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A CASE STUDY OF AN INTENSE UPPER CYCLONE OVER EASTERN AND NORTHERN EUROPE IN NOVEMBER 1959

by

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Abstract

A brief survey of the life history of an intense and long-lived upper cyclone is presented. The upper cyclone was formed from an upper cold trough, a degenerated remnant of a former long-wave trough. It moved along an anticyclonally curved path, seemingly passively in the direction of the prevailing flow. A certain gradual intensification was observed to occur, but the general structure of the cyclone, illustrated by several charts and cross sections, remained unchanged. An attempt is made to connect the thermal structure of the cold low and the distribution of the precipitation observed with the vertical velocity field.

1. *Formation of the upper cyclone*

A cut-off upper cyclone is often formed in the final stage of occlusion of an extratropical cyclone. In such a case the upper cyclone is always associated with a more or less intense surface cyclone. On the other hand, upper cyclones are sometimes formed without any occlusion process and without noteworthy deepening at the surface. A case studied by PALMÉN [6] and another studied by HSIEH [4] represent this type of formation, and the case presented in this paper falls into the same category.

In Fig. 1 a series of 500 mb topographies is presented, which indicate the formation of the upper cyclone in the region of the Ural Mountains. At 0000 GCT, Nov. 8, 1959, (Fig. 1c), a weak cyclonic centre was formed in the weak pressure trough which, during the preceding days, had been moving over the Arctic Sea and northern parts of the Soviet Union towards the east and southeast. A long narrow tongue of cold air lay along the axis of the trough, which in fact was degenerated remnant of the former long-wave trough which some days earlier had occupied the eastern part of the North Atlantic.

At approximately the same time as the cyclonic centre appeared in the trough, anticyclonic development upstream from the trough resulted in a considerable pressure rise and formation of the separate anticyclonic centre over Northern Russia (Fig. 1c). A very pronounced anticyclonic air current was observed over the Arctic Sea.

At 0000 GCT, Nov. 9, 1959, the well-defined cut-off upper cyclone was located south of the strong anticyclone extending from Western Siberia to Scandinavia. The curved line of the maximum cyclonic wind shear stretching to the east of the upper cyclone can be identified as a part of the former trough axis along which the cold air disappeared. The cross section in Fig. 2 shows that to the east of the upper cyclone the cold air tongue barely reached 700 mb level. Marked subsidence in the cold air mass is indicated by the pronounced stability and low relative humidity of the air. In the centre of the upper cyclone, by contrast, the cold air extended well above the 500 mb level, and the high relative humidity of the air implies that no significant subsidence had occurred there; ascending motion seems more likely in this central region.

During the period of the above-described development the situation at the surface remained practically unchanged. An extremely strong surface anticyclone with surface pressure in its central region around 1050 mb extended from the interior of Asia to Eastern Europe. The moving upper trough and later the upper cyclone were accompanied by a very weak cyclonic disturbance at the surface, which can be detected only by careful examination of the fields of the surface wind and pressure.

The development described above is essentially similar to the cases over North America studied by Palmén [6] and Hsieh [4]. However, the upstream anticyclonic development is much more pronounced in this case than in the upper-cyclone formations cited. The pressure field in Fig. 1d has the characteristics of a so-called blocking situation to which great persistence is attributed. Perhaps this fact gives a clue to the persistence of the upper cyclone studied in this paper.

J. BJERKNES [3] proposed a fairly simple explanation of the causes leading to the deepening of an upper trough. According to him, such a development is due to the advection of excessive anticyclonic vorticity downstream from the wave crest of the concentrated upper flow. The course of development described above fits in fairly well with the scheme given by Bjerknes. Although the sparse data do not allow any detailed analysis of the upper wind field in the Arctic, it is plausible that upstream from the degenerating upper trough the anticyclonic vorticity must attain quite high values, and as Bjerknes pointed out, this suffices for initiating and effecting the observed deepening of the trough.

2. *Movement of the upper cyclone*

The path of the upper cyclone at the 500-mb level is presented in Fig. 3. The upper air charts of Nov. 9—20 give evidence that the movement of the upper cyclone from day to day is determined by the prevailing tropospheric flow around the warm anticyclones. The curious loop between Nov. 10 and Nov. 15 can be explained simply by the weakening of the warm anticyclone over Western Siberia and formation of the new steering anticyclone over Northern Russia and Scandinavia; the upper cyclone was trapped in Nov. 13 by the anticyclonic flow around the new high.

It is interesting to note that the movement of tropical cyclones is assumed to be determined by the same principle. Because the large-scale pressure distribution in the case studied here resembles the permanent situation in the Tropics, it is not surprising that the path of the upper cyclone has several features in common with the typical tracks of easterly waves and hurricanes.

The well-known rule of SCHERHAG states that an upper cyclone (or a »drop of cold air») is steered by the gradient flow at the surface. This rule is affirmed in this case, with the reservation that the speed of the upper cyclone is smaller than that of the steering flow. In the region of highly persistent warm anticyclones the direction of the surface gradient wind and that of the mean tropospheric flow do not differ much, and consequently, in fact, the rule of Scherhag must be consistent with the more general steering principle assumed to be applicable in this case.

Berson [2] has approached the problem of movement of upper vortices from an interesting point of view. In the case described by him an anticyclone and an adjacent cut-off upper cyclone both revolved anticyclonally around a point located on the line connecting the vortex centres. The behaviour of the vortices is explained with the aid of a theory based on the hydrodynamic concept of a vortex pair. Superficial examination of the case treated in this paper gives the impression that the upper cyclone and the adjoining anticyclone behave qualitatively like the vortices in the case studied by Berson.

Obviously the concept of passive steering alone is not sufficient to explain the movement of upper cyclones. In a more complete theory the interaction between the upper cyclone and its environment must be taken into consideration, and probably, the internal dynamics of the upper cyclone as well.

3. *Structure of the upper cyclone*

The upper-air charts in Figs. 4, 5, 7 and 9 show the characteristic structure of the cold core upper cyclone. The intensity of the almost symmetric low is greatest in the middle and upper troposphere (Figs. 7b—c), while at the stratospheric and lower tropospheric levels it is not so pronounced (Figs. 7 a, d). At 1200 GCT, Nov. 16, no real low pressure centre existed below the 850 mb level, but only a low-pressure trough.

The general appearance of the upper cyclone discussed remained unchanged during its whole life-time. A slight deepening, however, was perceptible during the period Nov. 11—17. The sinking of the pressure surfaces in the centre of the cyclone could first be observed in the stratosphere, at the 200-mb level, and then successively at lower levels, until on Nov. 13 even at the surface a very weak and diffuse low pressure centre was formed. The deepening in the upper troposphere continued steadily at the rate of about —50 gpm per day. In the lower troposphere the deepening became slower and ceased transiently on about Nov. 16, but then began again, and at 1200 GCT, Nov. 17, the cyclone was deepest at all levels.

The main features of the thermal structure of the upper cyclone concerned agree with those described, for example, by Palmén, [6]. The cross sections in Figs. 6, 8 and 10 show that the lower troposphere was occupied by a pronounced body of cold air, sometimes termed a »cold dome». A zone of strong baroclinity separated it from the surrounding warm air, but no fronts involving that zone have been drawn. At the surface no fronts or frontlike discontinuities could be observed.

The most peculiar feature in the thermal field of this upper cyclone is the well-defined funnel-shaped surface of discontinuity in the middle and upper troposphere. It intersects the quasihorizontal pressure surfaces (Figs. 5, 7b, c, and 9) along a distinct line of minimum temperature, and thus represents a discontinuity surface in the temperature gradient field. Such formations are not infrequent in the atmosphere (PALMÉN [6], [8],) but they seldom extend from the upper tropospheric levels to well below the 500-mb surface, as in this case.

In conformity with PALMÉN, [6], the discontinuity funnel is drawn as a continuation of the tropopause. The analysis, however, could have been made along different lines. PALMÉN, [7], supposed that in the detailed analysis such tropopause funnels may be split into several quasi-horizontal leaves. ORIHATA [5] has studied a case where a similar discontinuity is well below and fully separated with the continuous subtropical tropopause over Japan. On the other hand, with small modifications the discussion given by REED and DANIELSEN [9] concerning the analysis of the tropopause in the vicinity of upper frontal zones supports the form of analysis used here.

The funnel-shaped discontinuity divides the upper cyclone into two parts of different character: the cold core vortex below and the warm core vortex aloft. The warm core part of the upper cyclone within the funnel seems to merge with the stratospheric vortex without any noticeable boundary.

In the thermal field of the upper cyclone certain changes occur at the same time as the upper cyclone is deepening. The minimum temperatures found near the centre of the cyclone at the 500, 700 and 850-mb surfaces drop and the areas bounded by fixed isotherms around the minima increase, indicating an expansion of the volume of the cold dome.

Because the cold dome is surrounded by warmer air on all sides, the cooling cannot be due to horizontal advection. Radiational effects, on the contrary, can with good reason be suspected to contribute to the temperature fall. The most obvious factor responsible for the observed cooling, however, is the ascending motion, which gives rise to the adiabatic cooling of the air. The existence of large-scale ascending motion in the region of the upper cyclone discussed is substantiated by the weather reports, which refer to stratiform middle clouds and to continuous snowfall as the predominant type of precipitation.

When the cross sections in Figs. 6, 8 and 10 are compared, it can be observed that the bottom of the funnel-shaped surface of discontinuity gradually descended. At 0000 GCT, Nov. 18, the sounding curve of Stockholm located it at the 590-mb level. At that time the thermal structure of the upper cyclone was most pronounced. The intense cooling in the lower troposphere and the advection of warm air from the south to the Baltic Sea and Finland created the very strong thermal gradient around the centre of the cyclone at the 500-mb surface (Fig. 9), and strengthened the solenoid field.

5. *Situation at the surface*

The surface chart in Fig. 11 presents the situation at 1200 GCT, Nov. 16. A strong and extensive high pressure area covered Eastern and Northern Europe. A zone of uniform easterly to southeasterly flow with almost straight isobars ran from the Caspian Sea to Southern Scandinavia. Across this zone a weak trough of low pressure extended from White Russia to Lake Ladoga. The upper-air charts for the same synoptic time in Fig. 7 show that this trough lay right below the upper cyclone discussed in the preceding sections. During Nov. 16—17 the trough accompanied the upper cyclone, when it moved westward.

An extended precipitation area was associated with the trough, but only in a restricted part of it did the measured amount of precipitation exceed 1 mm (in 12 hours). This area is denoted in Fig. 11 by cross-hatching. Thus the most intense precipitation occurred just to the east of the trough.

The disturbance described in many respects resembles the »easterly waves» in the Tropics. Their general appearance in the fields of pressure and wind is quite similar. The distribution of precipitation is alike and they both move westward on the southern edge of a strong warm anticyclone.

According to RIEHL [10], the vertical circulation in an easterly wave is as follows: when a parcel of air approaches the slowly moving pressure wave from the east, the upwardly increasing divergence forces it to ascend. After it has passed the wave crest, it descends in the field of the upwardly decreasing divergence. Overlooking other indications, the analogy between easterly waves and their northern counterparts gives sufficient reason to conclude that the vertical circulation in the low troposphere trough discussed above was similar to that in easterly waves·

A more definitive proof can be obtained by examination of the three-dimensional motion of the air in this special case.

In Fig. 12 a chart is presented which shows the distribution of pressure and some streamlines at the surface of the constant wet-bulb potential temperature ($\Theta_w = 0°C$) at 1200 GCT, Nov. 17, when the upper cyclone was situated over the Baltic Sea. As pointed out earlier, the upper cyclone and the associated surface trough moved westward at a slower rate than the air in the lower troposphere. Thus within the area bounded by the dotted line in Fig. 12, ascending motion of air can be expected. The distribution of the 12-hour precipitation shown in Fig. 13 is in fairly good agreement. The compatibility is augmented if the exceptionally heavy snowfall along the Swedish east coast south of Stockholm can be explained as the result of the coastal effect described by Bergeron [1], among others. The coastal effect is accentuated by the strong instability which was caused when the cold continental air (temperature $-5 - -10°C$) flowed over the warm surface of the sea (temperature $+3 - +5°C$). To the west of the surface trough the streamlines in Fig. 12 indicate descending motion of air. Excluding the coastal strip mentioned earlier the precipitation in Southern Sweden was negligible.

The analogy between easterly waves in the Tropics and the case treated in this paper consequently includes the vertical circulation of air in the lower troposphere as well. The demonstrated asymmetric vertical circulation of air beneath the upper cyclone contrasts with the characteristically axial-symmetric picture of the upper cyclone.

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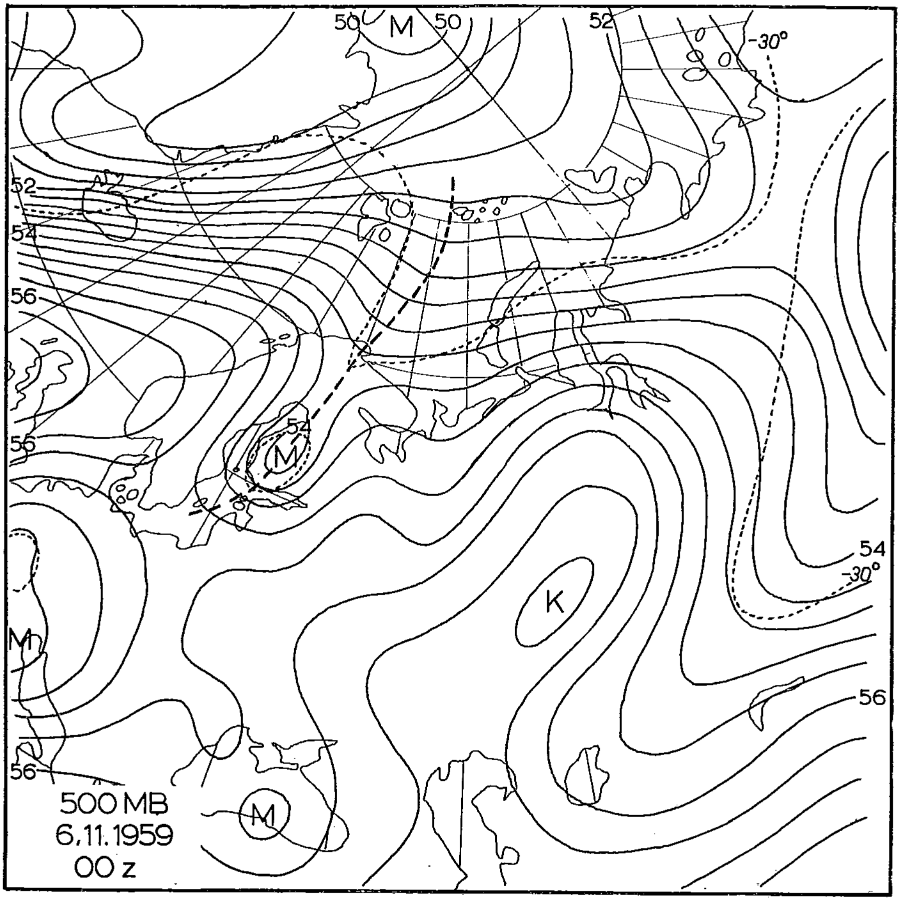

Fig. 1 a—d. 500-mb maps for 0000 GCT, November 6—9, 1959. Contours are drawn with 40 gpm intervals, height indicated in whole 100 gpm. Thin dashed line denotes —30°C isotherm, thick dashed line the axis of the cold upper-trough. M = Low, K = High.

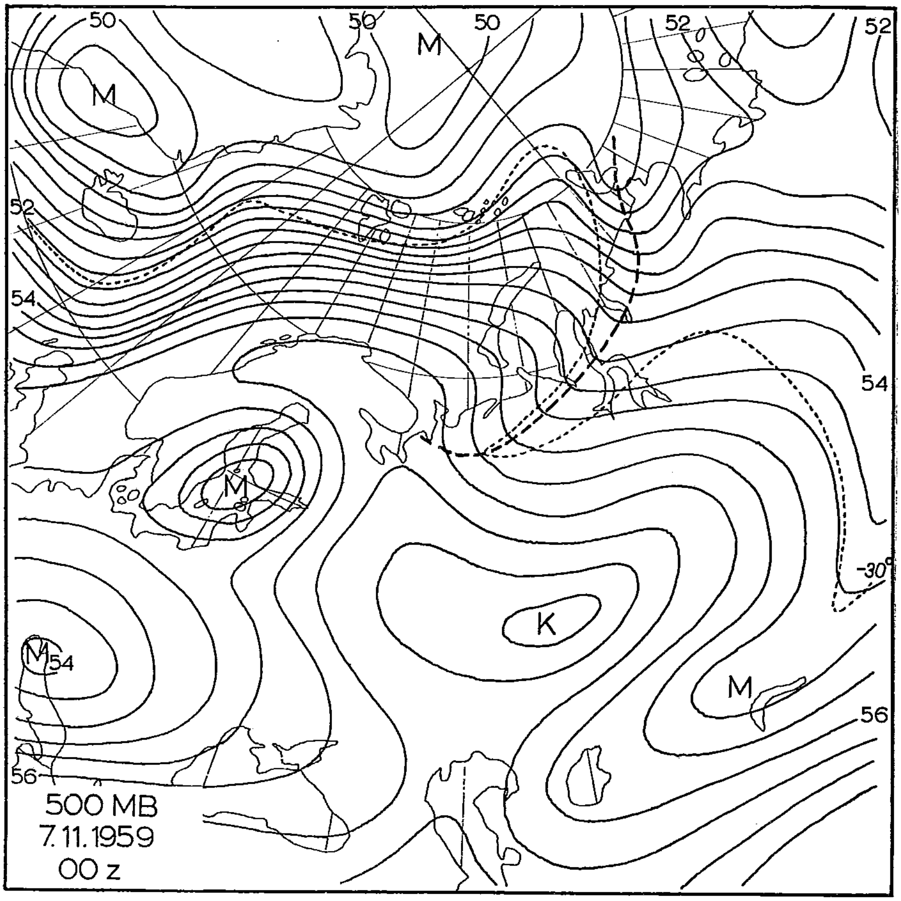

Fig. 1b.

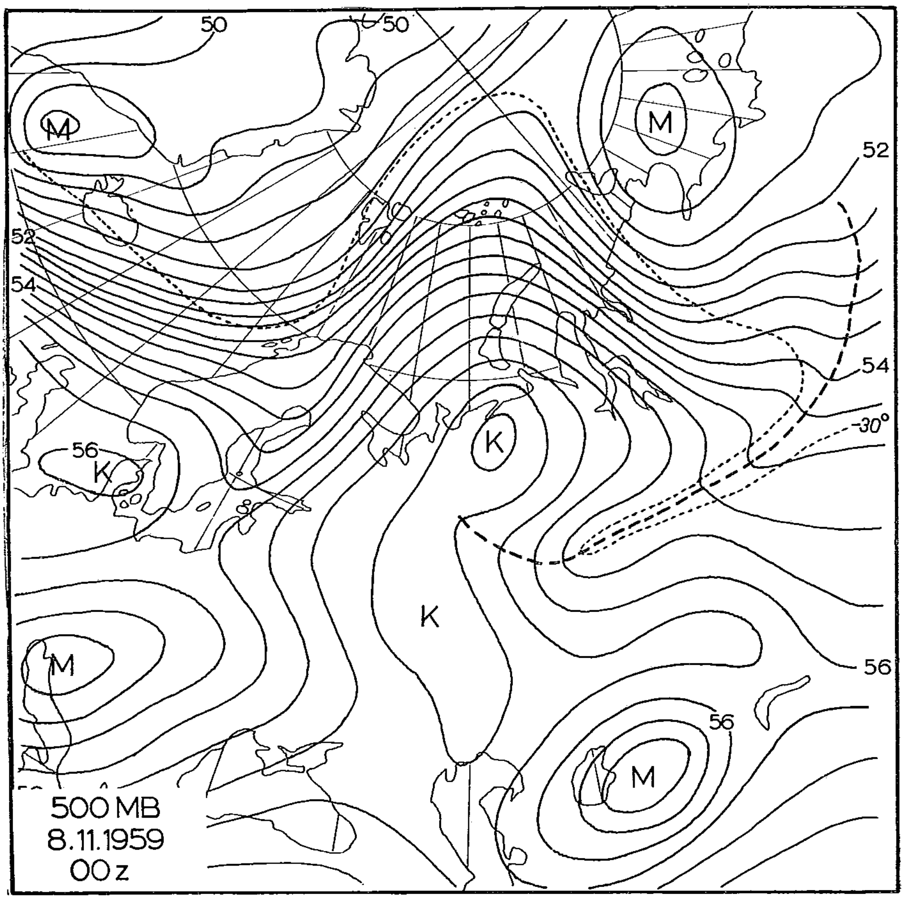

Fig. 1c.

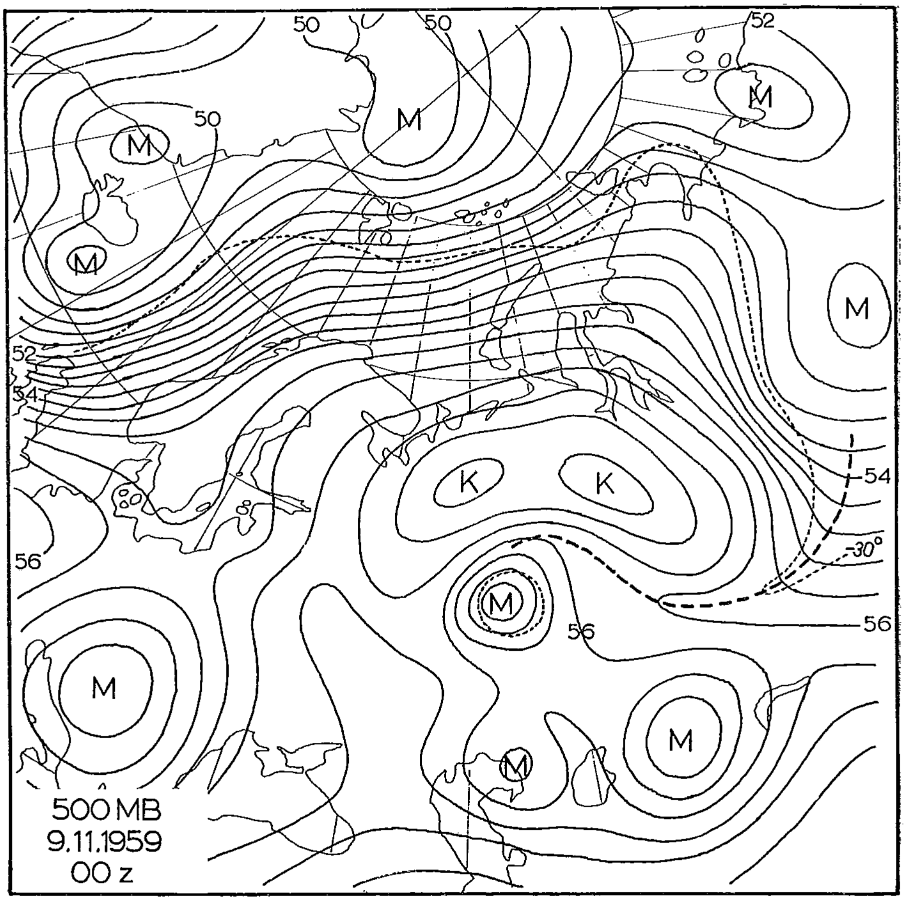

Fig. 1d.

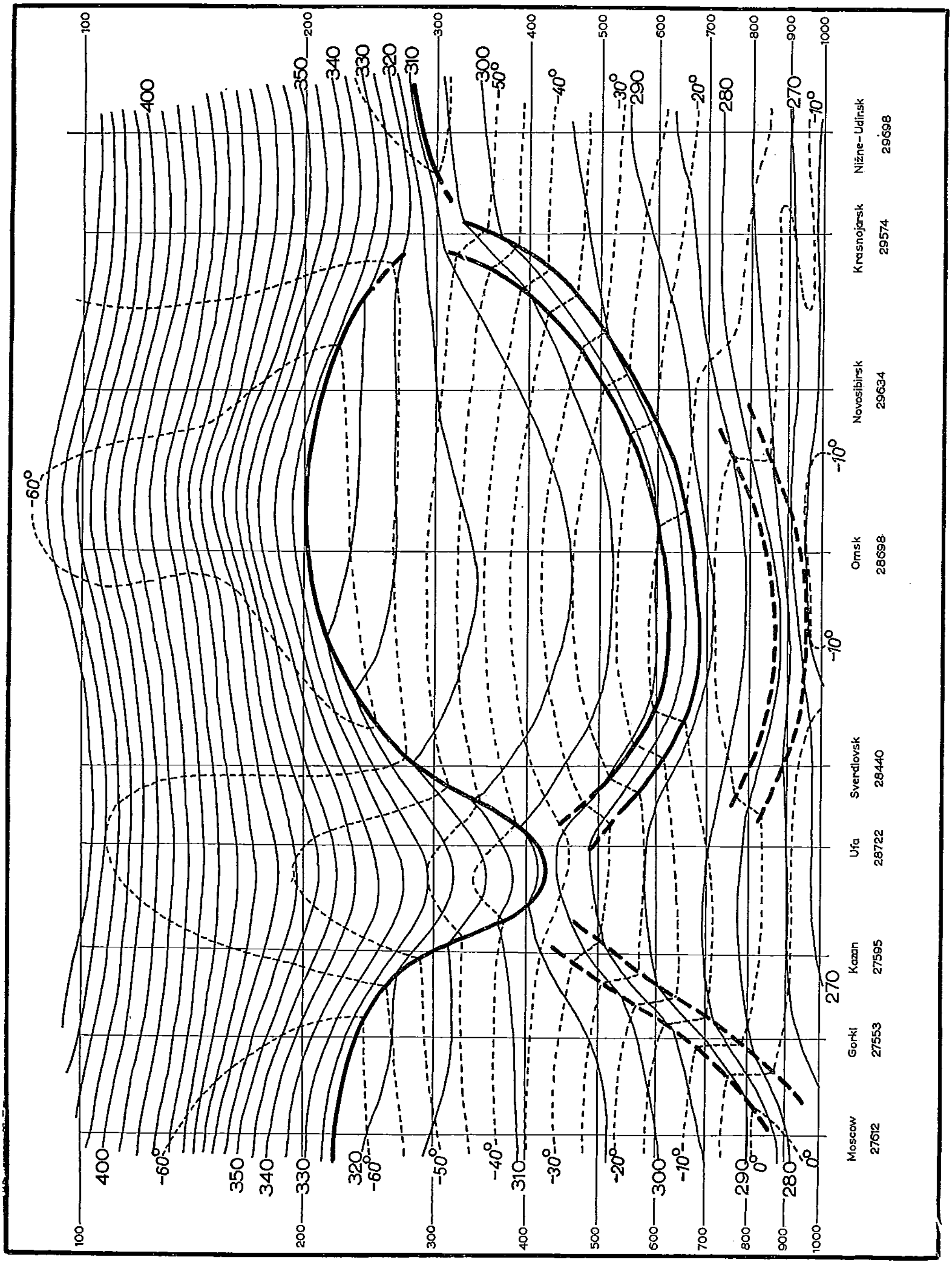

Fig. 2. Vertical section for 0000 GCT, November 9, 1959, across the upper cyclone and along the shear line denoted in Fig. 1d. Thin solid lines are isentropes, thin dashed lines isotherms. Thick lines denote lines along which the horisontal and/or vertical temperature gradient is discontinuous (*e.g.* tropopauses, boundaries of stable layers etc.).

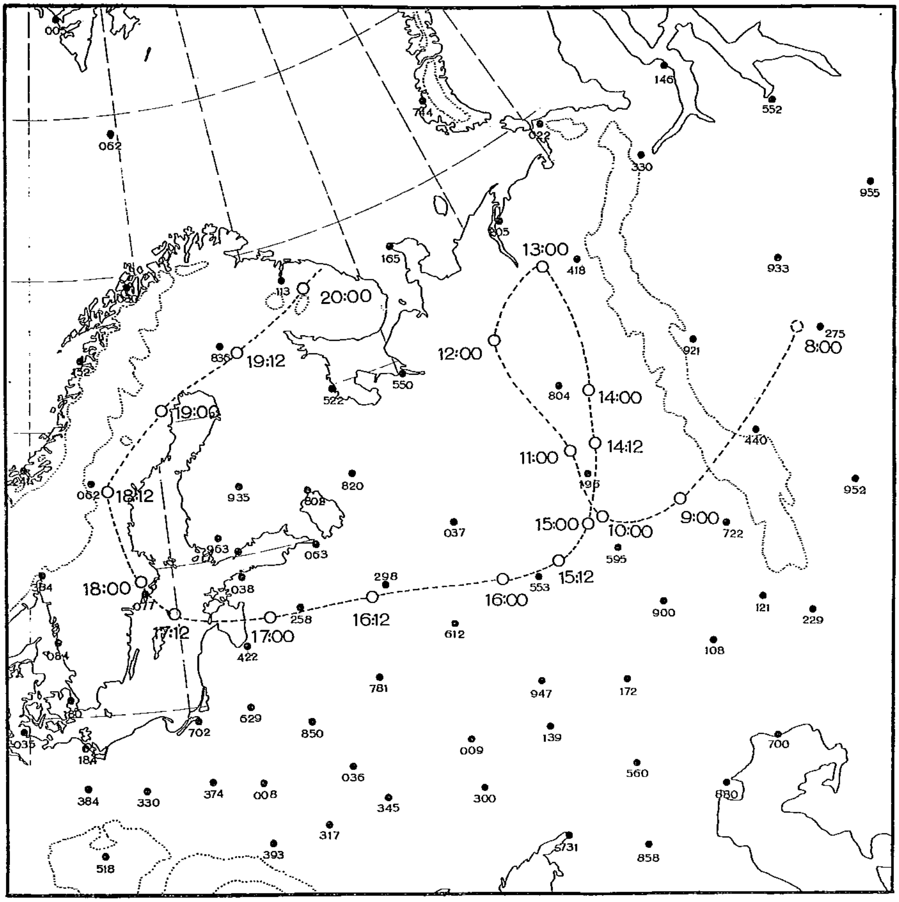

Fig. 3. The path of the upper cyclone at 500-mb level. Date and hour (GCT) are indicated at the respective positions of the upper-cyclone centre denoted by small circles.

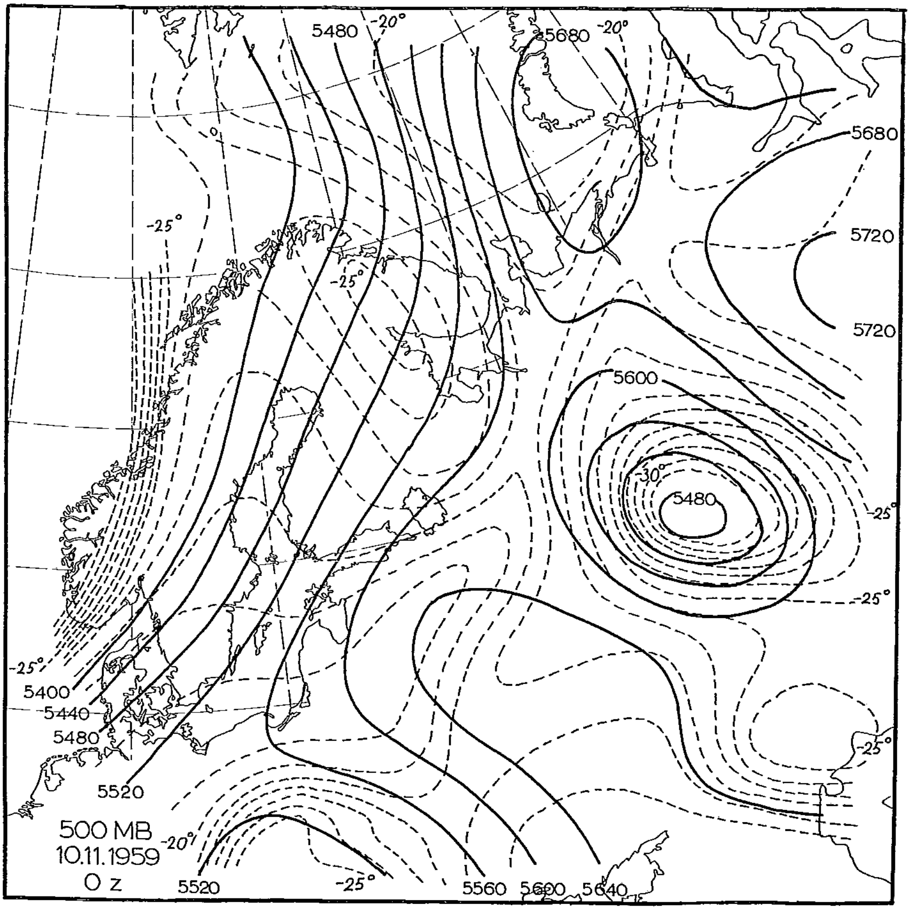

Fig. 4. 500-mb map for 0000 GCT, November 10, 1959. Contours are drawn with 40 gpm intervals, isotherms (thin dashed lines) for every 1°C.

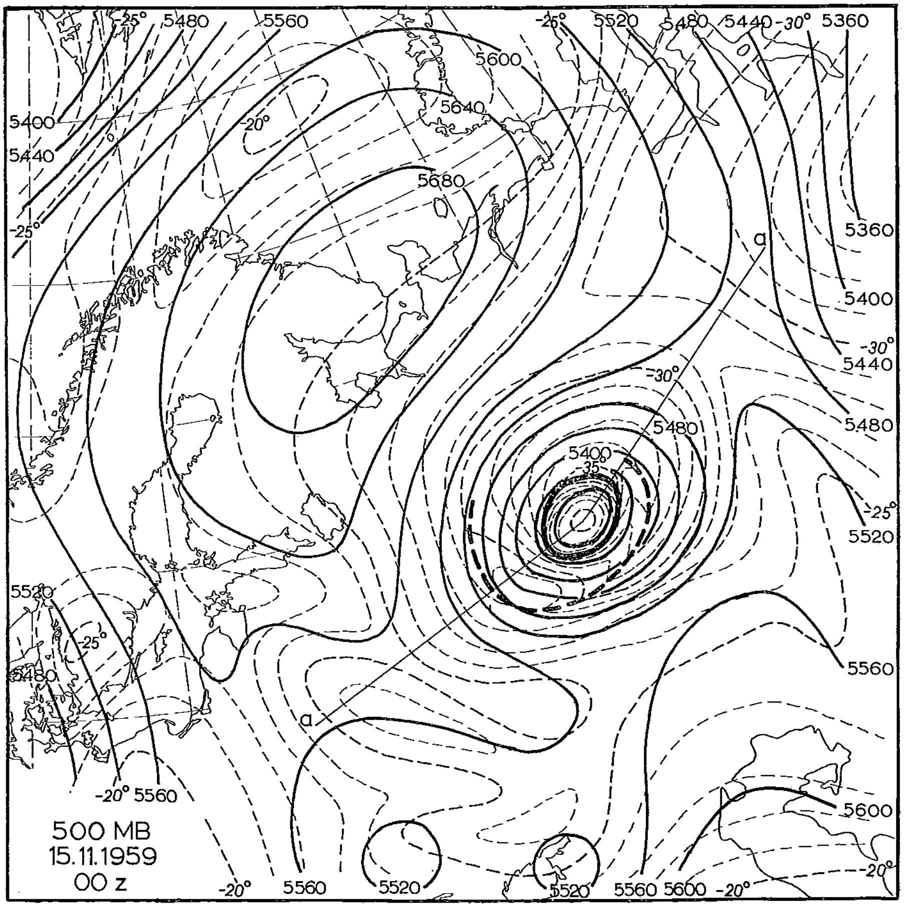

Fig. 5. 500-mb map for 0000 GCT, November 15, 1959. Thick solid line denotes the discontinuity in the field of the horisontal temperature gradient, other notations as in Fig. 4.

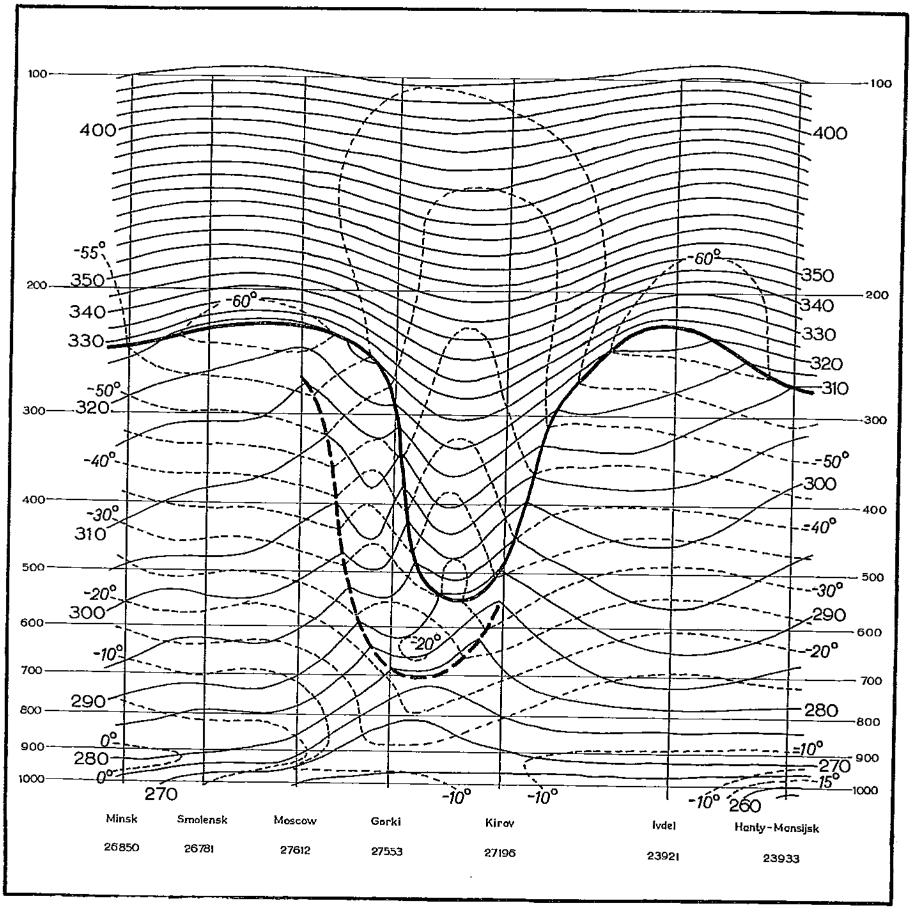

Fig. 6. Cross section for 0000 GCT, November 15, 1959, along the line a—a in Fig. 5. Notations as in Fig. 2.

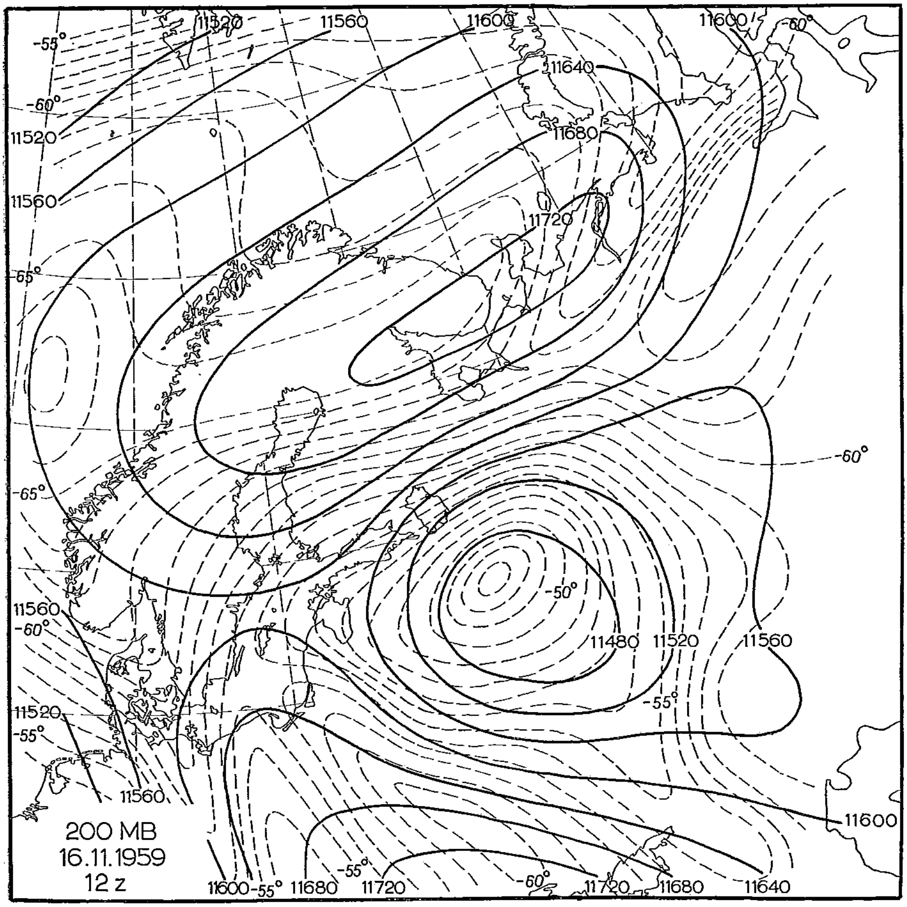

Fig. 7 a—d. Contour charts of selected isobaric surfaces at 1200 GCT, November 16, 1959. Notations as in Fig. 5.

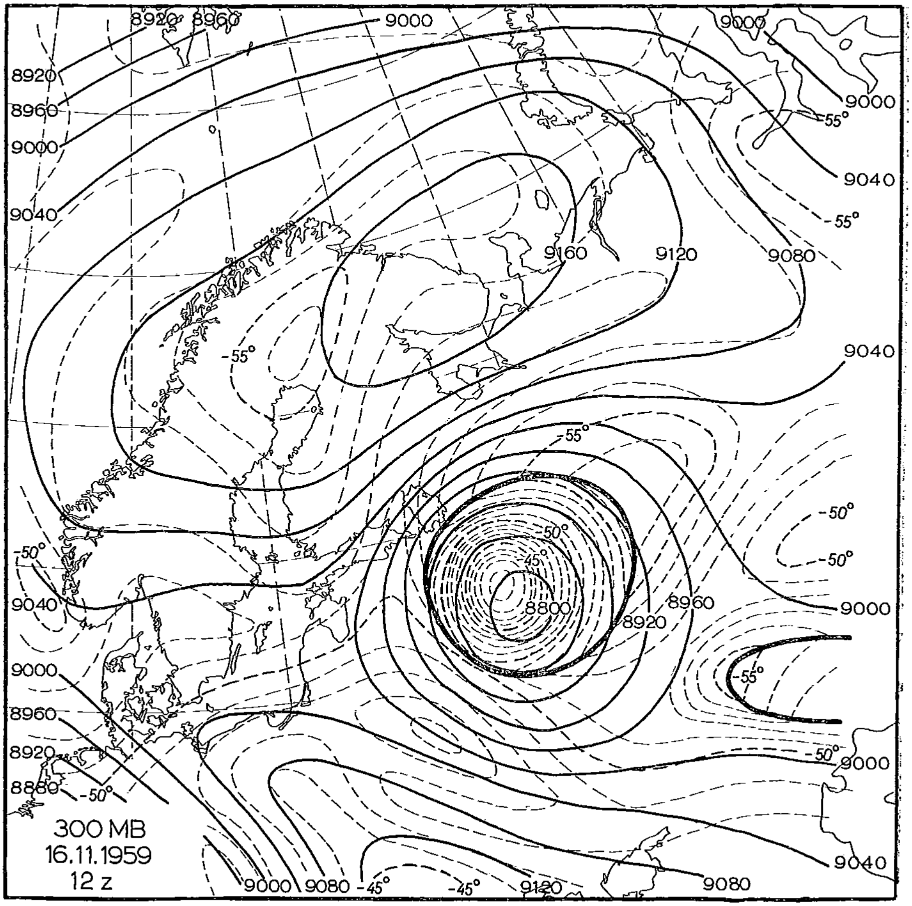
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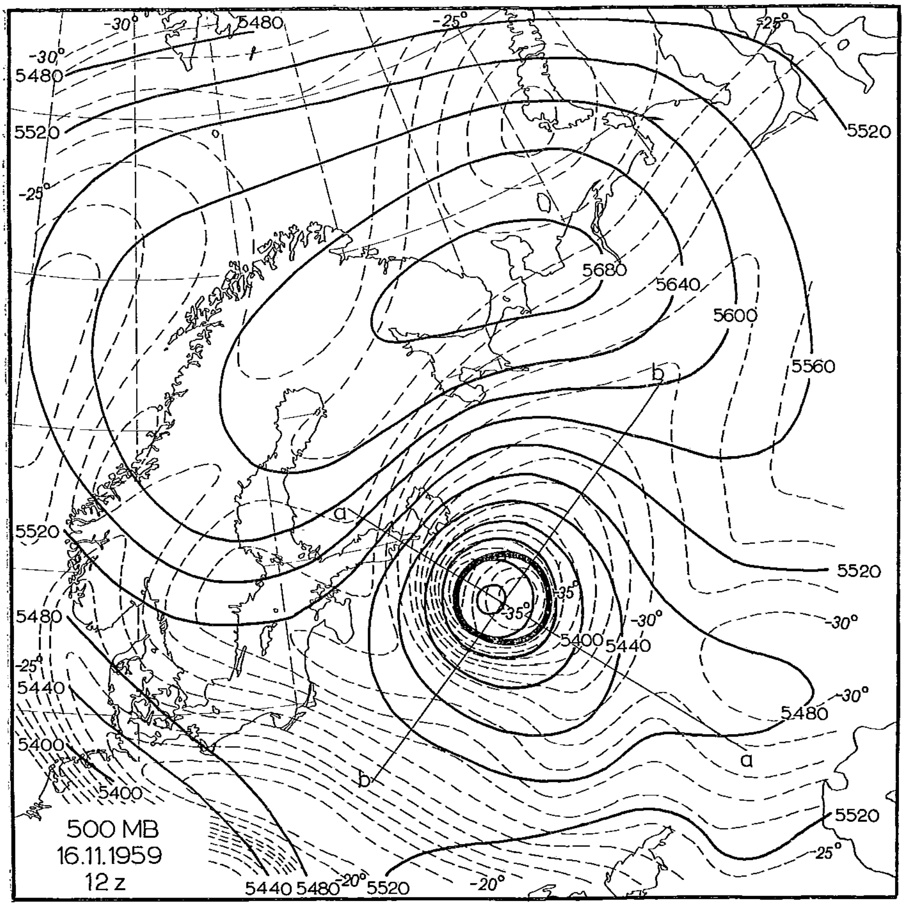
Fig. 7b.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a
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Fig. 7c.

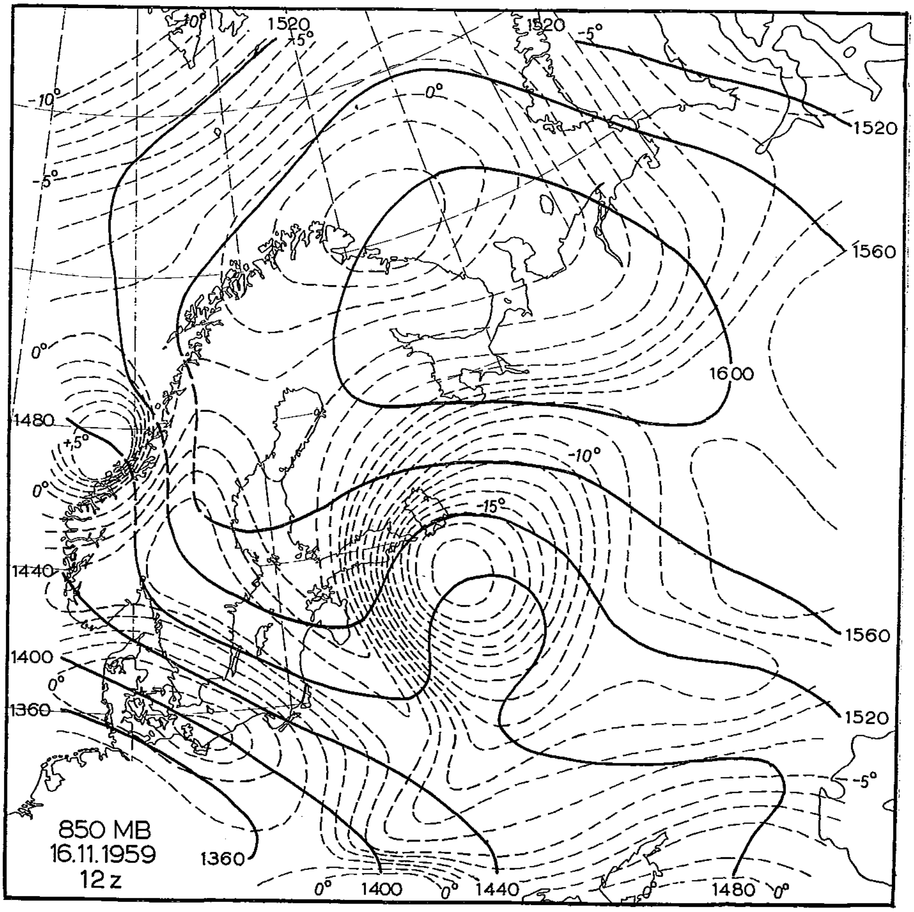
850 MB
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Fig. 7d.

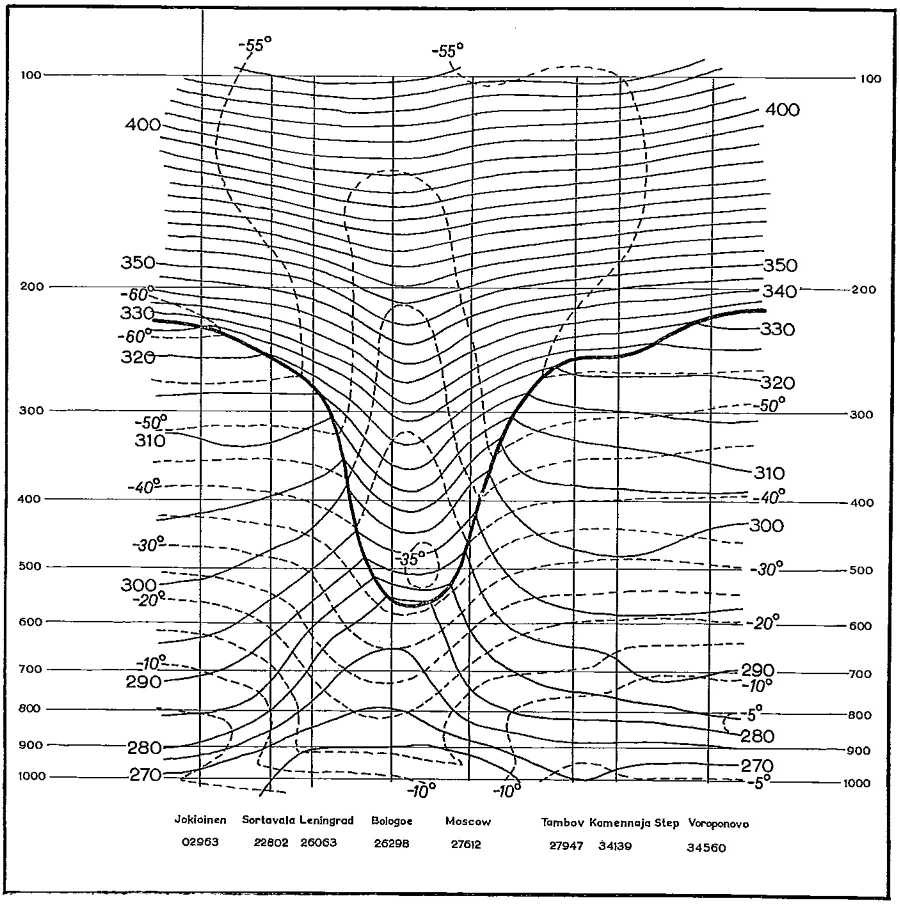
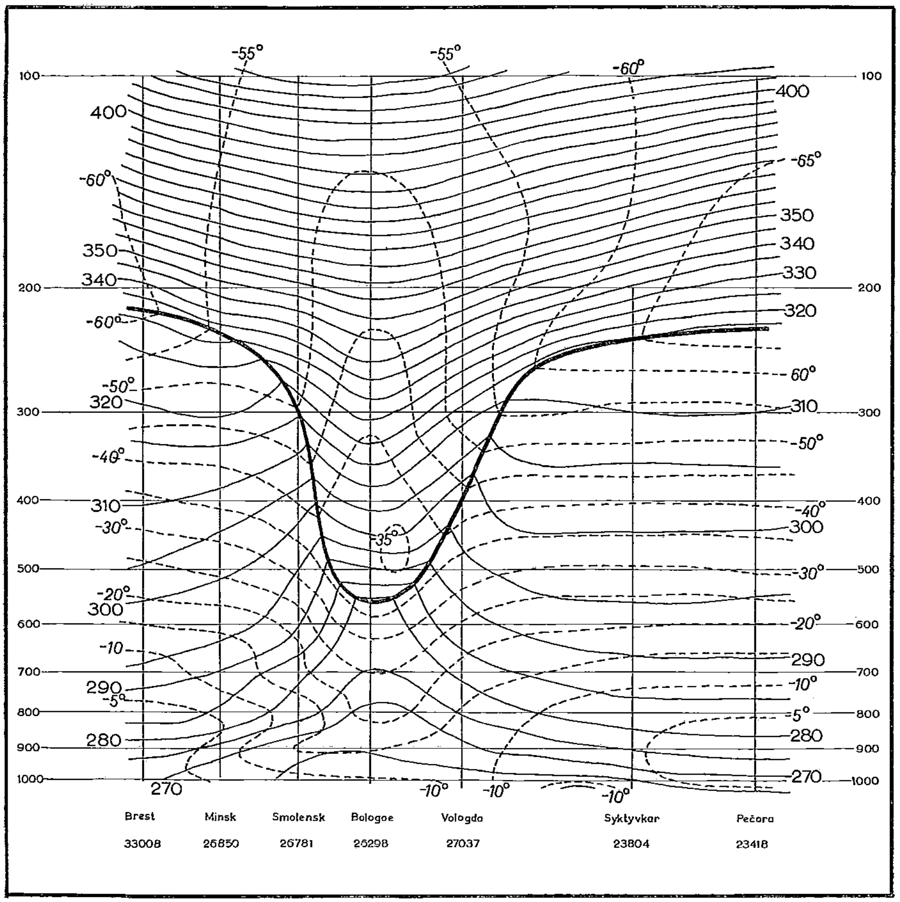


Fig. 8 a—b. Cross sections for 1200 GCT, November 16, 1959, along the lines a—a and b—b in Fig. 7. Notations as in Fig. 2.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Vologda
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Syktyvkar
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Pečora
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Fig. 8b.

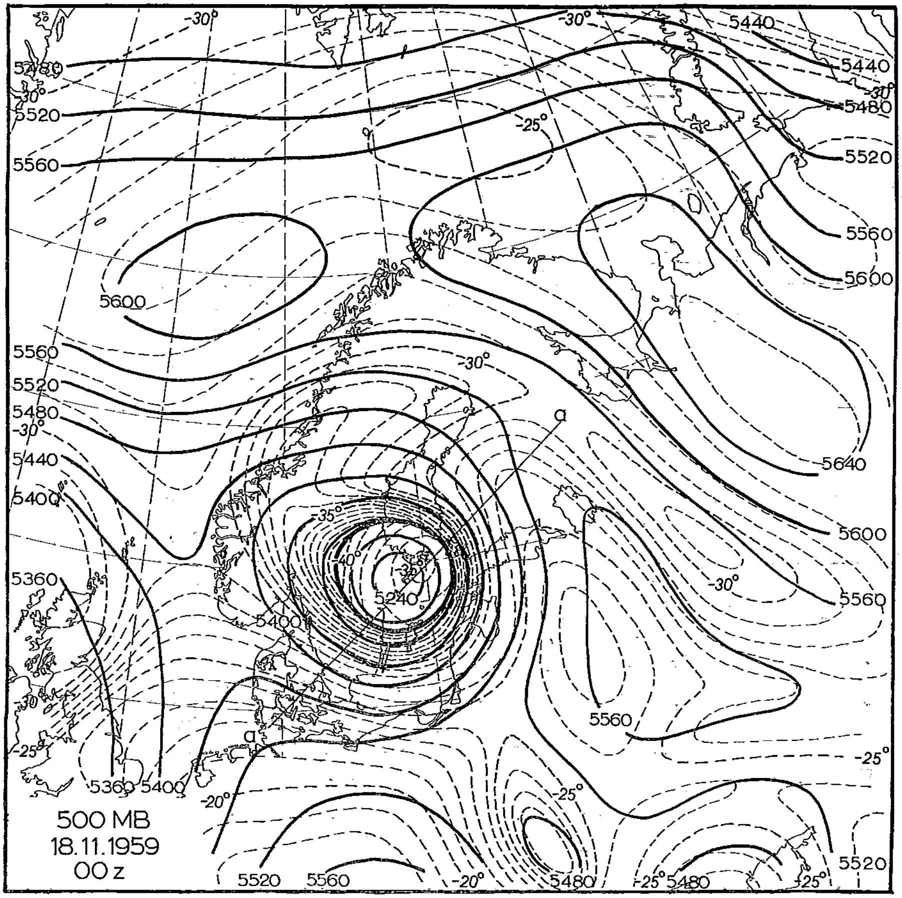

Fig. 9. 500-mb map for 0000 GCT, November 18, 1959. Notations as in Fig. 5.

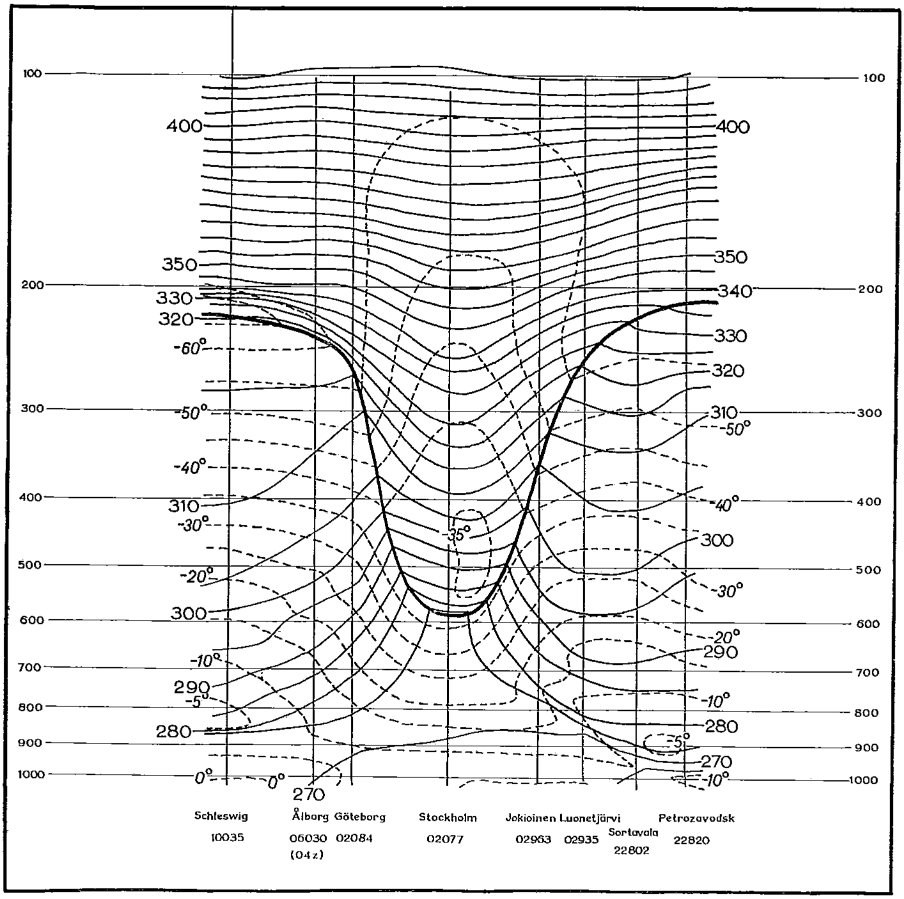

Fig. 10. Cross section for 0000 GCT, November 18, 1959, along the line a—a in Fig. 10. Notations as in Fig. 2.

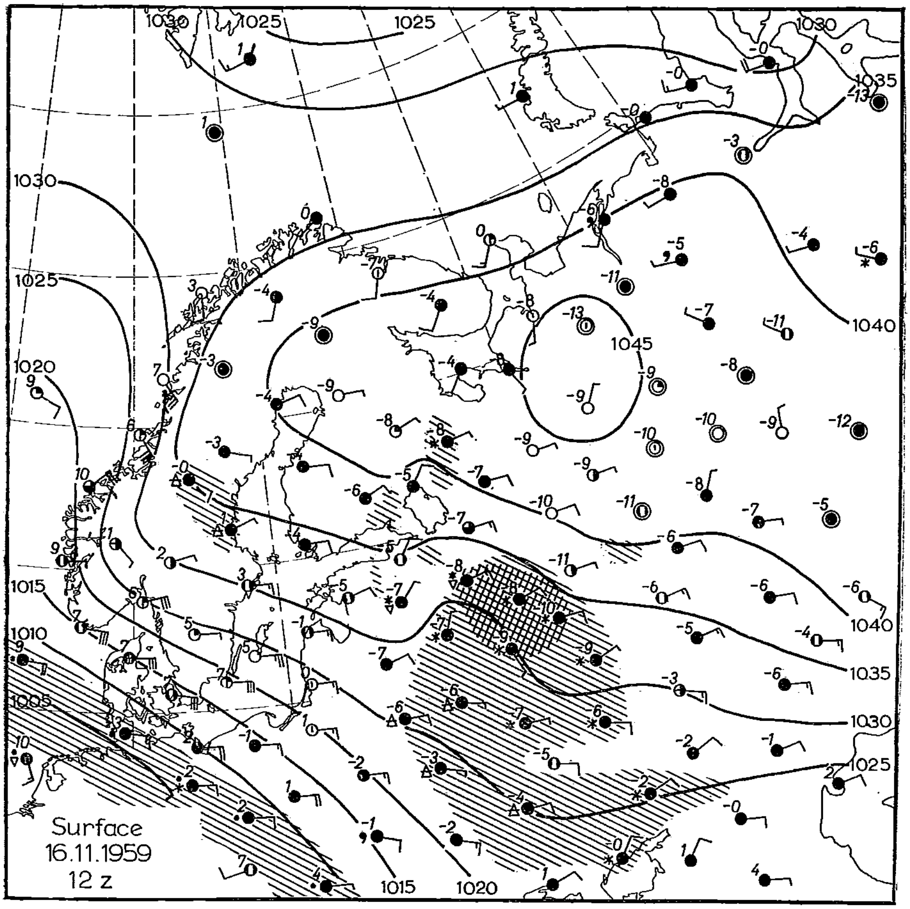

Fig. 11. Surface situation at 1200 GCT, November 16, 1959. Precipitation areas are hatched. Cross-hatching indicates an area where 12-hours amount of measured precipitation exceeds 1 mm.

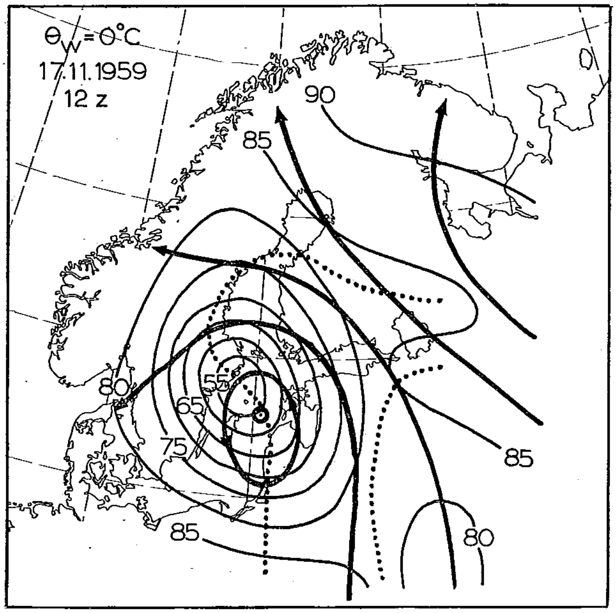

Fig. 12. Chart showing topography of the pseudo wet-bulb potential temperature Θ_{sw} = 0°C at 1200 GCT, November 17, 1959. Thin solid lines are isobars numbered in centibars, thick solid lines with arrowhead denote streamlines. The area where the streamlines indicate ascending motion of air is bounded by the dotted line.

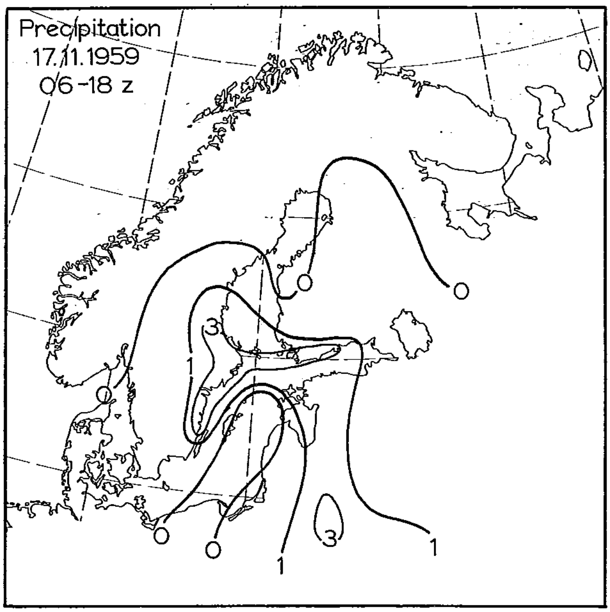

Fig. 13. The amount of precipitation in millimeters on November 17, 1959, between 0600—1800 GCT.

REFERENCES

1. Bergeron, T., 1949: The problem of artificial control of rainfall on the Globe, II. *Tellus,* **1,** 15—32.
2. Berson, F. A., 1951: A synoptic-aerological study of interaction between vortices. *Tellus,* **3,** 172—190.
3. Bjerknes, J., 1951: Extratropical cyclones. *Compendium of Meteorology,* American Meteor. Soc., Boston, Mass., 577—598.
4. Hsieh, Y-P., 1949: An investigation of a selected cold vortex over North America. *J. Meteor.,* **6,** 401—410.
5. Orihata, S., 1957: High-level cyclones south of the subtropical jet stream. *J. Meteor. Soc. Japan,* Ser. II, **35,** 45—51.
6. Palmén, E., 1949: Origin and structure of high-level cyclones south of the maximum westerlies. *Tellus,* **1,** 22—31.
7. —»— 1951: The aerology of extratropical disturbances. *Compendium of Meteorology,* American Meteor. Soc., Boston, Mass., 599—620.
8. —»— and K. M. Nagler, 1949: The formation and structure of a large-scale disturbance in the westerlies. *J. Meteor.,* **6,** 227—242.
9. Reed, R. J. and E. F. Danielsen, 1959: Fronts in the vicinity of the tropopause. *Arch. Met. Geoph. Biokl.* A **11,** 1—17.
10. Riehl, H., 1945: Waves in the easterlies and the polar front in the Tropics. *Dept. Meteor. Univ. Chicago, Misc. Rep.* No. 17.