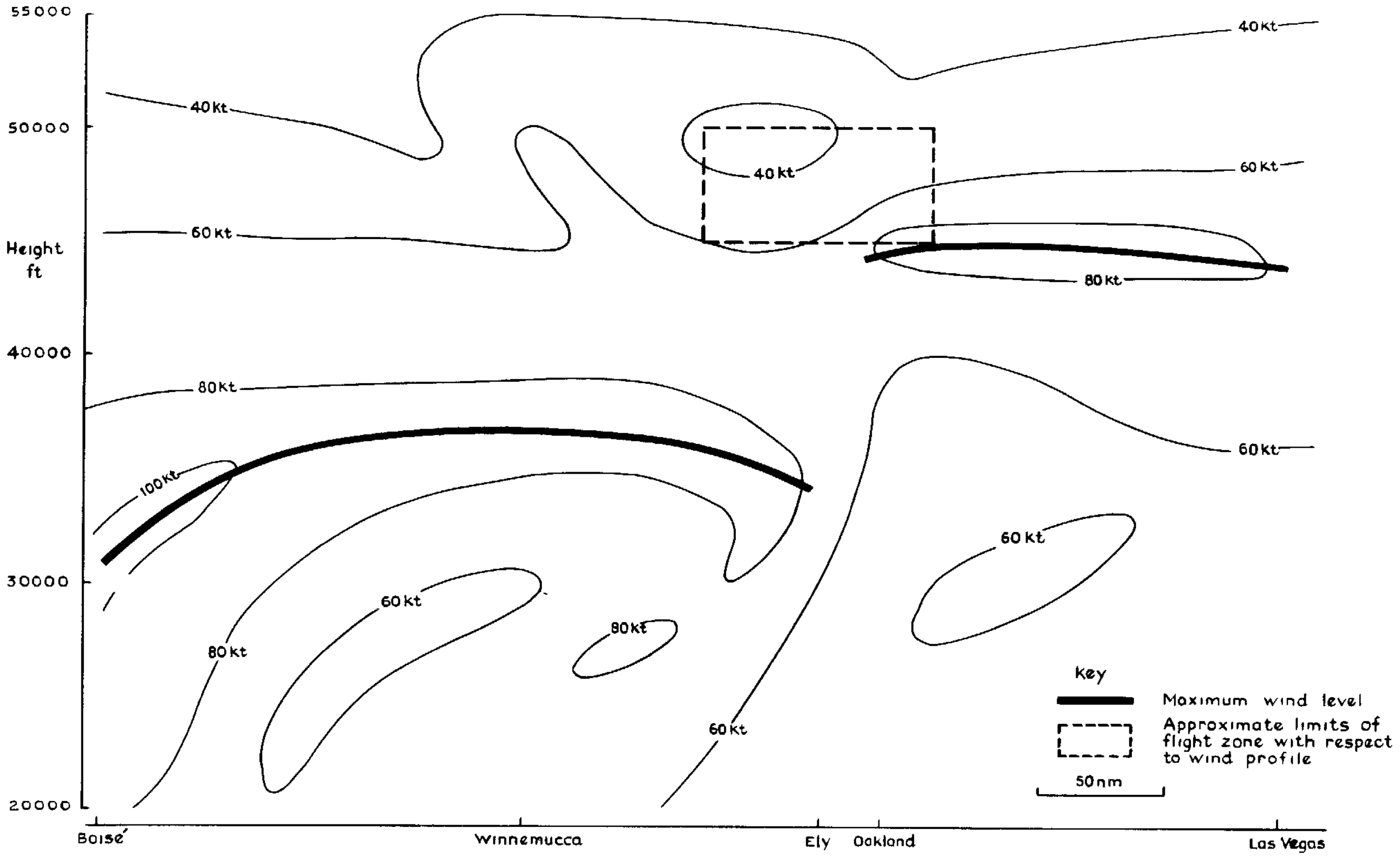


Fig.16 Cross section of winds from Boisé to Las Vegas on February 13

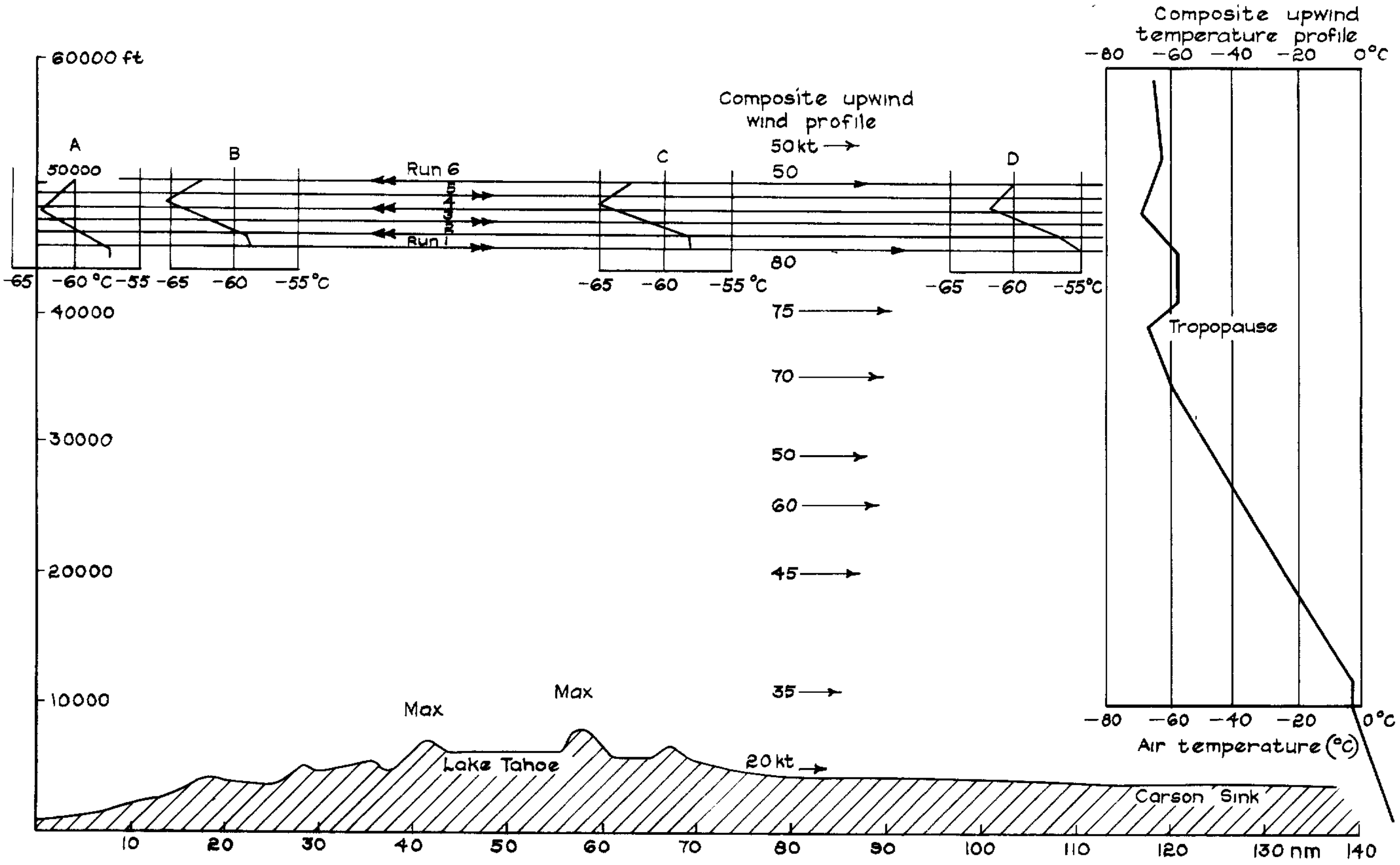


Fig. 17 Cross-section of flight in the Lake Tahoe area on February 13

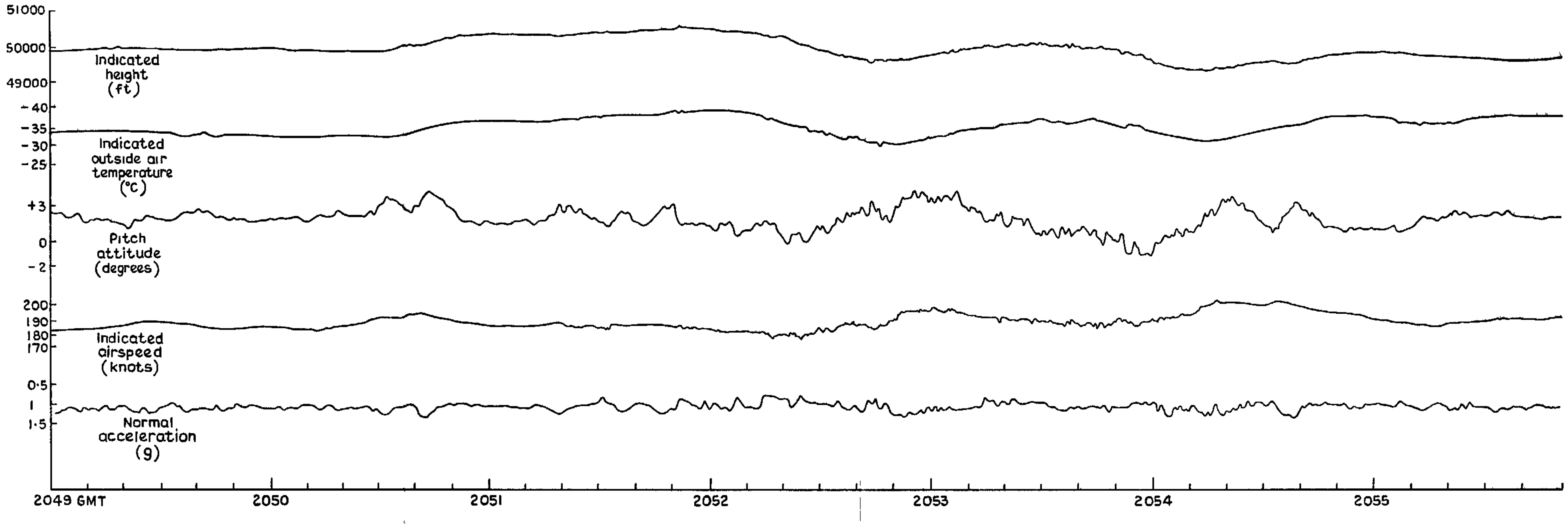


Fig.18 Copies of the original records for Run 4 of the flight of February 13

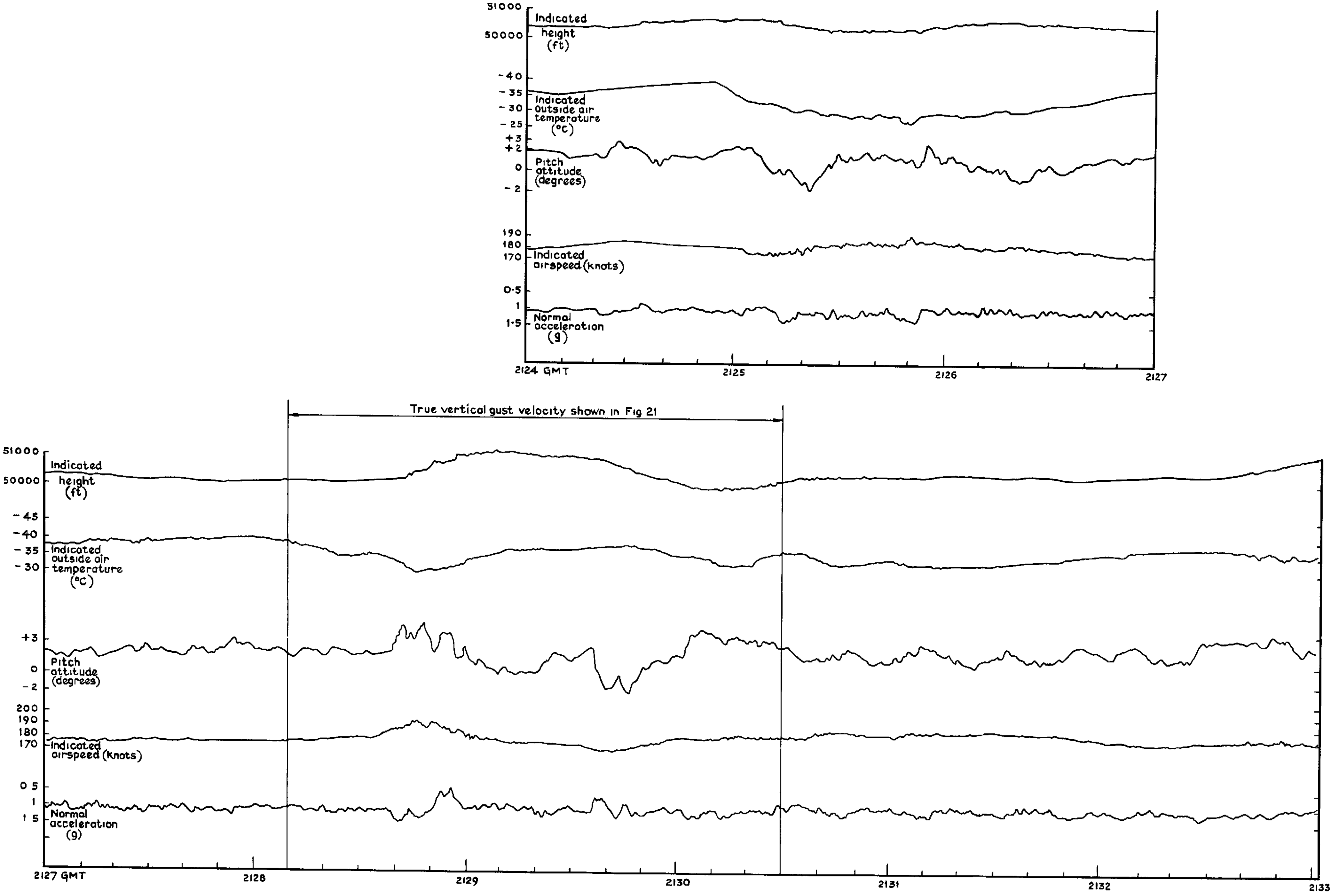


Fig.19 Copies of the original records for Run 5 of the flight of February 13

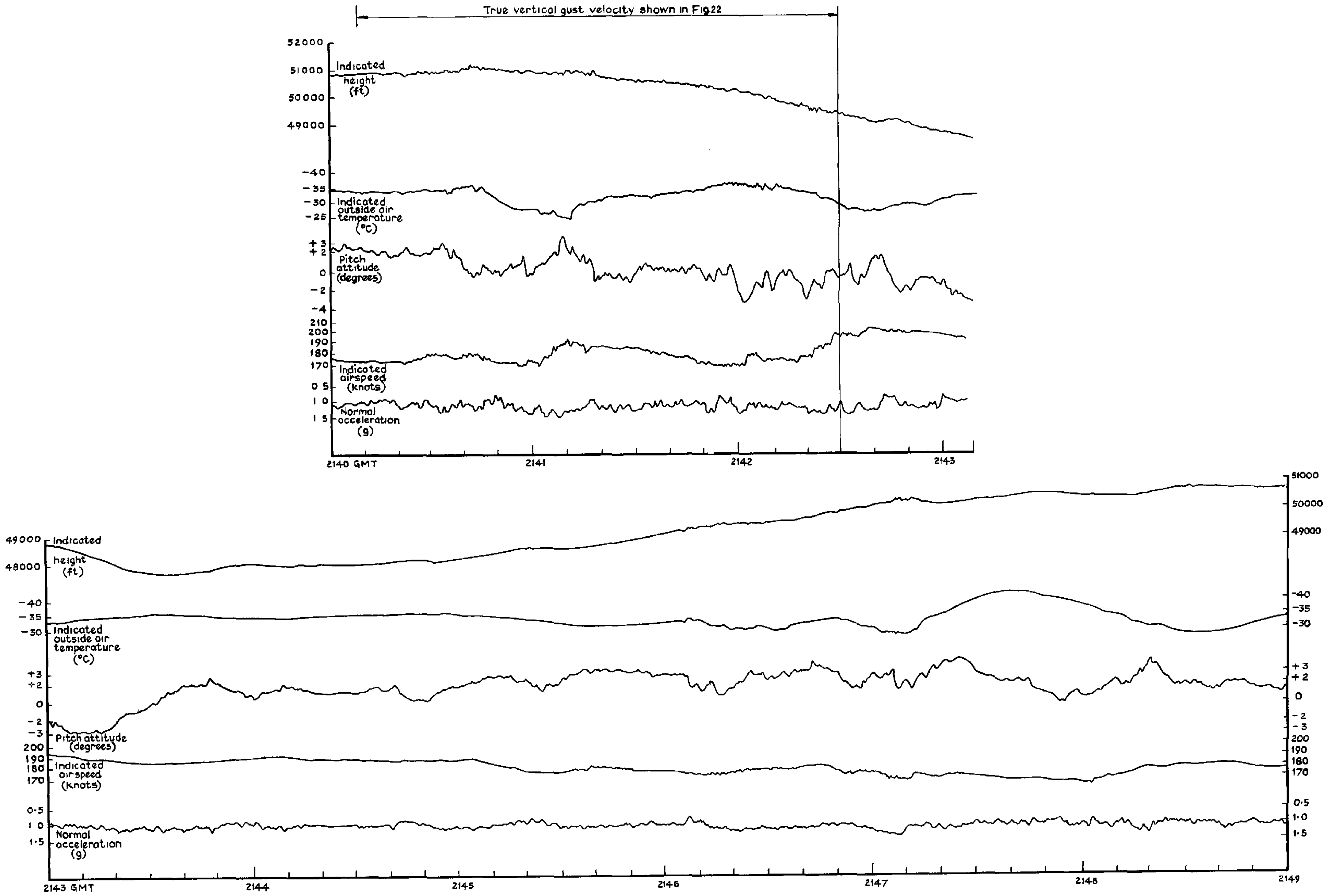


Fig. 20 Copies of the original records for Run 6 of the flight of February 13

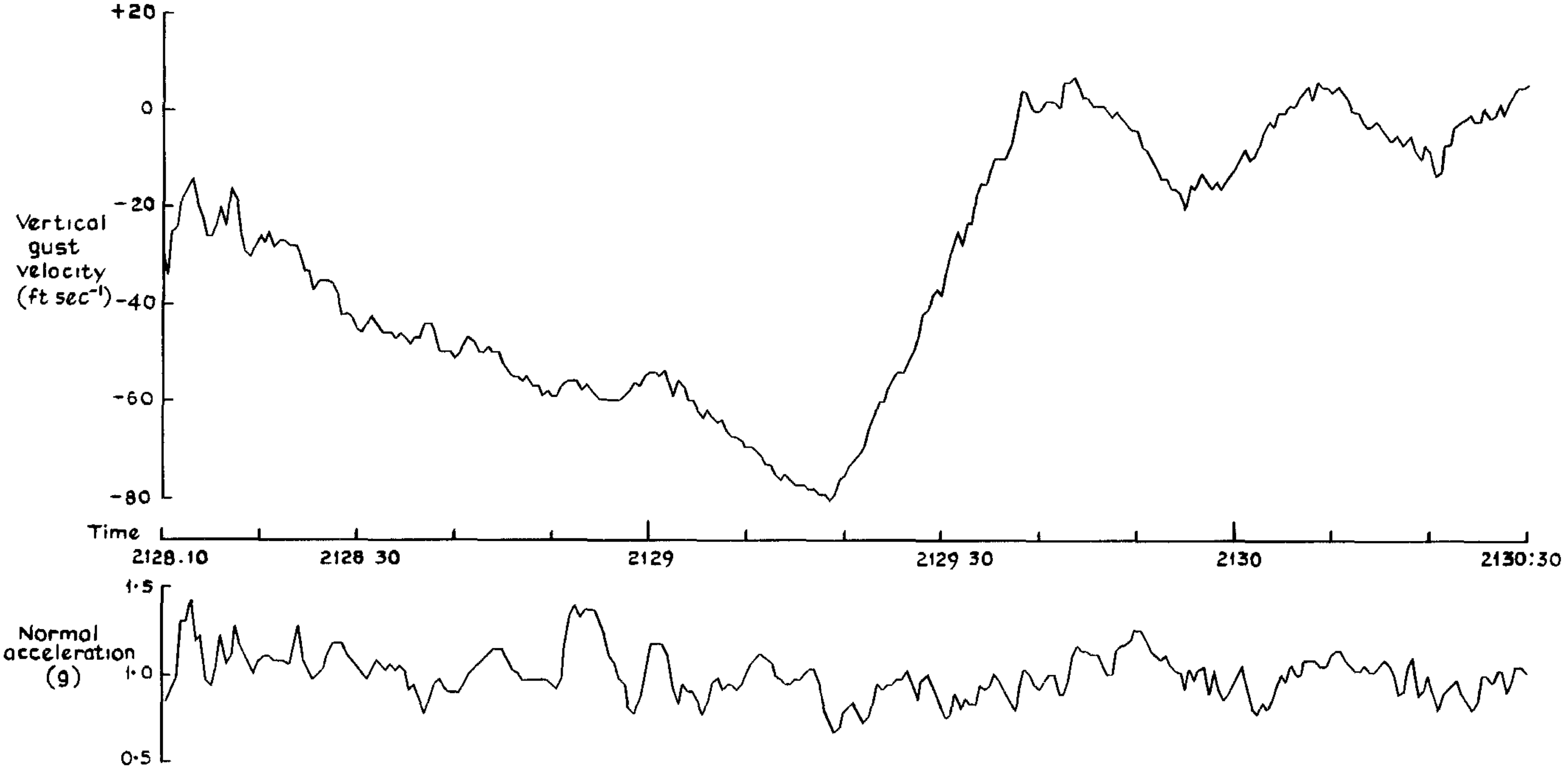


Fig 21 True vertical gust velocity on February 13 Run 5

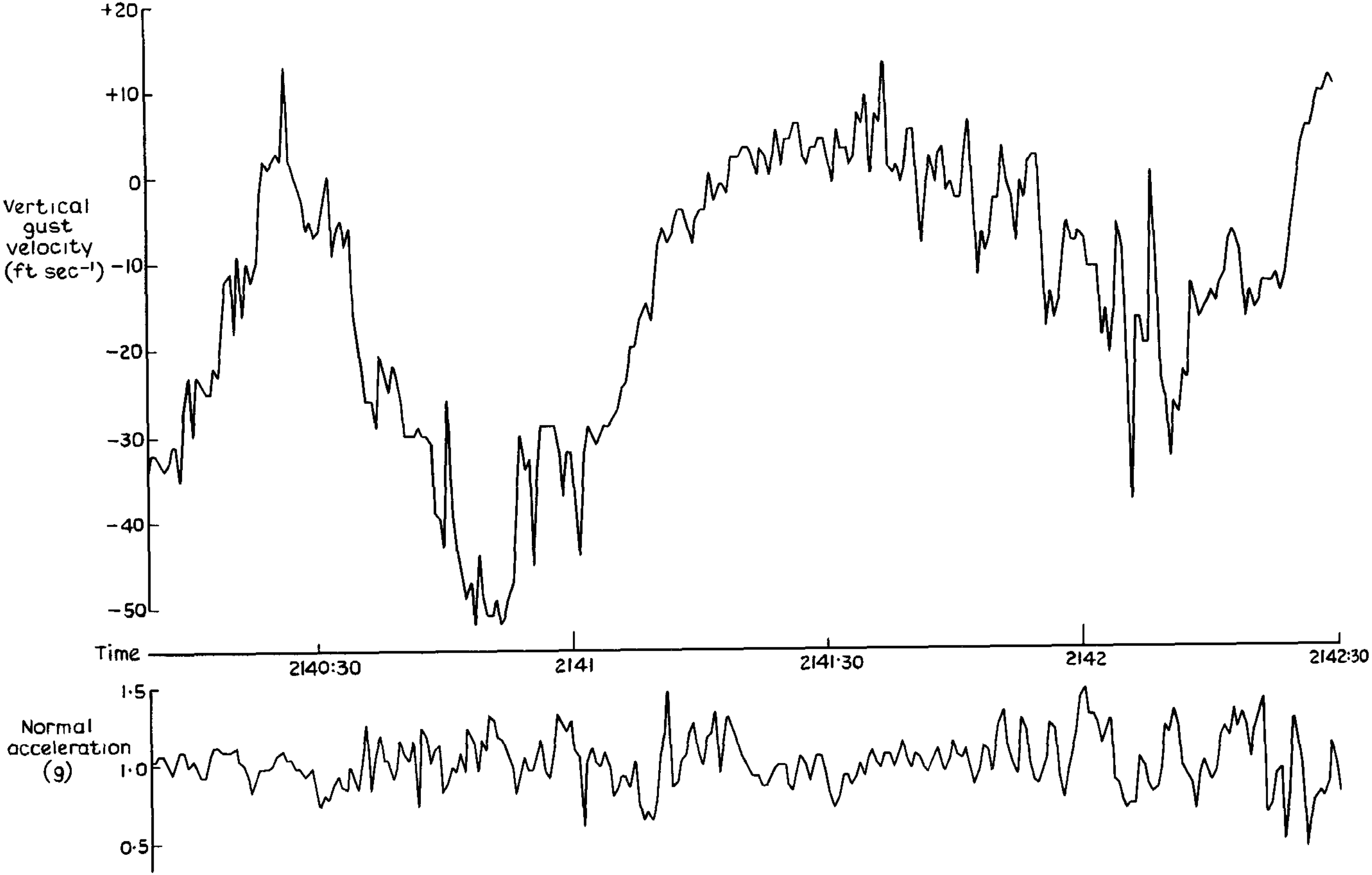


Fig.22 True vertical gust velocity on February 13 Run 6

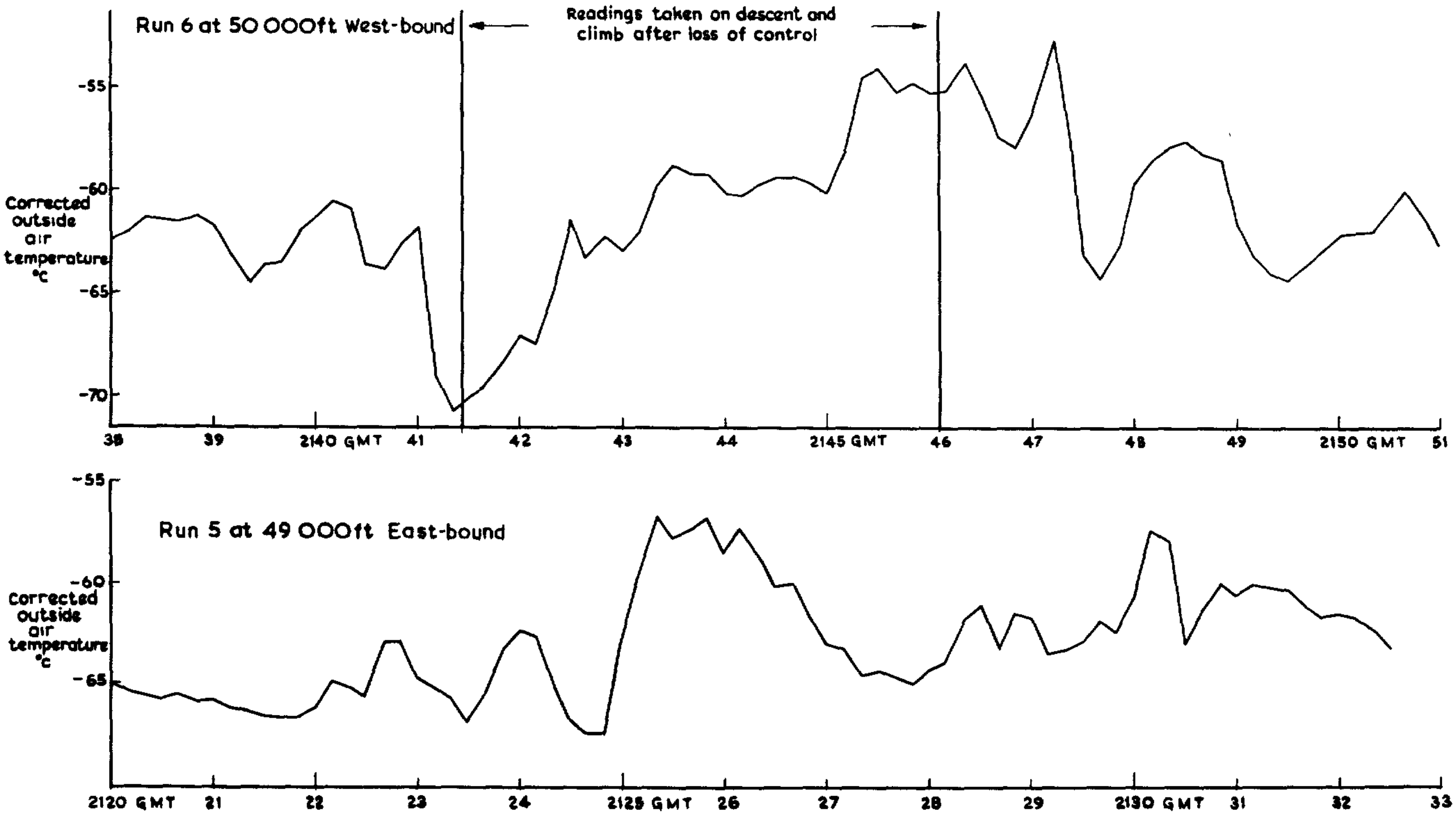


Fig.23 Outside air temperature versus time for Runs 5 and 6 of the flight of February 13

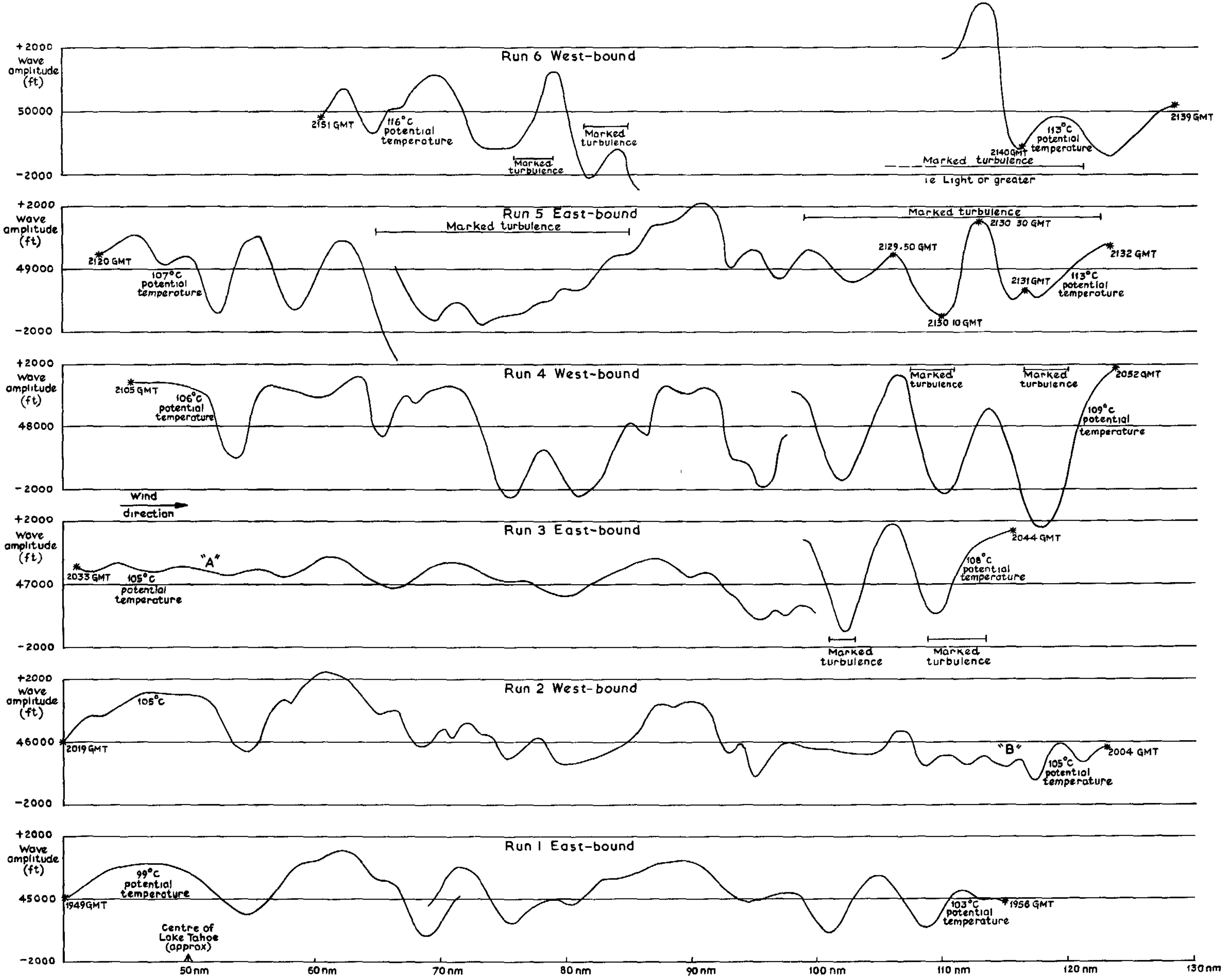


Fig. 24 Wave motion on February 13

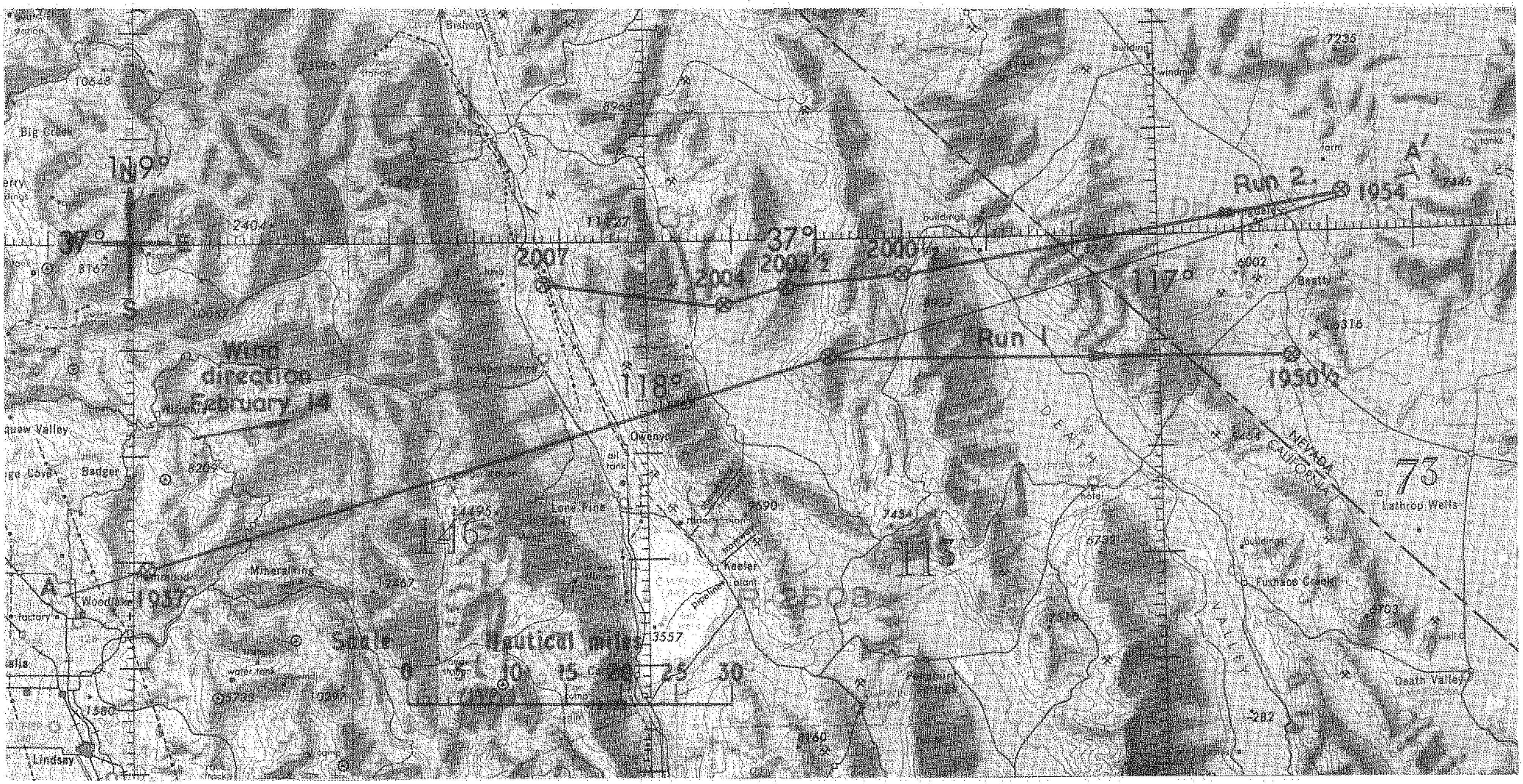
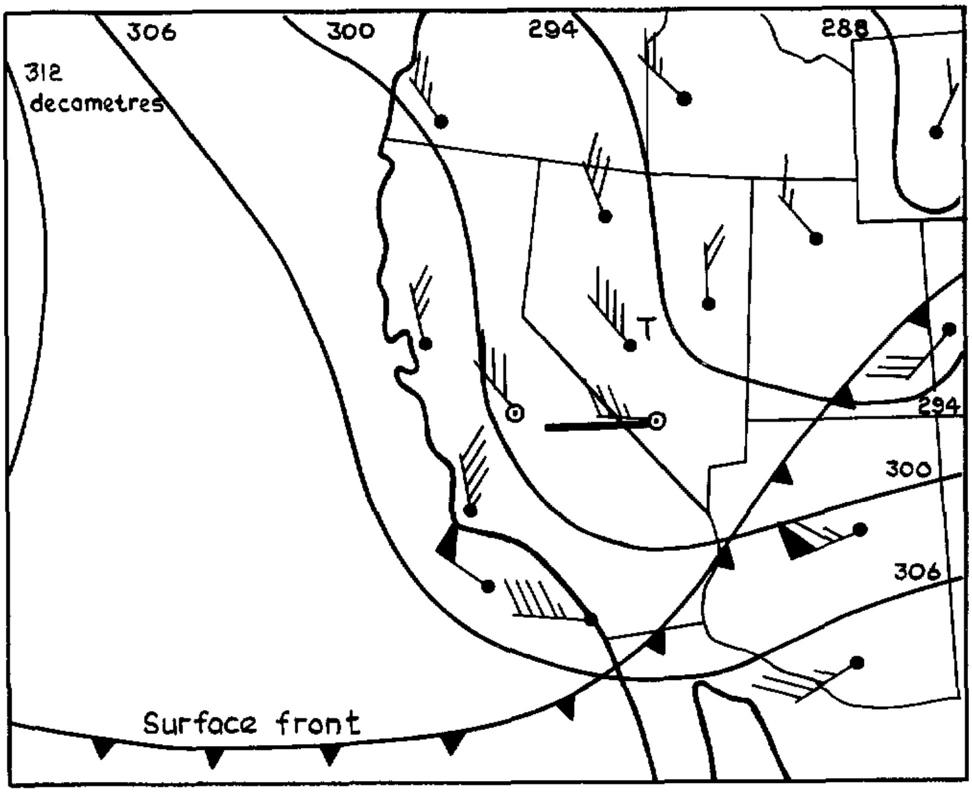


Fig.25. Ground tracks for the flight of February 14

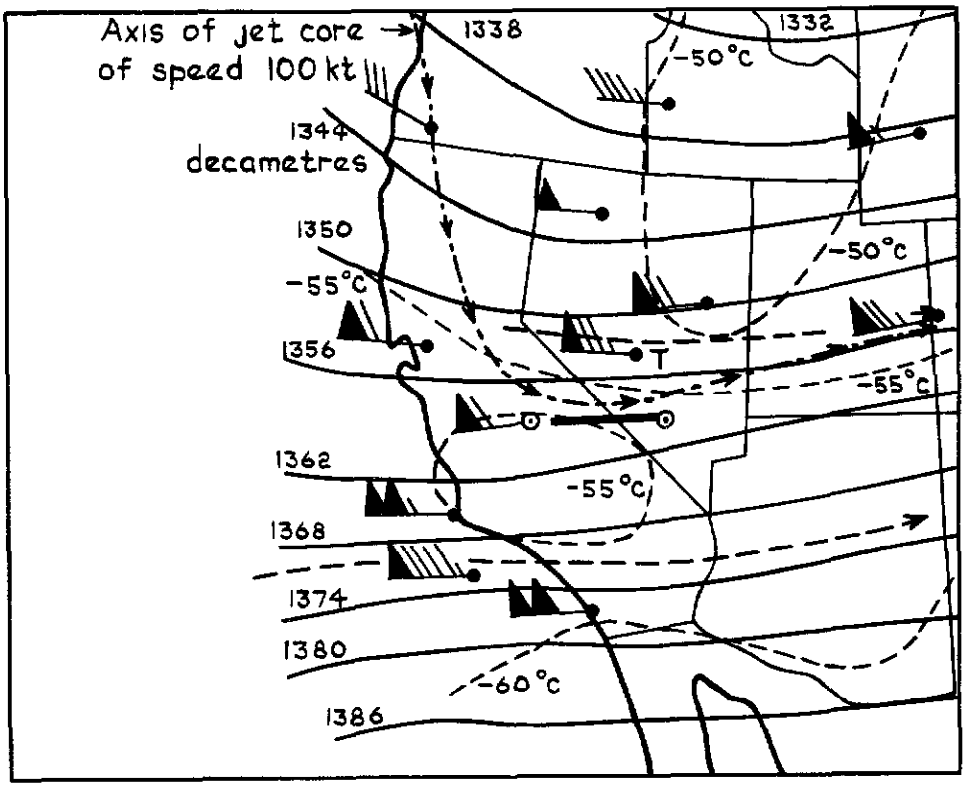


700mb contours (decametres) and winds at 2400GMT

⊙ Stations used for composite profiles

▬ Aircraft track

--- Maximum wind at 150 mb



150mb contours, wind and isotherms at 2400GMT

Fig. 26 Meteorological charts for February 14

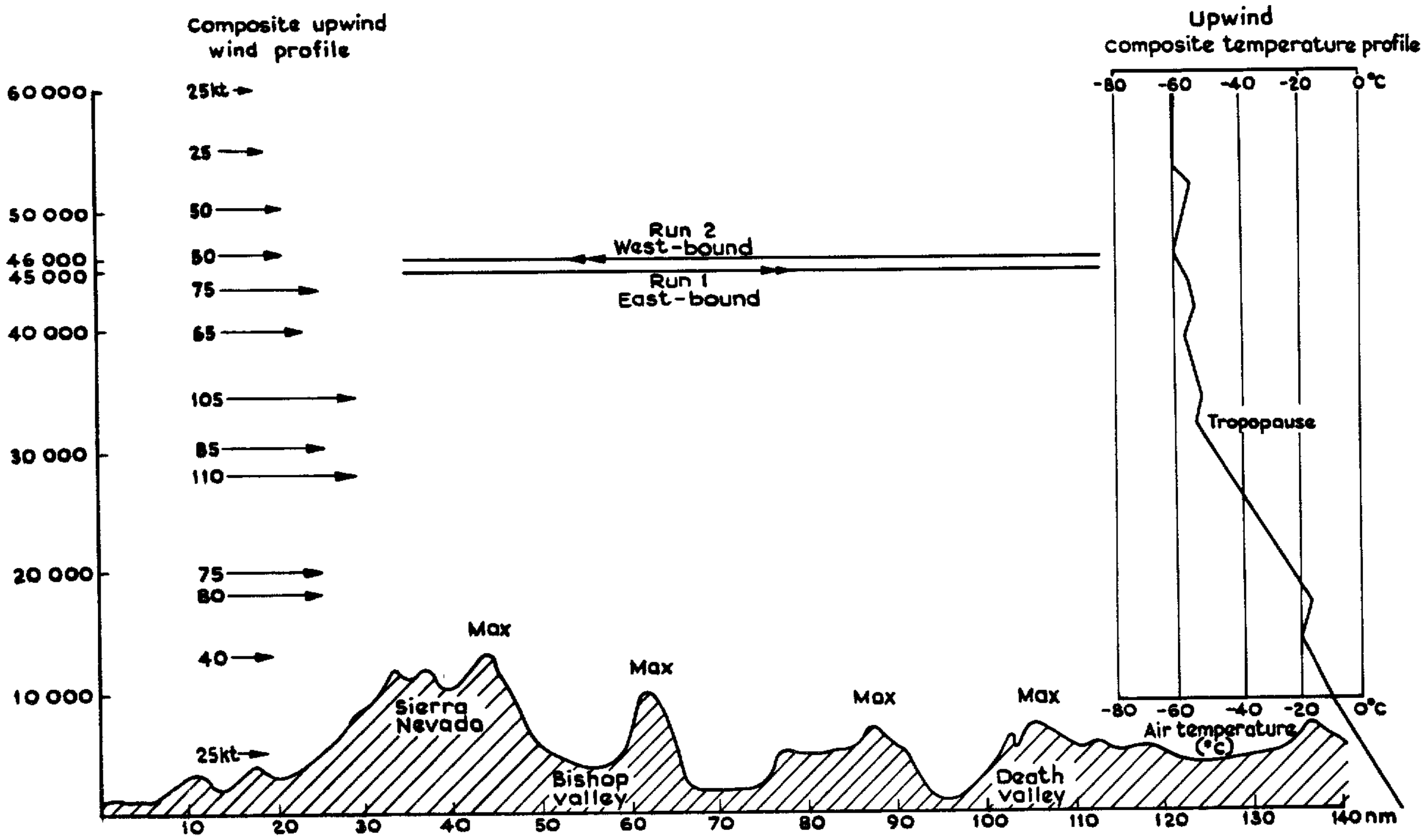


Fig. 27 Cross-section of flight in the Bishop Valley area on February 14

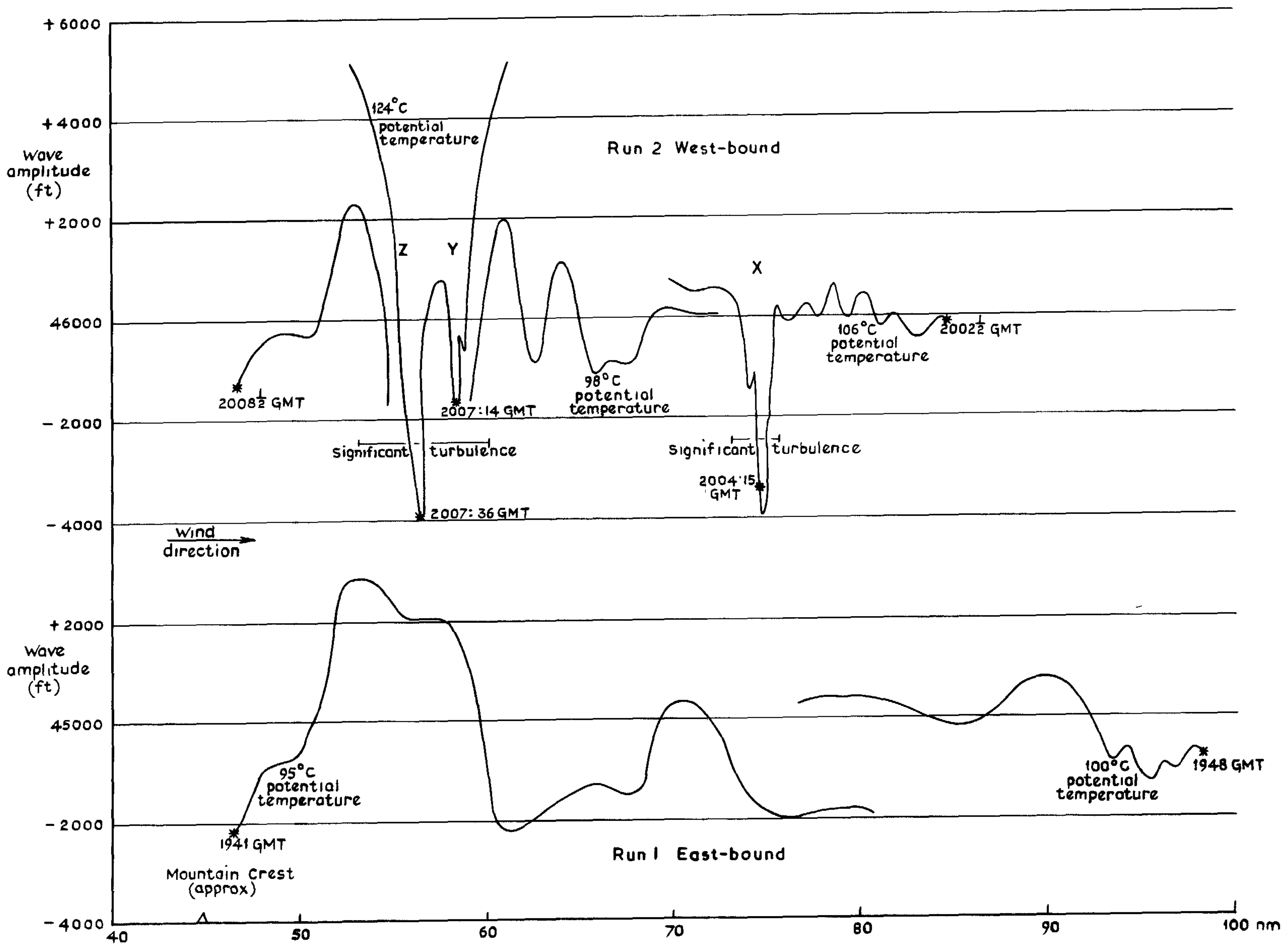
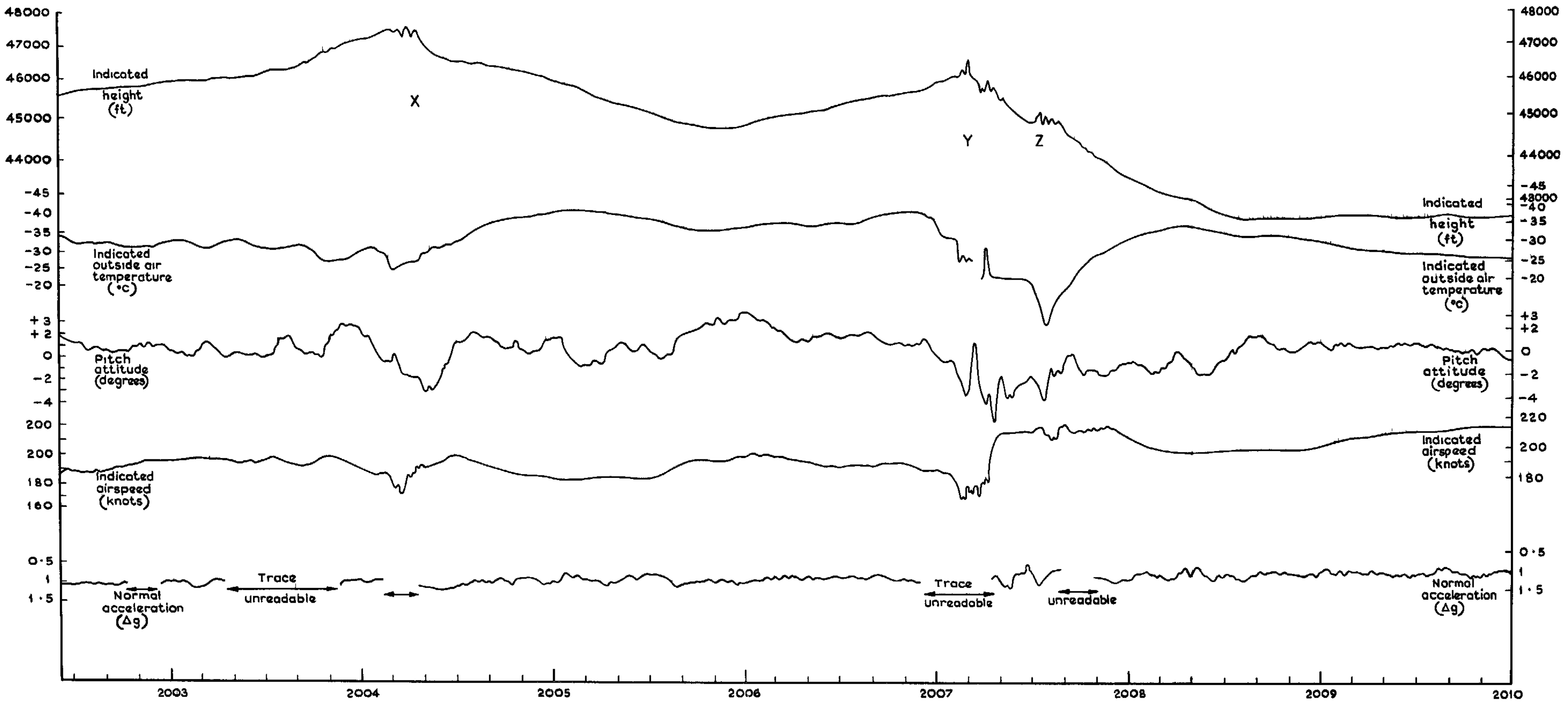


Fig.28 Wave motion on February 14



Run 2 West - bound

Fig. 29 Copies of the original records for the flight of February 14th

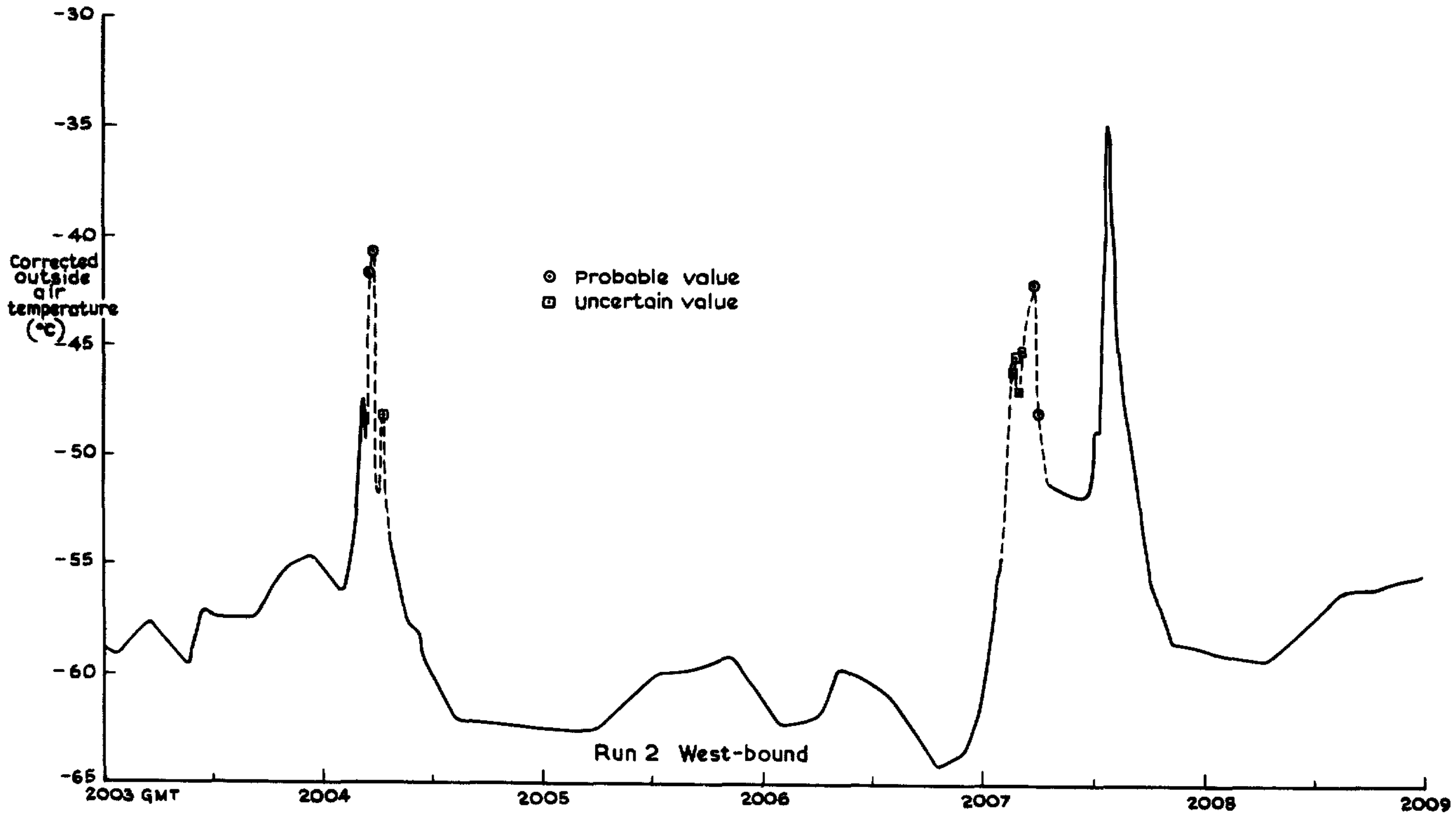


Fig.30 Outside air temperature versus time for February 14

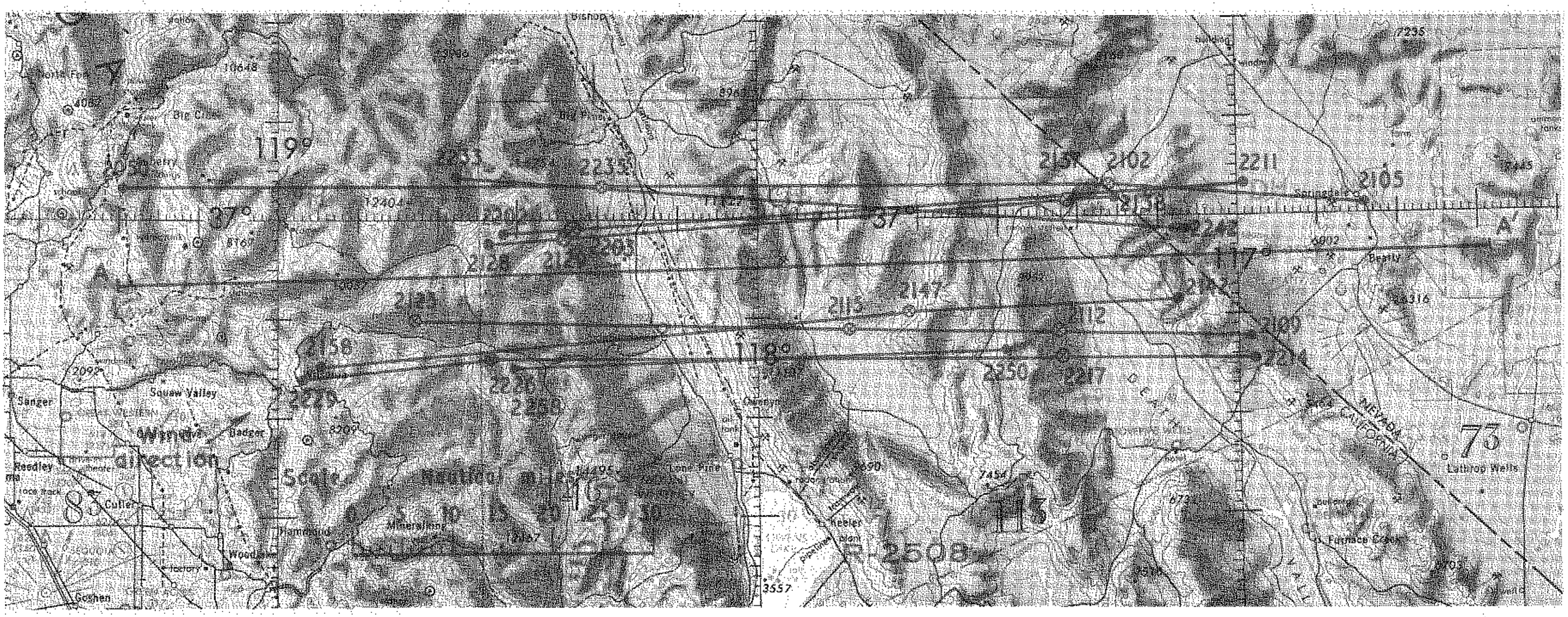
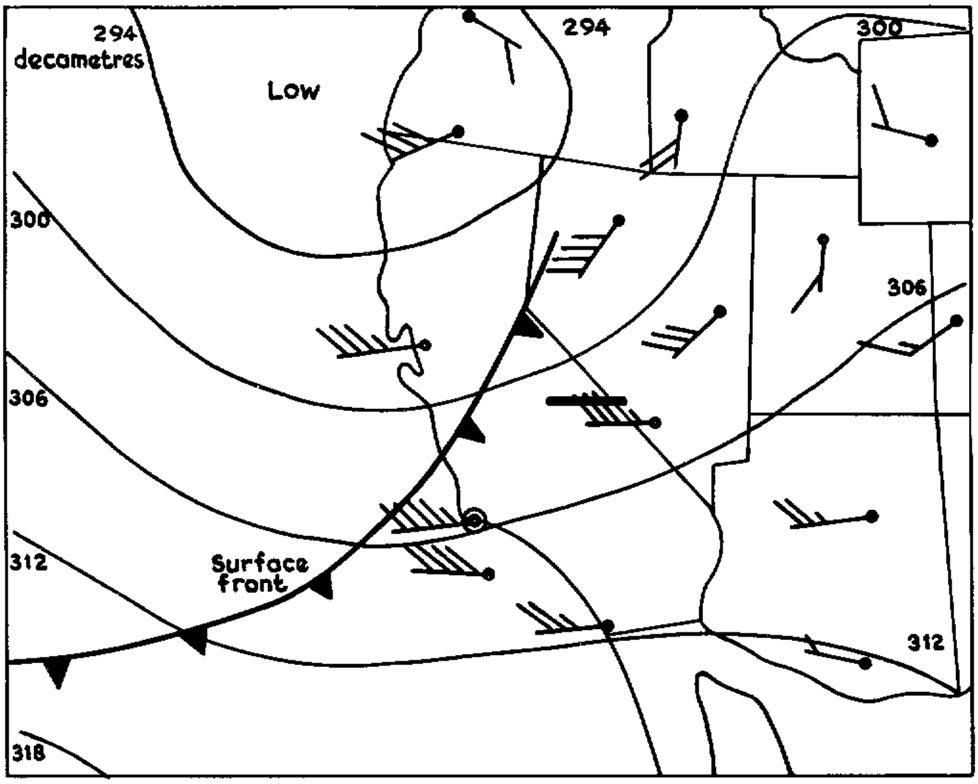
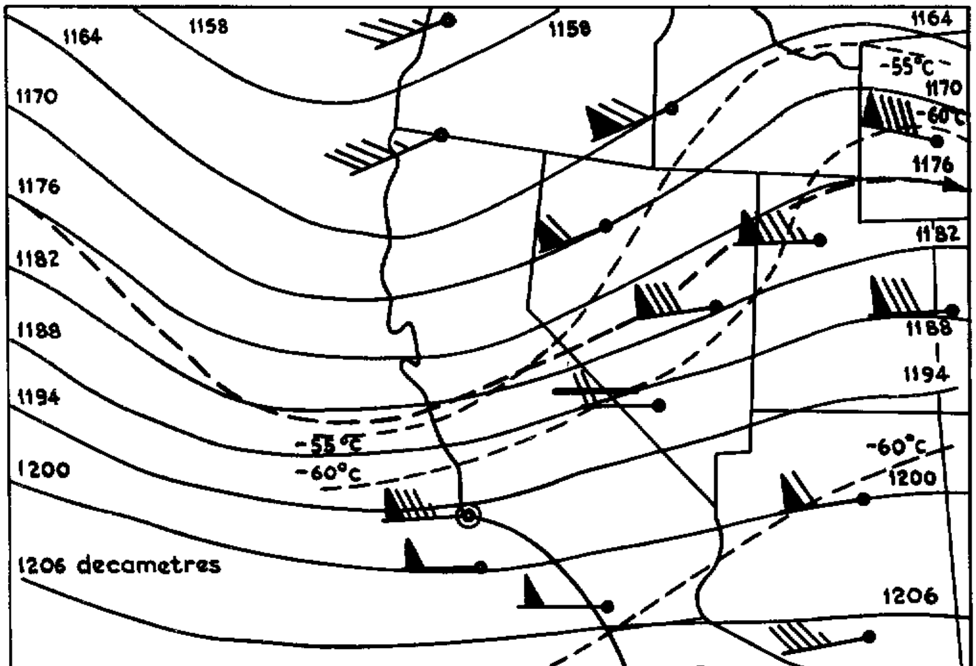


Fig.31. Ground tracks for the flight of January 30



700 mb contours (decametres) and winds at 2400 GMT

◎ Stations used for composite profile
—— Aircraft track
– – – Maximum wind at 200 mb



200 mb contours, winds and isotherms at 2400 GMT

Fig. 32 Meteorological charts for January 30

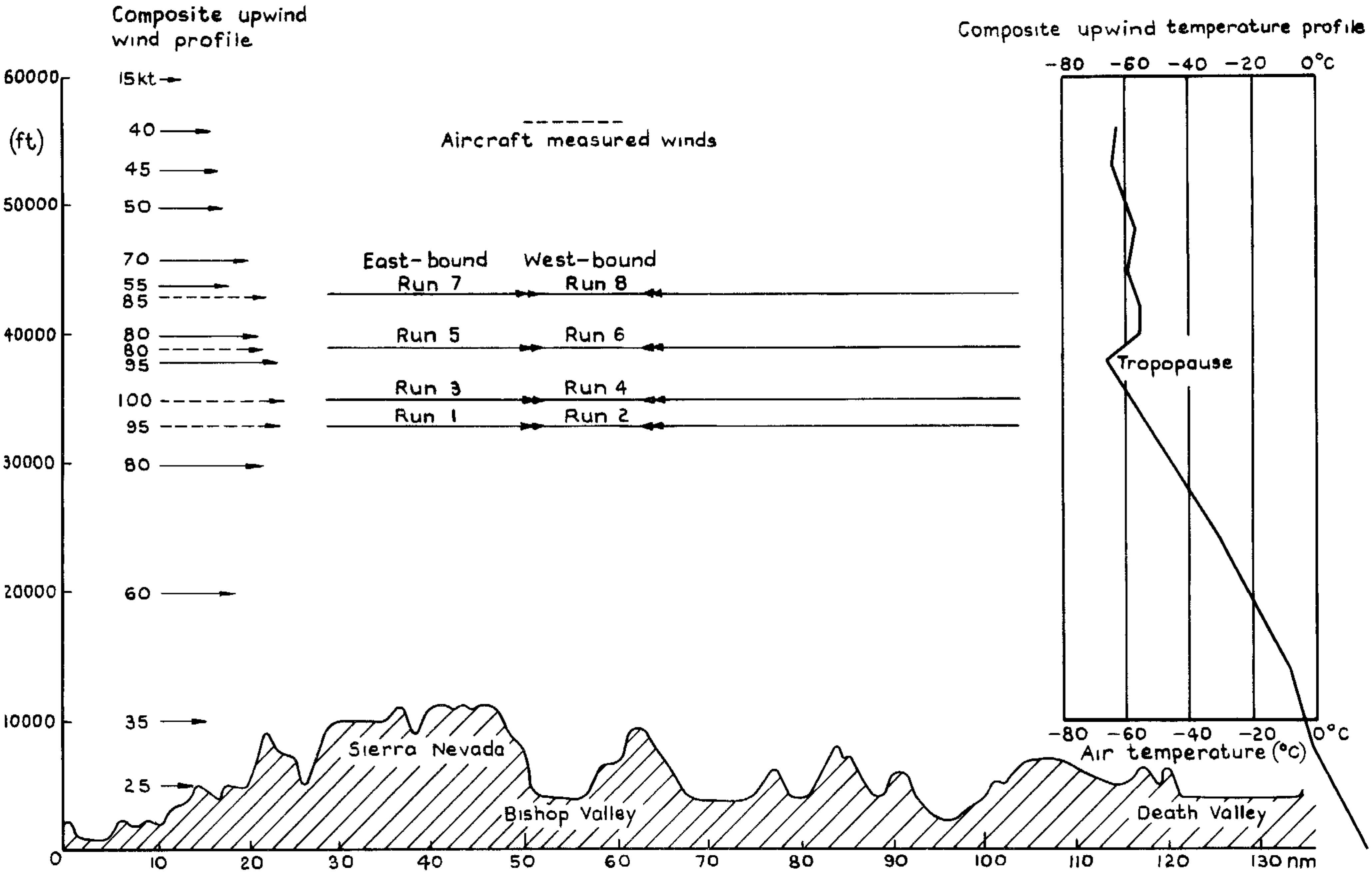


Fig. 33 Cross-section of flight in the Bishop Valley area on January 30

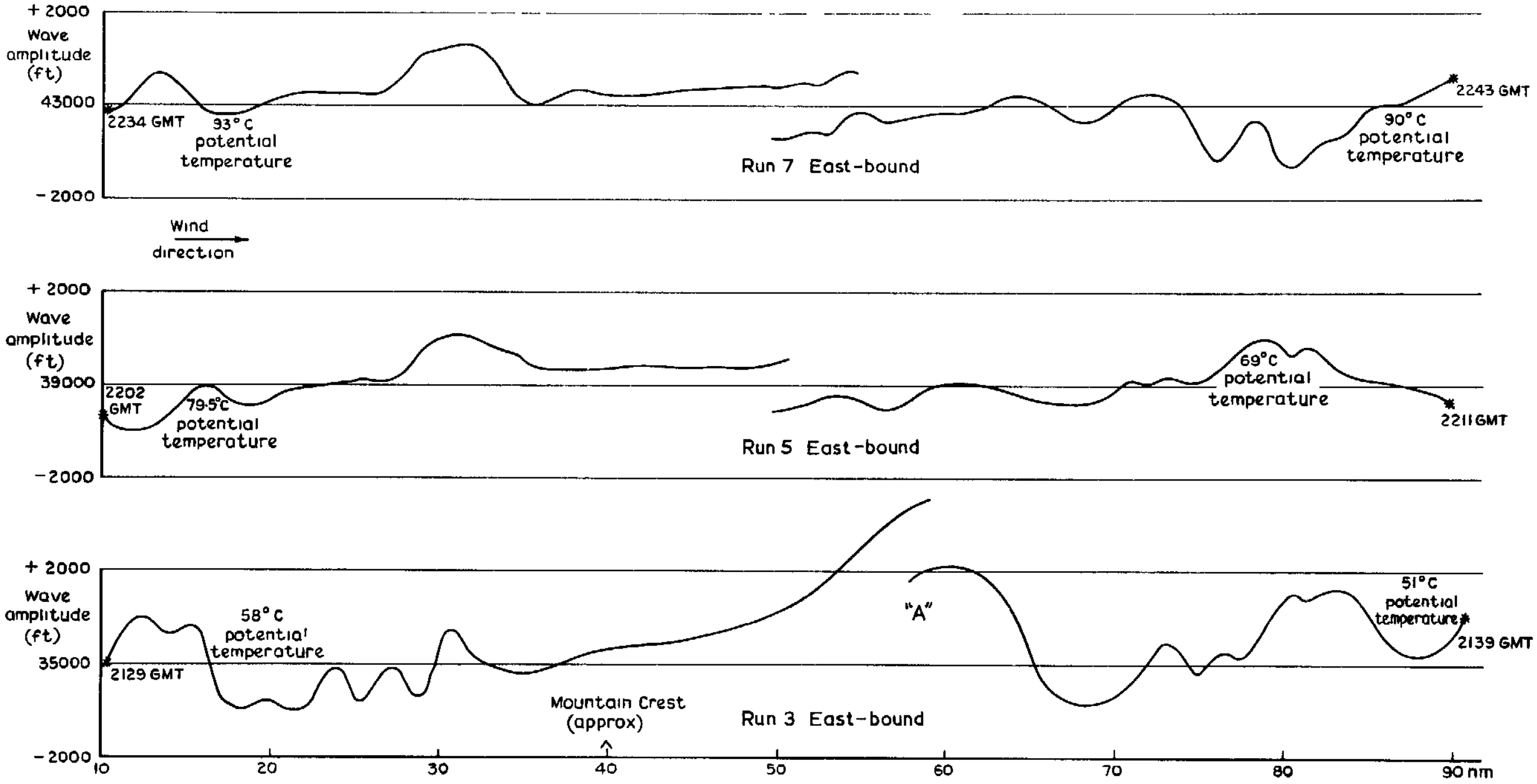
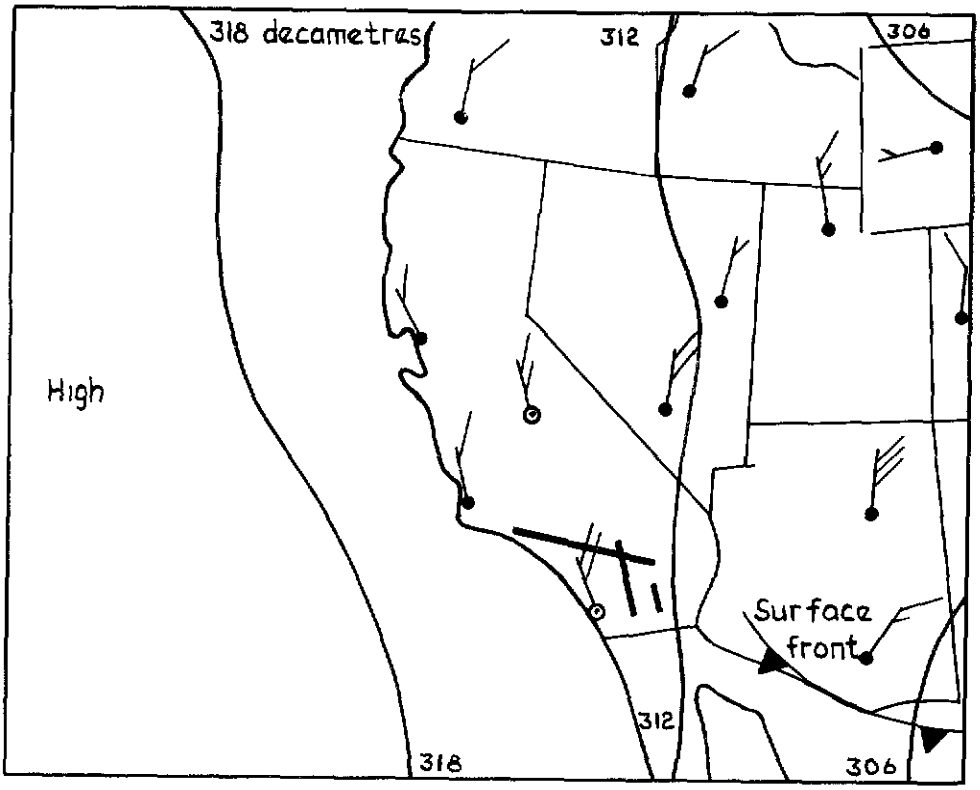


Fig.34 Wave motion on January 30

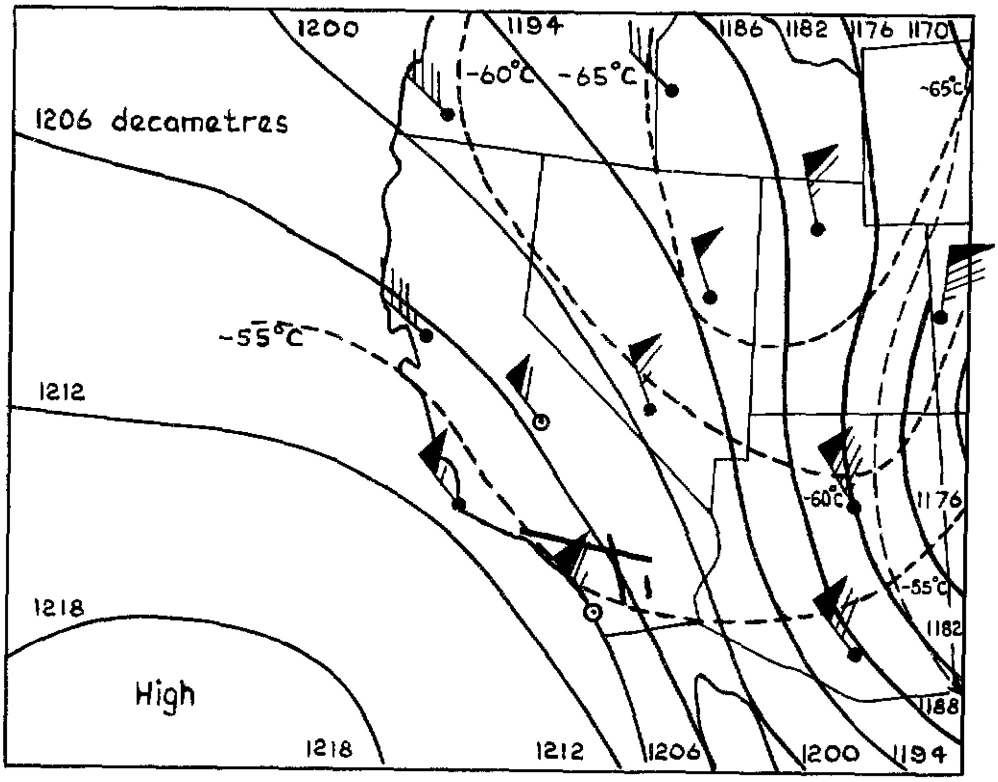


700 mb contours (decametres) and winds at 2400GMT

⊙ Stations used in composite soundings

━━━ Aircraft tracks

– – – Maximum wind at 200 mb



200 mb contours, winds and isotherms at 2400 GMT

Fig. 35 Meteorological charts for February 7

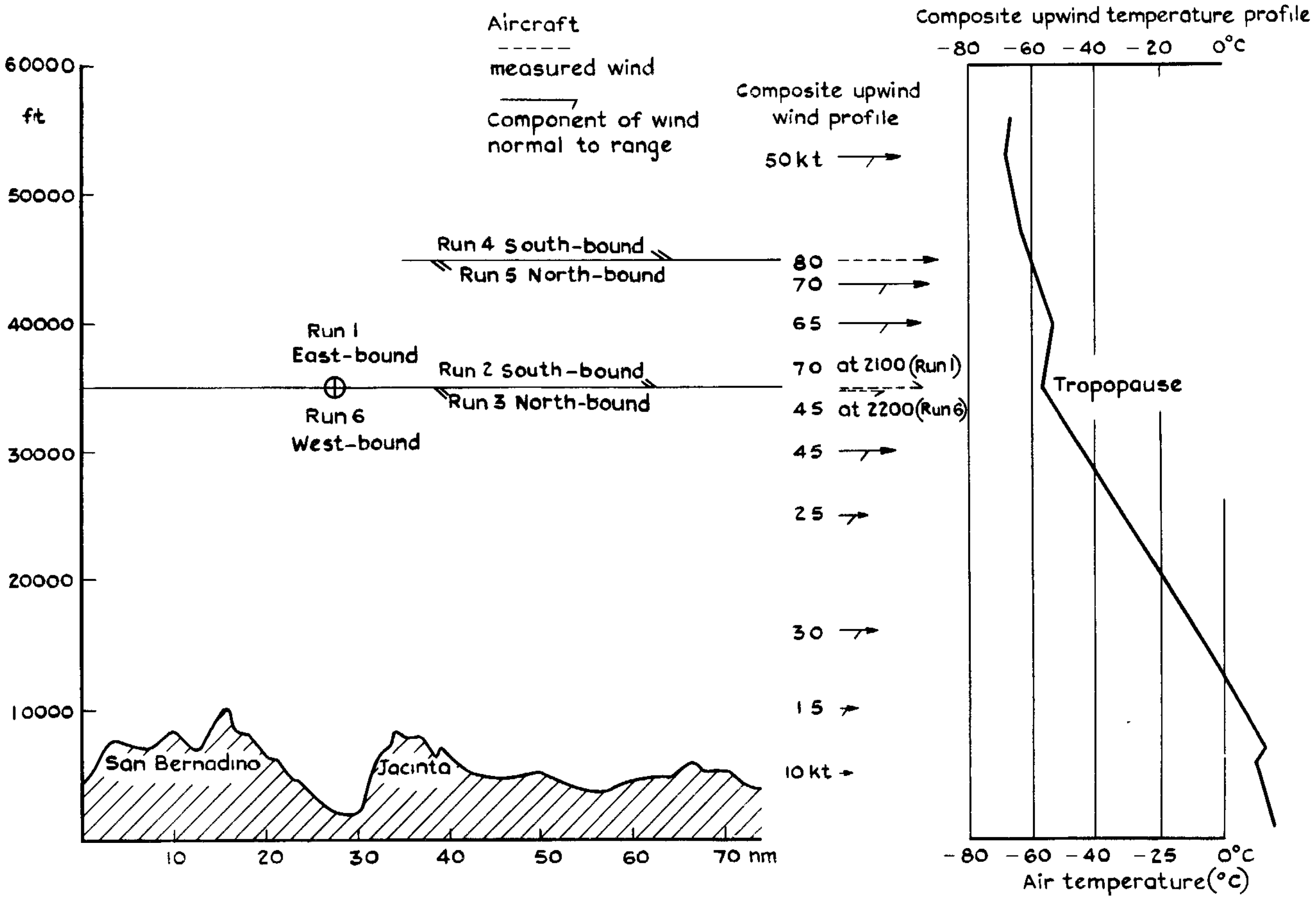


Fig. 36 Cross section of flight on February 7

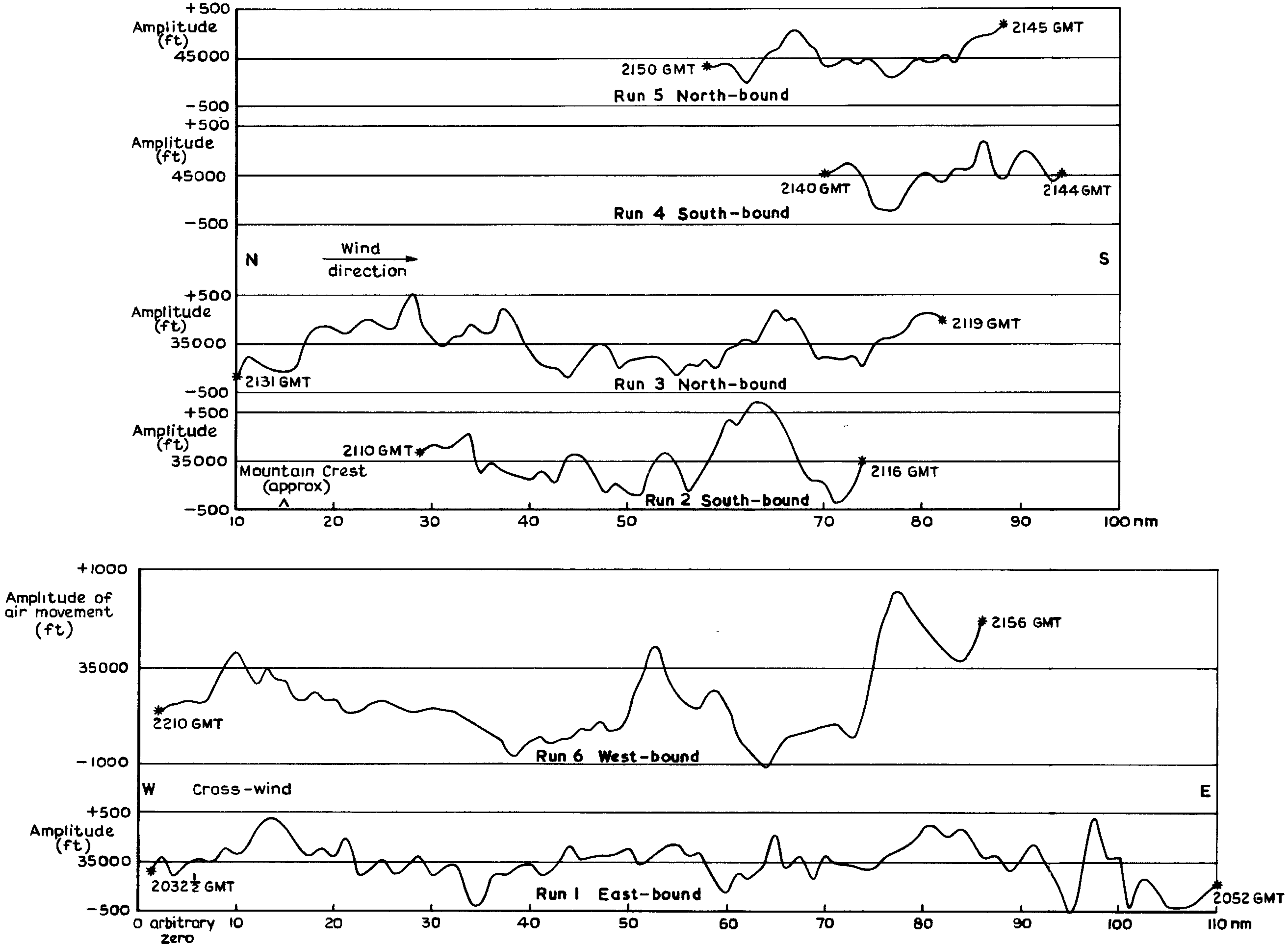
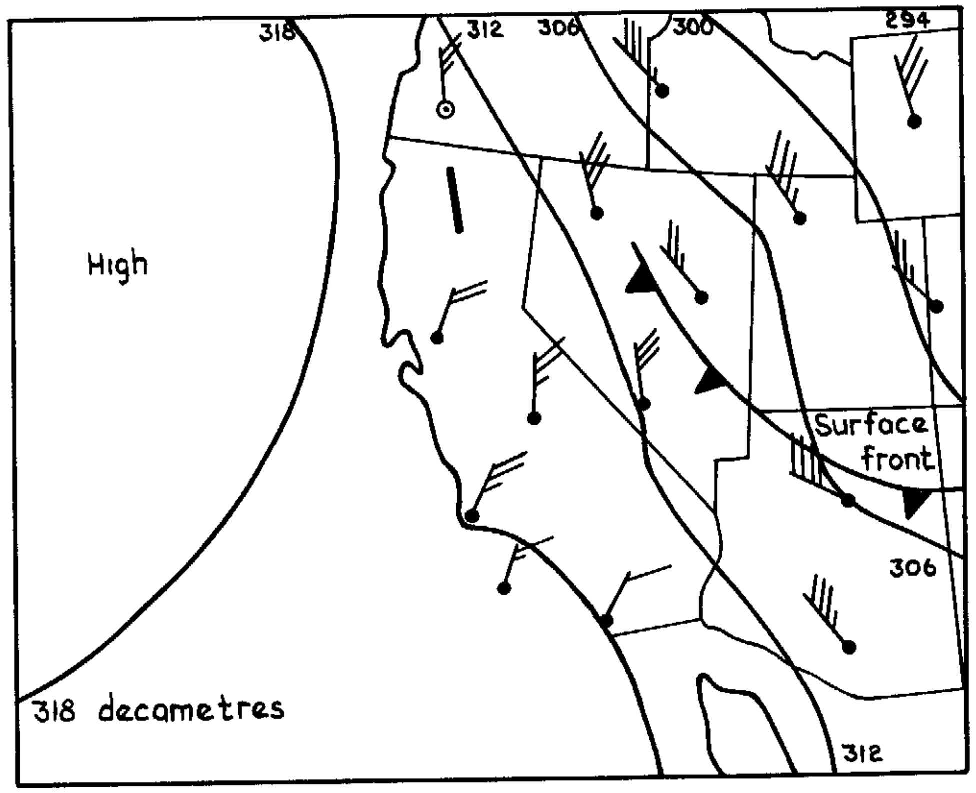
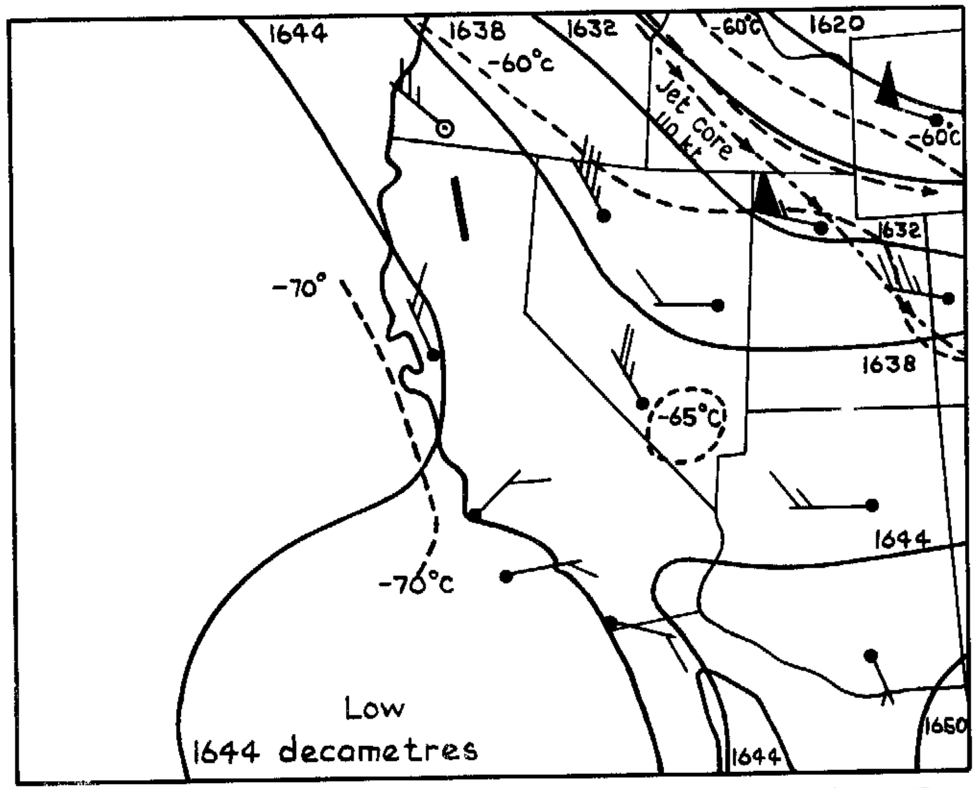


Fig.37 Wave motion on February 7



700mb contours (decametres) and winds at 2400GMT

⊙ Stations used in composite profile
—— Aircraft track
– – – Maximum wind at 100 mb



100mb contours, wind and isotherms at 2400GMT

Fig. 38 Meteorological charts for February 10

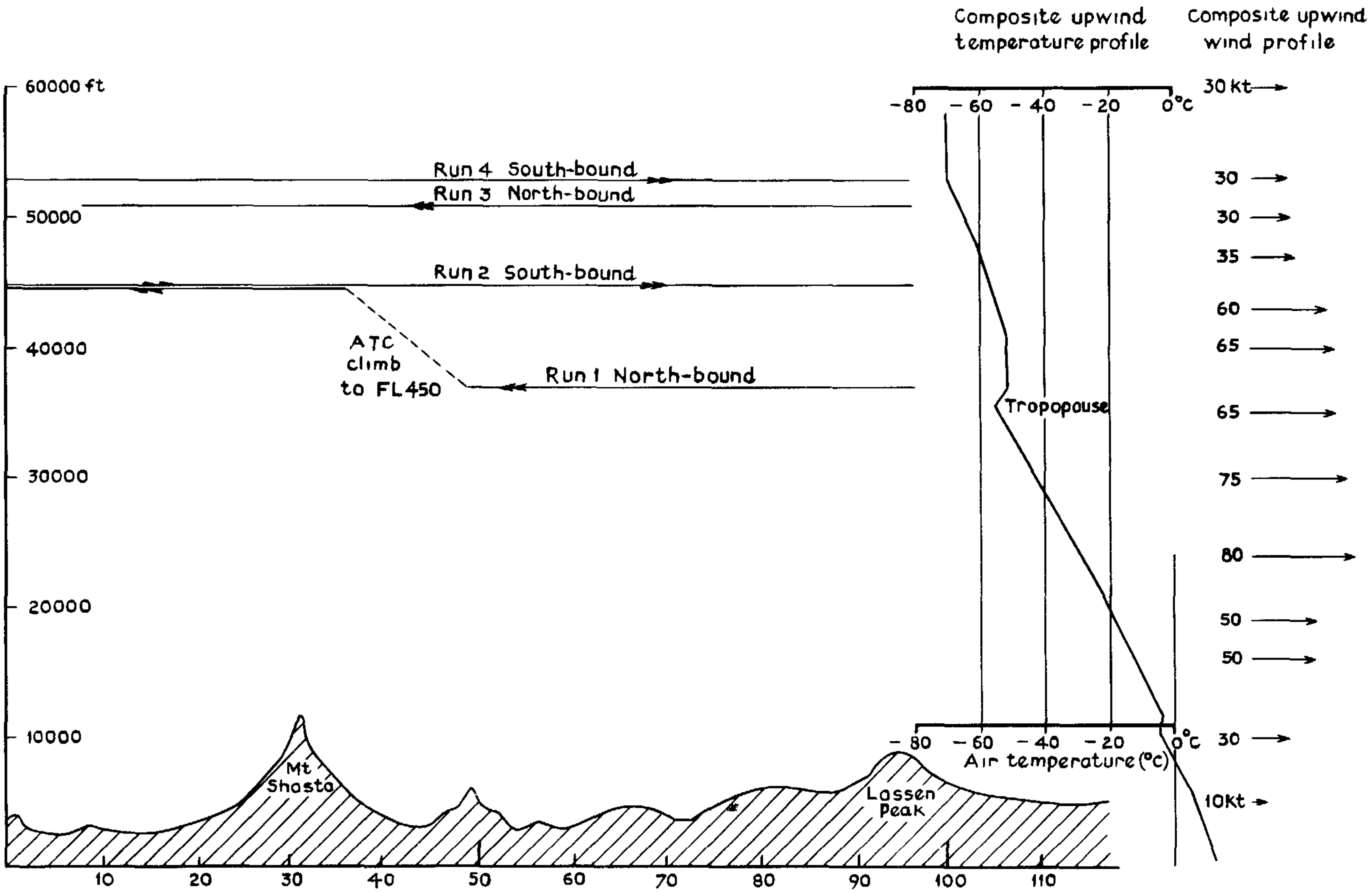


Fig 39 Cross section of flight over Mt Shasta on February 10

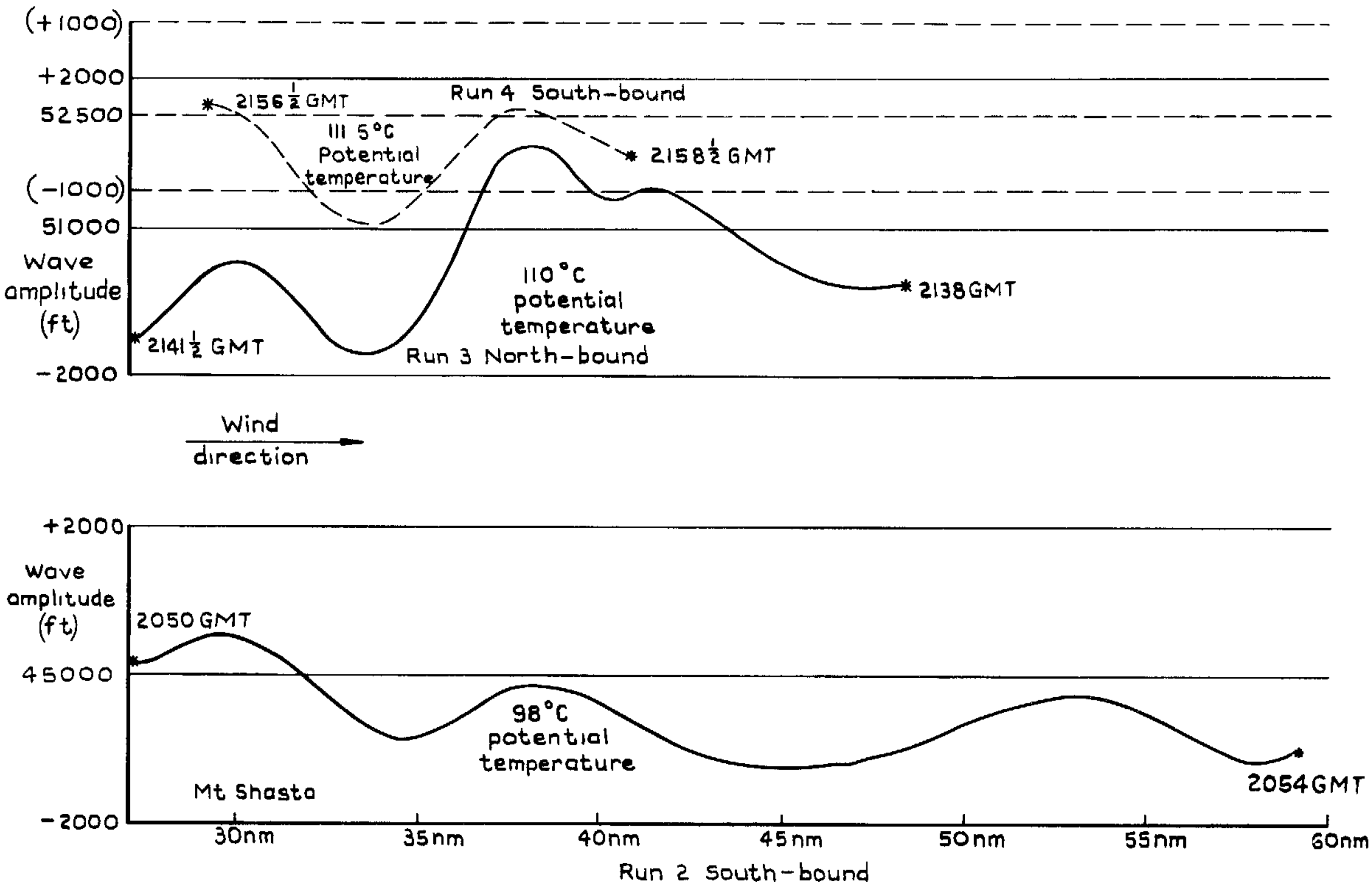
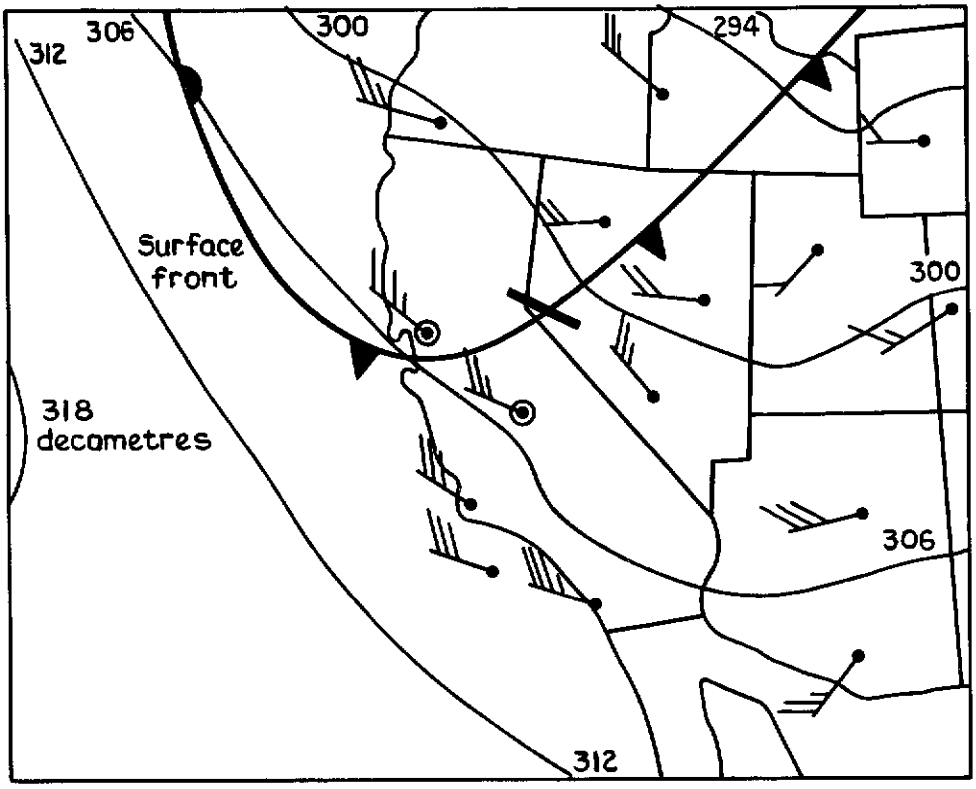


Fig. 40 Wave motion on February 10

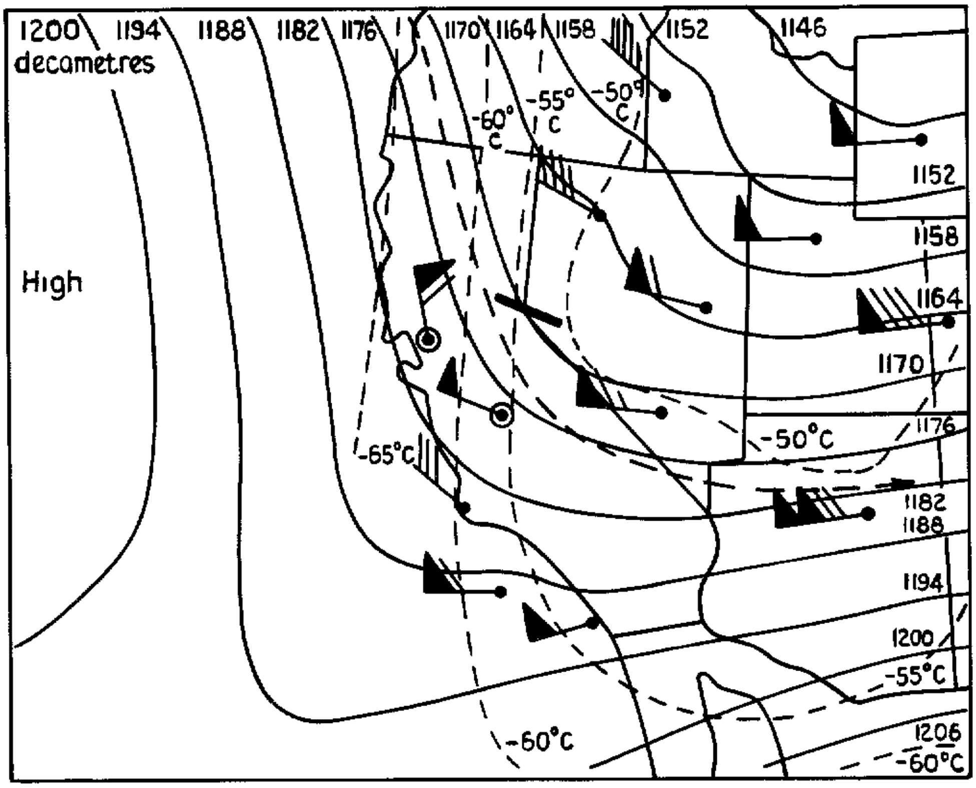


700 mb contours (decametres) and winds at 2400 GMT

⊙ Stations used for composite profiles

▬ Aircraft track

---- Maximum wind at 200 mb



200 mb contours, winds and isotherms at 2400 GMT

Fig.41 Meteorological charts for February 15

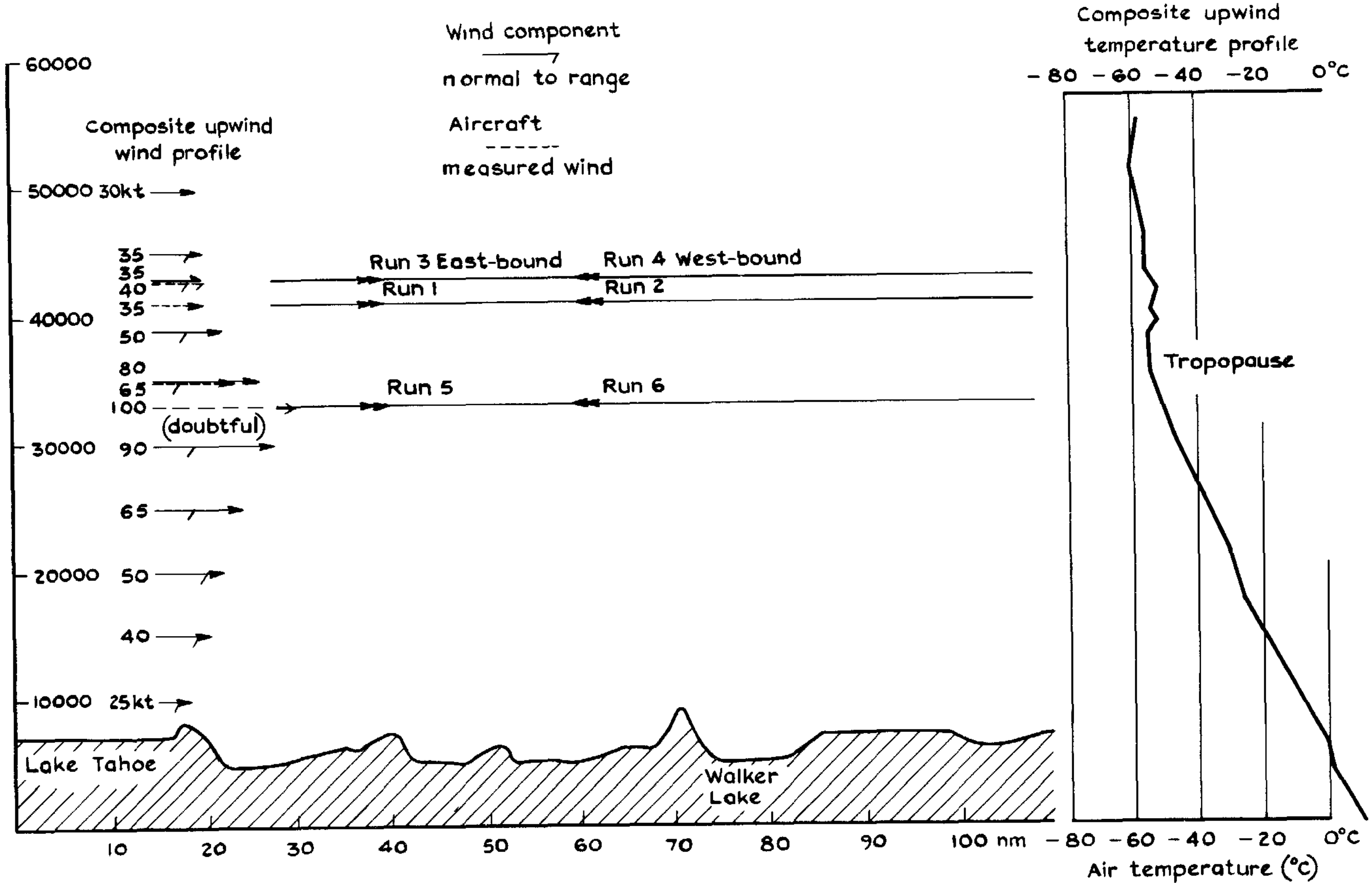


Fig. 42 Cross-section of flight on February 15

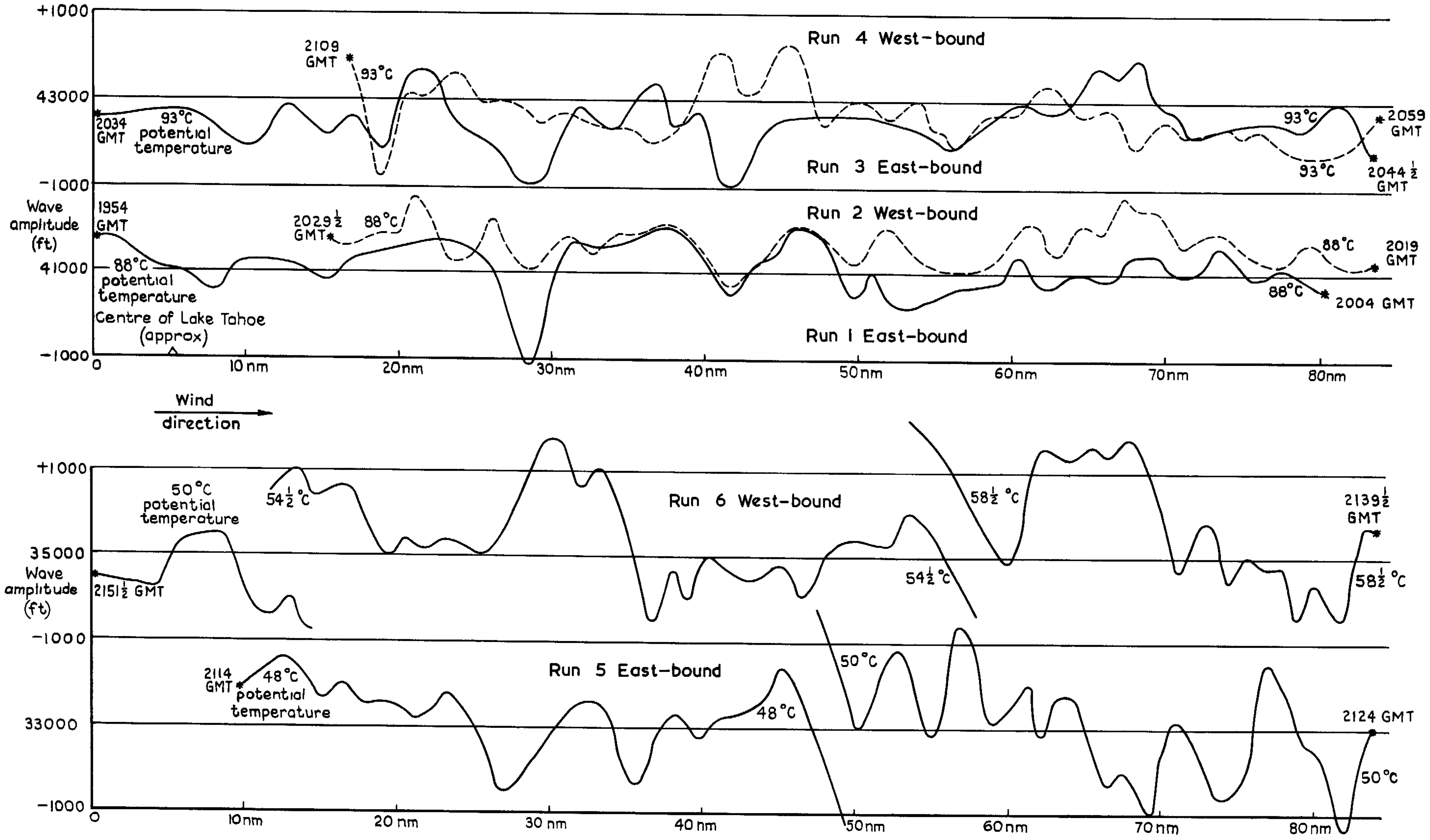


Fig.43 Wave motion on February 15

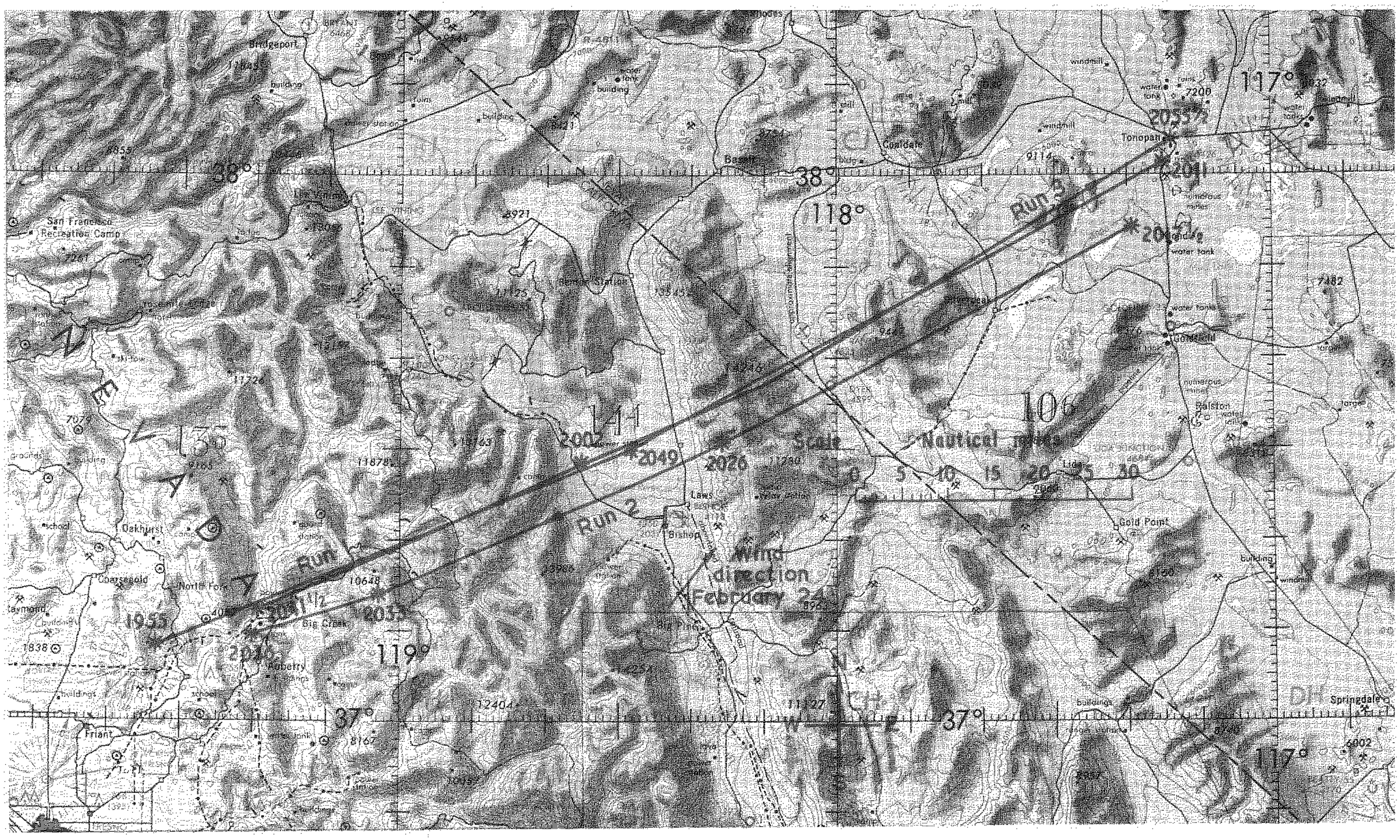
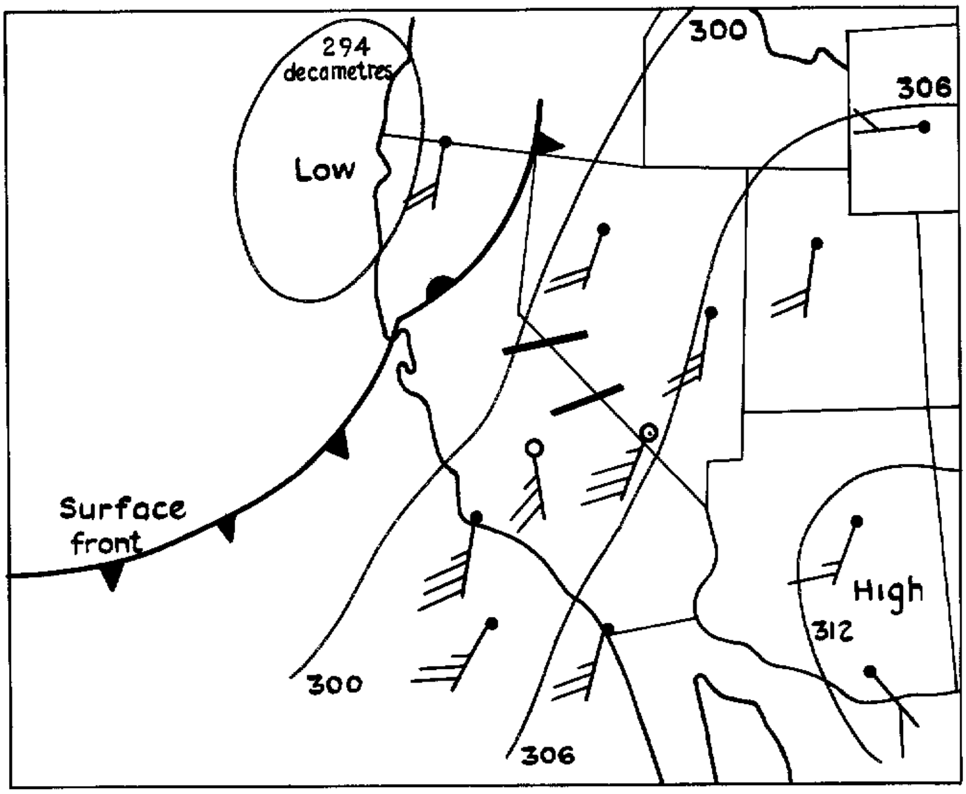


Fig.44. Ground tracks for the flight of February 24

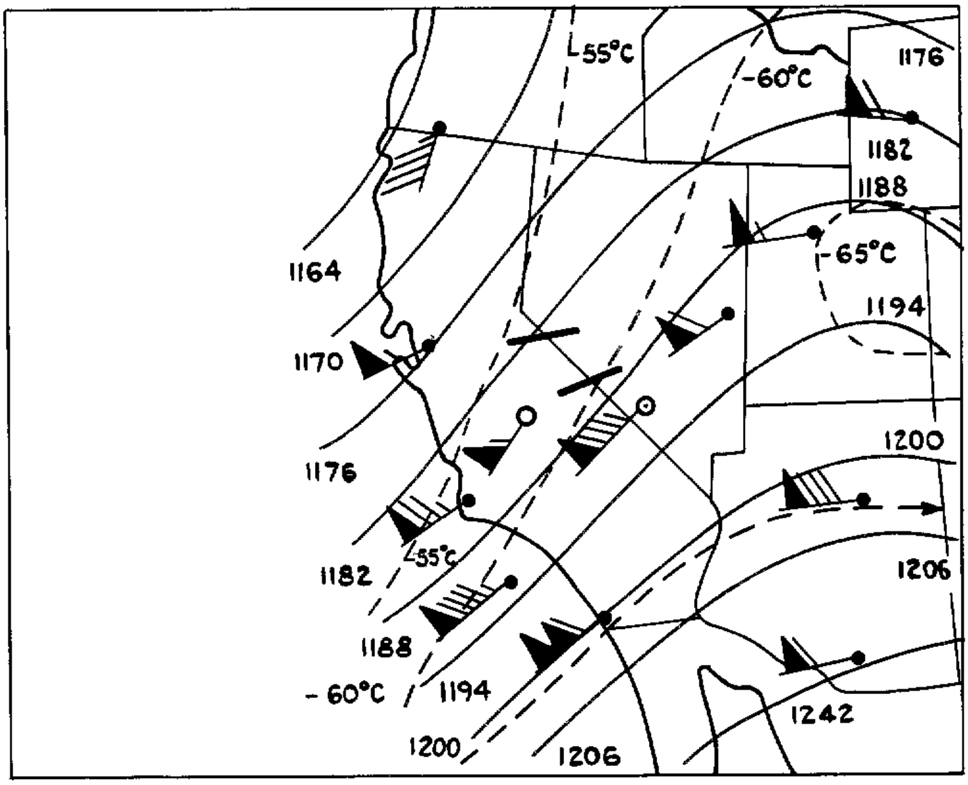


700 mb contours (decametres) and winds at 2400 GMT

⊙ Stations used for composite profiles

—— Aircraft track

---- Maximum wind at 200mb



200 mb contours winds and isotherms at 2400 GMT

Fig. 45 Meteorological charts for February 24

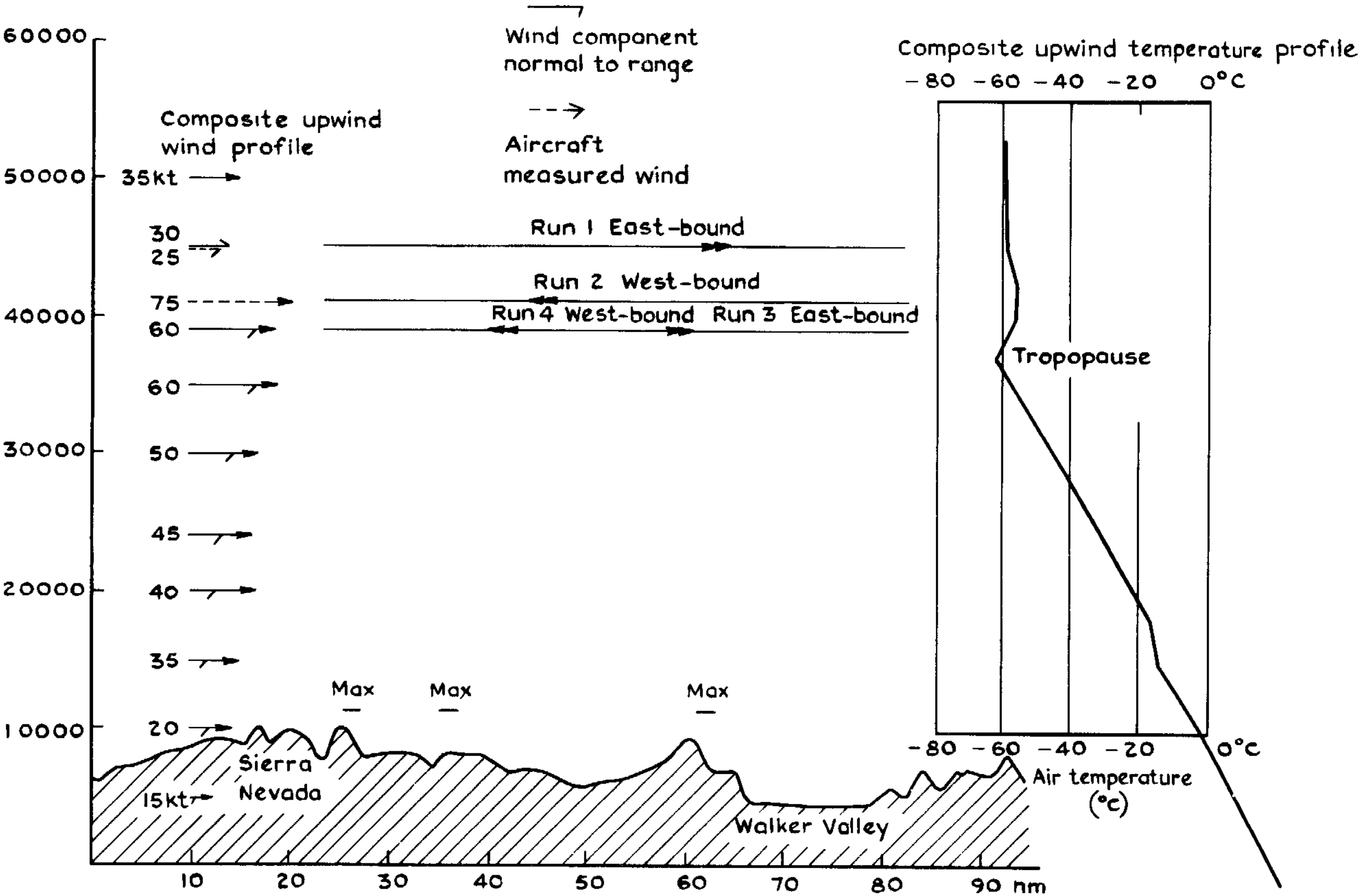


Fig. 46 Cross-section of flight in the Bishop Valley area on February 24

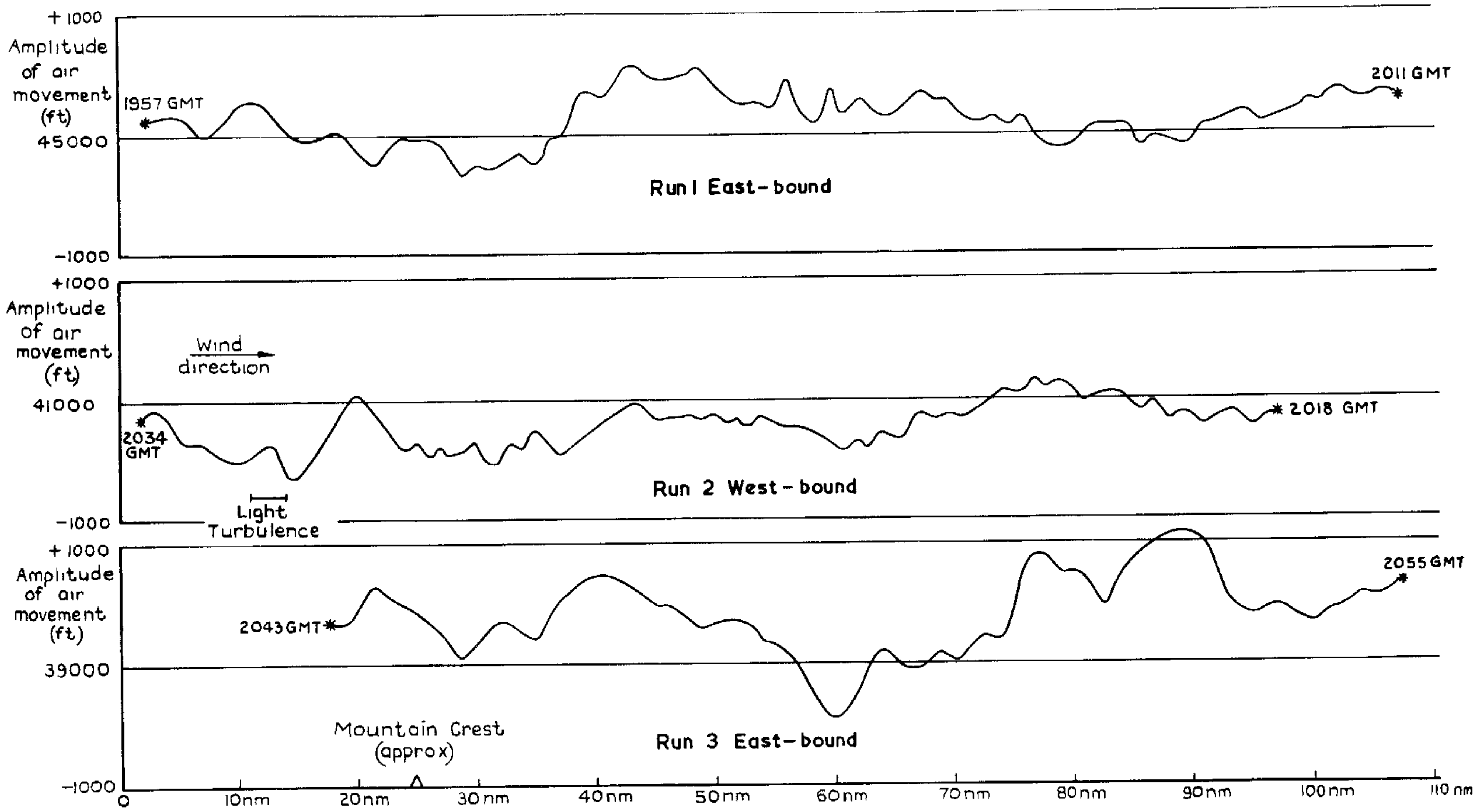
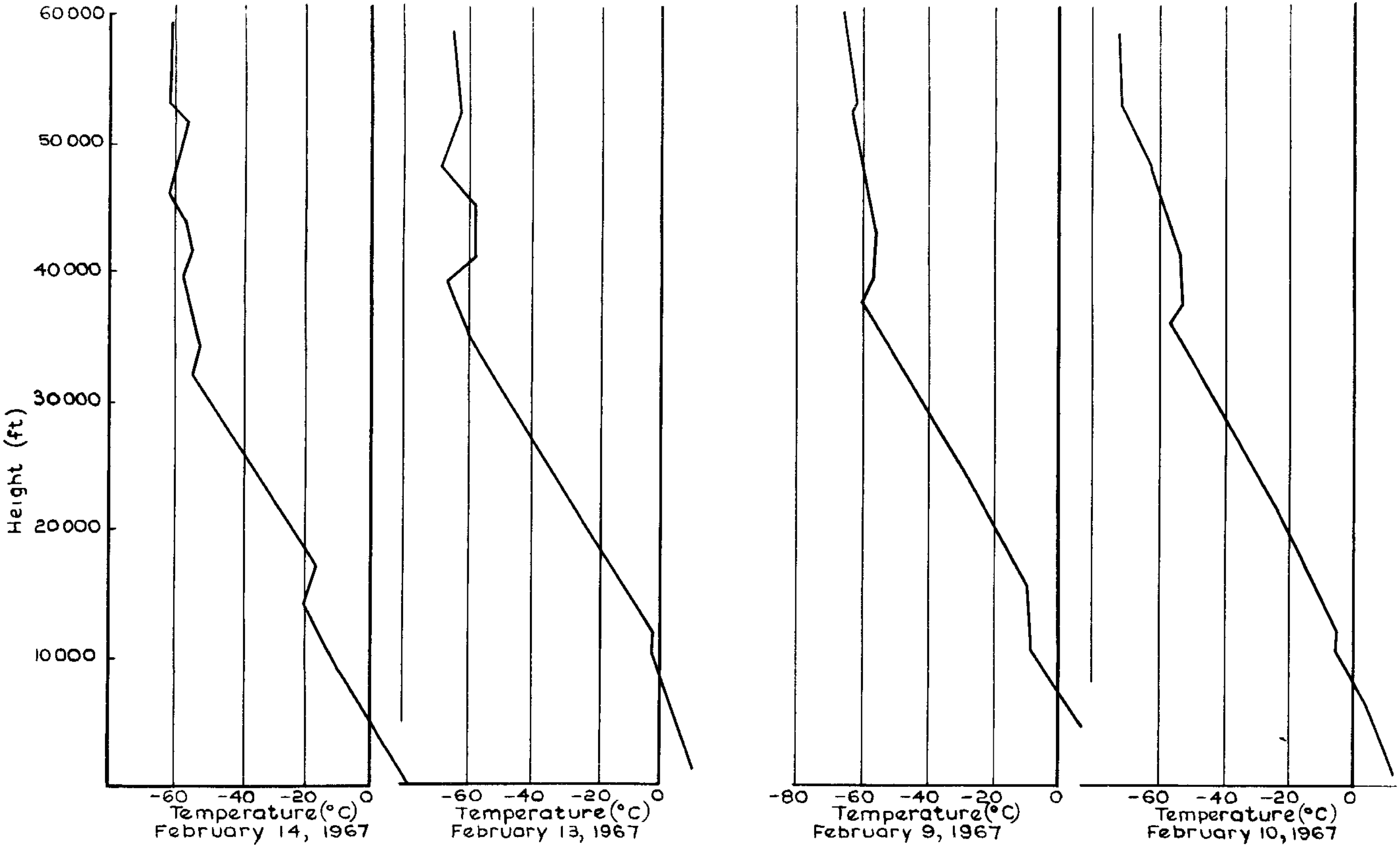


Fig. 47 Wave motion for Runs 1 to 3 on February 24



a Long waves, short waves and marked turbulence

b Long waves, no short waves or marked turbulence

Fig. 48 a&b Vertical temperature profiles on days of topographically induced waves in the stratosphere

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DETACHABLE ABSTRACT CARD

A.R C C.P No.1159
February 1970

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McPherson, A
Nicholls, J M

RESULTS OF A SERIES OF FLIGHTS IN THE STRATOSPHERE OVER MOUNTAINOUS TERRAIN IN THE WESTERN U.S.A DURING FEBRUARY, 1967

In a number of flights in the stratosphere over mountainous terrain in the western U.S.A., much valuable data was collected Flights were planned on the basis of tropospheric lee wave forecasts and were usually made along wind at heights from the tropopause to about 50000 ft over California and Nevada. Mountain waves, deduced from an analysis of the temperature along the flight track, were moderate or strong on four flights Moderate or severe turbulence and marked temperature changes were encountered on three flights The results give an insight into the severity of the stratospheric environment and the meteorological conditions in which the severe disturbances occur

A.R C. C.P No.1159
February 1970

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McPherson, A.
Nicholls, J. M.

RESULTS OF A SERIES OF FLIGHTS IN THE STRATOSPHERE
OVER MOUNTAINOUS TERRAIN IN THE WESTERN U S.A
DURING FEBRUARY, 1967

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McPherson, A.
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