The Atmospheric Micro-Structure and its Bearing on Clear-Air Turbulence (CAT)

A Preliminary Report

By
Elmar R. Reiter

Prepared for Navy Weather Research Facility
Under Contract Number 189(188)55120A

Technical Paper No. 39
Department of Atmospheric Science
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Introduction

In a previous report (Reiter and Hayman, 1962) it has been pointed out that gravity waves on stable interfaces seem to be responsible for many cases of CAT in the upper troposphere, and for most cases in the stratosphere. Since these gravity waves owe their existence to favorable conditions present in the atmospheric meso- and micro-structure, it is of paramount importance to explore these structural details in the free atmosphere.

In most instances, CAT research depended on the use of aircraft acceleration data. Useful as these may be, they give no clear indication

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* This paper has been prepared under Contract No. 189(188)55120A with U.S. Navy Weather Research Facility, Norfolk, Va. It has been presented on September 10, 1962 at the Fourth Conference on Applied Meteorology, Hampton, Va.

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of the actual physical structure of the atmosphere that harbors the observed turbulence. This is in part due to the fact that the resolution of wind- and temperature measurements obtained from an adequately equipped research aircraft does not match the micro-scale of CAT wave lengths. The response of the aircraft to gusts present in the atmosphere may be a quite intricate function of gust frequency, and depends largely on the elastic properties of the aircraft, its load conditions and attitude. Thus, it becomes extremely difficult to reduce acceleration data obtained from different types of aircraft to actual atmospheric conditions. Such a reduction is, however, essential for the understanding of the turbulent properties of the free atmosphere, especially if these properties should yield a projection of turbulence expectancies for future type aircraft (MacCready, 1962).

In view of these shortcomings of presently available data it is felt that new avenues of research into the detailed structure of the free atmosphere should be sought--not so much to supersede, but rather to complement aircraft measurements.

Photogrammetric Cloud Measurements

A statistical study by Clodman, 1962 (see also Clodman and Ball, 1959) indicates a strong correlation of CAT frequency over a given area, with terrain features, such as ranges of relatively small hills. Since orographic obstacles may--under favorable atmospheric conditions--produce a wide range of lee-wave phenomena, such a correlation should not be surprising.

For a study of orographically induced wave formations the region to the lee of the Rocky Mountains is particularly suitable because weather situations under which such wave formations occur are relatively frequent. In many instances these waves are manifest from spectacular cloud formations.

A field program has been conducted at Colorado State University (Reiter and Hayman, 1962) in the course of which photogrammetric measurements of wave formations at the cirrus-cloud level have been made. At the same time, time-lapse pictures of wave-clouds have been taken. From the latter a number of qualitative conclusions on the behavior of these waves could be drawn.

It became evident from these studies that the formation of large "standing" lee waves (wave lengths of about 30 to 50 km) frequently concurs with the appearance of shorter waves, also of the gravity-wave variety. These may cover a wide spectrum of wave lengths; they may be as short as 10^2 m, thus accounting for the wave phenomenon, which also should be expected in CAT.

An example of the formation of such waves along an orographically induced cirrus-shield is shown in Fig. 1.

From time-lapse pictures it became apparent that the wave-phenomena observed in cirrus clouds are also present in the surrounding clear air, thus making the application of cloud studies in CAT research possible: On occasions it was found that due to the passage of a meso-scale disturbance a cloud-sheet would rapidly expand horizontally and into the upstream direction; at the same time small waves which were originally present would also show up in the building-up cloud.

Some of these small waves, it was found, appear to be standing in space, as is the case with larger lee-waves. Some, however, seem to travel downstream approximately with the speed of the wind at this level. It should be concluded, therefore, that not only standing gravity waves near an obstacle, but also traveling gravity waves may be instrumental in the occurrence of CAT.

Figs. 2 and 3 describe such waves, traveling with the wind. These pictures were taken with a K-24 camera east of Fort Collins, Colo. on 13 April 1962 at 1443 and 1445-1/2 MST, respectively. The view in both figures is towards the southeast. They show a rapidly changing, orographically induced cirrus sheet with typical wave formations. Some of these wave trains, especially in the center of the picture, show a marked tendency for dissipation, thus corroborating a statement on the fleeting nature of these waves, which has been made earlier (Reiter and Hayman, 1962). The patchiness and short duration of many CAT cases could be explained by this dissipating tendency of gravity waves.

> Messrs. Serebreny and Clodman pointed out during the discussion following the CAT-session at Hampton, Va., that CAT cases seemed to be more patchy and short-lived over the continents, while over the oceans they sometimes appear to extend for hundreds of miles. The author's explanation for this phenomenon was that apparently over the continents, especially near mountain and hill ranges, there is a steady input of perturbation energy from the friction layer near the ground, which is absent over the oceans, except, maybe, for areas downstream from large-scale convective activity. It appears, therefore, that the atmosphere has to be less unstable towards wave formations over continents in order to contain CAT, than over oceans. On the other hand, since meso-scale conditions seem to prevail more or less uniformly over wide regions (Reiter, 1961a; 1962a) this "dynamic" instability will produce wide-spread CAT-conditions over the oceans, while over the continents, especially in mountainous regions most CAT observations seem to occur in

> the dissipating stage of a large perturbation-energy input into a "dynamically" more stable atmosphere. This is corroborated by DeVer Colson's (1962) statistical treatment of CAT cases: He finds that vertical shear values may have lower threshold values, and Richardson's numbers may be higher over the mountains, in order to produce CAT, than is the case over the Midwestern Plains.

Fig. 4 contains the projection of Figs. 2 and 3 on a horizontal plane, which was obtained from stereo-pairs of photographs (Reiter and Hayman, 1962). (The left-hand portion of Fig. 4 corresponds to Fig. 2, the right-hand portion to Fig. 3). Some of the wave features evident in the photographs are indicated by heavier black lines. The numbers give the height in thousands of feet of the respective cloud features. The straight double lines with arrows in the right portion of Fig. 4 indicate the 2 1/2-minute displacement of certain cloud features, which, on the average, was 30 m/sec. This corresponds rather precisely to the winds at jet-stream level, as revealed by the Denver sounding (Fig. 5; see also Figs. 8 and 9).

According to Fig. 4, the wavelengths revealed by the cloud pattern range between 80 m (uppermost part of Fig. 4a) to 450 m (left part of Fig. 4b). As may be seen from the photographs as well as from Fig. 4, the orientation of the different wave trains varies rather widely. In general, one may say that they run almost normal to the wind direction at this level, thus indicating rather weak vertical wind shears (Sekera, 1948). This, again, checks with the Denver wind sounding plotted in Fig. 5.

The variety of wave trains evident from the photographs, again, substantiates the patchiness of CAT, especially over mountainous terrain. The interference of various such wave trains, as it may be found, e.g., slightly above the center of Fig. 3, also may be an important factor in the generation of CAT.

No direct upper-air measurements were available at the time and the site at which the stereo-cloud photographs were taken. The results from the Denver soundings, which are released approximately 65 miles to the south of the observation site, are shown in Fig. 5. From the temperature and wind soundings (left and center of diagram) the Lyra- or Scorer Parameter

$$l^2 = \frac{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}{V^2}$$

has been computed (Lyra, 1940; Scorer, 1949). It is shown in the right-hand portion of Fig. 5.

It will have to be borne in mind that the soundings from which these computations have been made do not show all the details that might be expected. The slightly stable lapse rates between 250 and 200 mb on April 13 1200 GCT and April 14 0000 GCT may be indicative of a succession of shallow stable and adiabatic layers which have been smoothed out during the coding process (Danielsen, 1959). These layers would, of course, modify the computed Scorer-parameters. Nevertheless, the computations show a marked minimum of l^2 between 30.7 and 34.6 x 10^3 feet on 13 April 1200 GCT which agrees well with the heights at which the lower wave clouds in Figs. 2 and 3 appear (see numbers plotted in Fig. 4). A sharp increase in l^2 near 39.1 x 10^3 feet, again, lies not too far from the observed upper-wave cloud deck in Figs. 2 and 3 (see Fig. 4). This distribution of the l^2-parameter in the upper troposphere prevails almost unchanged until 14 April 0000 GCT. As may be seen at this map time, however, the rather steady decrease of l^2 in the lower troposphere which had been observed on 13 April 1200 GCT, and which, according to Scorer, is a prerequisite for wave-cloud formation, now is interrupted at 500 mb. In accordance with this, the waves in the cirrus-level over Fort Collins started to disappear between 1500 and 1600 MST (=2200 and 2300 GCT) on April 13.

From the foregoing it appears that the computation of lee-wave parameters in the vicinity of mountain ranges may prove to be a valuable aid in CAT forecasting. Although the aforementioned Scorer parameter usually yields larger wave lengths than are present in CAT*, the cloud observations indicate that longer lee-waves very frequently are associated with shorter, superimposed waves.

A Preliminary Case Study of Clear-Air Turbulence

Fig. 6 contains a plot of CAT-cases reported over teletype** on April 13, 1962. The intensity of turbulence is indicated by the inner circles, according to the legend. The outer circles represent a 24-hour clock, the filled-in portion of which gives the time at which CAT was observed. The position of the jet axes, and of the -44° C and -48° C isotherms at the 250-mb level are also marked in the figure for April 13, 1962 0000 GCT and 1200 GCT and for April 14 0000 GCT. From this diagram the rapid movement of the upper trough and of the associated CAT region may readily be seen.

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* The example of 13 April 1200 GCT shows a minimum value of l^2 of 0.087 between 30730 and 34650 ft. This would correspond to a wave length of about 3.5 km.

** The author is indebted to Mr. H. T. Harrison, United Air Lines, for making the teletype data available to him.

Figs. 7, 8 and 9 show the 250-mb flow and temperature patterns of April 13 0000 GCT and 1200 GCT, and of April 14 0000 GCT, together with moderate and severe CAT cases that occurred within $\pm$ 6 hours from the respective map time. The following becomes evident from these analyses:

(1) The confluence region of two jet streams near the upper trough shows a marked concentration of CAT cases.

> This has also been confirmed by Colson and Endlich during the discussion of their research results at the Hampton, Va. meeting.

(2) Most cases of CAT occur in or near regions with a strong horizontal temperature gradient at 250 mb which indicates the presence of a baroclinic stable zone intersecting this level. (Most of the CAT cases presented in Figs. 7, 8, and 9 were observed between 30,000 and 40,000 feet, thus making the 250-mb level representative for the average flow condition in the air-traffic layer from which most of the observations were collected). It has been pointed out in earlier papers (Reiter, 1960; 1961a; b; c; 1962b; Reiter and Hayman, 1962) that such stable baroclinic layers apparently are especially susceptible to gravity-wave formation, and therefore to CAT occurrence. It is noteworthy in this connection that the map time of April 13 0000 GCT shows the greatest density of CAT observations in the vicinity of this stable zone. (In comparing the three maps with each other one will have to be aware, of course, of a certain bias of the CAT data introduced by the location of air-traffic corridors). At this map time the observed horizontal temperature gradient has been strongest, too, in the confluence region of the two jet streams.

(3) Most CAT cases lie in a region of cold advection at the 250-mb

level, i.e. in a region of rather pronounced sinking motion. Since sinking tends to stabilize the atmosphere, conditions for the formation of gravity waves would be improved.

> This point actually deserves further research because some of the stabilizing tendency due to sinking will be offset by increasing cyclonic curvature which, according to the theorem of conservation of potential vorticity, should result in a de-stabilization of the atmosphere. Messrs. Young and Corwin (1962), Trans World Air Lines, reported on cases of CAT off the east coast of the United States which occurred in a weakly rising air current with increasing anticyclonic curvature. Here, again, the contribution of the potential-vorticity field may offset the de-stabilization to be expected from rising atmospheric motions.

(4) Kadlec (1962) reports on a significant correlation between CAT and shape and distribution of cirrus clouds. Although the cirrus formation shown in Figs. 2 and 3 reveal wave lengths similar to those present under CAT-conditions, only a few cases of light CAT were reported on April 13 in the Fort Collins area (indicated by a black square in Figs. 6 to 9). This may again be due, however, to a bias of CAT data with respect to flight corridors and flight altitudes. From what has been said in connection with Fig. 5 and in earlier papers by the author (op. cit.), one would expect CAT to occur in rather shallow layers which may or may not be intercepted by an aircraft.

It is worth mentioning that the CAT-cases observed on April 14 0000 GCT over Louisiana and Arkansas are lying close to a trajectory which 12 hours earlier originated in the Fort Collins region where the formation of waves traveling with the wind actually has been observed. At this point it cannot be ascertained, however, whether the perturbation energy leading to the formation of CAT actually has traveled all the way downstream from the main range of the Rocky Mountains, or whether it has been generated by the ranges of the Boston and Quachita Mountains, near which these CAT cases have been observed.

Acknowledgement

Mr. R. W. Hayman supervised the field program and reduction of cloud-photogrammetry data. Mr. J. Mahlman's help in the preparation of aircraft CAT-data is duly appreciated. Last, not least, the author's thanks go to the participants of the CAT-sessions conducted during the Hampton, Va. Conference on Applied Meteorology; their presentations and discussions contributed materially towards a clarification and solution of the problems which CAT research is faced with.

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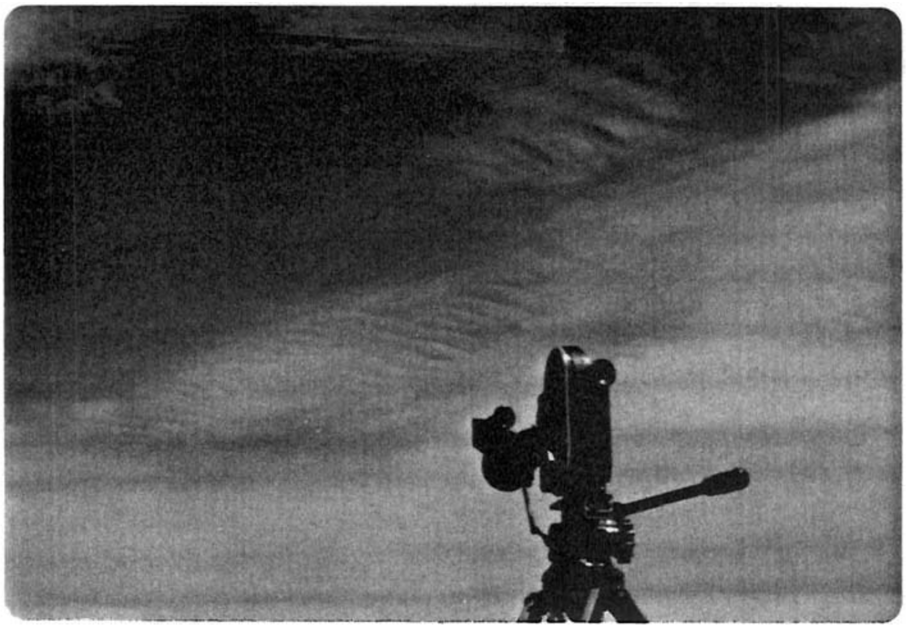

Fig. 1: Wave-cloud formation on a cirrus shield, 28 April 1962, 1130 MST, northeast of Fort Collins, Colo. The view is towards northeast. (Photo by E. R. Reiter).

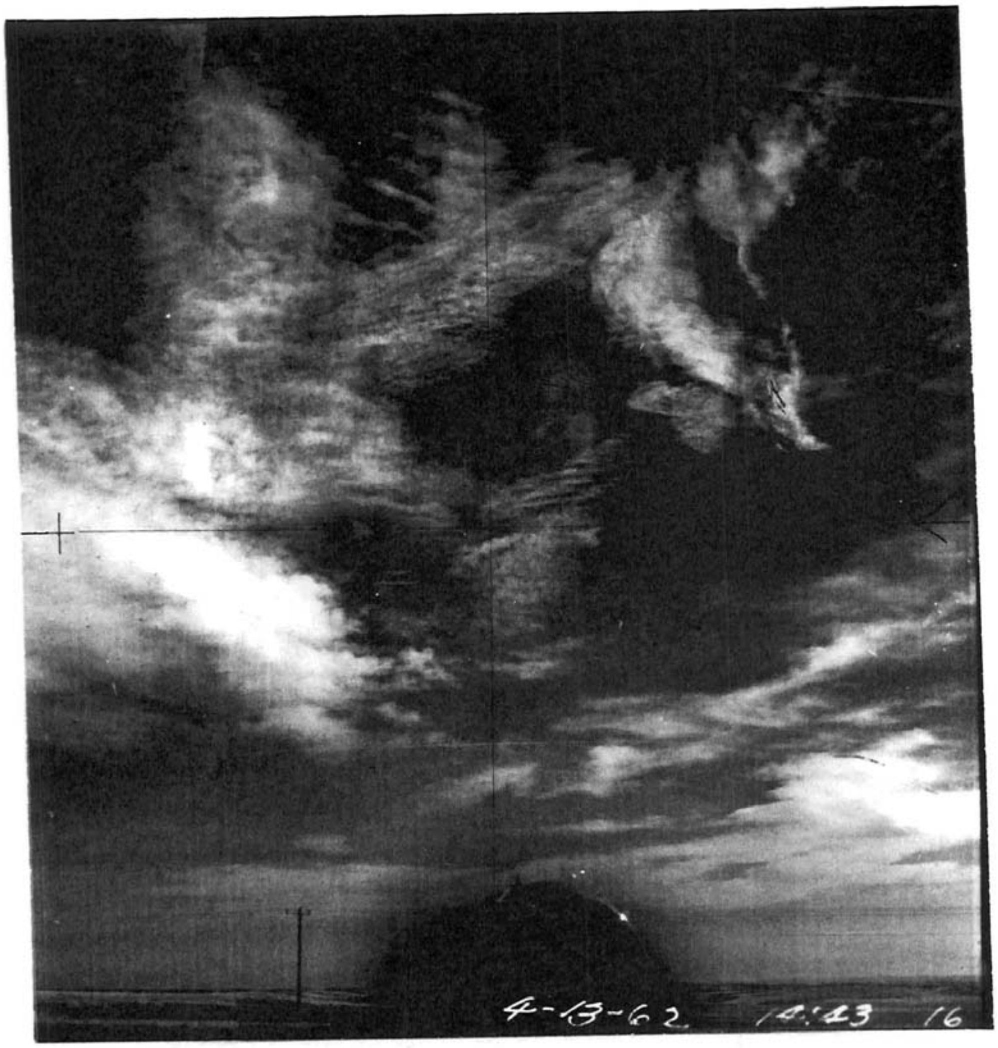

Fig. 2: Waves at cirrus level, 13 April 1962, 1443 MST photographed with a K-24 camera at Station "Foundation", northeast of Fort Collins, Colo., view towards southeast.

Fig. 3: Same as Fig. 2, only 2 1/2 minutes later.

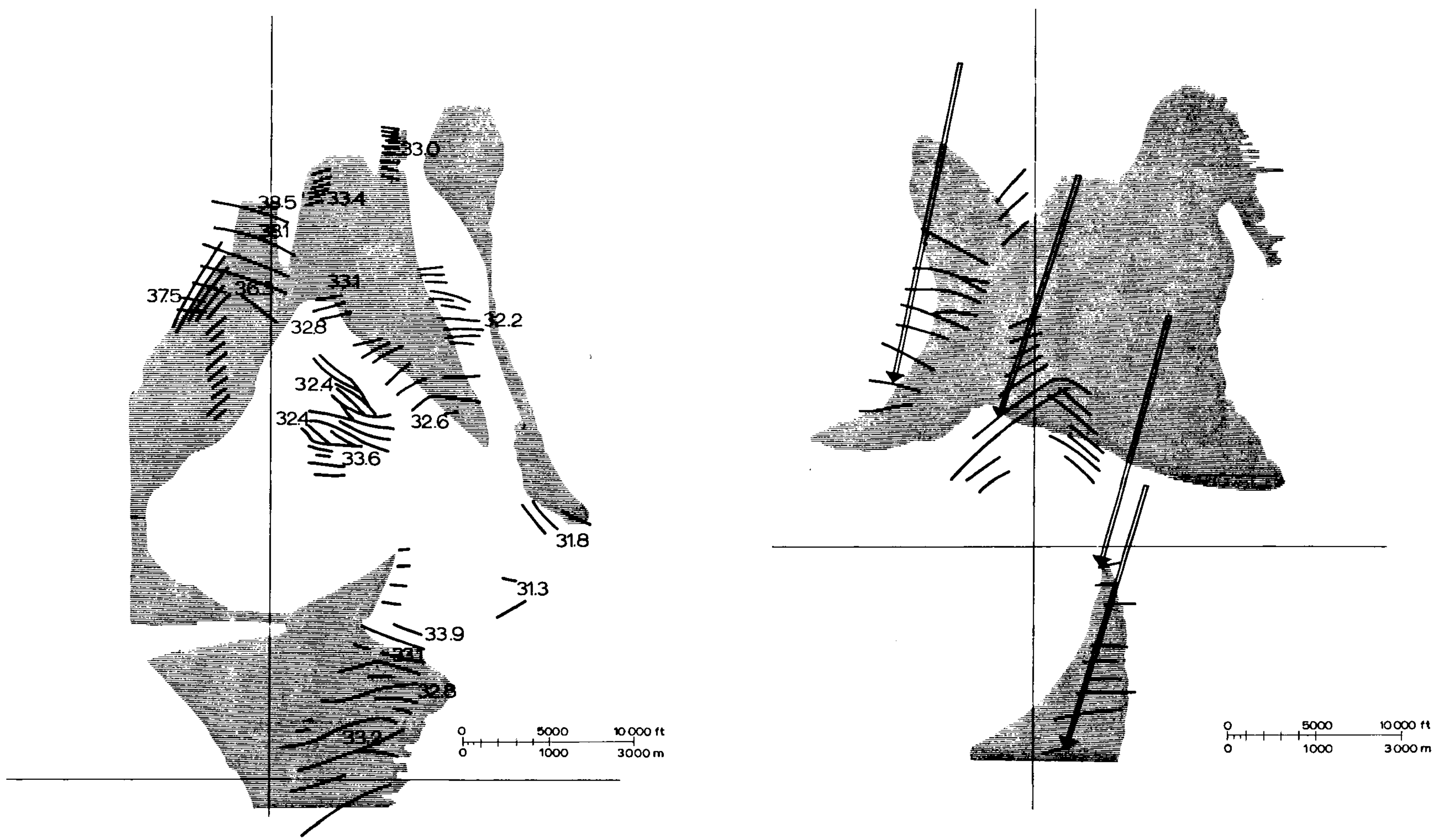

Fig. 4: Projection of waves at cirrus level obtained from stereo pairs of photographs. The left part of the diagram corresponds to Fig. 2, the right part to Fig. 3. Wave trains are indicated by lines. The numbers indicate the height of the cloud field in thousands of feet. The straight double lines with arrows mark the 2 1/2-minute displacement of certain characteristic features in the cloud pattern.

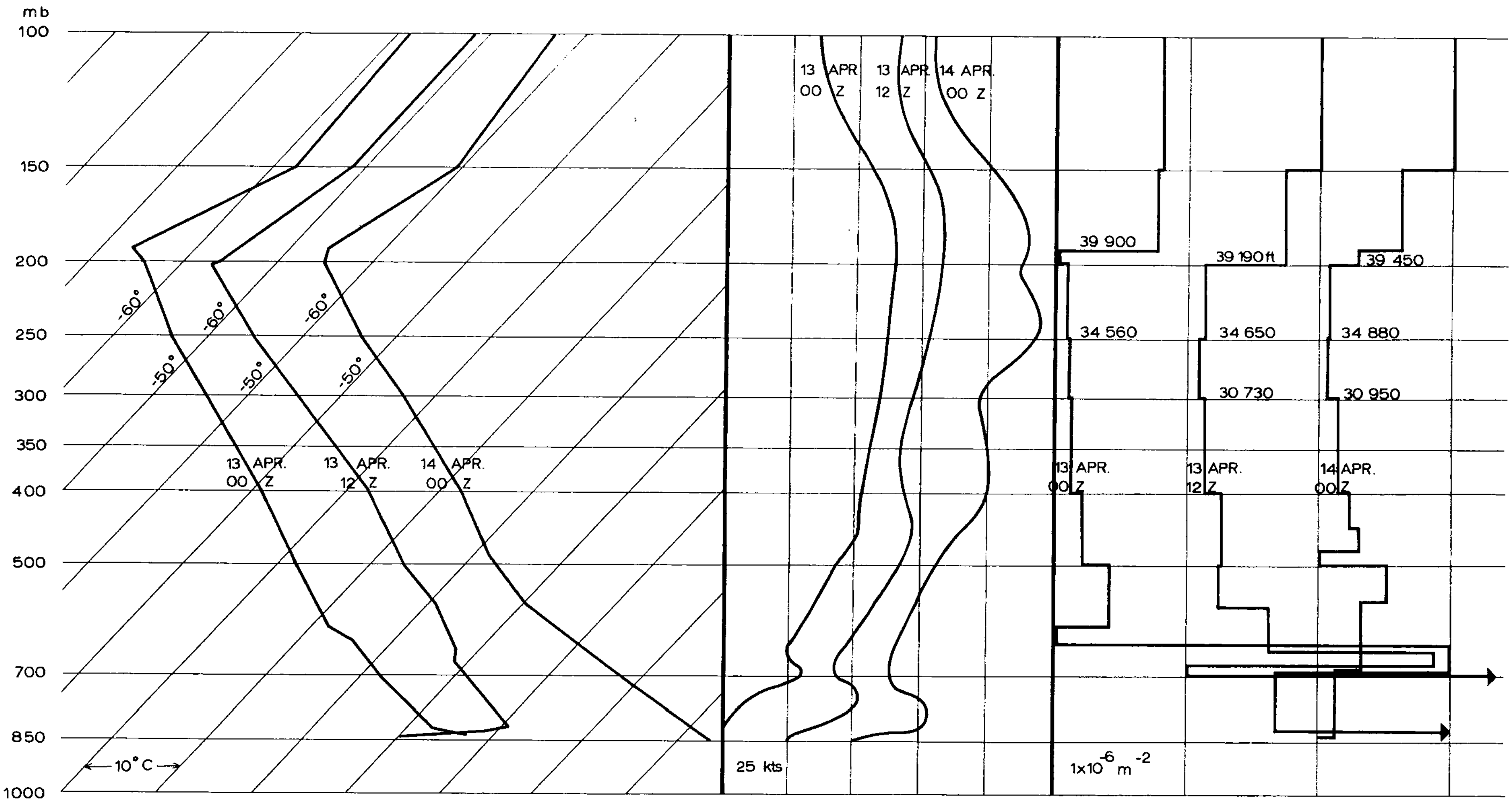

Fig. 5: Left side: Denver, Colo., soundings of 13 April 1962, 0000 GCT and 1200 GCT and of 14 April, 0000 GCT, on a USAF Skew T log p Diagram; consecutive soundings have been displaced to the right by a coordinate unit of 10^0 C.
Center: Denver wind profiles for same dates; consecutive profiles have been displaced to the right by a coordinate unit of 25 Knots.

Right side: Scorer parameter ℓ^2 for same soundings; consecutive profiles have been displaced to the right by a coordinate unit of 10^{-6} m^{-2}.

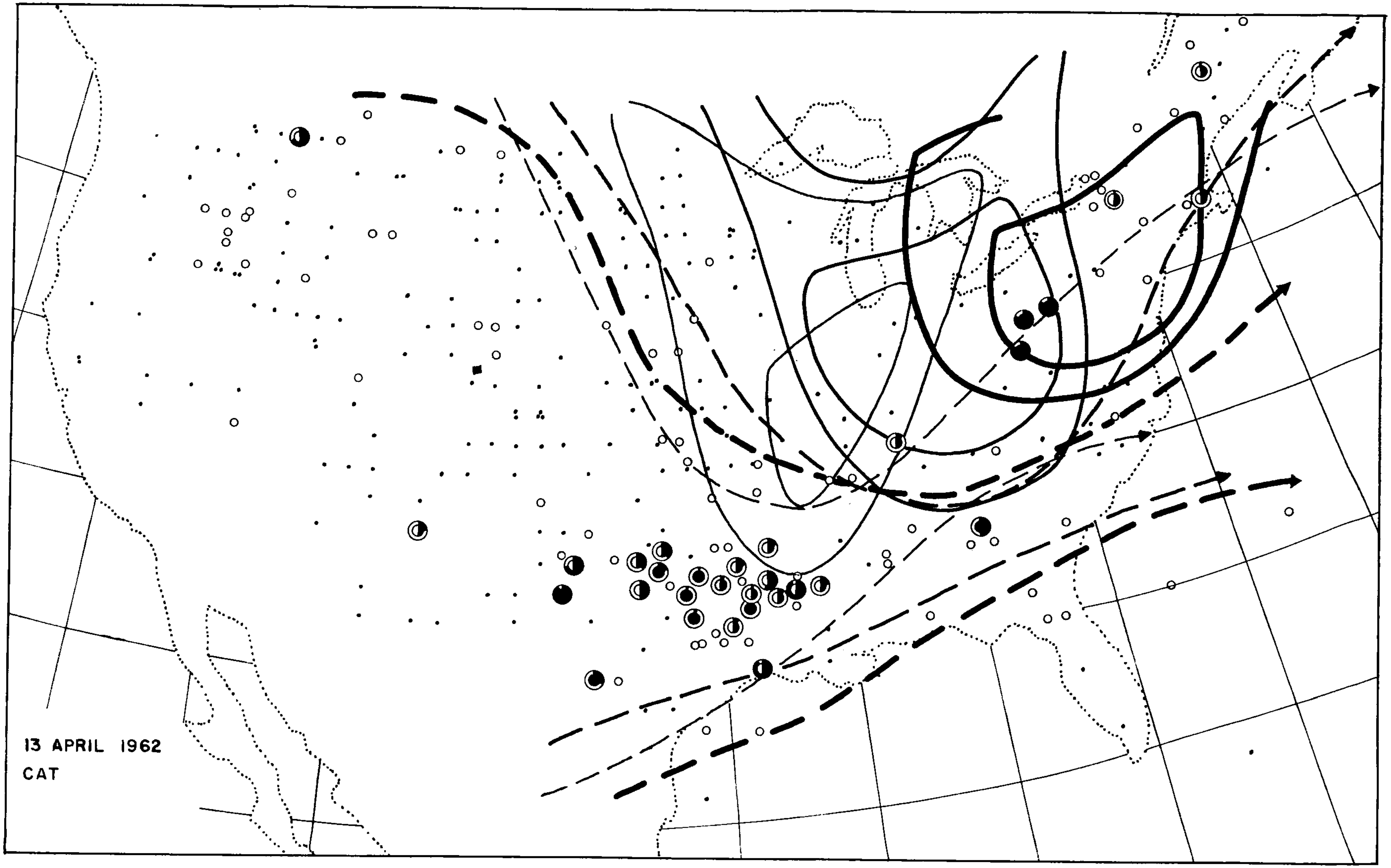

Fig. 6: Occurrence of CAT, 13 April 1962. The inner circles indicate the intensity of CAT. Full black circle: severe CAT; half of circle black: moderate CAT; small circle: light CAT; dots: no CAT. The outer circles stand for a 24-hour clock, the filled-in portions indicating the time of observation. Full lines mark the position of the -44° C (inner) and -48° C (outer) isotherms at the 250-mb level, dashed lines stand for the 250-mb jet axes; light, medium and heavy lines were used for the map times 13 April 0000 GCT, 1200 GCT and 14 April 1200 GCT.

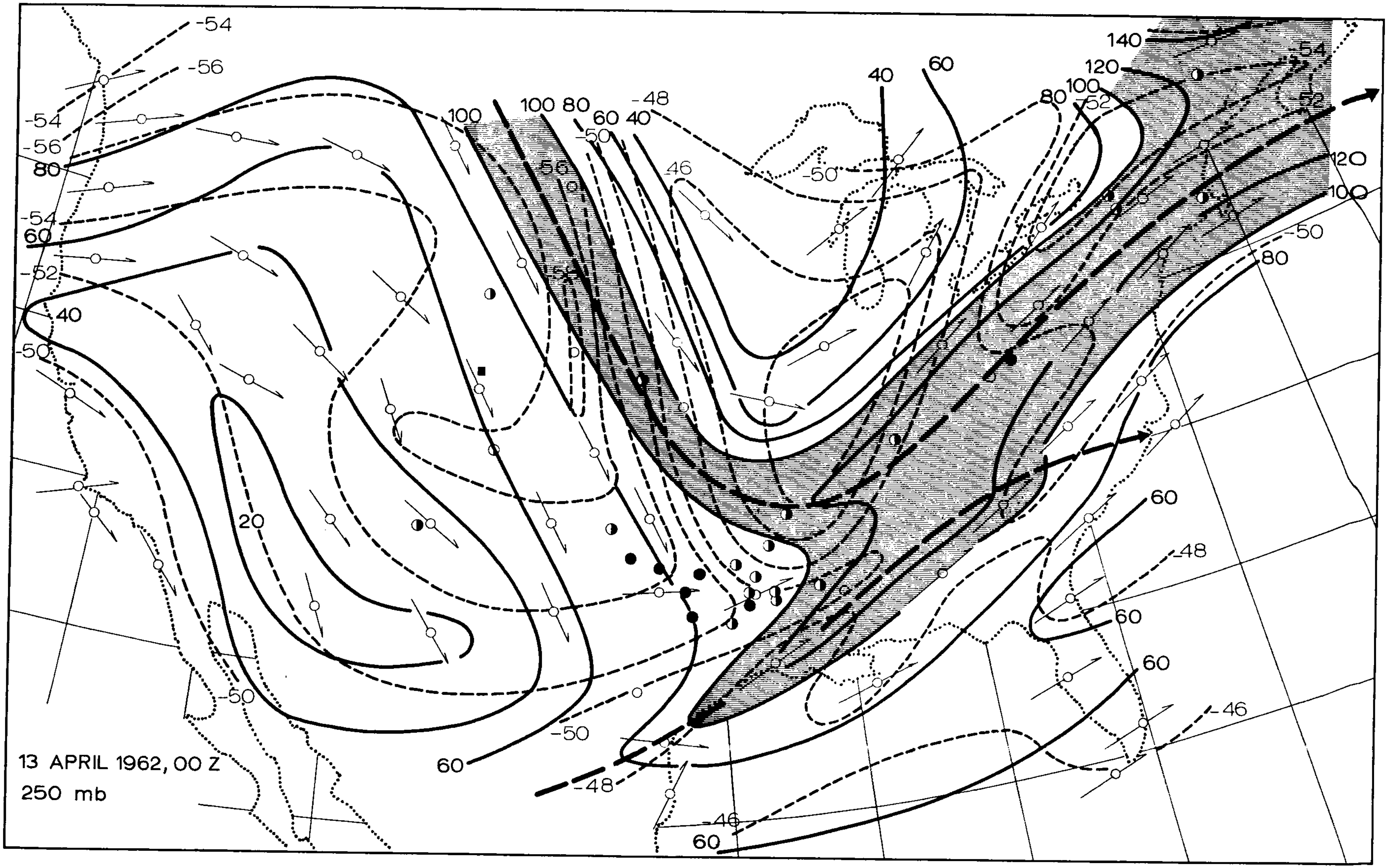

Fig. 7: 250-mb isotachs (areas > 100 knots shaded) and isotherms (^{0} C), 13 April 1962, 0000 GCT, and moderate and severe cases of CAT observed within ± 6 hours of map time.

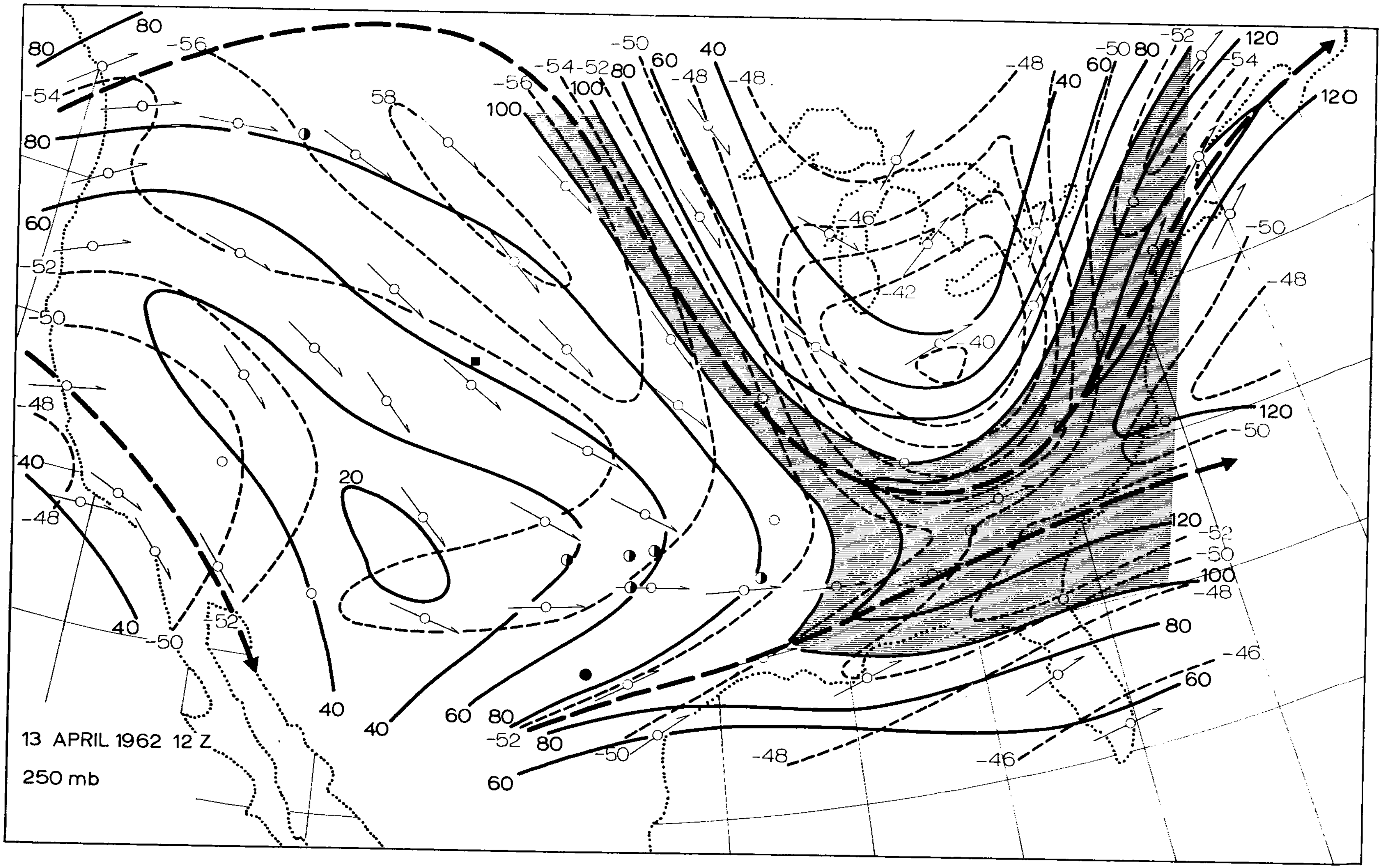

Fig. 8: Same as Fig. 7, except 13 April 1962, 1200 GCT.

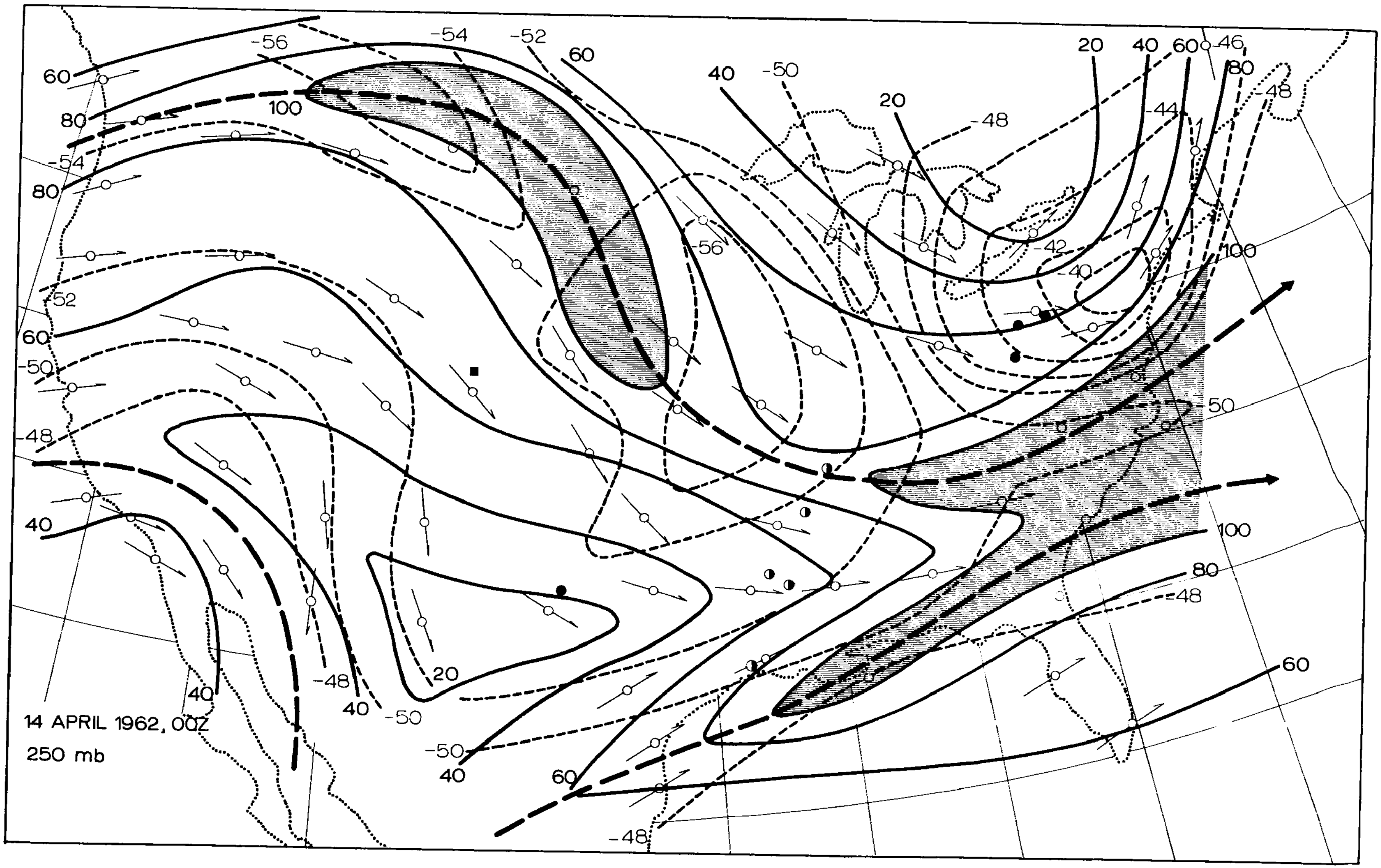

Fig. 9: Same as Fig. 7, except 14 April 1962, 0000 GCT.