Subtropical or Polar Front Jet Stream?

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Contract CwB-10879

Under Contract with Department of Commerce U.S. Weather Bureau

Technical Paper No. 66
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

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ABSTRACT

By means of satellite photographs originally analysed by Oliver et. al. (1964), it is shown that the Polar Front Jet Stream and the Subtropical Jet Stream do not behave as entities in regions where they approach each other closely. A cross-over of flow is observed whereby the subtropical current over-rides and merges with the polar-front jet. In the case of such flow patterns, current nomenclature of jet streams may be misleading.

INTRODUCTION:

In a recent study Oliver et. al. (1964) have described the observation of dark bands in TIROS V and VI cloud photographs which were associated with jet streams at tropopause level. Since cloud heights on the south side of these bands were appreciably higher than on the north side (ca. 35,000 ft. as compared with ca. 7000 ft, according to aircraft observations), the conclusion was reached that under favorable conditions a high-level cirrus deck may cast a shadow on low-level clouds, creating a dark band wide enough to appear on TIROS photographs.

From a comparison of aircraft observations with those taken from TIROS, it is evident that the cirrus bank shows large horizontal extent and has a sharply defined edge. Findings by Oliver et. al. agree well with those by Kadlec (1963, 1964), which were compiled from visual and photographic cloud surveys from commercial airline flights.

Fig. 1 shows one of Kadlec's cirrus distribution models, which he describes as follows:

"The northern polar jet stream is oriented in a trough-ridge pattern while the southern or subtropical jet stream is curved anticyclonically. The average distance across the cirrus pattern varies from approximately 400 nautical miles in the area of formation east and south of the upper trough to between 1,000 and 1,500 nautical miles in the ridge. This extensive area of cloud cover occurs when the two jet streams converge to within 300 nautical miles in the trough area. If the separation between the two jet streams is 400 nautical miles or more, two separate areas of cirrus may form with clear skies occurring between the two jet streams near and downwind of the ridge line. . . . . . . "

Thus, the condition for establishment of the observed cirrus distribution seems to be the merger and subsequent splitting of polar front (PFJ) and subtropical jet streams (STJ), if we were to adopt--at least for the moment--the classical nomenclature of describing the flow pattern near tropopause level.

Galloway (1958, 1963) and McIntyre (1958), in describing the Canadian three-front, three-jet streams model, allow for similar weather patterns in which jets associated with air mass differences between cA, mA, P and T air masses approach each other closely.

CROSS-OVER OF JET STREAMS:

In a recent publication Reiter and Nania (1964) have commented on the fact that trajectories on isentropic surfaces do not support the classical model of confluence and diffluence of PFJ and STJ. Figs. 2 and 3 show the 250-mb flow patterns on 13 April, 1962, 00 and 12 GMT, which look very similar to the model presented in Fig. 1. A relatively large number of clear-air turbulence (CAT) occurrences was reported near 00 GMT of that day in the entrance region of the two jet-streams. The northern one of these two jets had its core near 300 mb to the west of the trough, whereas the southern jet showed highest velocities near the 200-mb level.

Fig. 4 contains trajectories on the 320°K isentropic level traced backwards and forwards for 12 hours each, starting in the CAT region. (Trajectory origins indicated by double circles). From this analysis it appears that air in the northwesterly jet branch submerges beneath warm air traveling within the southwesterly jet. This submerging occurs along a well developed "convergence line" evident from the sharp turning of wind over northern Texas and Arkansas in Fig. 2. In vertical cross sections this region is characterized by a relatively shallow zone, sloping from north to south, in which the wind backs sharply with height (as much as 65 degrees within a 100-mb layer). It is within this layer of directional wind shear that the observed CAT occurred. The southwesterly jet, according to Fig. 4, overrides the northwesterly one, and the air within it follows an ascending motion while doing so. (Pressures in mb along the trajectories are indicated by heavy numbers). Cyclonic shears are very strong in this southwesterly flow east of the trough. This apparent cross-over of flow has prompted Reiter and Nania to mark jet axes as indicated by heavy dots in Fig.3.

JET STREAM OF NOVEMBER 20, 1962:

Fig. 5, reproduced from the paper by Oliver et al., shows a mosaic of TIROS VI pictures on 20 November, 1962, 1355 GMT. Observed cloud heights are given along the edge of the cloud photographs. The dark "shadow" line is clearly visible, extending approximately from Huntington (HTW), West Virginia, beyond Boston (BOS), Massachusetts. Especially in the Baltimore (BAL) region the abrupt change in cloud heights is well substantiated by pilot reports, as noted by Oliver et al. TIROS V, passing the region at 1448 on the same day, gave further proof of the "shadow line" in essentially unchanged position.

Figs. 6 and 7 show 250-mb winds and temperatures for 20 November, 1962, 00 and 12 GMT. A strong southwesterly jet stream crosses the central and eastern United States. Over Texas a shear line with strong cyclonic shears separates this flow from a northerly jet branch. Another jet branch, from the northwest, "merges" with the southwesterly flow east of the Great Lakes region. It is in the confluent area between these two jet branches that Oliver et al. discovered the cloud-shadow band described above.

The region underneath the shear line is characterized by clear skies in agreement with a study by Hsieh (1950) (Figs. 8 and 9). Precipitation is observed in the right rear quadrant of the strong jet maximum produced by the merger of the two jet branches, in line with the vorticity distribution and the resulting upper divergence pattern.

Further comparison between 250-mb and surface charts shows that the region of diffluence between "PFJ" and "STJ" - again using classical nomenclature - overlies a high-pressure cell, located north and to the rear of a quasi-stationary frontal system. This "high," which migrates slowly eastward, was produced by a cold outbreak and is not part of the subtropical high-pressure ridge above which one would normally find the STJ (Palmén, 1954; Krishnamurti, 1961 a, b). Thus, even from a superficial inspection of the upper flow pattern it would seem unorthodox to call the southern one of the two jet branches a STJ even though it occurs at rather high levels. According to Fig. 10, which shows a cross-section from Moosonee (MO), Ontario, to Burrwood (BRJ), Louisiana, for 20 November 1962, 12 GMT, the southern jet branch is found near Shreveport, Louisiana, slightly below the 200-mb level. (Other call letters in this cross-section stand for: Sault Ste. Marie= SSM, Green Bay=GRB, Peoria=PIA, Columbia=CBI, Little Rock= LIT, Shreveport= SHV, Jackson=JAN, and Lake Charles=LCH). Highest velocities are found between potential temperatures of 330 and 340^{o}K. The northern jet branch is located in this cross-section over Green Bay, Wisconsin, near 300 mb, and at a potential temperature of approximately 325^{o}K.

Marked baroclinicity prevails throughout the troposphere underneath both jet branches. A frontal zone appears especially well established beneath the southern branch. This fact also disqualifies this jet stream as a STJ, for which one normally finds the baroclinicity confined to the upper troposphere above the 400- or 500- mb level.

Fig. 11, showing relative humidity and wind direction in the same cross-section as Fig. 10, indicates dry subsiding air within the shear line (i. e. the region with northerly winds) between the two jet branches. This also conforms to Hsieh's (1950) model of shear-line development. Moist air and precipitation is observed beneath the southern jet branch. Some low-level cloudiness and occasional reports of snowfall spread beneath the northern jet branch. A "motorboating" layer of dry air with its base at 10,00 to 15,000 ft sharply defines the vertical extent of any cloudiness in this region.

Although the TIROS V mosaic (Fig. 5) does not reach far enough west to corroborate cloud conditions in Fig. 11, we may assume that cirrus clouds, if present, broke off slightly to the north of Shreveport, remaining on the anticyclonic side of the southern branch as postulated by Kadlec's model. Cloud heights in this region should be at, or below, the 30,000 ft. level.

From there on eastward the edge of the cirrus band follows the axis of lowest temperatures on the 250 mb sfc. Warm advection in this region would indicate rising motions, especially since the local temperature changes in this area were close to zero (Fig. 12).

Fig. 13 shows wind speeds and potential temperatures in a cross section from Moosonee (MO), Ontario, to Jacksonville (JAX), Florida. (Other call letters stand for: Maniwaki=MAN, Buffalo= BUF, Pittsburgh=PIT, Huntington=HUN, Greensboro=GSO, and Charleston=CHS). This cross-sectional plane intersects the main jet maximum in a region where the two jet branches attain their closest proximity. The core of strongest winds lies between 330 and 340°K, which corresponds to the potential temperature range at which the southern jet branch appeared in Fig. 10. The jet core in Fig. 13 is located near the 200-mb level at Huntington, West Virginia. The wind measurements at Huntington terminate around 300-mb probably because of high winds (78 mps at termination of sounding). Peak winds are 95 mps if one interpolates the strong cyclonic and anticyclonic shears into the Huntington region. Extrapolation of the vertical wind profile at Huntington gives at least a 95 mps wind at the maximum wind level.

In Fig. 14, which shows wind directions and relative humidities in the same cross-section as Fig. 13, we notice that moist air extends to relatively high levels underneath the jet core. The cirrus shield observed in Fig. 5 ends abruptly on the anticyclonic side of a broad and diffuse baroclinic zone which contains "motorboating" humidity reports. This dry air is indicative of subsidence from stratospheric levels through the "tropopause gap." Such motions have been observed in conjunction with transport of radioactive debris from the stratosphere to the troposphere (Reiter, 1963 a). In view of the evidence from Figs. 6, 7, 10 and 13 and the orientation of the cirrus edge in Fig. 5, it appears that at least in this case the subsidence of stratospheric air within the baroclinic frontal zone beneath a jet stream is most effective in regions where two well developed jet branches are merging. Corroboration still has to be sought from similar cases.

Figs. 15 and 16 show wind velocities and pressures on the 320° and 330°K isentropic surfaces. The cirrus cloud deck observed in Fig. 5, lies between these two isentropic levels and south of the baroclinic zone (Fig. 14). The shadow band seems to coincide with the main jet axis on these isentropic surfaces. Rising motion in the region of upper-tropospheric clouds agrees well with flow towards lower pressure values on these two surfaces, even though the motion cannot be considered strictly adiabatic because of release of latent heat of sublimation. This effect may be considered small, however, at levels close to the tropopause.

Unfortunately, the present quality of humidity measurements in the atmosphere does not allow an estimate in Figs. 13 and 14 of how far upwards the separation between dry and moist air underneath the jet stream continues. The dry region within the "jet-stream front" of Fig. 14 seems to be associated with potential temperatures above 304°. Twelve hours earlier (20 November, 00 GMT) the sounding of International Falls indicates a stable layer below the tropopause (216 mb) with potential temperatures ranging from 319.5°K near the base of this layer (278 mb) to 336°K at tropopause level. Winds in this layer are reported to be 35 mps from 331 degrees. From Fig. 6 it appears that this stable layer over International Falls was subject to strong cyclonic shears in the northwesterly jet branch under nearly straight-flow conditions. The potential vorticity in this layer may be estimated from the expression $P = Q_z \cdot \frac{\partial \theta}{\partial p}$. Measuring from Fig. 6 and from the sounding of International Falls values of $Q_z \cong \frac{\partial V}{\partial n} + f = 20.27 \text{ sec}^{-1}$ and $\frac{\partial \theta}{\partial p} = \frac{16^\circ}{60 \text{ mb}}$, we arrive at $P \cong 54 \times 10^{-9}$ g^{-1} cm. sec. deg.

A trajectory along the 320° K isentropic surface, starting in this stable region over International Falls on 20 November, 00 GMT, terminates 12 hours later close to the cross-sectional plane of Fig. 13 near Pittsburgh. From Fig. 15 we may estimate a radius of streamline curvature in this region of approximately 6° of latitude. The absolute vorticity is approximately $Q = (V/R) + \frac{\partial V}{\partial n} + f \cong 37.4 \times 10^{-5}\ \mathrm{sec}^{-1}$ and the potential vorticity within the stable and strongly shearing layer slightly south of Pittsburgh (Fig. 13) is $P \cong 50.7 \times 10^{-9}\ g^{-1}$ cm. sec. deg.

Thus it appears that the cyclonic side of the northwesterly jet branch merges completely with the southwesterly one, generating subsidence motion within a dry, stable layer of strong cyclonic shears and high values of potential vorticity.

From the cross-section in Fig. 10 it is evident that highest values of potential vorticity within the southwesterly jet branch are associated with potential temperatures of 330° to 350°K. Values of P of the same order of magnitude appear within the same potential temperature range in Fig. 13 over Pittsburgh. Since in the latter cross-section only one jet maximum appears, we may conclude that the cyclonic side of the southwesterly jet branch overrides the cyclonic side of the northwesterly one, forming a deep region of strong horizontal shears.

Relative humidities beneath the northern jet branch in Fig. 11 are quite high. Nevertheless, adiabatic descent of approximately 80 mb would cause "motorboating" measurements like that in Fig. 14. Assuming a steady state, a descent of at least 50 mb is indicated from Green Bay (GRB) to Pittsburgh (PIT) along the 330°K isentropic surface. In agreement with the earlier case study by Reiter and Nania (1964), the dry air in the jet stream front is associated with a slight northerly component of flow, while the moist air containing the observed cirrus clouds shows a southerly wind component. Thus, the subsidence of air from the northern jet branch underneath the southern branch is corroborated by a rotation component $\frac{\partial \vec{v}}{\partial z} > 0$.

Reiter and Nania (1964) have commented on the fact that "clear-air turbulence" (CAT) is frequently found in regions of turning of wind with height as is the case where two jet branches are "crossing over", generating a large vertical wind-shear vector (see also Reiter, 1964). Fig. 17 contains CAT reports over the eastern United States within $\pm$ 6 hours of map time. A number of these reports lies in the region where winds are backing with height (Fig. 14). Although the thermal stability in this region is considerable (Fig. 13), the prevailing vector-wind shears produced by $\frac{\partial V}{\partial z}$ and $\frac{\partial\,(\mathrm{direction})}{\partial z}$ obviously provide the supply of turbulent kinetic energy observed in CAT (Reiter and Burns, 1965).

A number of moderate to severe CAT reports lie close to the shadow band reported by Oliver et al. All of them obviously occur at levels lower than the cirrus cloud deck, except for one report at 35,000 ft near Nantucket Island.

CONCLUSIONS:

Shadow bands in TIROS cloud photographs, such as the one observed by Oliver et al. between two "merging" jet branches may be used to illustrate the deficiencies of standard jet-stream nomenclature:

(1) Two well established jet branches, apparently approaching each other and departing again judging from 250-mb analyses, may not necessarily meet all characteristic criteria of PFJ and STJ. Especially the criteria that baroclinicity underneath the STJ is confined to the upper troposphere, and that low tropospheric frontal systems should be absent, are not satisfied in the present case - even though the southern jet occurs at a level (ca. 200 mb) normally assigned to STJ. One, therefore, should exercise caution in applying established nomenclature. The frontal system over the Gulf of Mexico (Figs. 8 and 9) suggests that the southwesterly jet branch may actually be the remnant of an old PFJ (Reiter, 1961, 1963 b).

(2) Even the Canadian three-front, three jet stream model does not account for the flow from one jet branch into the other described in the foregoing study, and illustrated by the cirrus cloud deck which terminates abruptly in a well-defined edge. The implications from such "cross-over" flow may be of importance in stratospheric - tropospheric mass exchange, as well as in estimates of large-scale eddy transport processes. It should make some difference, for instance, whether one considers the axis of the STJ meandering around the hemisphere (Krishnamurti, 1961 a, b) as an approximate streamline, or whether one allows for a direct inflow of air from the STJ into the regions occupied by the PFJ. More research is needed for quantitative estimates of such possible effects.

(3) Ever since Schaefer's (1953) study, much discussion has appeared in meteorological literature about the correlation and the relative position of cloud forms to jet streams. No unified solution to this problem can be offered as yet, and in view of the complex vertical - motion patterns around jet streams, the existence of a simple solution seems questionable. At least in the present case,

though, a seeming discrepancy can be resolved: if one had hoped that cirrus clouds, when present, would remain on the anticyclonic side of jet streams, the crossing over of such cloud banks from one jet branch to another, as observed by Oliver et al. and by Kadlec, apparently was not in strict accordance with expectations. However, if jet axes are constructed as outlined in this paper, allowing the southern jet branch to cross over the northern one, the observed high-level cloudiness remains on the anticyclonic side of the flow.

(4) The observation of "shadow bands" depends on favorable satellite attitude and sun angle. By incorporating satellite radiation data one may be able to detect similar high- and low-level cloud distributions, even in the absence of "shadow bands." No such studies have been made as yet.

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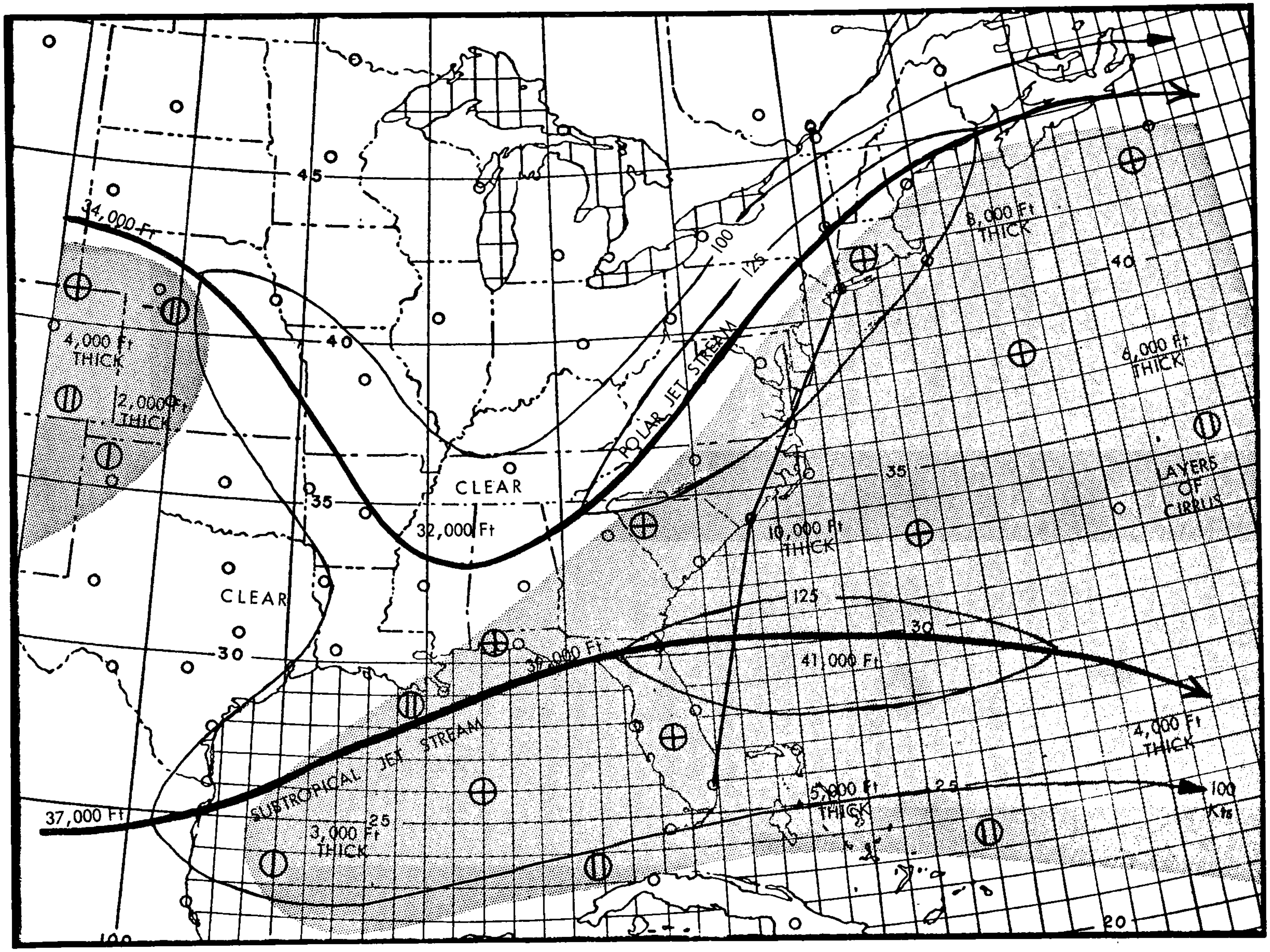

Fig. 1: Schematic cirrus distribution (shaded area) near merging jet streams. Jet axes indicated by heavy lines isotachs by thin lines. (After Kadlec, 1964).

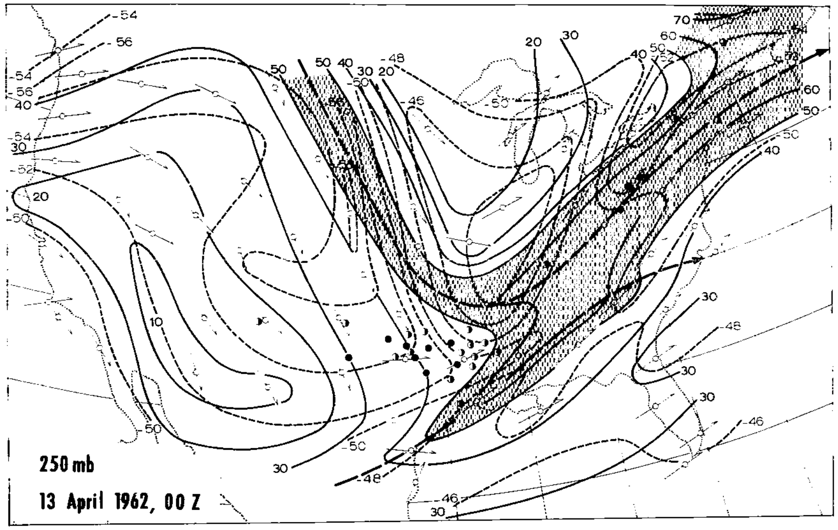

Fig. 2: 250-mb isotachs (solid lines, m/sec, areas with > 50 m/sec shaded) and isotherms (dashed lines, °C), 13 April 1962, 00 GMT. Jet axes indicated by heavy dashed lines with arrows. (After Reiter and Nania, 1964).

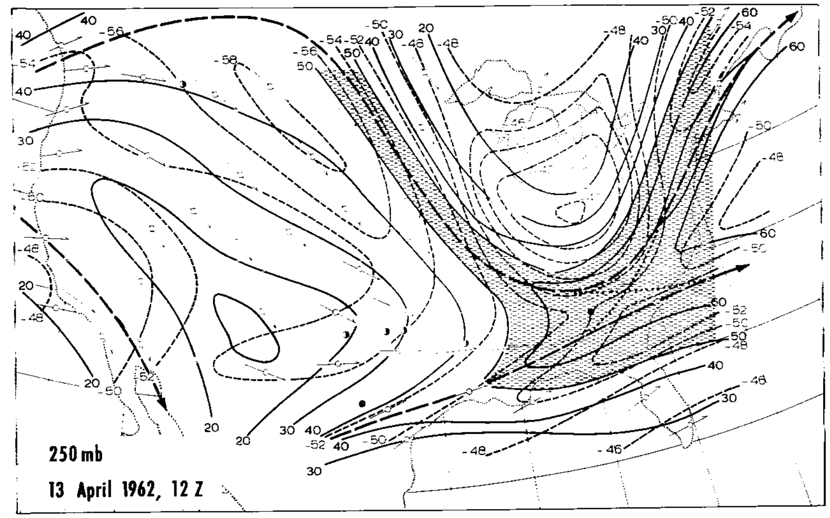

Fig. 3: Same as Fig. 2, except 13 April 1962, 12 GMT. Dotted lines indicate cross-over of jet axes. (After Reiter and Nania, 1964.

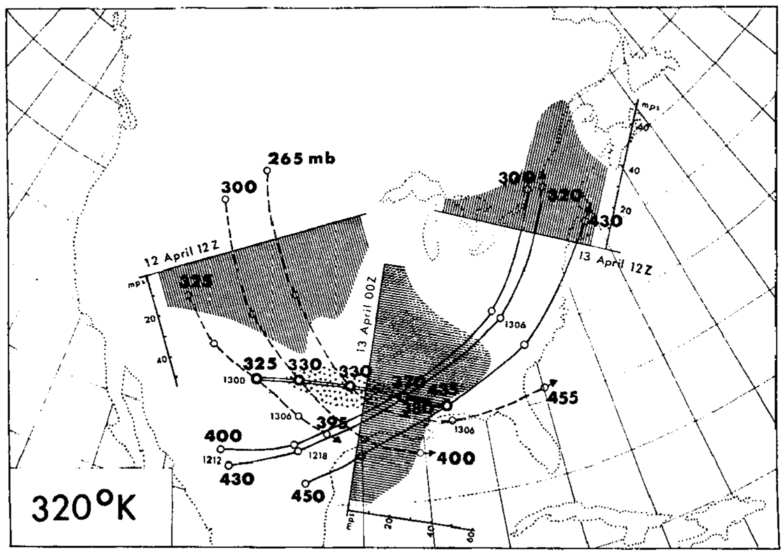

Fig. 4: Trajectories along 320° K isentropic surface tracing the air motion backward and forward from the location at 13 April 1962, 00 GCT, marked by double circles. The single circles give trajectory positions at 6-hr intervals. Dashed trajectories belong to the northwestern jet branch, solid trajectories to the southwestern one. The northernmost of the solid trajectories marks the air motion immediately to the south of the discontinuity of wind direction in the CAT region. (This region is marked by irregular shading). The double line extends along the axis of the CAT region. Isentropic wind profiles with scale in mps are entered along the solid base lines which run approximately normal to the upper flow. The profiles have been constructed for map times as indicated. (After Reiter and Nania, 1964).

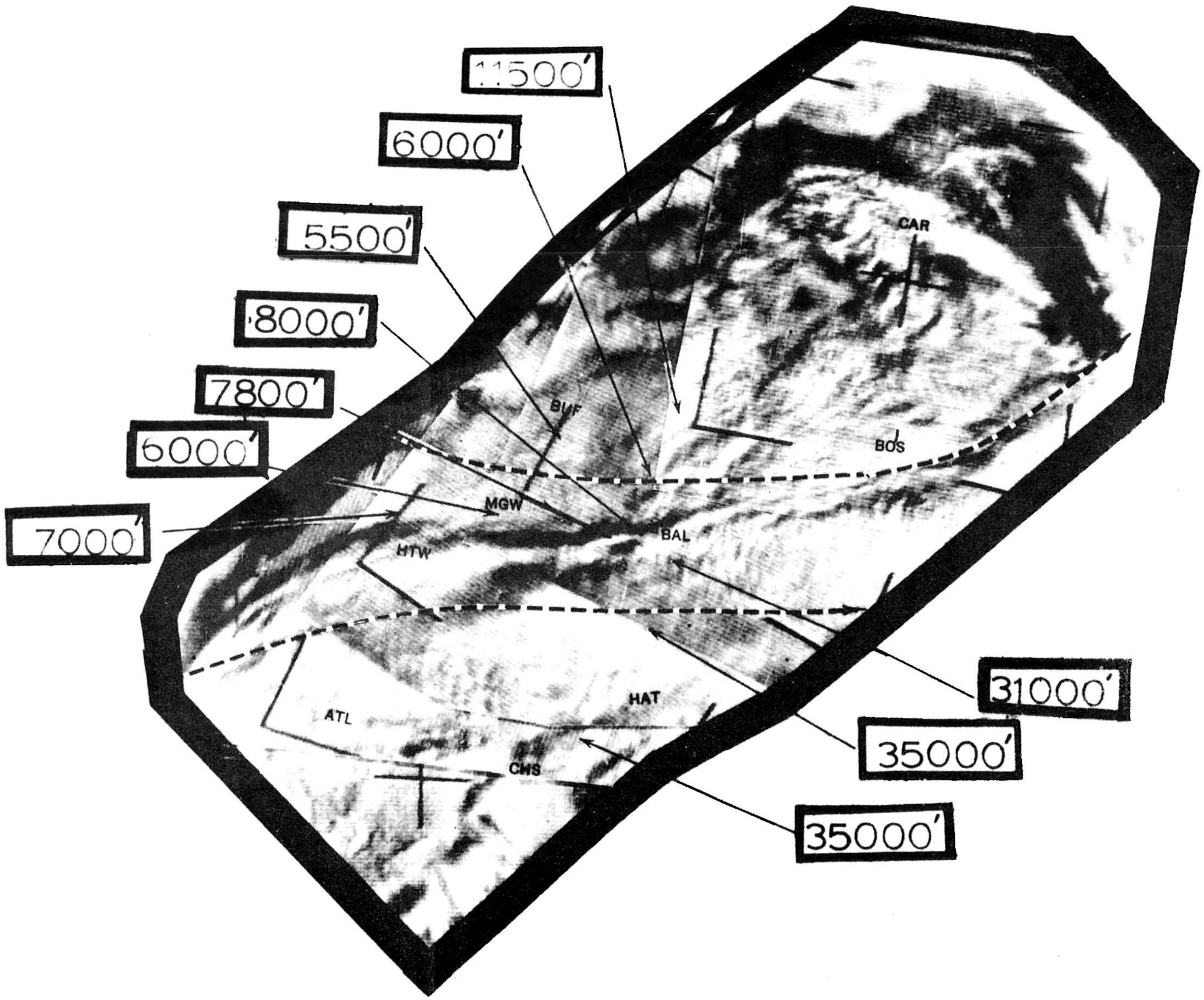

Fig. 5: A mosaic of pass 0922, TIROS VI, 1355 GMT, November 20, 1962. Height of cloud tops reported in feet. Dashed lines indicate 200-mb jet stream positions as analyzed by NMC. A dark streak ("shadow band") is clearly visible between the two jet axes. (After Oliver et al. 1964).

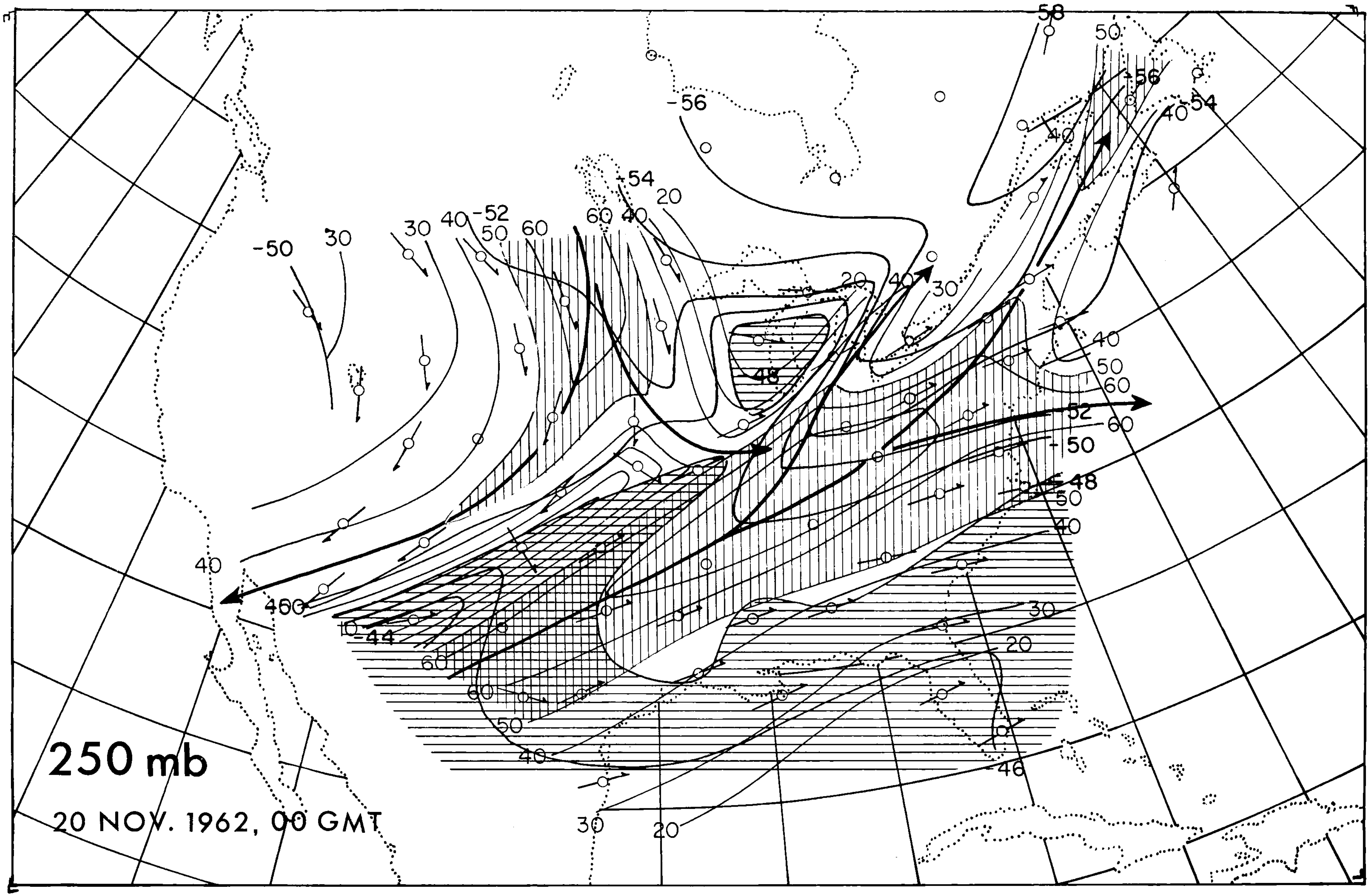

Fig. 6: 250-mb isotachs (black lines, m/sec; areas with > 50 m/sec shaded) and isotherms (red lines, °C; areas warmer than - 48° C are shaded) for 20 November 1962, 00 GMT.

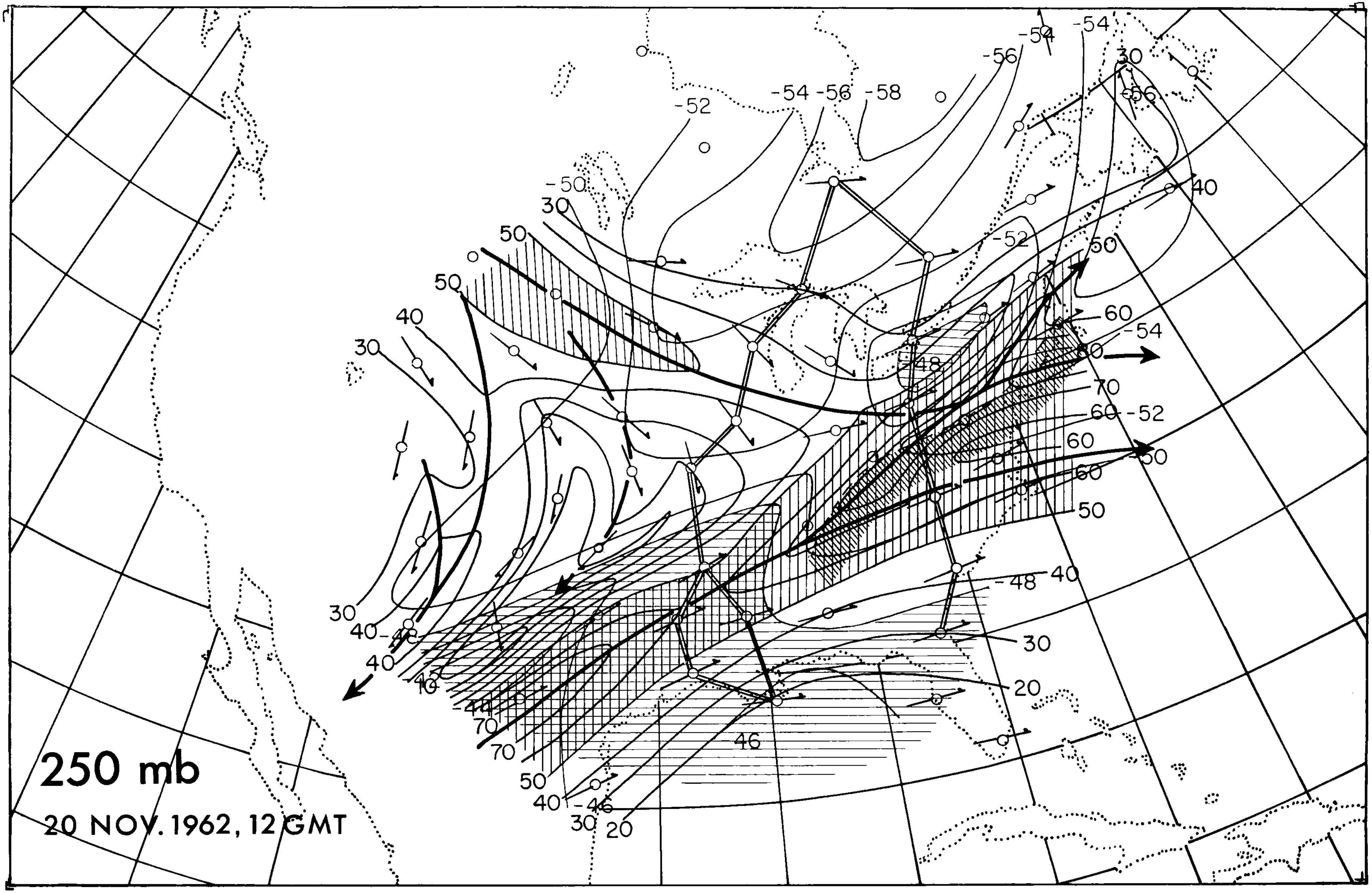

Fig. 7: Same as Fig. 6, except 20 November 1962, 12 GMT. Planes of cross-sections shown in Figs. 10, 11, 13 and 14 are indicated by double black lines. North edge of red-hatched band corresponds to shadow band observed by TIROS VI.

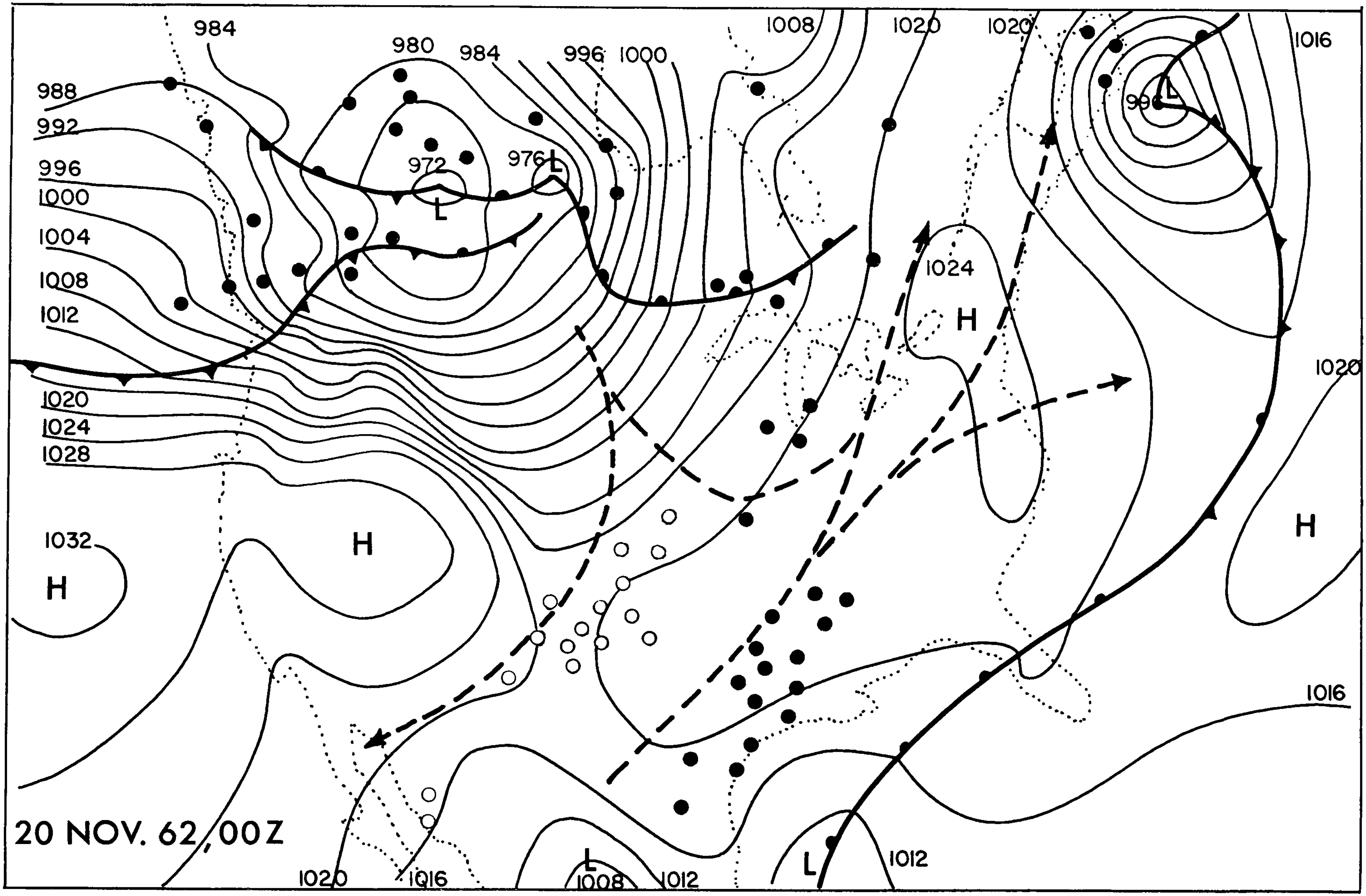

Fig. 8: Surface chart, 20 November 1962, 00 GMT. Open circles: clear skies; black circles: precipitation.

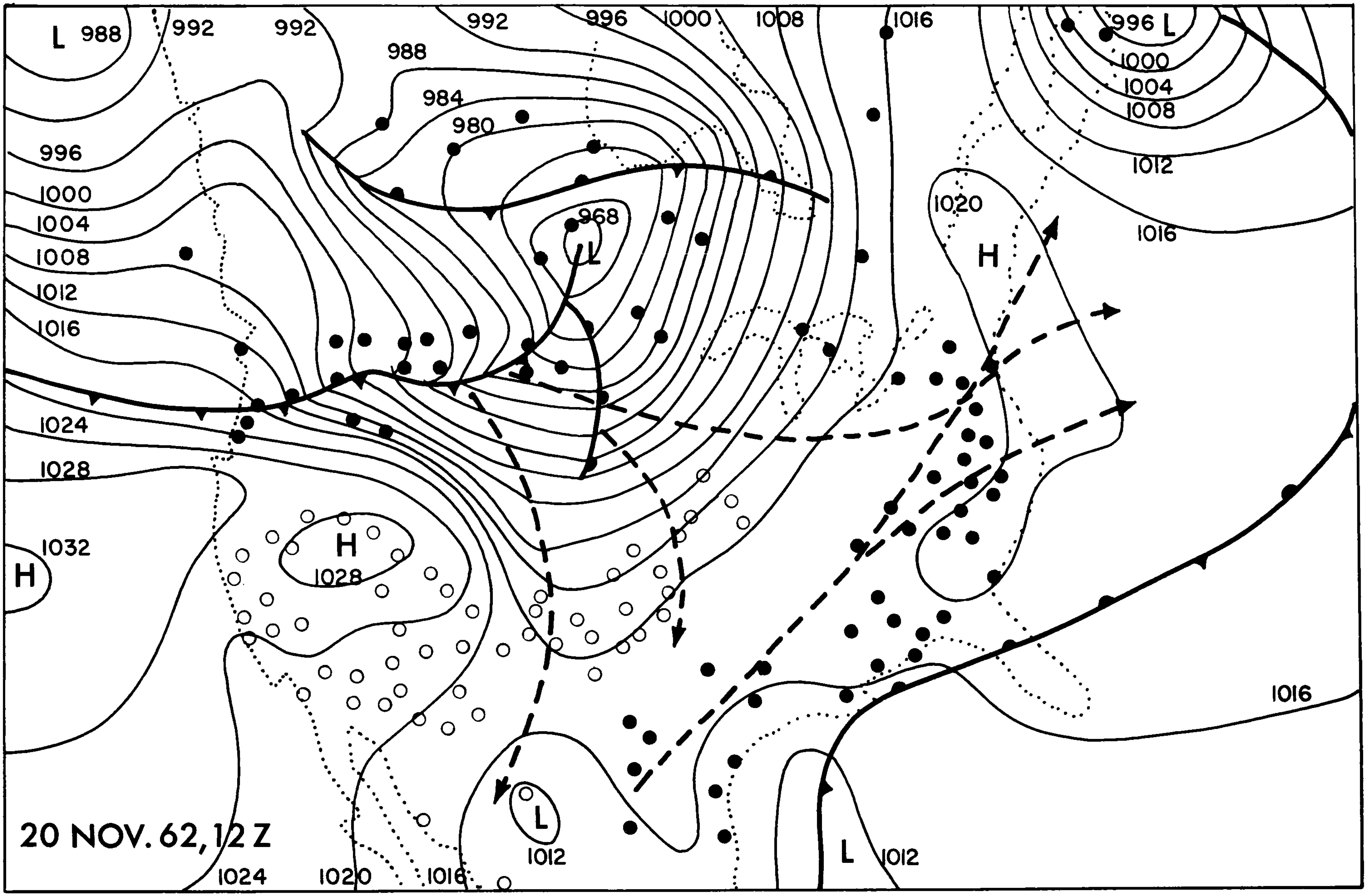

Fig. 9: Same as Fig. 8, except 20 November 1962, 12 GMT.

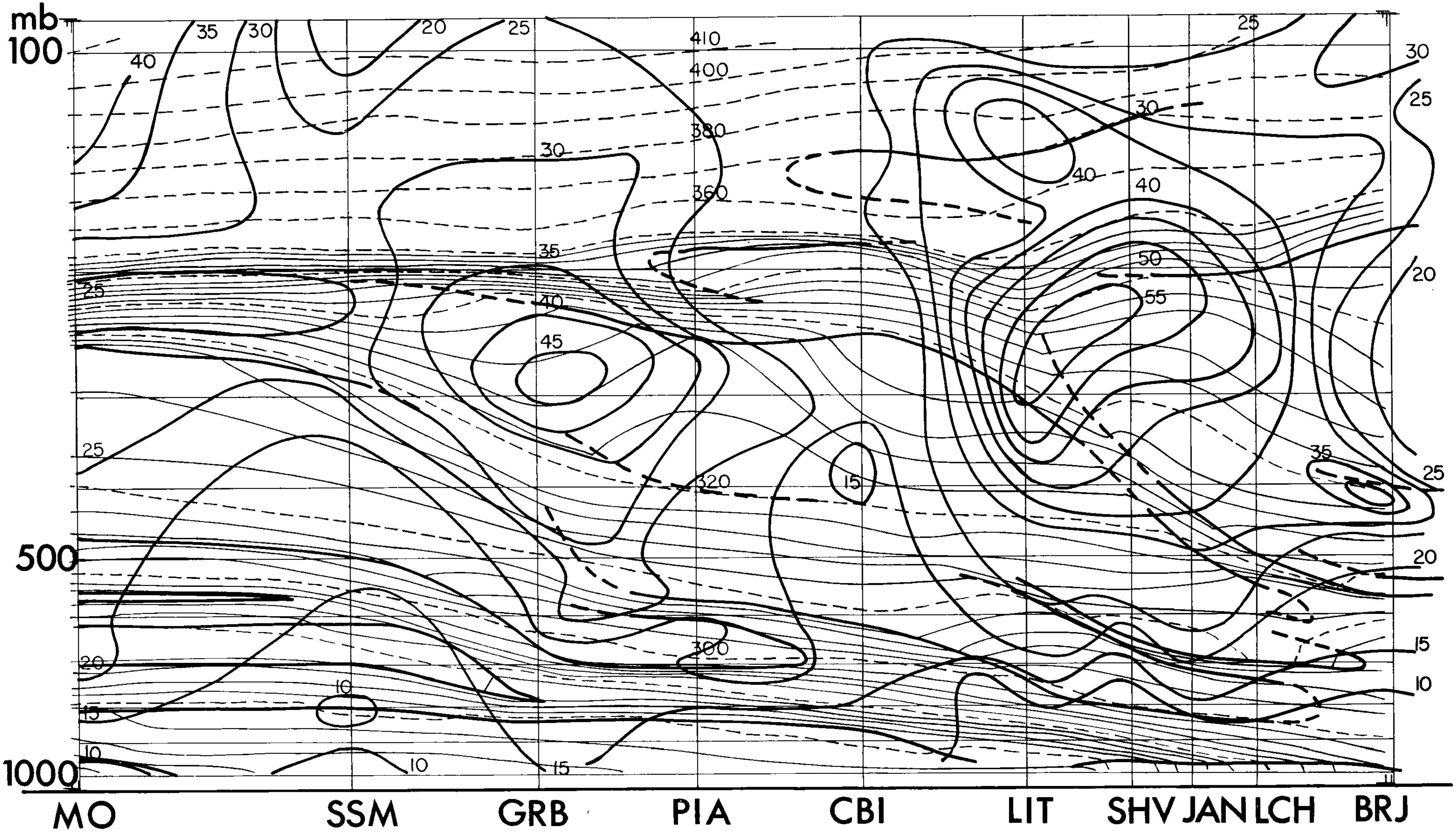

Fig. 10: Cross-section from Moosonee, Ontario, to Burrwood, Louisiana, 20 November 1962, 12 GMT. Black lines: wind speeds (m/sec); red lines: potential temperatures. Stable layers and tropopauses are marked in blue.

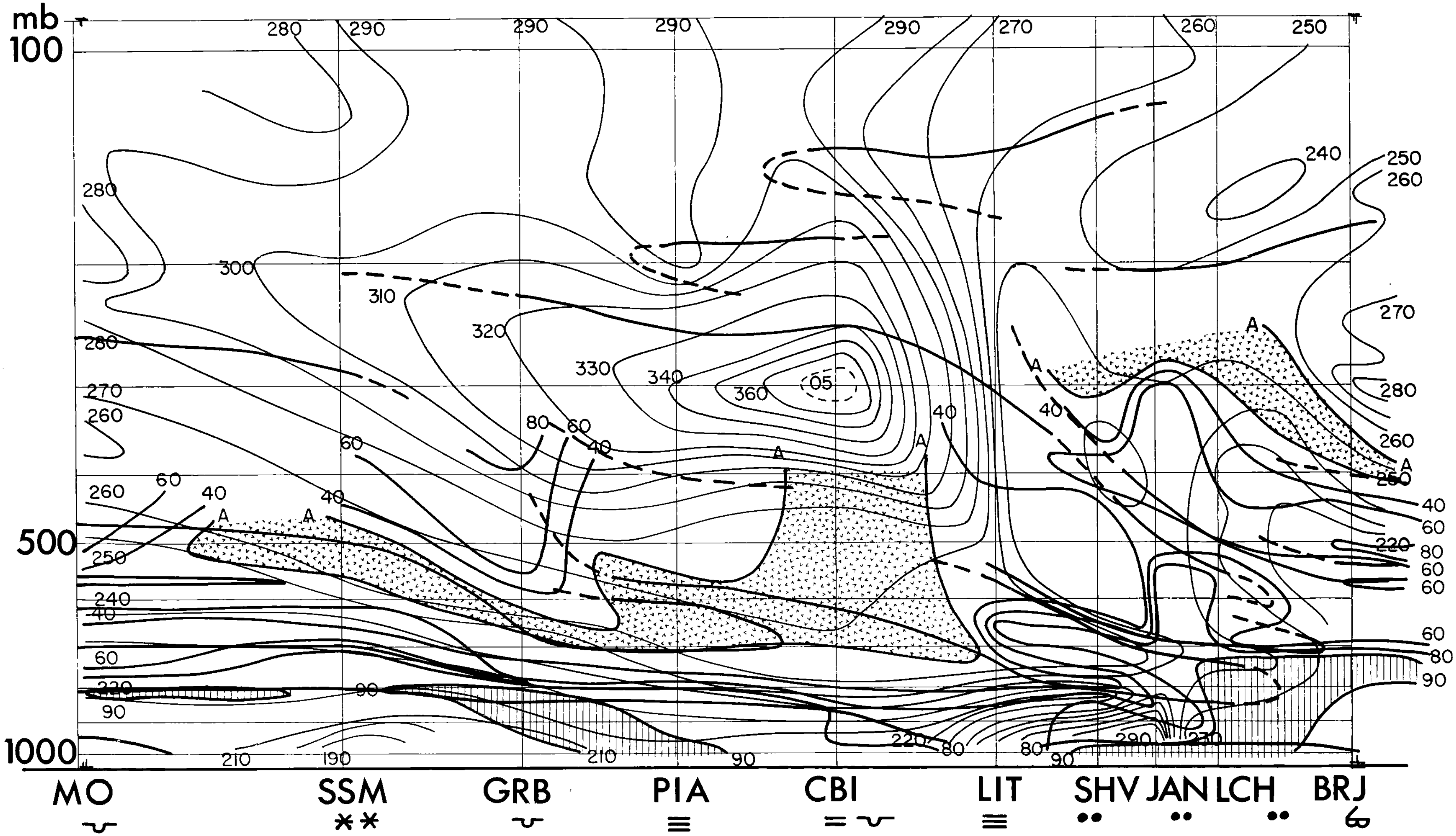

Fig. 11: Same section as in Fig. 10, except: black lines: isogons (degrees); red lines: relative humidity (per cent); "motorboating" regions (marked by letter "A"), and regions with humidity > 90 per cent are indicated by different shading.

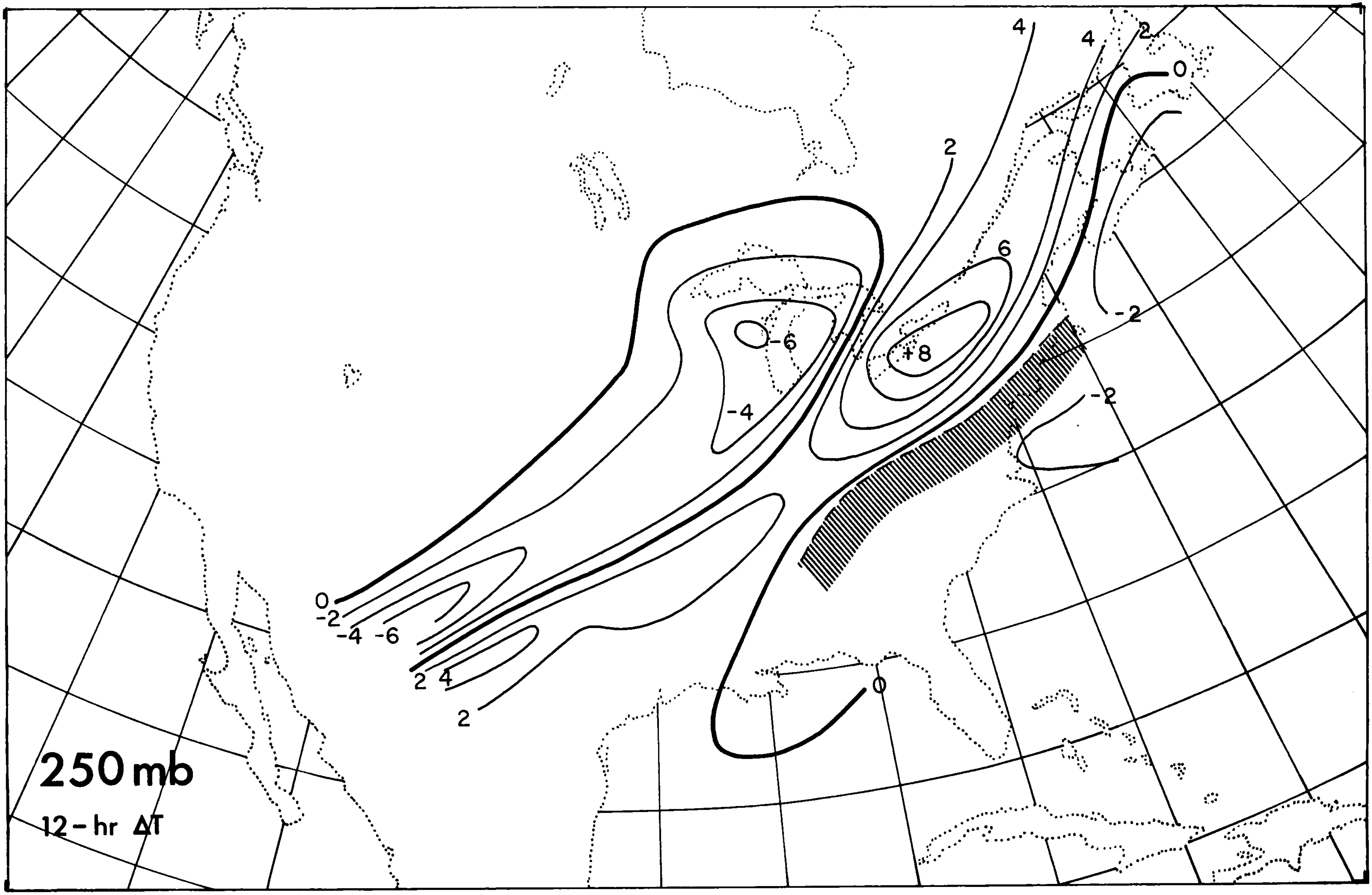

Fig. 12: 12-hour temperature changes (°C) at 250 - mb level from 00 GMT to 12 GMT on 20 November, 1962.

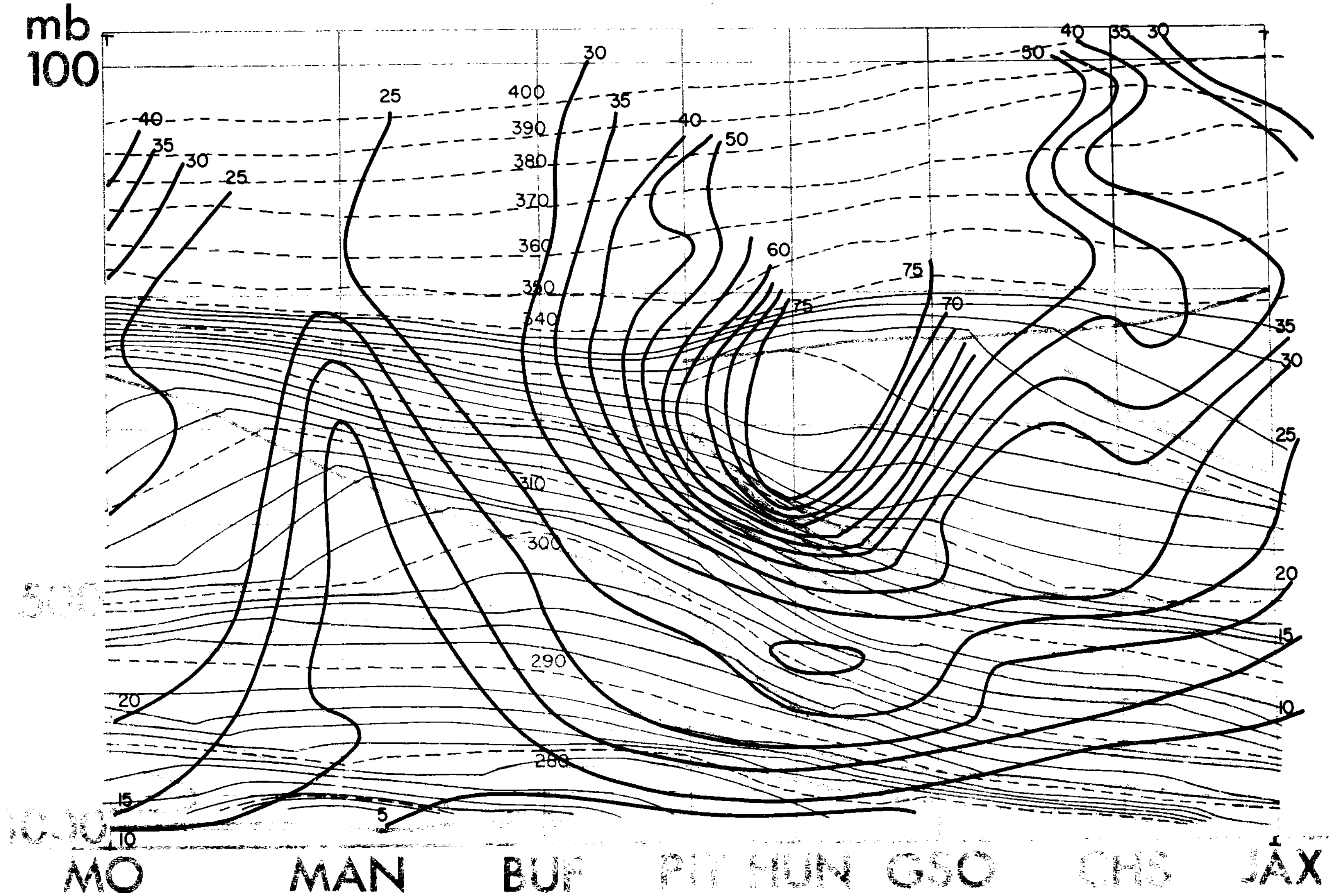

Fig. 13: Cross-section from Moosonee, Ontario, to Jacksonville, Florida, 20 November 1962, 12 GMT. Black lines: wind speeds (m/sec); red lines: potential temperatures. Stable layers and tropopauses are marked in blue.

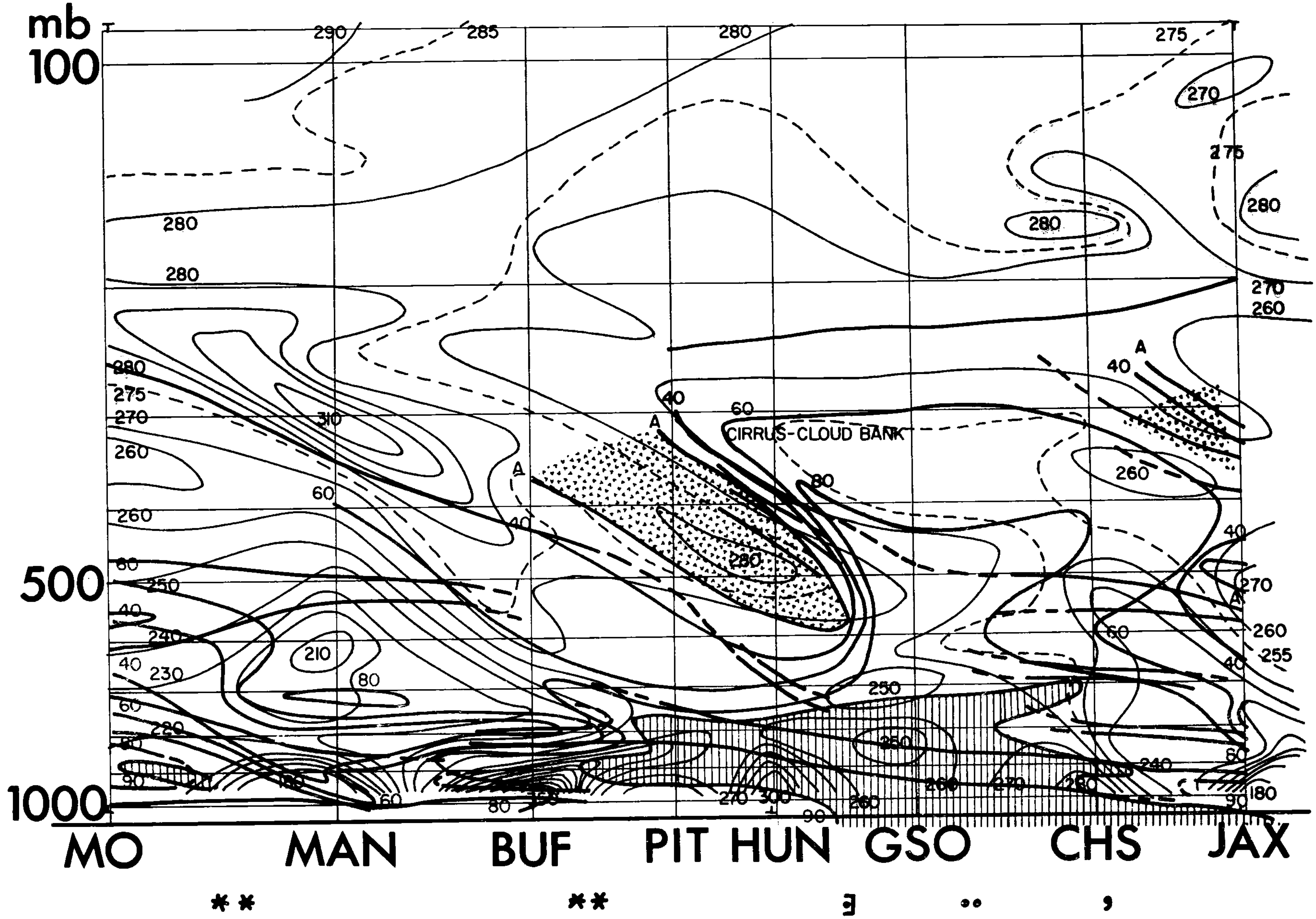

Fig. 14: Same section as in Fig. 13, except: black lines: isogons (degrees); red lines: relative humidity (per cent); "motorboating" regions (marked by letter "A"), and regions with humidity >90 per cent are indicated by different shading.

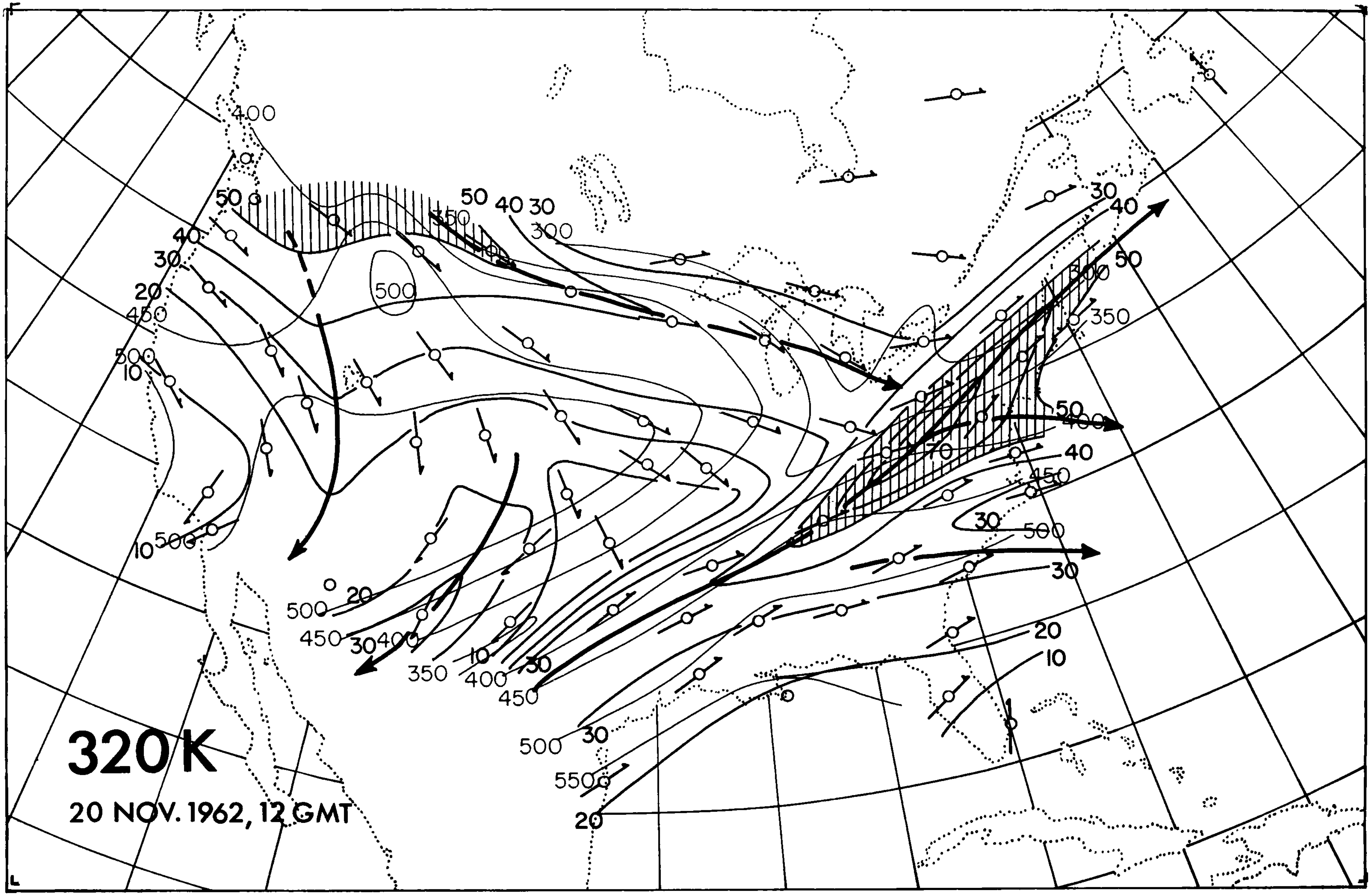

Fig. 15: Isotachs (black lines, m/sec; areas with > 50 m/sec shaded) and pressures (red lines, mb) at 320° K isentropic surface, 20 November, 1962, 12 GMT.

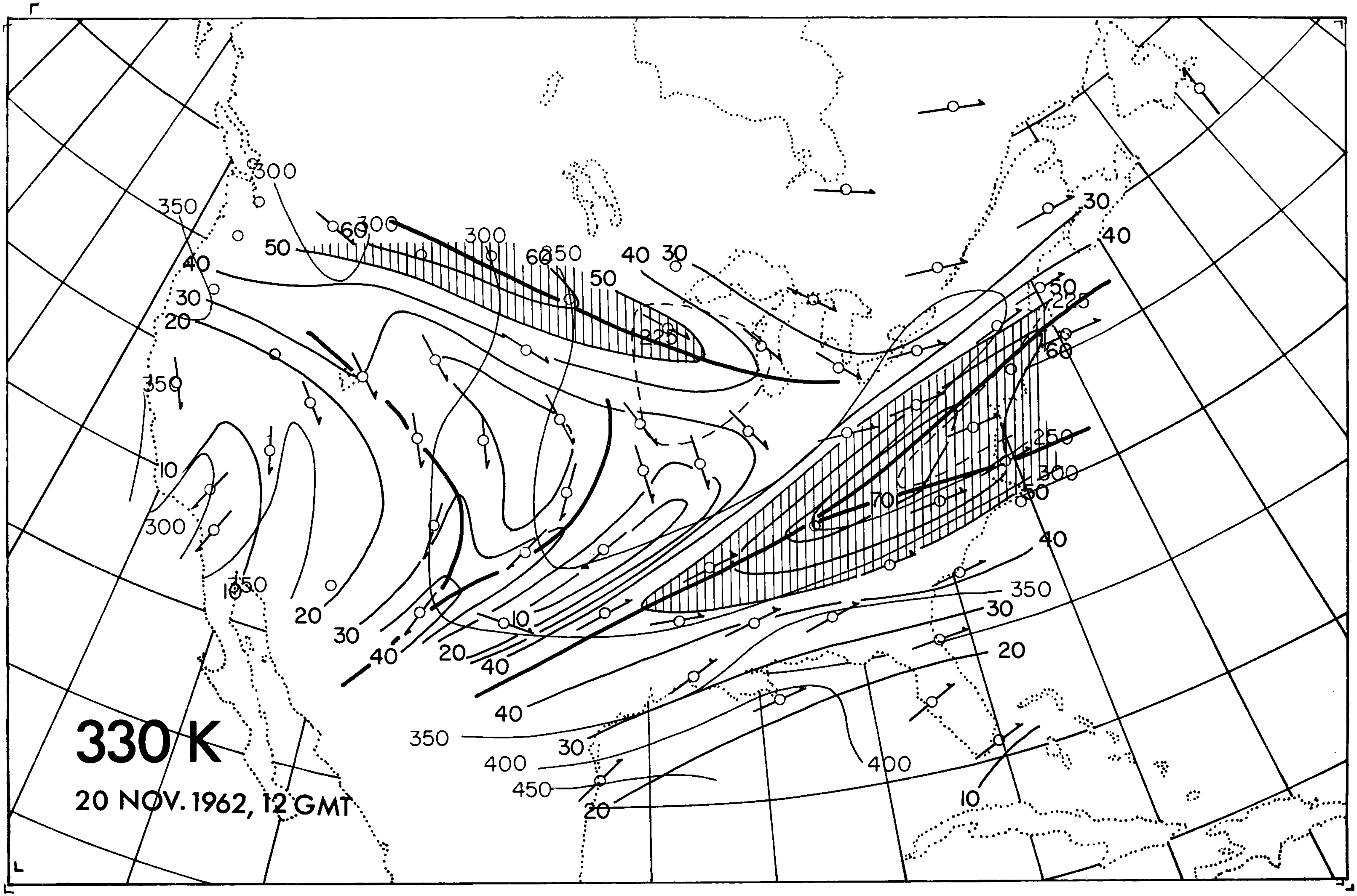

Fig. 16: Same as Fig. 15, except 330° K isentropic surface.

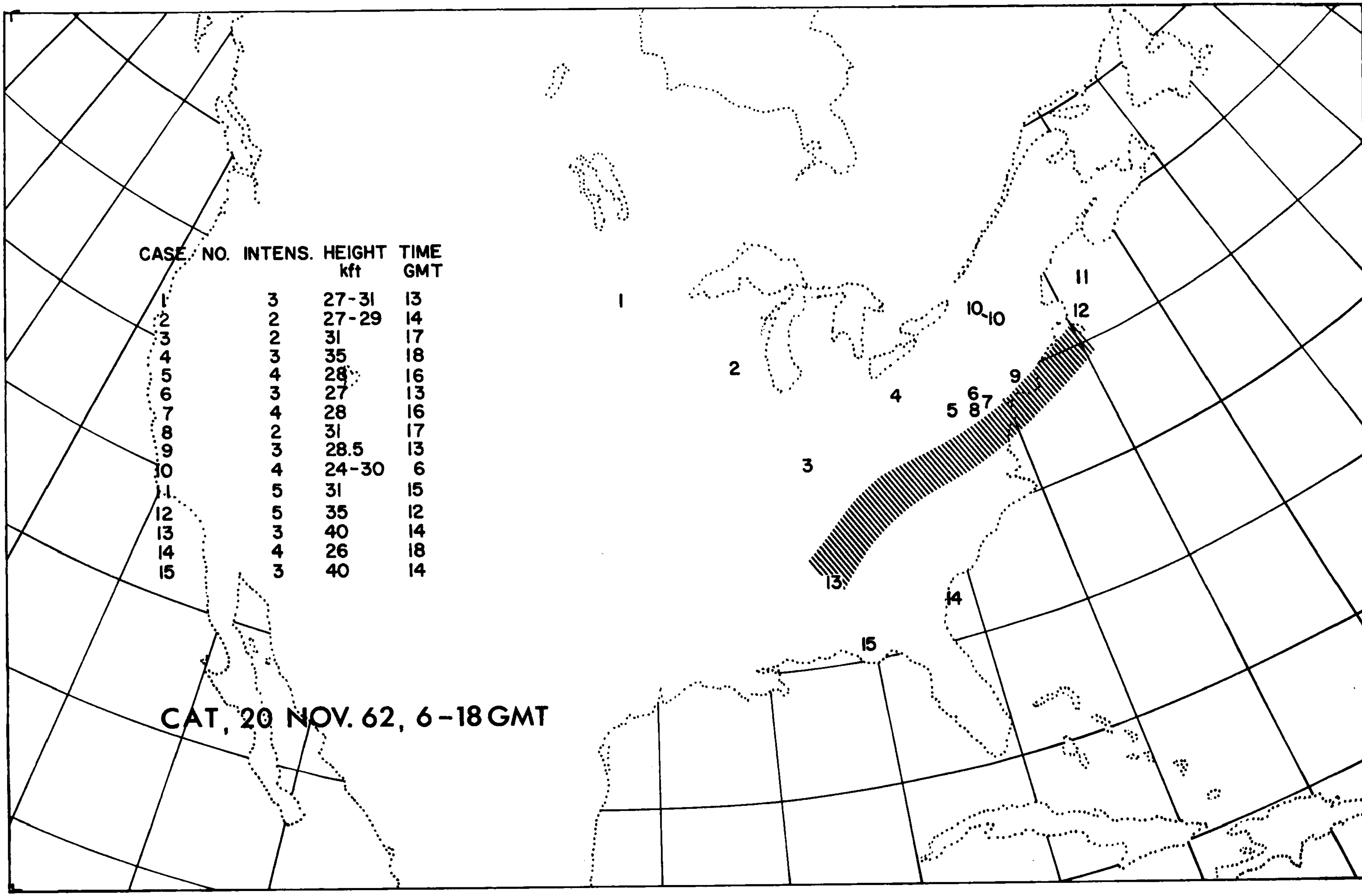

Fig. 17: CAT occurrence over the eastern United States, 20 November 1962, 06 GMT to 18 GMT. The north edge of the hatched band corresponds to shadow band observed by TIROS VI.