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DAY-TO-DAY VARIATIONS IN THE TROPOPAUSE

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SUMMARY

A series of 6-hourly charts have been drawn in detail showing the topography of the tropopause over a period of one month. The features of this series of charts are compared with previous studies of the tropopause, and the existence and behaviour of discontinuities in the tropopause surface are illustrated; these are most marked in association with the jet stream but minor disturbances occur elsewhere. The tropopause " funnels ", reported by Palmén, are described and discussed. An analysis of the movements of the tropopause with the aid of estimated air trajectories suggests that the tropopause usually moves as a material surface embedded in the air current, and that of the changes of tropopause height at one place about half are to be explained by the horizontal advection and about half by the vertical air movements.

§ 1—INTRODUCTION

The increasing amount of flying at levels of 30,000 to 40,000 ft. has drawn attention to the need for an improvement in our knowledge of the structure and dynamics of the upper troposphere and lower stratosphere. The tropopause is an important feature of this layer of the atmosphere, and an understanding of the nature of the changes which it undergoes and their relation to other features of the weather situation is essential to the proper analysis and forecasting of meteorological conditions around 35,000 ft.

During the Second World War, 1939–45, an extensive network of radio-sonde observations was established over Europe and North America, and has been maintained since with the addition of observations from ocean weather ships in the North Atlantic. Most of these soundings reached the tropopause, so that material is now available for the drawing of comprehensive charts of the topography and structure of the tropopause; it is possible to draw charts at 12-hr. intervals over a wide area, and up to 1952 charts at 6-hr. intervals could be drawn in the immediate vicinity of the British Isles.

Before 1939 upper air soundings which reached the tropopause were irregular and generally unrelated in time or space. Analysis of them was therefore primarily on a statistical basis following the pioneer work of Dines[1*]. Strong correlation was found between the height of the tropopause, the pressure at 29,500 ft. (9 Km.) and the temperature in the middle troposphere, and a smaller correlation with surface pressure. However, as will be seen, these relations are of only limited use in predicting short-term fluctuations of the tropopause. In addition to the statistical treatment of observations of tropopause height, several analyses have been published of data obtained from sequences of aerological soundings at short intervals of time, and of soundings on international aerological days. Such aerological analyses, notably those of Bjerknes[2], Palmén[3] and Nyberg[4], have drawn attention to certain features of tropopause behaviour in relation to the weather systems of the troposphere. However, no comprehensive synoptic analysis based on the routine radio-sonde ascents of the post-war years appears to have been published.

A detailed analysis of the topography of the tropopause was therefore undertaken for one month, May 1949, and the results of the analysis are described in the present Memoir. The aim of the investigation was to ascertain whether a self-consistent analysis of the tropopause is possible,

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* The index numbers refer to the bibliography on p. 38.

to recognize and describe characteristic modes of behaviour of the tropopause and relate them to the synoptic situation in the troposphere, and, finally, to consider whether the observed behaviour of the tropopause gives any indication of the physical processes involved. The study is to be regarded as a preliminary to further investigation ; the various modes of tropopause behaviour require further study on more extensive data, and the present paper is intended primarily to indicate the lines on which such work might proceed. It may also form a basis for relating physical research on the tropopause to synoptic studies.

In § 2 various theoretical and practical ideas are outlined in order to present a brief survey of present knowledge regarding the tropopause. Subsequently the scheme of the investigation is described in § 3, followed by some statistical results in § 5. Various modes of behaviour of the tropopause are described in § 7 and the relation of present results to earlier investigations and to theoretical problems is discussed in § 8.

§ 2—THEORETICAL AND OBSERVATIONAL KNOWLEDGE OF THE TROPOPAUSE

Reasons for stratosphere and tropopause.—The accepted explanation of the division of the atmosphere into troposphere and stratosphere was given by Gold[5] and Humphreys[6], who regarded the temperature of the stratosphere as determined essentially by the requirements of radiative balance, and the troposphere as a region in which the turbulent transfer of heat upward was dominant. On this basis it would be natural to regard the tropopause as the upper limit of convective turbulent exchange, and the sharp change of lapse rate at the tropopause as a change from a lapse rate determined by turbulence to one determined by radiation. However, although usually steep, the lapse rate immediately below the tropopause is not normally suitable for penetrative convection either of dry or moist air, and, moreover, although turbulence has been reported by aircraft at these levels it appears to be the exception rather than the rule. It therefore seems unlikely that penetrative convection is proceeding actively and continuously at levels immediately below the tropopause as it is, for example, below the inversion which limits convection in the lower layers of a summer anticyclone.

In the absence of persistent convection from below, it would be surprising that the change of lapse rate should remain as sharp as it is found to be were there no other factors operative. In an atmosphere with homogeneous radiative properties radiation as well as turbulence would tend to smooth such a discontinuity. Evidence as to the detailed structure of the lapse rate near the tropopause is not available, but it is noteworthy that the radio-soundings which observe temperature at levels separated by approximately 5 mb. (450 ft.) fail to detect any departure from a discontinuous change in lapse rate on the majority of occasions.

It may be argued that the temperature lapse rate in the troposphere is to be regarded as determined primarily by a form of turbulence, in which the turbulent elements are not the individual cloud cells but the depressions and anticyclones of the large-scale circulation which result in an oblique upward and downward exchange of air from low levels in low latitudes to high levels in high latitudes (as described by Eady[7]). However, the exchange of air in the region immediately below the tropopause by this process would seem to be too slow to account for the sudden change of lapse rate at the tropopause. Moreover, the lower stratosphere is known to take part in the circulation of depressions and anticyclones, and it is not clear why the large-scale turbulent process should have a sharply defined upper limit.

Goody[8] has recently discussed the radiative conditions at the tropopause and shown that a sudden change of lapse or inversion is possible provided that a constant lapse rate in the troposphere maintained up to the tropopause by turbulent transfer of heat is postulated. However, in view of the preceding considerations it seems doubtful if this assumption can be justified. It would seem more natural to attribute the sudden change in lapse rate at the tropopause to an abrupt change in the radiative properties of the atmosphere at the tropopause level. A rapid decrease of humidity of the air upward is known to be a feature of the lower stratosphere although not always identifiable with the tropopause (Shellard[9]) ; a sudden change in the haze content has also been observed (Brewer[10]). The different radiative loss from a moist or hazy troposphere compared with the overlying drier cleaner air may well account for the sharp change of lapse rate at the tropopause (Möller[11]). The cause of the low water content of the temperate stratosphere is still undetermined. Frost points measured within the stratosphere are normally found to lie between −80° and −120° F. (Shellard[9]). So far as is known temperatures below −110° F. occur regularly only near the tropopause in the equatorial belt, and this has led Brewer [12] to suggest that air is transferred from troposphere to stratosphere in the equatorial belt and re-absorbed in the troposphere in the temperate regions, thus maintaining the dryness of the temperate stratosphere. Bannon and Goldie have suggested a similar circulation for slightly different reasons[13]. However, temperatures below −80° F. do occur at the tropopause over England from time to time at all seasons (Dewar[14]), and if the transfer of air from the troposphere is a fairly rapid process it might also occur in temperate and subtropical latitudes, and the derivation of part of the stratospheric air in this way is not ruled out.

To summarize the explanations of the tropopause : the broad features of vertical temperature distribution within the atmosphere may be regarded as determined by the requirement of radiative equilibrium in the upper layers (the stratosphere) and of convective and turbulent transfer of heat in the lower layers (the troposphere). Whether this explanation can be pressed to explain the sudden change in lapse rate at the tropopause is more doubtful, and an alternative explanation lies in the different radiative properties from troposphere and stratosphere associated with their different dust and water contents, the sharp change of lapse rate being associated with the rapid transition in these properties. The choice between these two has some bearing on the interpretation of the daily changes in the tropopause, because on the latter the tropopause would be expected to move up and down with the air itself, whereas on the former evidence might be found of the tropopause moving downward with respect to the air as turbulence slackened and radiative balance extended to lower levels and moving upward as turbulence increased in the troposphere.

Statistical properties of the tropopause.—The statistical method has proved well adapted to codifying knowledge regarding the behaviour of the tropopause. The high correlation between the tropopause height and temperature and conditions within the troposphere was first emphasized by Dines[1] in 1919. Since then the broad correctness of the results has been confirmed by several investigators, and probably the most reliable evaluation of the correlation coefficients is that by Priestley[15]. The statistical relation between tropopause height and the synoptic situation has also been investigated by Durst and Swinbank[16]. The most important relations are

(i) positive correlation between tropopause height and temperature in the middle troposphere, e.g. at 500 mb. (+0·65)

(ii) positive correlation between tropopause height and surface pressure (+0·49)

(iii) positive correlation between temperature at the tropopause and pressure at the tropopause (+0·75).

The values in brackets are the correlation coefficients evaluated by Priestley.

Although these correlations are substantial, about 40 per cent. of the variance of the tropopause height remains unexplained. Moreover, most of the correlation of the tropopause height with the 500-mb. temperature and surface pressure arises from the association of these three factors in the " long-wave pattern " of the hemispherical flow. This is brought out in Figs. 1 and 2 which show the contours of the tropopause (Fig. 1) and the contours of the 500-mb. surface, the long-wave pattern (Fig. 2), over a wide area. The correlations are therefore representative of the oscillations of the tropopause which occur over wide areas and over periods of several days.

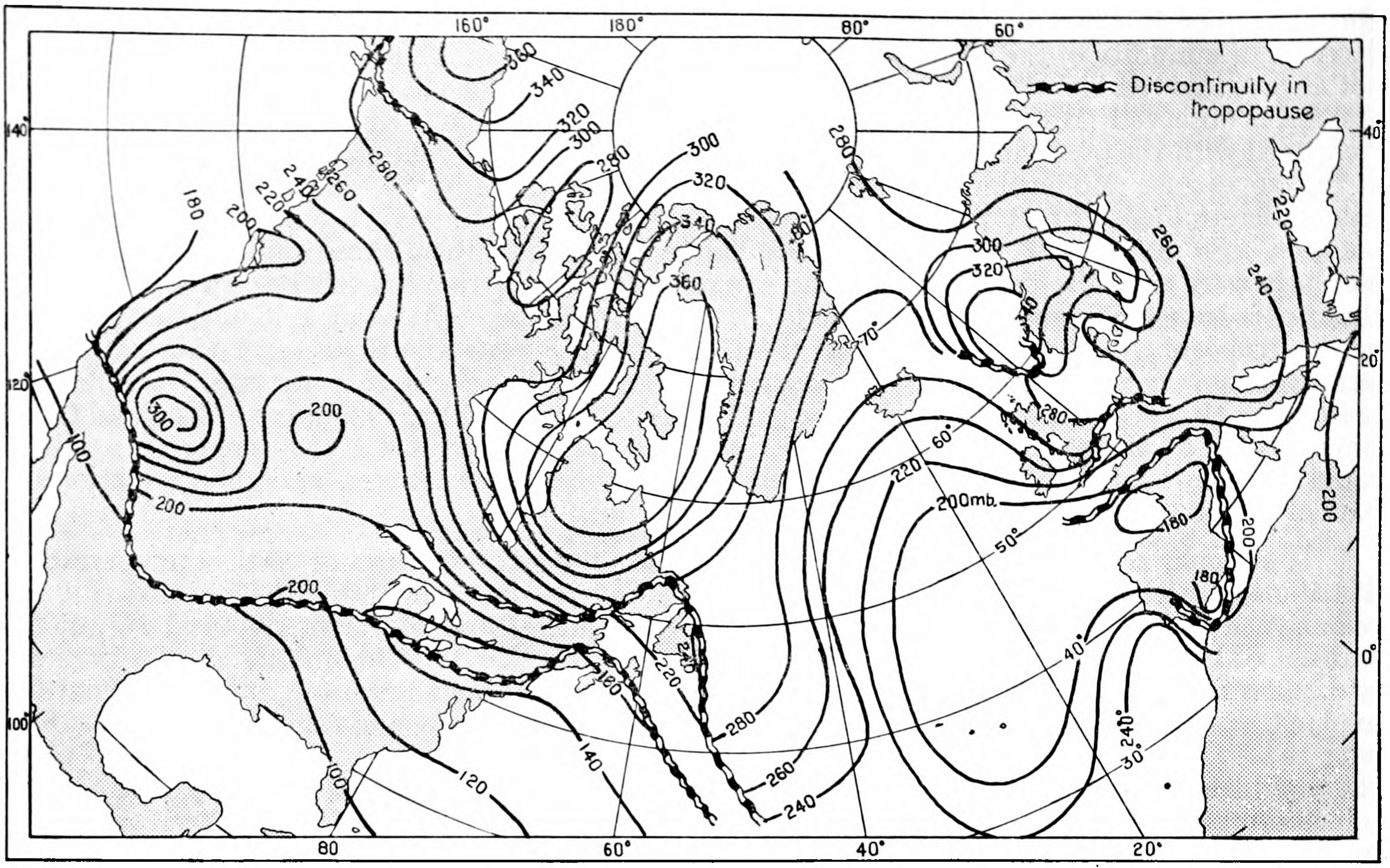

FIG. 1—ISOBARS ON THE TROPOPAUSE, 0300, MAY 7, 1949

The correlations are not necessarily representative of the smaller-scale variations (on the scale of individual depressions and less, nor of the short-period changes in tropopause height, 24-hr. or less). The contribution to the correlations of the longer-period oscillations is illustrated in Fig. 3, in which are plotted the 6-hr. values of tropopause height and height and temperature of the 500-mb. level at Larkhill in May 1949.

Nevertheless, Björkdal[17] has suggested the use of the regression between tropopause height and temperature in the middle troposphere 16,400 ft. (5 Km.), for the purpose of completing contour charts of the tropopause over areas of limited observations. The method is, however, probably restricted to delineating the broader features of the long-wave pattern, and, although it may be valuable for completing the fringes of a chart, it is doubtful it it can provide any help for the improvement of the finer detail of tropopause topography within a network of observations as complete as that over Europe and the British Isles.

Priestley[15] has also made use of statistical methods in order to predict 12-hr. changes in the height of the tropopause. He does not quote the correlation coefficients between the 12-hr. change in tropopause height and the 12-hr. change in 500-mb. temperature or surface pressure, and it is probable that these correlations are smaller than those between the original data of heights and temperature. Nevertheless Priestley's table suggests that, if the change of 500-mb. temperature and surface pressure can be correctly predicted, the sign of the change in tropopause height can be correctly given from the statistical relations on about 50 per cent. of occasions, and would be incorrectly given on about 15 per cent.—the remainder being undetermined. Priestley realizes that such relationships alone are inadequate for the forecasting of the changes in the tropopause, and it was the purpose of the study here reported to collate some of the additional knowledge which is required on the day-to-day disturbances of the tropopause.

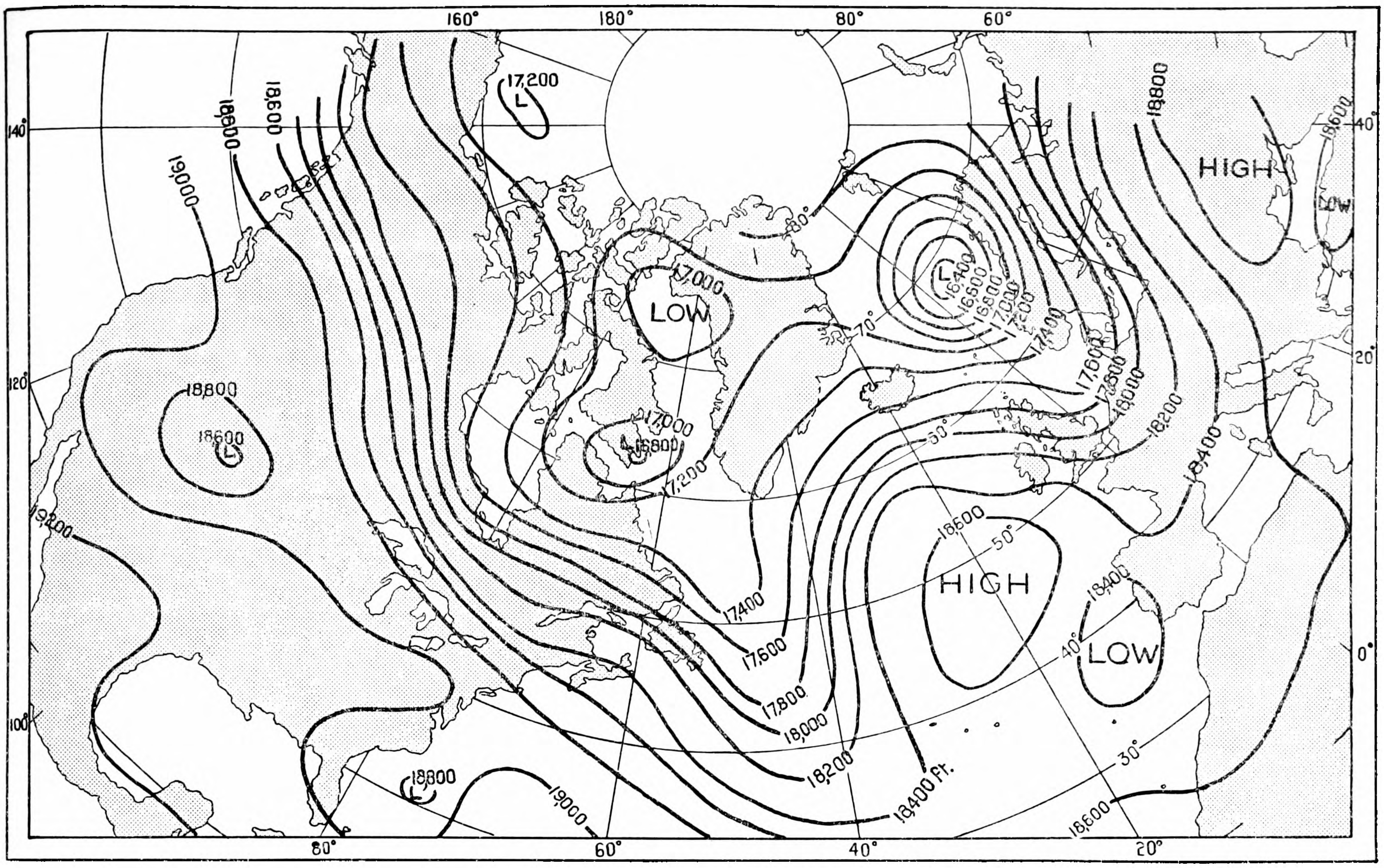

FIG. 2—CONTOURS OF THE 500-MB. SURFACE, 0300, MAY 7, 1949

Another limitation of the linear correlation technique as applied to the tropopause problem is illustrated by the fact demonstrated by Palmén[18] that as surface pressure decreases below 990-mb. the corresponding average height of the tropopause ceases to decrease and commences to increase. The average height of the tropopause corresponding to certain surface pressures is given by Palmén as follows :—

	Surface pressure (mb.)						
	976	987	993	1007	1017	1025	1034
Tropopause height (ft.)	27,760	25,890	25,330	28,440	32,640	35,470	37,890
Tropopause height (Km.)	8·46	7·89	7·72	8·67	9·95	10·81	11·55

Synoptic studies of the tropopause.—Even before a coverage of upper air soundings was available permitting the study of the tropopause on a synoptic basis, Dines[19] had deduced, from the nature of the correlations between pressure and temperature at the tropopause and in the troposphere, that the observed variations in the tropopause height must be the result of both horizontal and vertical motions. The analyses of the tropopause from the subsequent serial ascents and " aerological day " data owes much to the influence of Palmén. Palmén[18] emphasizes the importance of vertical motion as well as horizontal advection in displacing the tropopause, and introduces the idea of the re-formation and dissipation of the tropopause by dynamical convergence and divergence.

The various views on the causes of variations of tropopause height are probably best made clear by a consideration of the tropopause oscillation in association with a system of progressive troughs and ridges. One of the first aerological analyses of such a system was given by Bjerknes[2].

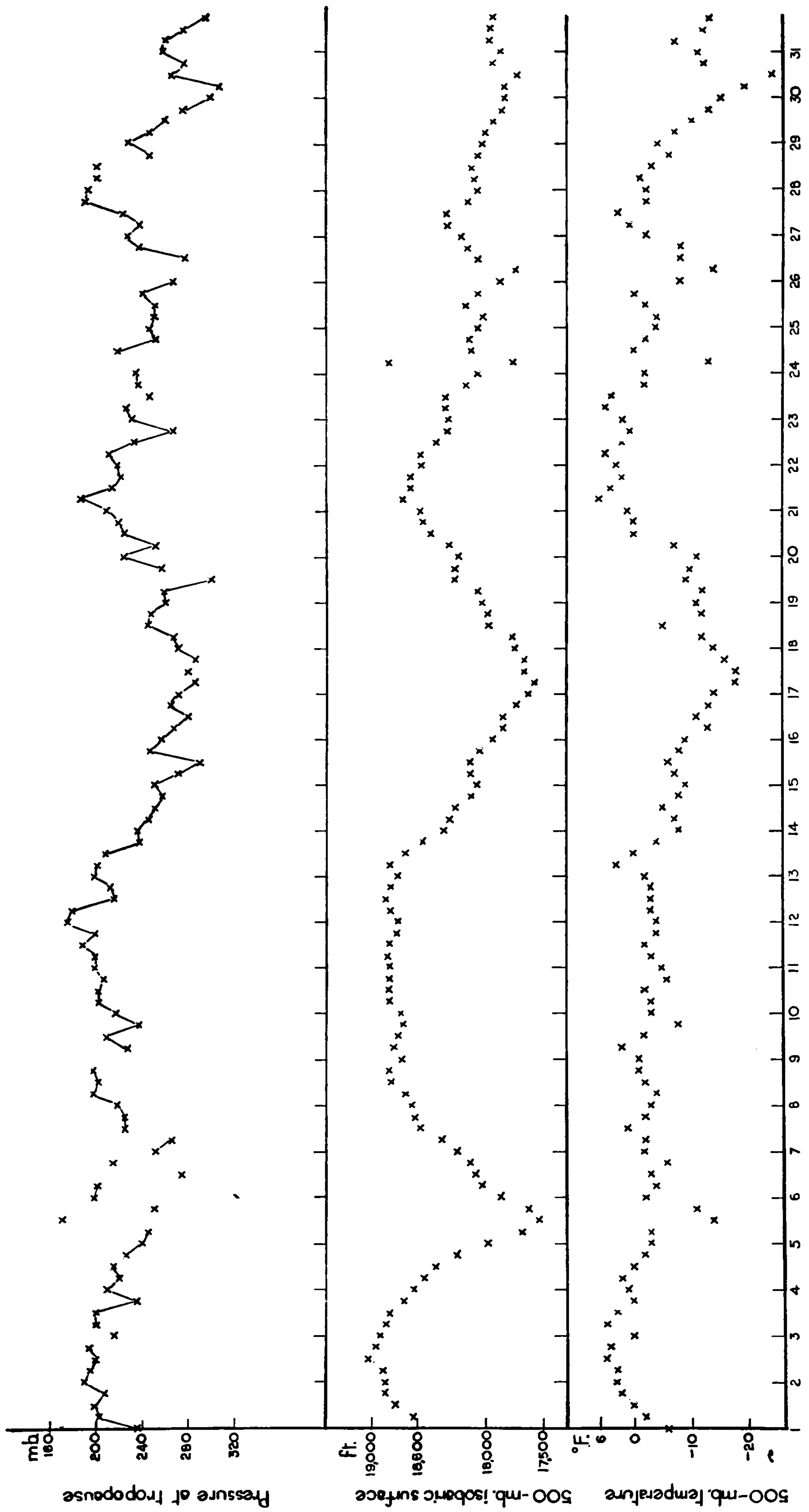

FIG. 3—PRESSURE AT THE TROPOPAUSE, HEIGHT OF 500-MB. SURFACE AND TEMPERATURE AT 500 MB. AT 6-HR. INTERVALS, LARKHILL, MAY 1949

In the upper diagram points have been joined by a line where they have been treated as lying on a continuous tropopause surface during the analysis—gaps indicate tropopause discontinuities

He attributes the tropopause oscillation primarily to horizontal advection of high tropopause in association with warm air from low latitudes and low tropopause with cold air from high latitudes. Bjerknes was studying a depression with an open warm sector, and he recognizes that vertical motion may have more influence on the tropopause in occluding depressions. Bjerknes also finds that the tropopause ridge lies ahead of the surface pressure trough, and the tropopause trough is ahead of the surface pressure ridge, but the tropopause wave is in phase with the pressure wave in the upper troposphere which is displaced backwards with respect to the pressure oscillation at lower levels. Bjerknes's model of the tropopause oscillation in association with a warm-sector depression is illustrated diagrammatically in Fig. 4 and has been widely reproduced. The basis of this analysis is a single continuous tropopause, but in later papers Bjerknes has followed the technique of Palmén which will now be described.

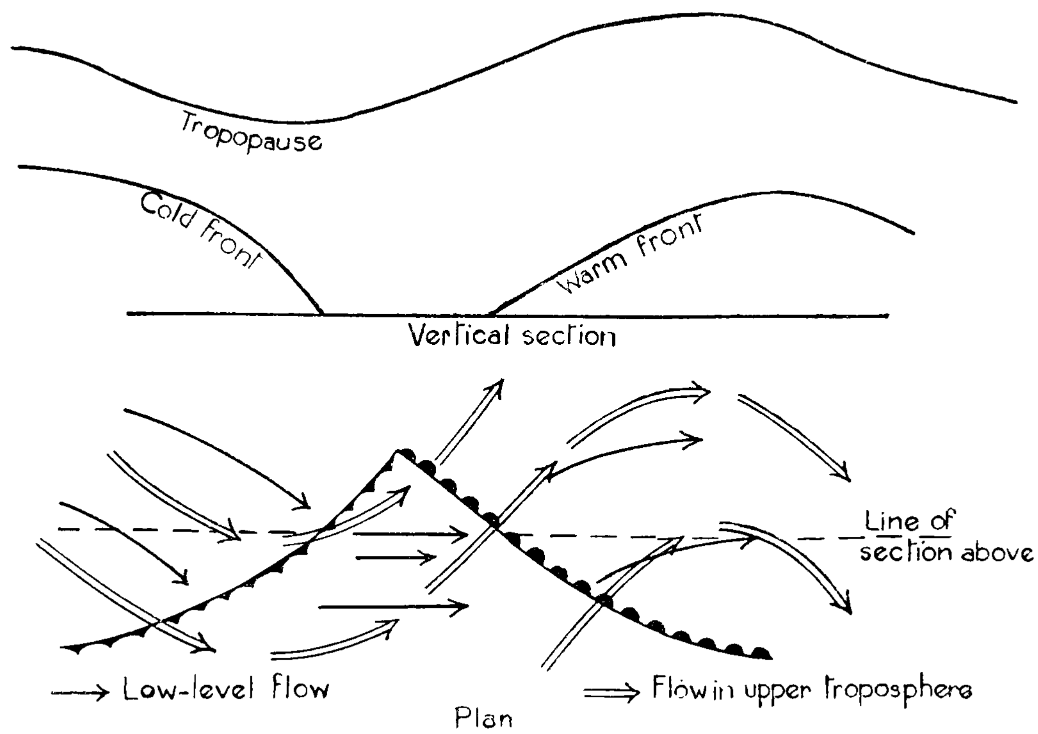

FIG. 4—BJERKNES MODEL OF A WAVE DEPRESSION

Palmén's earlier studies[3, 18, 20, 21], were mainly concerned with deep, rapidly occluding depressions. Palmén found that the tropopause behind a deep and active depression was often at a lower level and lower potential temperature than in the original cold air mass. He concluded that not only was vertical motion of the air important in lowering the tropopause behind a depression, but also that the tropopause dissolved at its old level and re-formed at a new lower level behind a deep depression. Support for the idea of the re-formation of the tropopause at a lower level also came from the ill defined nature of the tropopause on some of the ascents in these deep depressions ; these soundings showed several levels of change of lapse rate which could be interpreted as tropopauses in process of formation and decay. The process of re-formation of the tropopause at a new level was regarded by Palmén as the result of dynamical effects—horizontal divergence combined with vertical convergence. Such a system results in upward motion and an increasing lapse rate below the new tropopause level, and downward motion above the new tropopause with a decreasing lapse rate or increasing inversion above it. The vertical circulation envisaged by Palmén in association with developing depressions and anti-cyclones is illustrated in Fig. 5. The vertical circulation is additional to the horizontal movements of the tropopause. Bjerknes and Palmén[22] have jointly published some further observations regarding the depression of December 26–28, 1928, and concluded that in the later stages of this depression vertical motion had an important influence on the tropopause although Bjerknes's original analysis[2] stressed only the advective effect. Goldie[23] has also stressed the importance of the vertical circulation in distorting the tropopause, but in contrast to Palmén he appears to regard the tropopause as a continuous and persistent material surface. Douglas[24] has also regarded all three processes, advection, vertical motion and re-formation, as operative in determining the configuration of the tropopause, but he has stressed radiation and turbulence as factors likely to lead to the dissipation and re-formation of the tropopause rather than the dynamical divergence and convergence stressed by Palmén. Refsdal[25] has also emphasized the radiative effect.

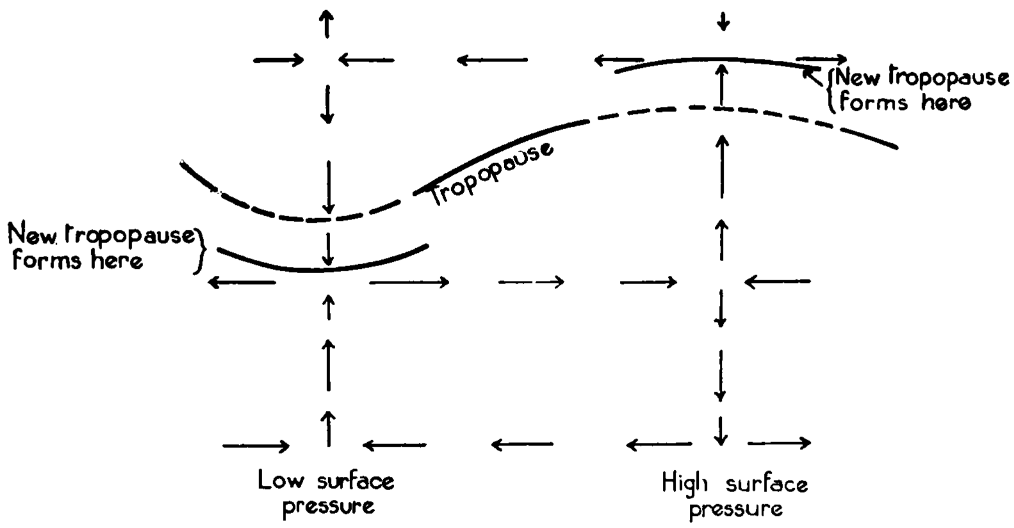

FIG. 5—VERTICAL CIRCULATION ASSOCIATED WITH DEVELOPING DEPRESSIONS AND ANTICYCLONES ACCORDING TO PALMÉN

The idea that the tropopause may re-form and dissipate dynamically and thus result in two or more discontinuities of lapse rate at the lower boundary of the stratosphere, has led to the introduction into aerological analyses of the " multiple ", " foliated " or " laminated " tropopause. The most complete exposition of this analytical technique is given by Bjerknes and Palmén[26]. They regard every discontinuity of lapse rate near the base of the stratosphere as a tropopause, and where there is more than one such discontinuity the tropopause is regarded as multiple. As a working hypothesis it is assumed that each individual tropopause has a constant potential temperature throughout its extent, and the potential temperature is thus used to identify individual tropopause sheets. When descending air motion takes place it is supposed that the lowest tropopause sheet will be intensified and become dominant, and when upward motion takes place the upper tropopause is expected to become dominant. Individual tropopause sheets are therefore regarded as incipient discontinuities of lapse rate which can be intensified into a well defined discontinuity in a suitable divergent horizontal wind field. Bjerknes and Palmén[26] are very tentative in regard to the origin of the series of tropopause layers, but appear to regard them as probably formed by irregular penetration of convection to various levels in the equatorial belt ; they also consider an explanation based on radiation to be possible.

Observational evidence from soundings reaching the tropopause does show that more than one change of lapse rate is not unusual. However, multiple tropopauses do not appear to be nearly so widespread as the Bjerknes and Palmén analysis would suggest.

This form of analysis with multiple tropopauses has been adopted in several other analyses by various authors including van Mieghem and Nyberg. These are listed in the bibliography on page 38 (see Nos. 27 to 32), but the main interest of these papers lies in the tropopause behaviour found to be associated with particular synoptic systems.

More recently, meridional atmospheric cross-sections have been prepared extending over a wider area than any of the earlier studies, and in these the authors have analysed the tropopause of the northern hemisphere into two or three discontinuous sheets. For example, Palmén and Nagler[33] recognize three distinct tropopause sheets on some vertical cross-sections which they have drawn, namely a real tropical tropopause south of latitude 40° N. and at a level near 100 mb., an extratropical tropopause between latitudes 35° and 47° N. and at a level between 300 and 200 mb., and a polar tropopause at about the 300-mb. level further north. The southernmost of these two discontinuities had been recognized over northern India by Ramanathan and

Ramakrishnan[34] as early as 1933, and attributed by them to a large-scale folding of the tropopause resulting from meridional circulations in the vertical plane. The northern discontinuity noted by Palmén and Nagler is associated with the jet stream, and will be discussed further in § 7, page 16.

These discontinuities in tropopause level shown on meridional sections are on a much greater scale than the separation of individual tropopause laminae on the earlier model of Palmén ; the separation is usually 5,000 to 10,000 ft. in height and 40° to 80° F. in potential temperature for the former compared with 3,000 ft. and 10° F. for the latter. The various treatments of the tropopause in meridional sections are made clear in Fig. 6 in which is shown the mean tropopause according to Ramanathan[35] with an indication as to how folding may give rise to a discontinuity ; this may be compared with Fig. 7 in which an outline of an individual section by Palmén and Nagler[33] is given. It is interesting to note that recent evidence from high-altitude radio-sondes (Scrase[36] and Gutenberg[37]) has shown that temperature in the stratosphere frequently begins definitely to increase upward at a level of about 60,000 ft. in extratropical latitudes. This is about the same level as the equatorial tropopause, and the discontinuity may indeed be more or less continuous with it. This level is rather lower than the previously accepted level of the base of the upper warm ozone layer, but it does not appear necessarily desirable to regard this change of lapse rate from isothermal or slight lapse to inversion as a high-level tropopause in temperate latitudes as Scrase[36] appears to do.

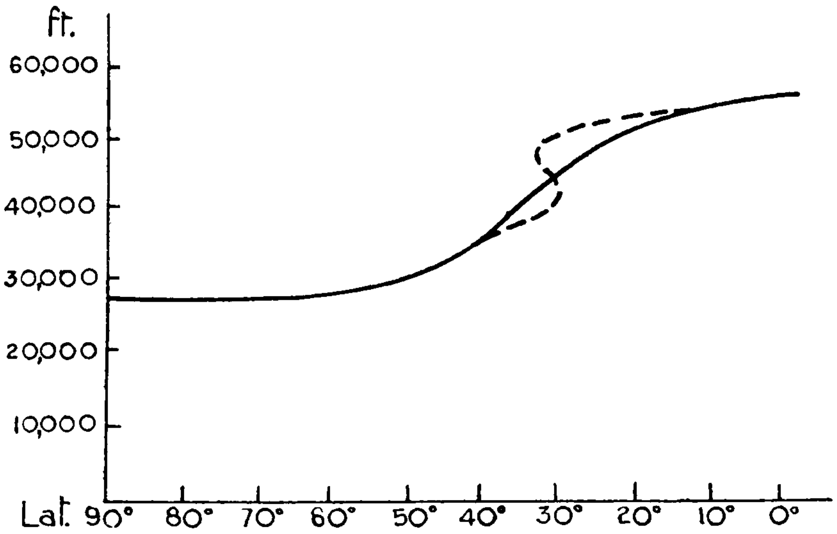

FIG. 6—MEAN LATITUDINAL VARIATION OF THE TROPOPAUSE AS GIVEN BY RAMANATHAN FOR WINTER WITH THE MANNER IN WHICH A DISCONTINUITY MIGHT ARISE BY FOLDING AS INDICATED BY RAMANATHAN AND RAMAKRISHNAN[34]

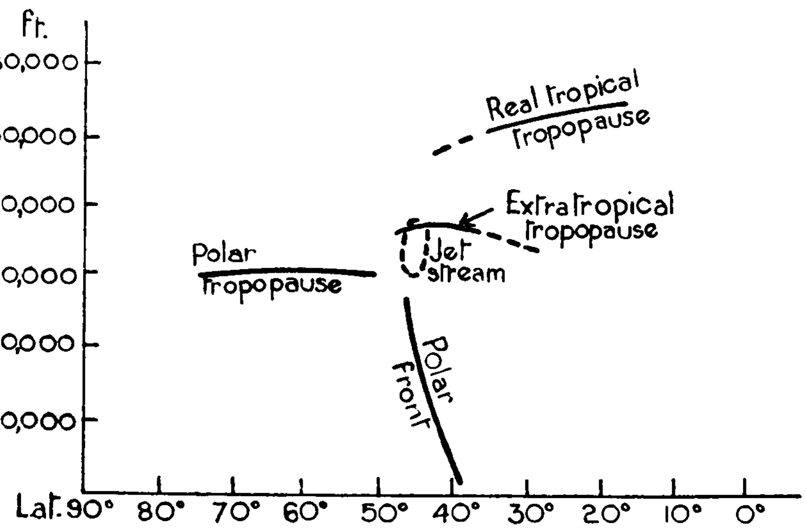

FIG. 7—MERIDIONAL CROSS-SECTION OVER AMERICA FOR 0300, NOVEMBER 30, 1946, AS GIVEN BY PALMÉN AND NAGLER[33]

Definitions of the tropopause.—It will be clear from the preceding account of the various treatments of the tropopause problem that different authors have defined the tropopause in different ways, and that some of the difference between their results arise from this. It is therefore convenient to list some of the methods used by investigators to define the tropopause.

In recent Meteorological Office practice the position of the tropopause has been determined according to the following convention which differs slightly from that given by Dines[1].

Type I.—When the stratosphere commences with an abrupt change in lapse rate to an inversion, the tropopause is at the base of the inversion.

Type II.—When the stratosphere commences with an abrupt change to a lapse rate of less than 1·1° F./1,000 ft. (2° C./Km.) or to an isothermal condition, the tropopause is at the height of that change.

Type III.—When there is no abrupt change of lapse rate, the tropopause is taken as the height of the level at which the lapse rate first becomes less than 1·1° F./1,000 ft. (2° C./Km.), provided that it does not subsequently exceed this value for any subsequent 3,280 ft. (1 Km.) layer.

These definitions of the level and the type of the troposphere were intended primarily for statistical purposes, but have also been applied in the drawing of synoptic charts of tropopause topography. They are not entirely unambiguous, particularly in respect of the emphasis to be put on the requirement of an abrupt change. There has been a tendency in interpretation to consider a tropopause as Type I when an inversion exists, whether abrupt or not, when perhaps greater emphasis on the requirement of an abrupt change would have placed the tropopause at such a change at a lower level.

Although a rigid definition of the tropopause is required for statistical analysis it may be possible to leave something to personal judgement when synoptic analysis is undertaken ; this may be desirable in order to maintain continuity in space and time. Bjerknes[2] writes " On first sight one would place the tropopause simply where the lowest temperature occurs, while the true tropopause, which is lower down, passes for an insignificant feature in the upper troposphere. To arrive at a coherent system it is necessary to admit the diminution of the vertical lapse rate of temperature as a sign of the true tropopause ". In a later paper Bjerknes and Palmén[26] regard all sudden decreases of lapse rate in the upper troposphere and lower stratosphere as defining a characteristic point of the tropopause. Recently Flohn and Penndorf[38], accepting Palmén's analysis of laminated tropopauses, have suggested that no attempt should be made to define a single tropopause level, but that a tropopause layer should be substituted extending downward a conventional distance from the level at which isothermal conditions are reached.

§ 3—PRESENT SERIES OF TROPOPAUSE CHARTS

In order to make a study, as unbiassed as possible, of the day-to-day changes in the tropopause, it was decided to plot and analyse a month's series of contour charts of the tropopause with considerably greater attention to continuity and detail than is possible during routine analysis. Contours of the tropopause are drawn daily at the Central Forecasting Office at Dunstable and published in the *Daily Aerological Record*, but these charts are drawn only at 24-hr. intervals and full advantage is not made of continuity with intermediate soundings. A subsequent comparison of the two sets of charts revealed few differences in respect of the broad distribution of high and low tropopause but there were significant differences in detail.

The present series of charts were plotted and analysed for 6-hr. intervals. Plotted data were (i) the pressure at the tropopause, (ii) the potential temperature at the tropopause, and (iii) the observed wind at the reported level nearest to the tropopause. The topography of the tropopause was delineated by means of isobars drawn at 20-mb. intervals. The charts also contained an analysis of the surface pressure field and surface fronts in order to assist in relating the tropopause changes to ordinary synoptic developments. One month's charts were plotted, those for May 1949. That month was selected on account of the availability of data, but proved to contain an interesting variety of weather types.

In order to assist in maintaining the continuity in the sequence of tropopause charts, trajectories of the air at tropopause level were drawn, based on the observed winds and on a specially constructed series of 200-mb. charts. Trajectories were estimated for 24 hr. centred on each upper air sounding within the British Isles made at either 0300 or 1500 G.M.T. All data for the plotting of the charts were taken from the tephigrams plotted at the Central Forecasting Office from the telegraphic messages received. The placing of the tropopause was reconsidered in respect of each sounding, and all significant changes in lapse rate near the tropopause level were recorded.

In the drawing of the isobars on the tropopause, soundings which appeared discordant with the requirements of continuity in time or space were re-examined, and, if two or more discontinuities of lapse rate existed, that which gave better continuity was accepted as the tropopause, irrespective of whether or not this accorded strictly with the Meteorological Office convention quoted in § 2, page 11. In areas without observations the trajectories were used to complete the chart on the assumption that the tropopause was a material surface moving with the air.

In the drawing of the tropopause charts it was found difficult to regard the tropopause as a continuous surface. Discontinuities of level were therefore accepted, and indicated where they were believed to exist. Evidence for the existence of real discontinuities lies in the disappearance of the tropopause at one level and its reappearance at another in a sequence of soundings, together with intermediate soundings showing changes of lapse rate at both levels. A useful criterion for the existence of such a discontinuity is a substantial change of potential temperature at the tropopause. The nature and origin of these discontinuities will be further discussed in later sections.

§ 4—ACCURACY OF THE DATA REGARDING THE TROPOPAUSE

Before examining the results of the investigation it is convenient to consider the magnitude of the errors to be expected in the determination of the tropopause pressure and potential temperature from a radio-sounding. Harrison[39] has stated that, apart from systematic errors caused by radiation and affecting all instruments in the same way, the probable error of the observed pressure in the higher troposphere and lower stratosphere is about 5 mb. and of the observed temperature about 1° F. These errors refer to the pressure and temperature at the position of the instrument at the time, and do not refer to the errors of pressure computed hydrostatically nor to temperature on pressure surfaces.

The diurnal variation of pressure and potential temperature at the tropopause has been evaluated for the individual sounding stations during the month concerned. The mean of the tropopause pressure and potential temperature, for the standard hours averaged over the five stations making 4 daily soundings, is given in Table I. The absence of any systematic variation in the mean presssure between the synoptic hours suggests that systematic errors in pressure are negligible. The small variation in potential temperature may be real or instrumental. It implies a diurnal oscillation of temperature with an amplitude of 3° to 4° F. This variation is however smaller than random errors.

TABLE I—MEAN PRESSURE AND POTENTIAL TEMPERATURE AT THE TROPOPAUSE AVERAGED OVER ALL SOUNDINGS AT ALDERGROVE, LIVERPOOL, DOWNHAM MARKET, LARKHILL AND CAMBORNE FOR EACH SYNOPTIC HOUR

May 1949

	Hour of observation (G.M.T.)			
	0300	0900	1500	2100
Pressure (mb.)	243	243	240	244
Potential temperature (°F.)	127	130	132	128

During the course of a radio-sounding, observations of pressure, temperature and humidity are made once during each rotation of the fan-operated switch. This leads to discrete observations of temperature for about every 5-mb. change of pressure near the tropopause. On account of the discrete nature of the observations a probable error of about 3 mb. would be expected in the pressure at the tropopause, and combining this with the 5-mb. probable error of the pressure element an estimate of 6 mb. is derived for the total probable error of the pressure at the tropopause.

The temperature at the tropopause is subject to no other error than the 1° F. probable instrumental error noted above. However, the potential temperature is derived from both the temperature and pressure observations and will be affected by errors in both. At the levels where the tropopause occurs, a change of 1 mb. in pressure (at constant temperature) results in a change of 0·75° F. in the potential temperature, and a change of 1° F. in temperature (at constant pressure) results in a change of potential temperature of about 1·5° F. Combining the effects of the uncertainties in pressure and temperature at the tropopause an estimate is obtained of the probable error of the potential temperature at the tropopause as about 5° F.

The following section is concerned more with the errors of the difference of pressure and potential temperature at the tropopause in two soundings. The estimates of errors in this section may be summarized as follows :—

Estimated root-mean-square error in tropopause pressure	= 9 mb.
Estimated root-mean-square error in difference of two tropopause pressures	=13 mb.
Estimated root-mean-square error in tropopause potential temperature	= 7° F.
Estimated root-mean-square error in difference of two potential temperatures	=10° F.

§ 5—ADVECTIVE CONTRIBUTION TO SHORT-PERIOD CHANGES IN THE TROPOPAUSE

As indicated in § 3, trajectories were drawn of the estimated air movement during 24 hr. centred on each of the available tropopause observations in the British Isles for each of the main hours of observation, 0300 and 1500 G.M.T. A total of some 460 trajectories were drawn, based on observed winds whenever possible but often on the contours of the 300-mb. or 200-mb. surfaces. Geostrophic motion was assumed and interpolation made as appropriate.

These trajectories have been used to assess the importance of advection in causing the observed changes in the tropopause, by comparing the magnitude of the changes of pressure and potential temperature of the tropopause following the air trajectory with the changes taking place at fixed points. In considering the use of the trajectories in this way it is important to realize that these trajectories have been used to maintain consistency in the drawing of the tropopause charts themselves. The changes in tropopause pressure and potential temperature might therefore appear to be smaller than is in fact so. In order to minimize this effect only those trajectories have been used upon which it was possible to establish reasonably reliable values of pressure and potential temperature from soundings close to the track of the air.

Table II gives the root-mean-square values of the change in potential temperature and pressure at the tropopause over 6-, 12- and 24-hr. periods. This is given both for fixed points (the figures are averages for the nine sounding stations in the British Isles) and also for points along the estimated horizontal trajectory of air at the tropopause level.

It will be noted that the changes following the air motion are substantially smaller than those at a fixed point, and it follows that advection plays an important part in the bringing about of the observed changes. Advection probably accounts for about half the observed change of tropopause pressure at a point and almost all the observed changes in potential temperature apart from the effects of instrumental error.

The changes in potential temperature following the air motion show little significant increase with the length of the period. They are also slightly smaller than the estimated instrumental error of 10° F. (see § 3). It is concluded that the differences which are observed in potential temperature along the trajectory are primarily due to instrumental errors, and that the real changes are too small to be detected statistically. There are indeed a small number of cases of larger changes and these are discussed in § 7, page 33.

TABLE II—ROOT-MEAN-SQUARE VALUES OF THE 6-, 12- AND 24-HR. CHANGE OF PRESSURE AND POTENTIAL TEMPERATURE AT THE TROPOPAUSE FOLLOWING THE AIR MOTION AND AT A FIXED POINT

May 1949

The figures in brackets represent the values when allowance has been made for observational uncertainty.

		6-hr. change		12-hr. change		24-hr. change	
Number of trajectories		343		391		78	
				millibars			
Pressure	following the air motion	15·4	(8·0)	20·2	(15·5)	26·1	(23·0)
	at a fixed point	29·5	(26·1)	36·1	(34·0)	41·6	(39·6)
				degrees Fahrenheit			
Potential temperature	following the air motion	7·4		8·7		8·6	
	at a fixed point	15·1	(12·0)	16·9	(14·3)	19·1	(16·8)

The figures in brackets in Table II represent the root-mean-square value of the pressure changes when allowance has been made for mean-square errors of 13 mb. and 10° F. due to observational uncertainty (see § 4). Following the air motion these figures increase rapidly with time at first, but later more slowly, showing that the vertical motion tends to retain the same sign over at least 12 hr. An average vertical speed of about 5 mb./hr. is suggested as normal at the tropopause level.

§ 6—COMPARISON WITH THE ORIGINAL RECORDS FOR LARKHILL

In order to ascertain how far the tropopause, as determined from telegraphic reports and adjusted to meet the requirements of continuity, also represented a singular point in the temperature and wind soundings, the original records from the Larkhill soundings were examined in relation to the tropopause level used to draw the chart series. It was found that the tropopause was normally associated with a sudden change of lapse rate which was indistinguishable from a true discontinuity using only the observations of the radio-sonde. The level selected as the tropopause from the plotted tephigrams, and used in the drawing of the tropopause charts, was found to coincide with a sudden change in lapse rate on 108 out of the 123 soundings which reached the tropopause during the period. There was no sharp change of lapse rate on 13 of the remaining soundings, but on two soundings a sharp change existed at a level which, although appearing to define the tropopause, was inconsistent with the tropopause maps which had been drawn on the basis of continuity.

Examination of the wind soundings showed that significant changes of wind usually occur at or near the tropopause. However, the nature of these changes and their relationship to the level of the tropopause varied a great deal from one sounding to another, and it does not seem likely that wind structure can be used to identify the tropopause.

§ 7—CHARACTERISTIC FEATURES OF THE TROPOPAUSE CHARTS

With only a month's charts as a basis the discussion of various recurrent features of the tropopause charts cannot be conclusive, but it is regarded as adequate to distinguish the main types of tropopause behaviour. The various features deserve further study, and might provide useful synoptic models which can be introduced into the analysis of tropopause charts in association with the related developments in the troposphere, even when observations are insufficient to be conclusive. These models may also be used in analysing and forecasting upper winds at levels near or just above the tropopause.

Folding of the tropopause.—It has been noted by several authors, notably Bjerknes and Palmén[26] and Kraus[40], that in advance of a warm front the level at which tropical air first replaces the polar air may lie above the tropopause in the cold air—this is the highest level at which the tropical air is warmer than the polar—and that in the stratosphere the front, if it exists, must have cold-front characteristics. The structure near the tropopause of at least some warm fronts is therefore believed to be as indicated in Fig. 8. On this basis a sounding at point D would be expected to lie within the troposphere from D to C and again from B to A. It would show two tropopause levels, C and A. The same structure is also described by Nyberg and Palmén[31], Nyberg[4] and van Mieghem[41]. Probably the earliest reference to this structure was due to Goldie[42].

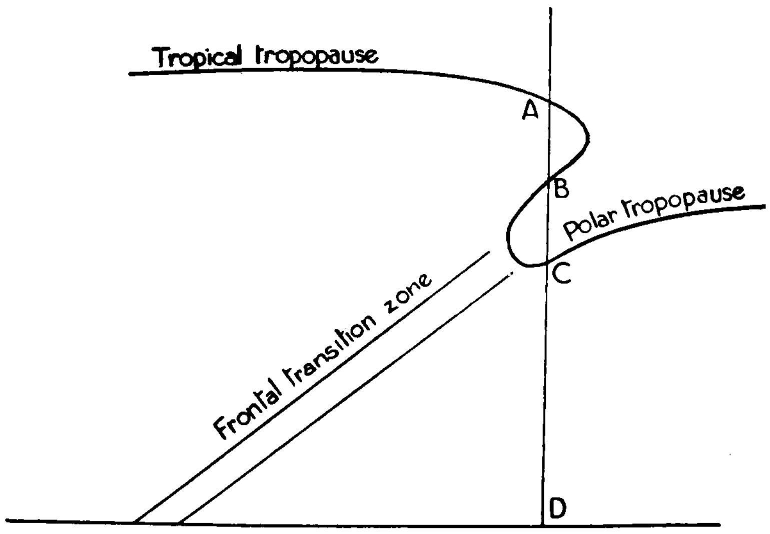

FIG. 8—SCHEMATIC CROSS-SECTION THROUGH A WARM FRONT SHOWING FOLDED TROPOPAUSE

Some 12 distinct examples of folds in the tropopause of essentially similar type were found on the tropopause charts for May 1949 in association with warm-front systems. In addition one similar fold was observed to form behind a cold front and another occurred without any associated surface frontal systems. In fact, a folded tropopause occurred with all the major warm-front

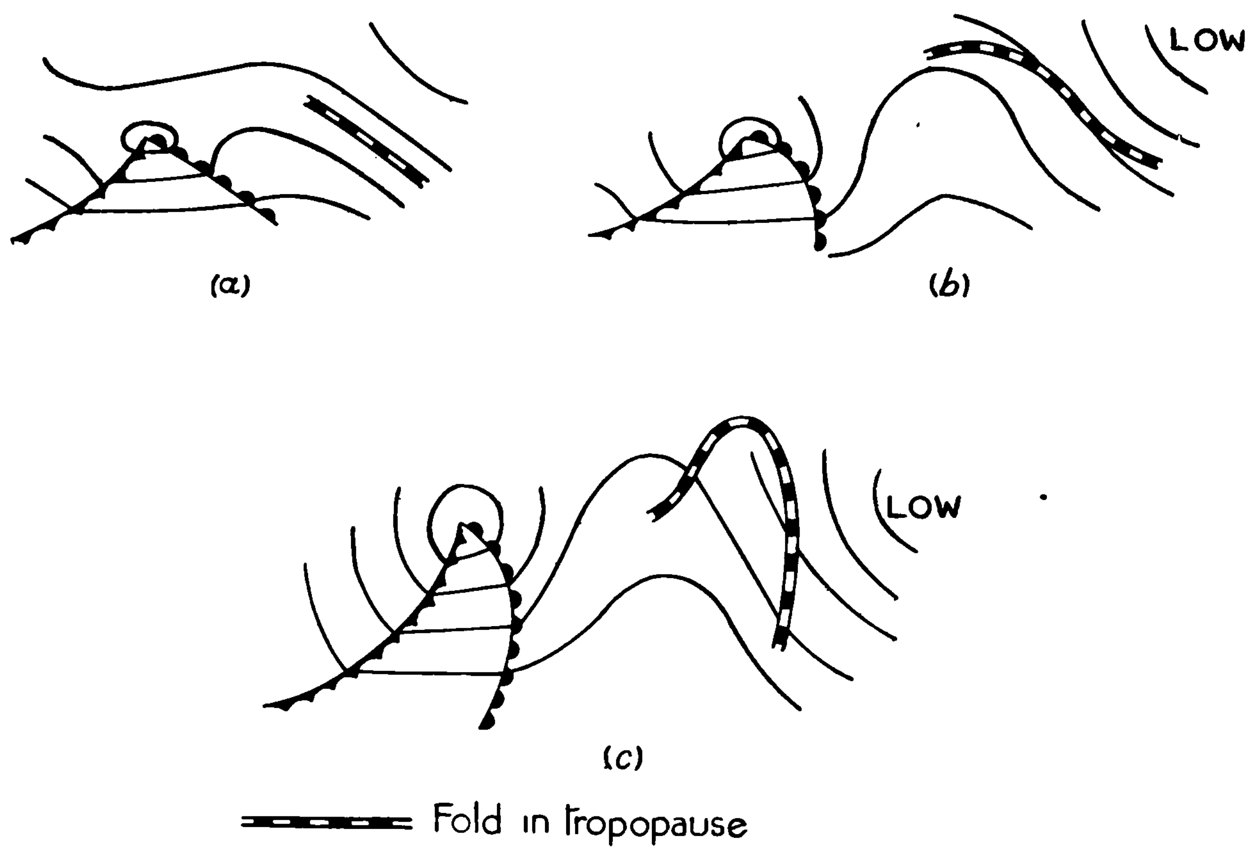

FIG. 9—SCHEMATIC RELATION OF FOLDED TROPOPAUSE TO FRONTAL SYSTEM IN THE HORIZONTAL

systems for which adequate observational coverage was available during the period, although the folded structure did not necessarily extend throughout the length of the front. The relationship of the fold or discontinuity in the tropopause to the front is displayed pictorially in Fig. 9. These diagrams are intended only to bring out what are regarded as the significant features ; the details varied considerably from case to case.

The first formation of the folded tropopause appears to take place from 500 to 1,000 miles ahead of the surface warm front and to be well to the right of the track of the depression centre. Subsequently the folded structure may become more extensive, and the line of the discontinuity tends to conform to the shape of the front but to be displaced 600 to 1,000 miles ahead of it. The limit of the high-level tropopause often appears to undergo a process analogous to occlusion ; this will be described in the following subsection. The fold has been found to lie above a variety of pressure systems, but is usually east of the axis of the ridge of surface high pressure. It does not seem possible to identify its position by any feature of the surface synoptic chart.

There is a close association between the folded tropopause and the jet stream. The cases noted all occurred in association with a jet stream and most of them first appeared near the axis of the central part of the jet stream. There may be some tendency for the tropopause discontinuity to be a little to the left of the axis of the jet stream. It is quite probable that the folding process is closely associated with the dynamics of the jet stream. Namias and Clapp[43] have shown that it might be expected that the entrance to a jet stream should be associated with a transverse component in the circulation as represented in the schematic transverse section Fig. 10. This is on account of the fact that air entering the jet stream is strongly accelerated, and therefore deflected across the isobars to the left to a greater extent than the less accelerated air above and below.

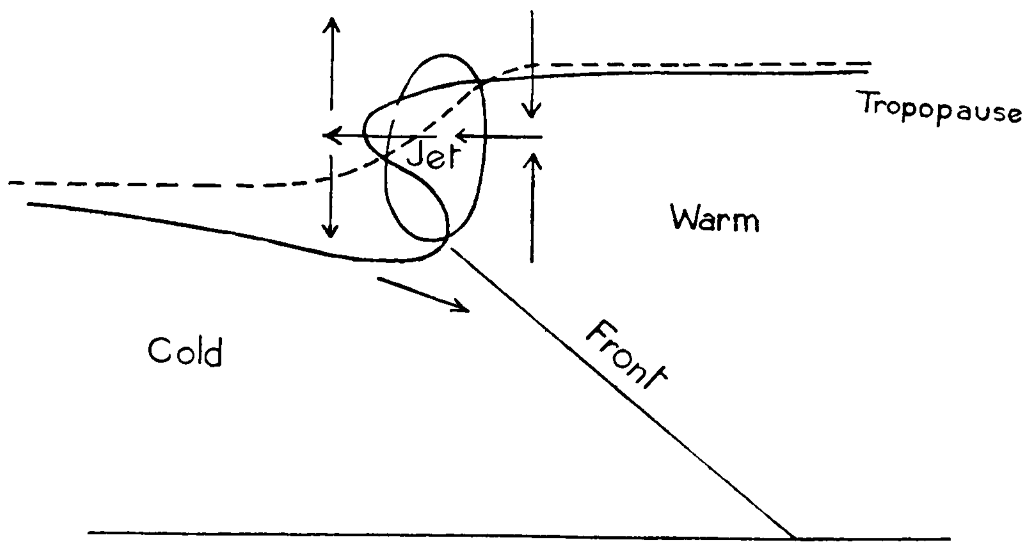

FIG. 10—SCHEMATIC SECTION THROUGH THE CONFLUENT ENTRANCE TO A JET STREAM
Looking east

The confluent entrance to the jet stream brings together air from widely different localities ; often arctic and tropical air come into close juxtaposition. This leads to an increase in the slope of the tropopause in the vicinity of the jet stream as indicated by the dashed line in Fig. 10. The transverse circulation, such as is indicated in the figure, would create an additional distortion of the tropopause to the final position indicated by the solid line, and thus would result in the folded structure observed. Reported wind soundings have been examined for evidence of the transverse flow necessary to produce the folded structure, but the observations are inconclusive. In some cases there appears to be a component of wind across the general slope of the tropopause, which is greater at the higher level of the tropopause than at the lower, but the difference is of the order of 5 to 10 kt., and is therefore difficult to distinguish from errors in the soundings. A transverse component of this magnitude would however be quite adequate to produce the observed folded structure.

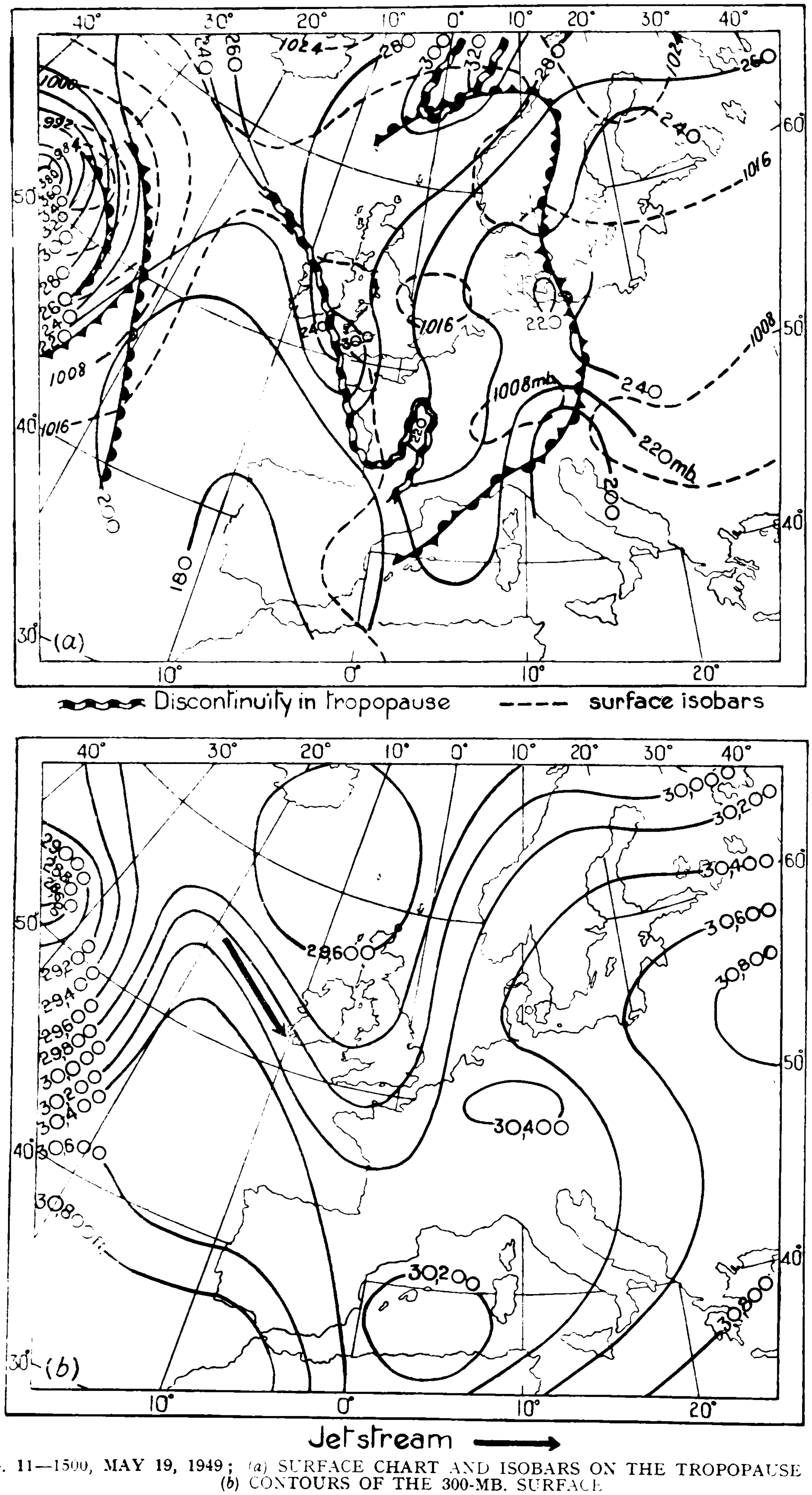

FIG. 11—1500, MAY 19, 1949; (a) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (b) CONTOURS OF THE 300-MB. SURFACE

An example of a folded tropopause is that of May 19, 1949. Fig. 11 shows the surface positions of the fronts and isobars at 1500 superimposed upon the contours of the tropopause. The fold in the tropopause extends from north-north-west to south-south-east parallel to the warm-frontal systems some 700 miles to the west. Fig. 11 also shows the contours of the 300-mb. surface and the position of the associated jet stream. Fig. 12 shows a sequence of upper air soundings from Larkhill. Wind soundings from Larkhill and Camborne do not give any indication of the transverse current round the jet stream which has been suggested as a possible cause of the folded tropopause. However, the possibility remains that the folding process had already taken place up-stream. A sounding at Aldergrove on May 6, 1949, is reproduced in hodograph form in Fig. 13. It illustrates this possibility. This sounding was taken in the central part of a jet stream during the period when the formation of a folded tropopause was first detected. The fairly uniform direction of shear from 700 to 300 mb. can be regarded as defining the thermal gradient and the axis of the jet. The small component of the wind at 250 mb. transverse to this axis may indicate a circulation through the jet stream at this level. However, the detailed study of a large number of wind soundings through jet streams would be needed to establish this.

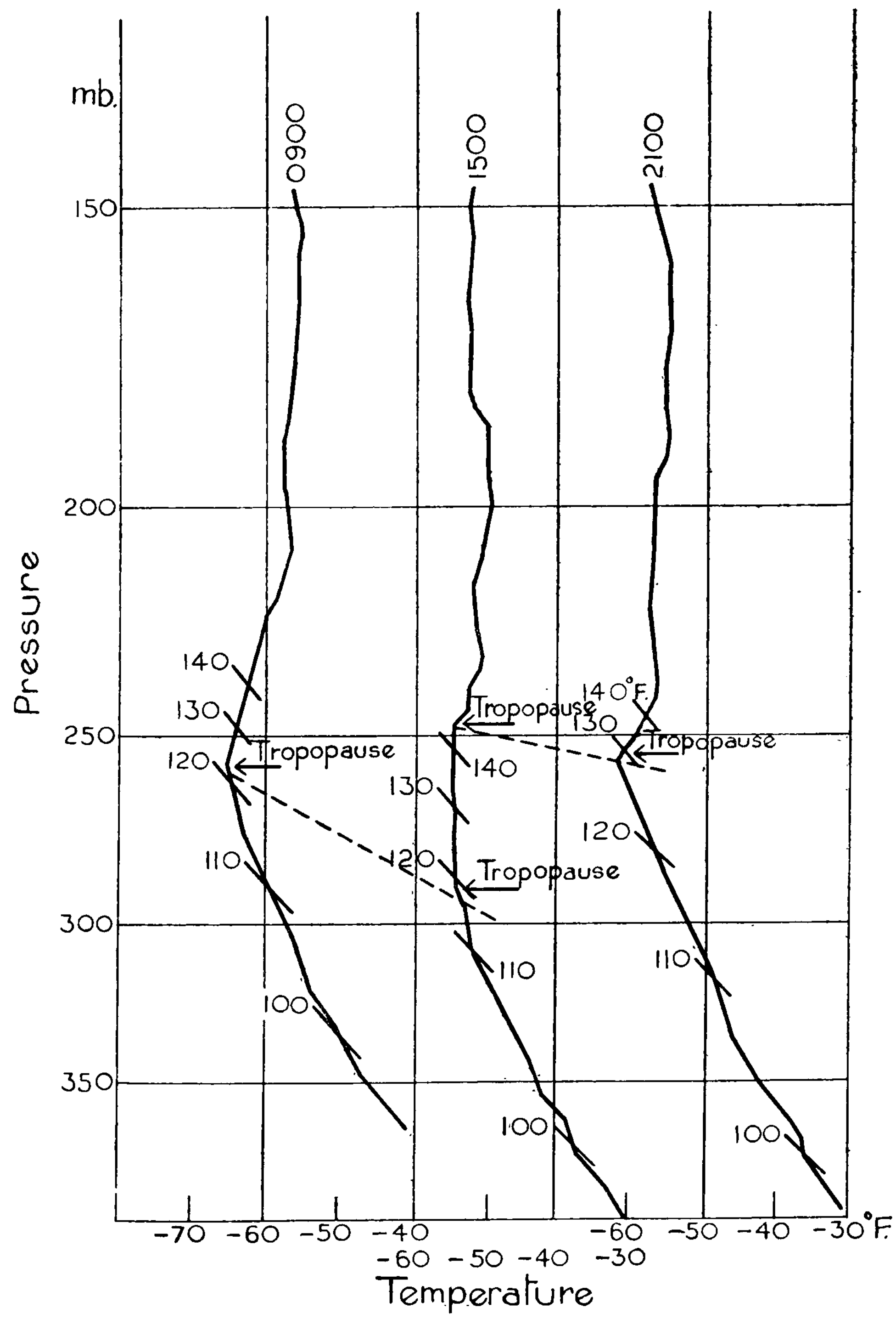

FIG. 12—TEMPERATURE SOUNDINGS, LARKHILL, MAY 19, 1949

Short sloping lines are segments of dry adiabatics at potential temperatures indicated

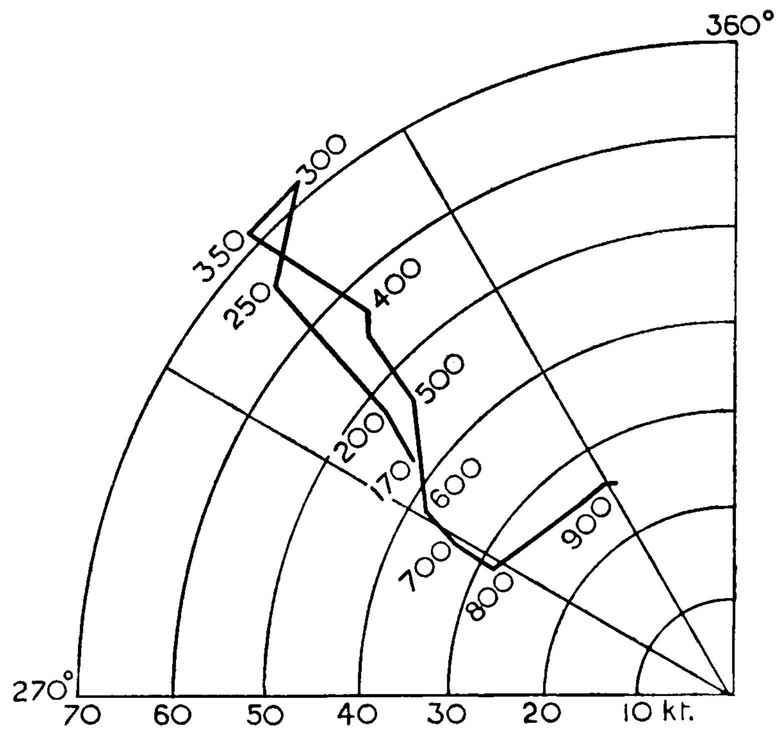

FIG. 13—HODOGRAPH OF WIND SOUNDING, ALDERGROVE, 2100, MAY 6, 1949

Routine soundings at 6-hr. intervals are inadequate to investigate the rapidity of the change of tropopause level in association with the folded structure. Nyberg and Palmén[31] noted changes of 6,600 to 13,000 ft. (2 to 4 Km.) in the level of the tropopause in 2-hr. in a situation of this type.

Occlusion of tongues of high tropopause.—In the preceding subsection it has been indicated that a discontinuity of the tropopause often arises by folding in association with a jet stream. The discontinuity (here regarded as defined by the limit of the high tropopause sheet) usually lies slightly to the left of the axis of the jet stream. At the exit from the jet stream, or sometimes at a marked trough line in the flow, the limit of the upper tropopause sheet is distorted as indicated schematically in Fig. 14, leading to a rather narrow tongue of high tropopause extending from the left exit of the jet stream. Such tongues were noted eight times on the tropopause charts for May 1949. With one exception they were short-lived features with a life of only a little over 12-hr., and were destroyed in a very similar manner to that in which warm tongues disappear during the occlusion process of depressions.

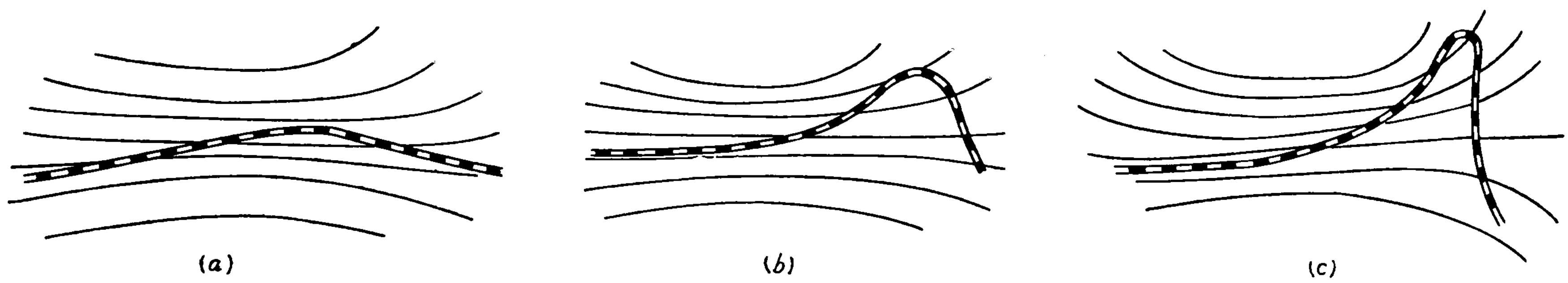

FIG. 14—DISTORTION OF THE FOLDED TROPOPAUSE AT THE EXIT FROM THE JET STREAM ILLUSTRATED BY HORIZONTAL DISPLACEMENTS AT THE "FOLD"

An examination of the changes in tropopause height following the estimated air movement suggested that the tropopause within the tongue descended and became less well defined, while at the same time a new tropopause at a lower level became more definite, probably forming out of the lower branch of the folded tropopause. The examination of a series of soundings, through approximately the same air column as it moved along, indicated that this process could be the result of approximately adiabatic air movements, in which the air at the level of the high tropopause descended and air at the level of the lower tropopause underwent little change of level.

Such a system of air movements requires vigorous divergence of the air between the two levels, and indeed such divergence is to be expected dynamically to the left of the exit from a slow-moving jet stream because the air on the left side of the jet stream has considerable cyclonic vorticity which must be lost at the exit (if the air moves faster than the characteristic configuration of contours).

The whole process appears to transfer relatively small volumes of air from the troposphere to the stratosphere.

An example of the formation and occlusion of a tongue of high tropopause is given in the charts for 0300, 1500 G.M.T., May 5, and 0300 G.M.T., May 6, 1949. A folded tropopause had developed in association with a jet stream extending from north-north-west to south-south-east off the west coasts of the British Isles, and the approximate limit of the high tropopause is indicated on the chart for 0300, May 5, Fig. 15. The corresponding limit has been indicated on the next chart, Fig. 16, for 1500, May 5, 1949, and could have been reached by motion following the observed and estimated winds at that level. However, on the third chart Fig. 17 for 0300, May 6 the high tropopause was no longer a significant feature over a large part of the area, which should have been reached by air initially within the high tropopause area, and the tongue has been shown as correspondingly reduced. Some estimated trajectories of air at tropopause level are shown in Fig. 16. Contours of the 200- and 300-mb. surfaces are given in the lower parts of Figs. 15, 16 and 17.

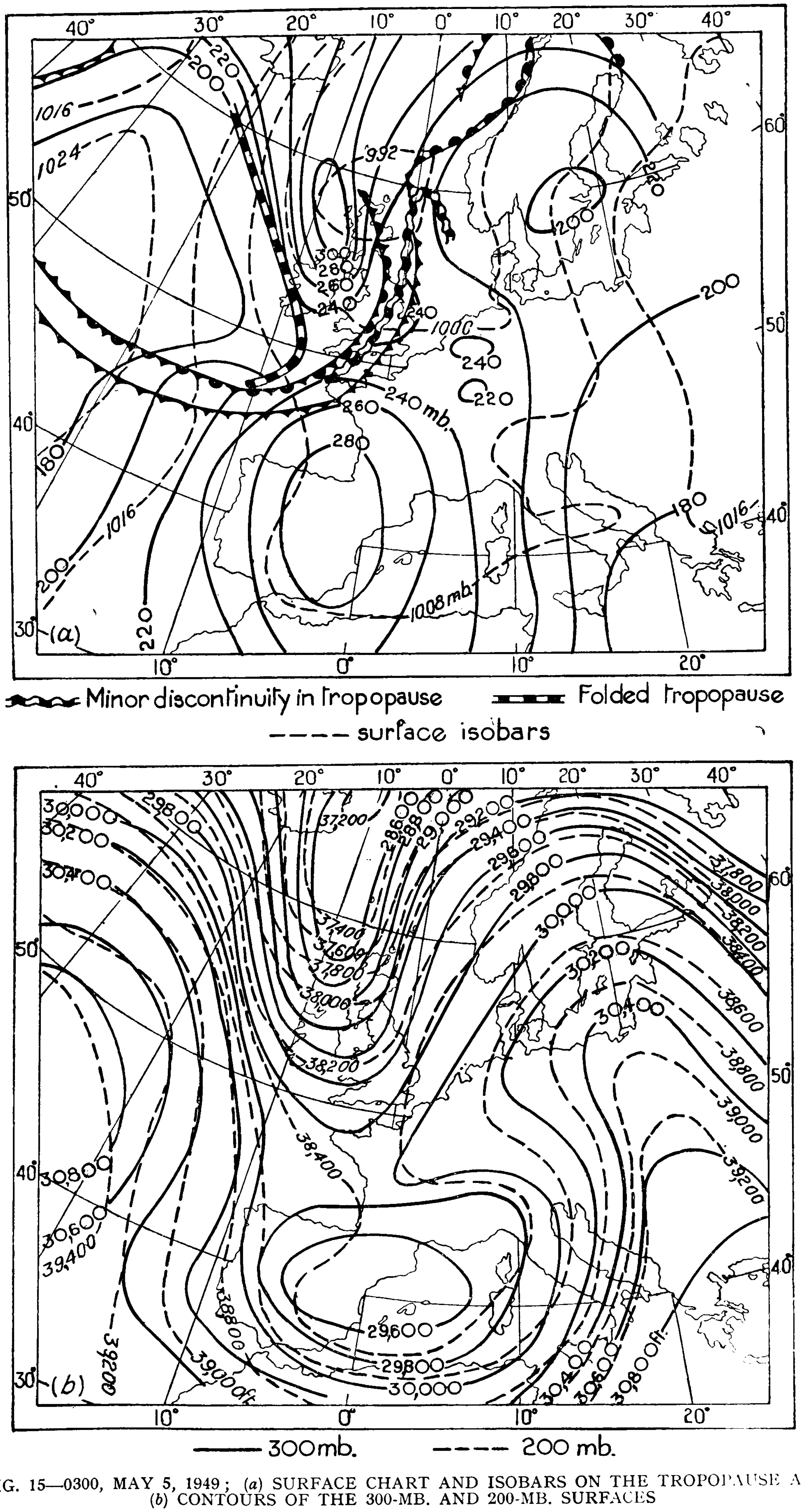

FIG. 15—0300, MAY 5, 1949; (*a*) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (*b*) CONTOURS OF THE 300-MB. AND 200-MB. SURFACES

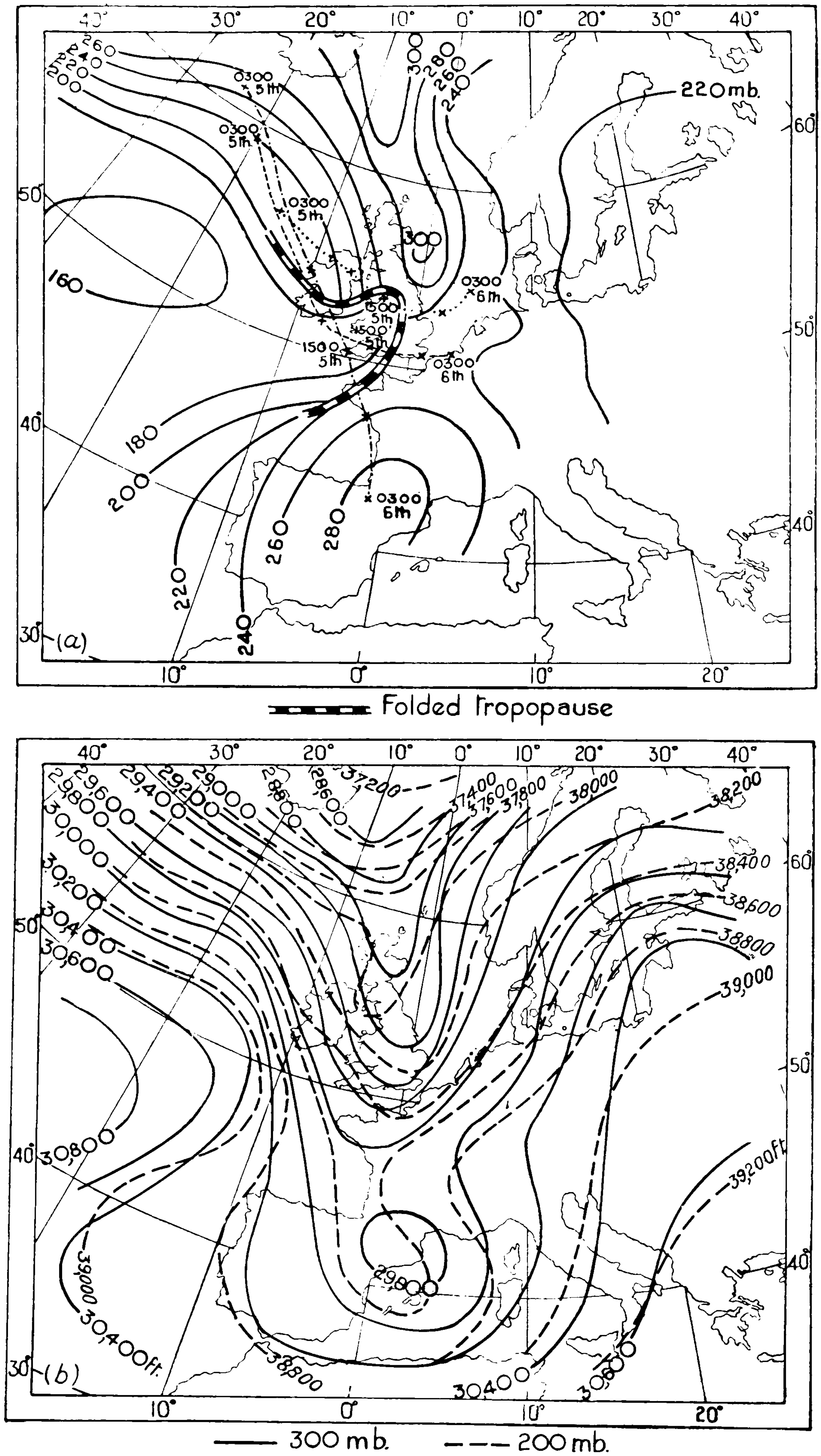

FIG. 16—1500, MAY 5, 1949 ; (*a*) ISOBARS ON THE TROPOPAUSE AND ESTIMATED TRAJECTORIES OF AIR AT TROPOPAUSE LEVEL AND (*b*) CONTOURS OF THE 300-MB. AND 200-MB. SURFACES

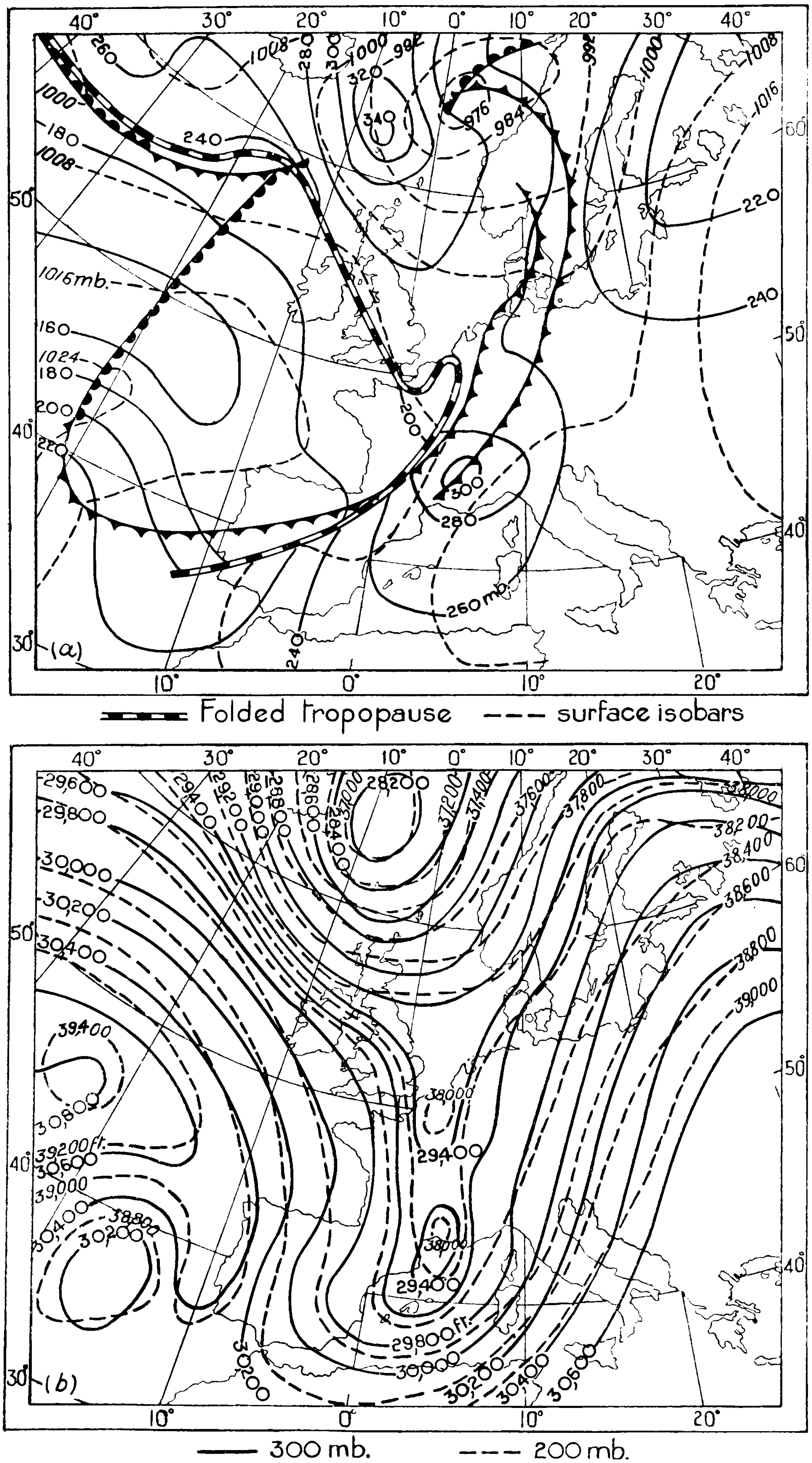

FIG. 17—0300, MAY 6, 1949; (a) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (b) CONTOURS OF THE 300-MB. AND 200-MB. SURFACES

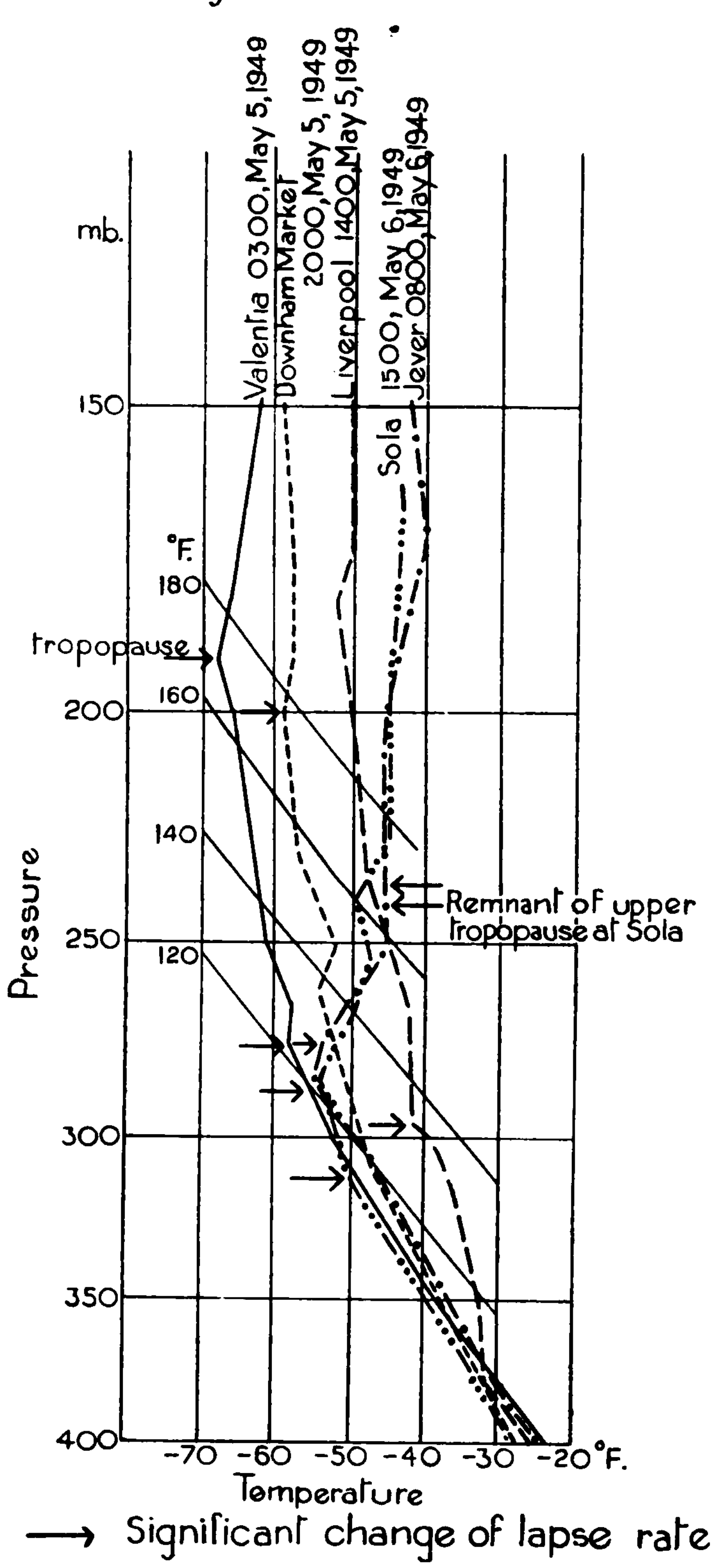

FIG. 18—TEMPERATURE SOUNDINGS, MAY 5–6, 1949
ILLUSTRATING THE OCCLUSION OF A HIGH-LEVEL TROPOPAUSE
Sloping lines are segments of adiabatics at potential temperatures indicated and arrows indicate the tropopause or other significant changes in lapse rate

The dissolving of the high-level tropopause by subsidence and its replacement by a lower tropopause is illustrated in Fig. 18 by means of temperature soundings from a selection of stations plotted on a thermodynamic diagram (log pressure against temperature). Valentia may be regarded as typical of a sounding with a high tropopause near the fold before the distortion commenced. The Liverpool and Downham Market soundings were taken in the tongues of high tropopause, and those at Sola (Norway) and Jever (Germany) in the area which it would have been expected to reach had it not dissolved. The soundings at Sola show traces of the upper tropopause at a potential temperature close to that at which it was previously observed.

Tropopause funnels.—Any sequence of charts of the contours of the tropopause reveals the presence of centres of low tropopause. These features have been discussed in several synoptic studies, notably by Palmén[3, 18], Bjerknes and Palmén[26], Bjerknes, Mildner, Palmén and

Weickmann[30] and van Mieghem[41]. Centres of low tropopause develop frequently in association with vigorously deepening depressions, and subsequently become centred over the old depression when it becomes slow moving and fills.

As has been indicated in § 2, Palmén has suggested that the formation of such areas of low tropopause is the result both of the descent of the air at the tropopause level together with the dissolution of the tropopause and its re-formation at a lower level as the result of vigorous horizontal divergence. Palmén uses the expression " tropopause-trichter " (tropopause funnel) to describe the resulting systems of low tropopause which have several characteristic features.

The tropopause contour charts for May 1949 contained 12 centres of low tropopause. These were all persistent features with a life of from 2 to 7½ days. All the examples during this period were associated with descent of the tropopause during their initial stages. In some, but not all, of them there was evidence of a re-formation of the tropopause at a lower level from the fact that the potential temperature at the tropopause in the centre of the tropopause depression became substantially lower than previously observed anywhere on the tropopause in the region of formation.

Out of the 12 examples of tropopause funnels studied, 9 formed in association with active but rather slow-moving depressions—it is probable that depressions developing close to the tip of a cold trough or to the left of a diffluence in the thermal pattern are particularly likely to lead to the development of a tropopause depression. Three of the examples studied were not initially associated with any recognizable surface pressure system. With two exceptions the tropopause low later became associated with a cold pool in the troposphere and an associated slow-moving depression.

The formation of tropopause funnels appears to be closely associated with the flow pattern near the tropopause level. Nine of the twelve occurrences were associated initially with well-defined troughs at 300 mb., which in several instances subsequently developed closed circulations ; the remaining examples were associated with closed 300-mb. circulations from the earliest traceable stage. Evidence from the trajectories drawn for air at tropopause level suggests that the air usually subsides as it approaches the trough line from the west and ascends as it leaves the area on the eastern side. However, there usually appears to be a central core in which the air remains near the upper trough line and moves with it, even when no closed 300-mb. contours are present. The structure is indicated schematically in Fig. 19. It seems probable that the central core consists of essentially the same air at tropopause level through much of its history

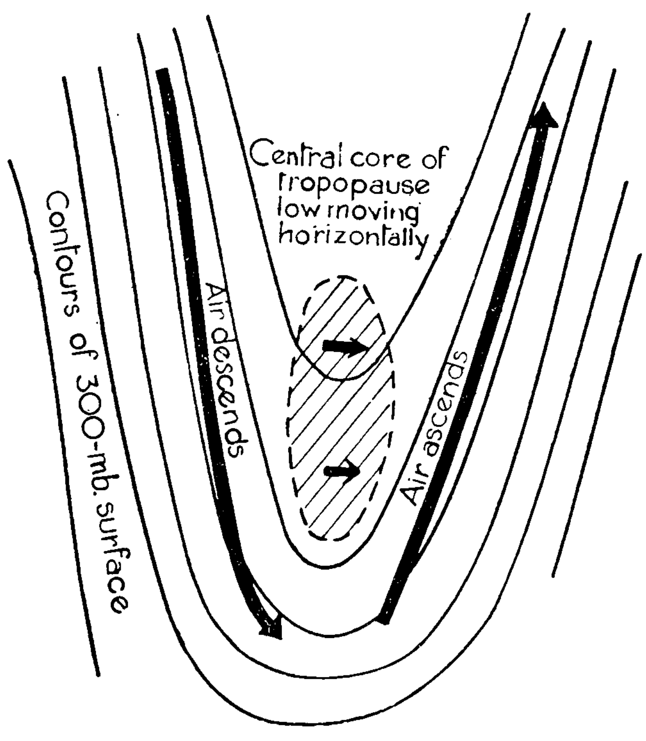

FIG. 19—SCHEMATIC RELATION BETWEEN TROPOPAUSE LOW AND 300-MB. CONTOURS

and that its movement is primarily due to horizontal advection. On the other hand the air passes through the outer regions of the tropopause depression which is maintained in these areas by the dynamical descent and ascent associated with the flow pattern.

In its later stages a tropopause funnel is often associated with a closed low at 300 mb., but in the cases studied it appears to have been situated sufficiently eccentrically for its motion to be explained by advection. Motion of the centres of fully established tropopause funnels was generally slow, 20 kt. or less, and often tortuous. In their earlier stages when associated with an open trough at 300 mb. speeds of up to 45 kt. appeared to be normal.

An important feature of the structure of tropopause funnels is the presence of a very low tropopause in the central region—usually well below the 300-mb. level and sometimes below 400-mb. The potential temperature at this tropopause is usually between 80° and 95° F., which is often well below the potential temperature at the tropopause in any of the air masses entering into the original circulation. It is not possible to say on the present evidence whether radiational cooling in the upper atmosphere could be sufficiently rapid to bring about this change, but examination of the potential temperature change along the large number of trajectories drawn at tropopause level (see § 5) suggests that the radiational effect is normally much smaller than this. It is also significant that the low central tropopause appears to be continuous with the lower boundary of an adjacent cold front in many cases. The tropopause is apparently well defined within the central core but on its fringes is often difficult to place ; this also is consistent with a discontinuous structure as shown schematically in Fig. 20.

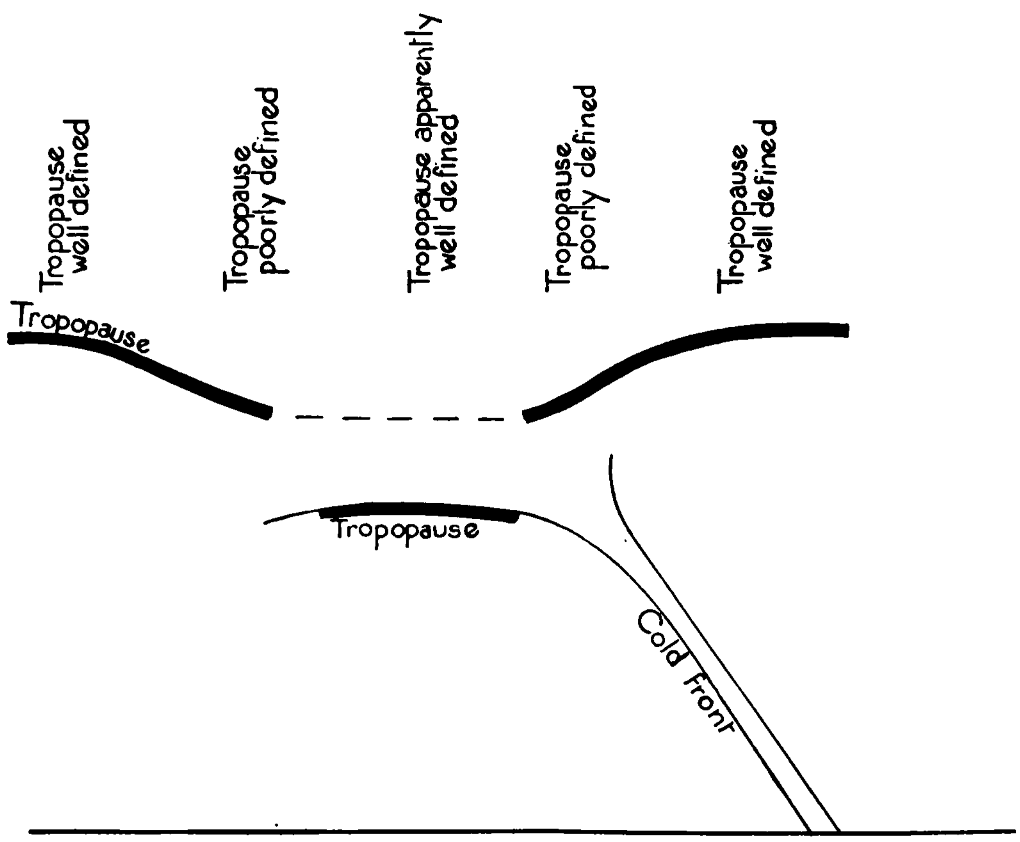

FIG. 20—SCHEMATIC CROSS-SECTION THROUGH A TROPOPAUSE FUNNEL

The tropopause funnel with a closed wind circulation appears to be a dynamically stable system. Collapse of the system is often associated with the overrunning of a higher tropopause associated with the approach of a vigorous warm-frontal system. When this occurs the decay of the tropopause funnel is rapid and it may effectively disappear from the charts in 12 to 24 hr. The process appears to be associated with the rapid descent of air in the tropopause funnel and its ultimate absorption into the troposphere.

The structure and behaviour of a tropopause funnel is illustrated by the system of May 15–21, 1949. Charts of the pressure at the tropopause are reproduced at 24-hr. intervals (Figs. 21 to 25)

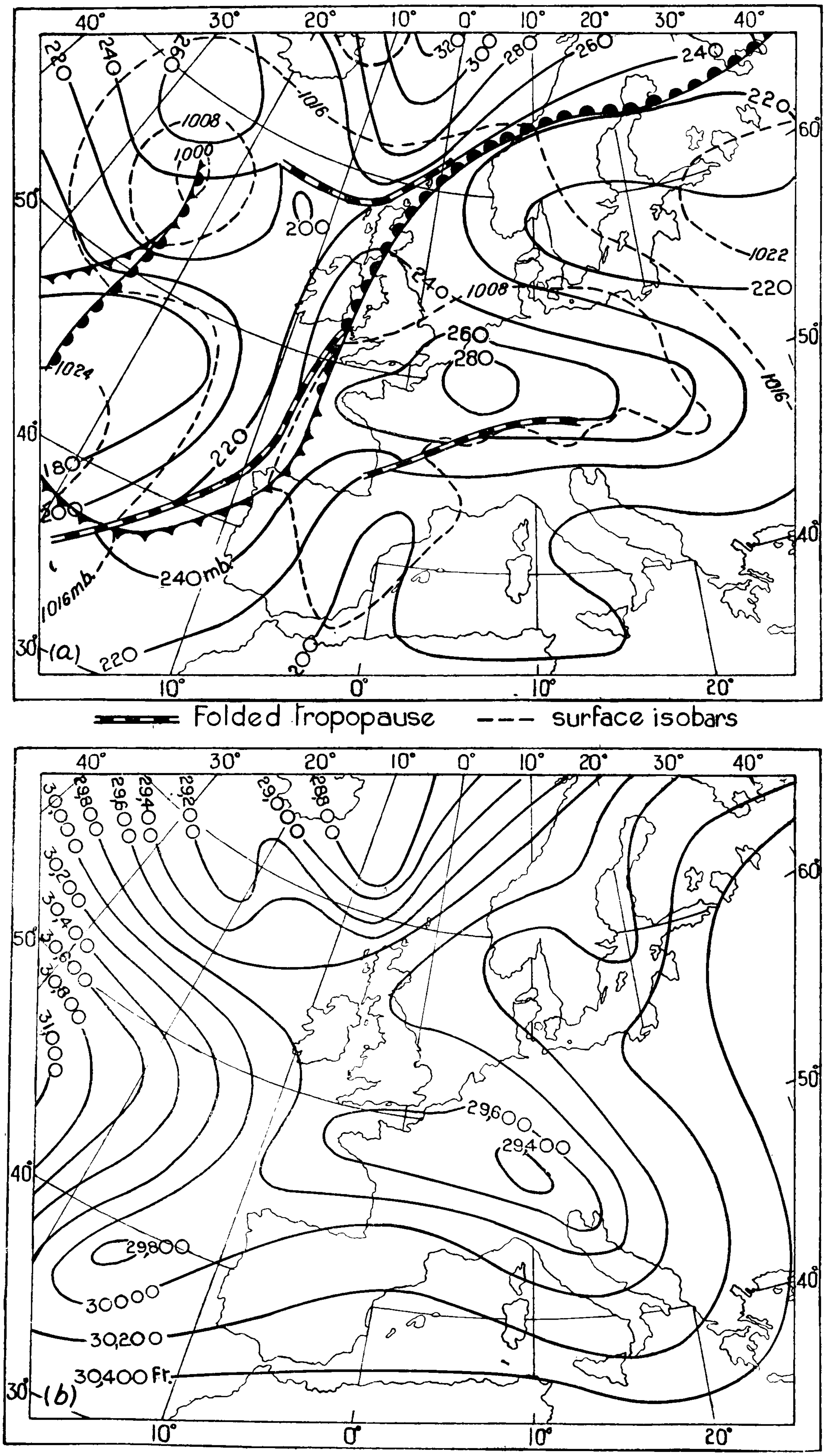

FIG. 21—0300, MAY 15, 1949; (*a*) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (*b*) CONTOURS OF THE 300-MB. SURFACE

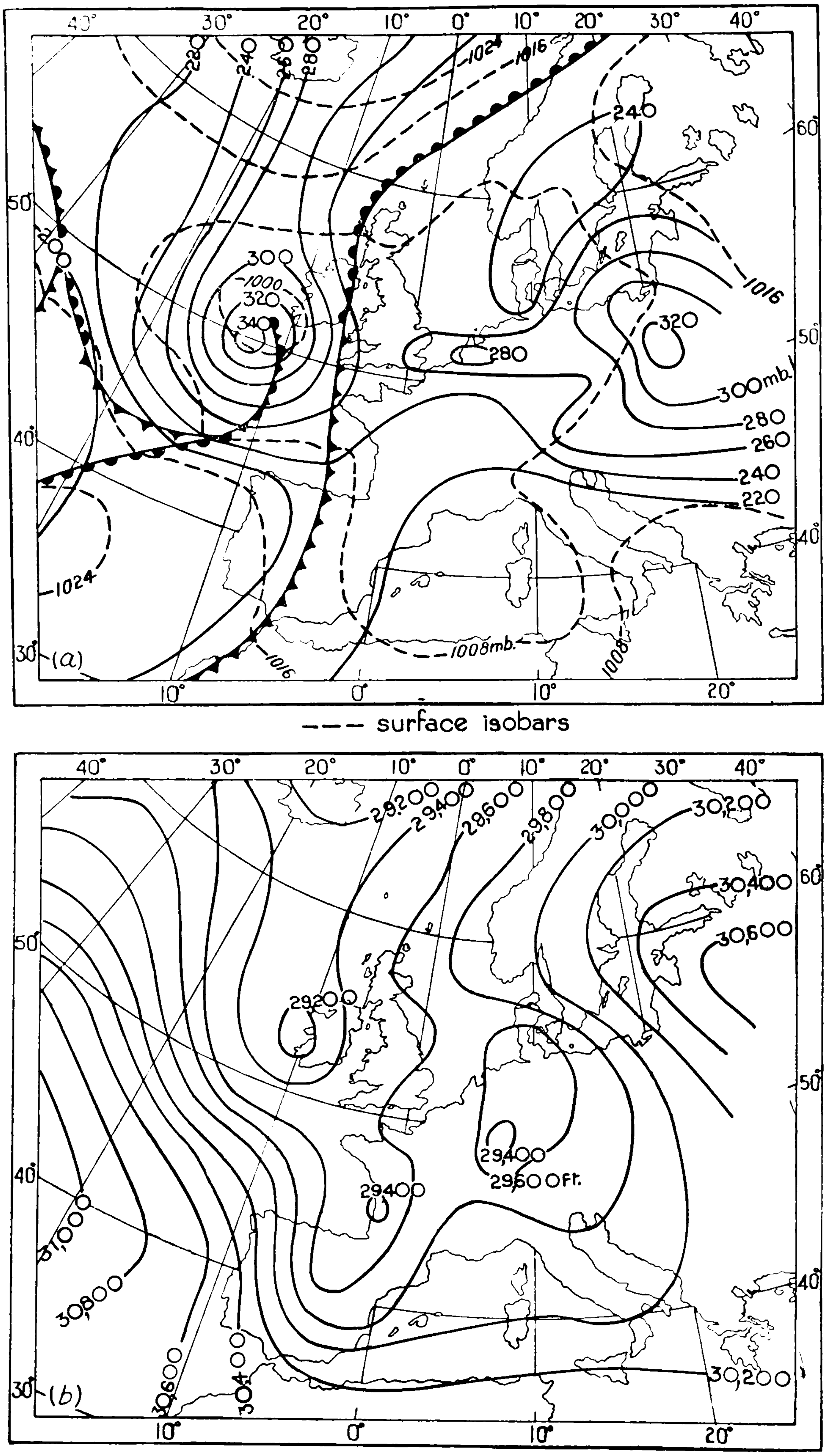

FIG. 22—0300, MAY 16, 1949; (a) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (b) CONTOURS OF THE 300-MB. SURFACE

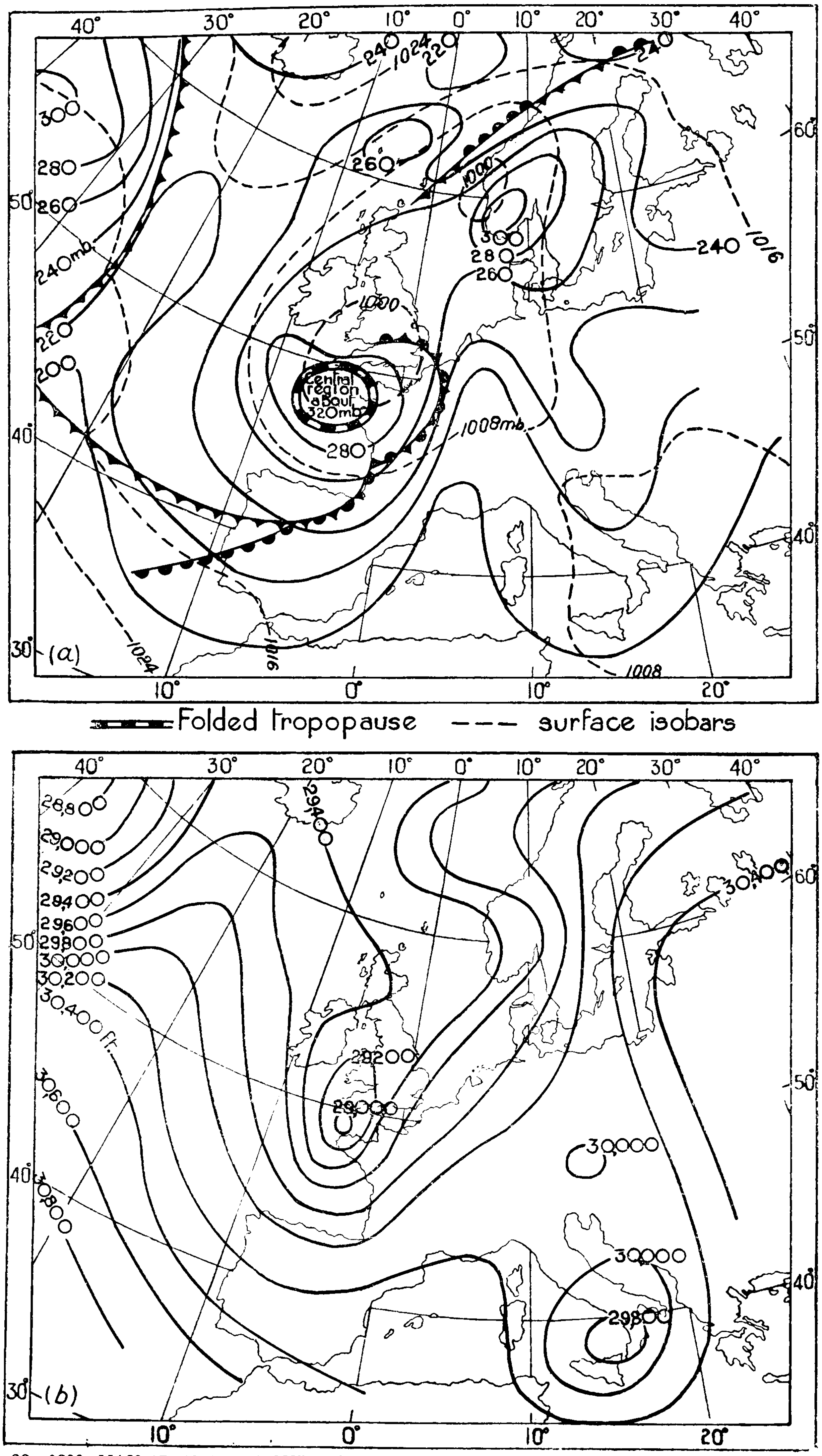

FIG. 23—0300, MAY 17, 1949; (a) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (b) CONTOURS OF THE 300-MB. SURFACE

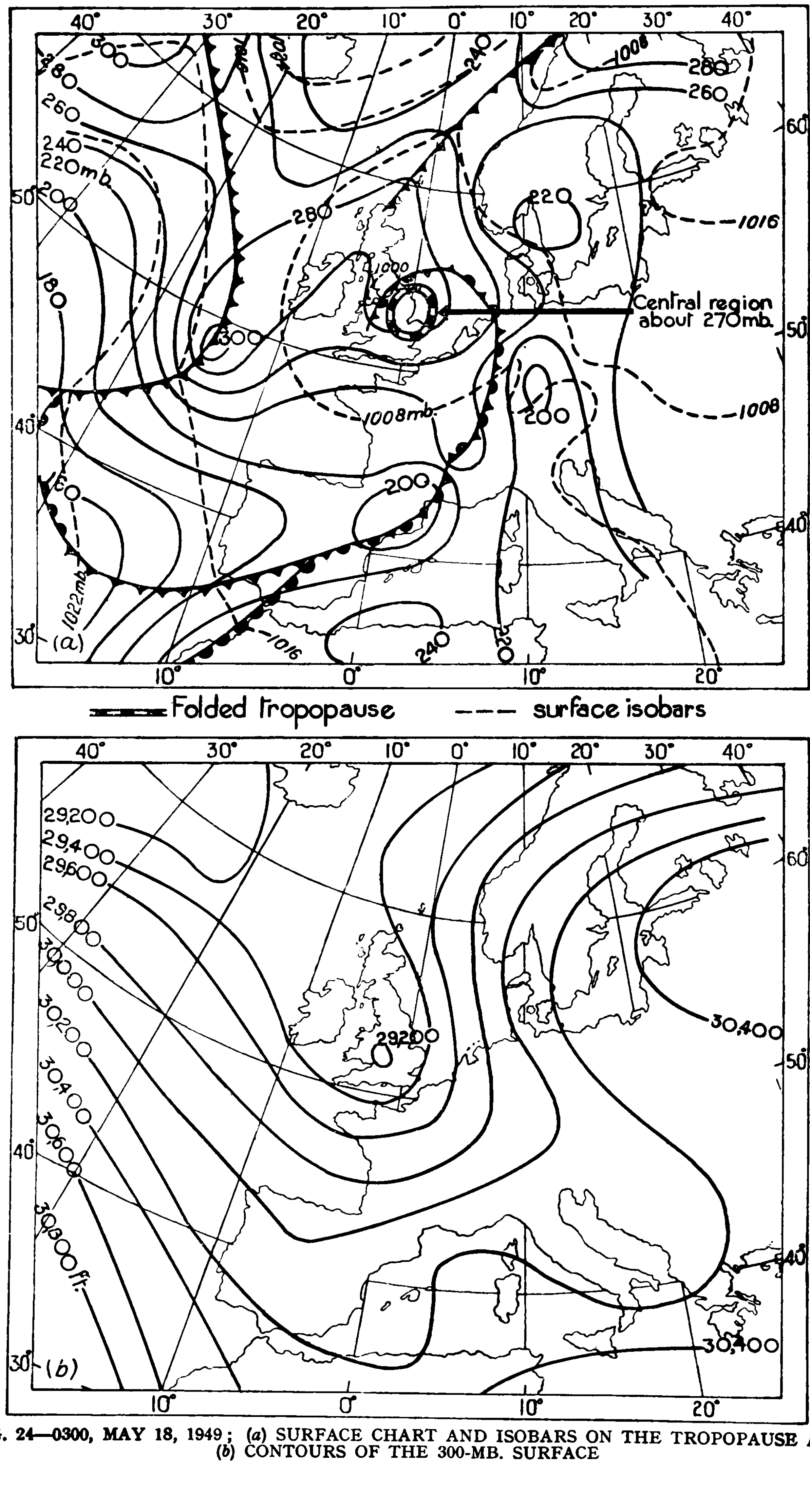

FIG. 24—0300, MAY 18, 1949; (*a*) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (*b*) CONTOURS OF THE 300-MB. SURFACE

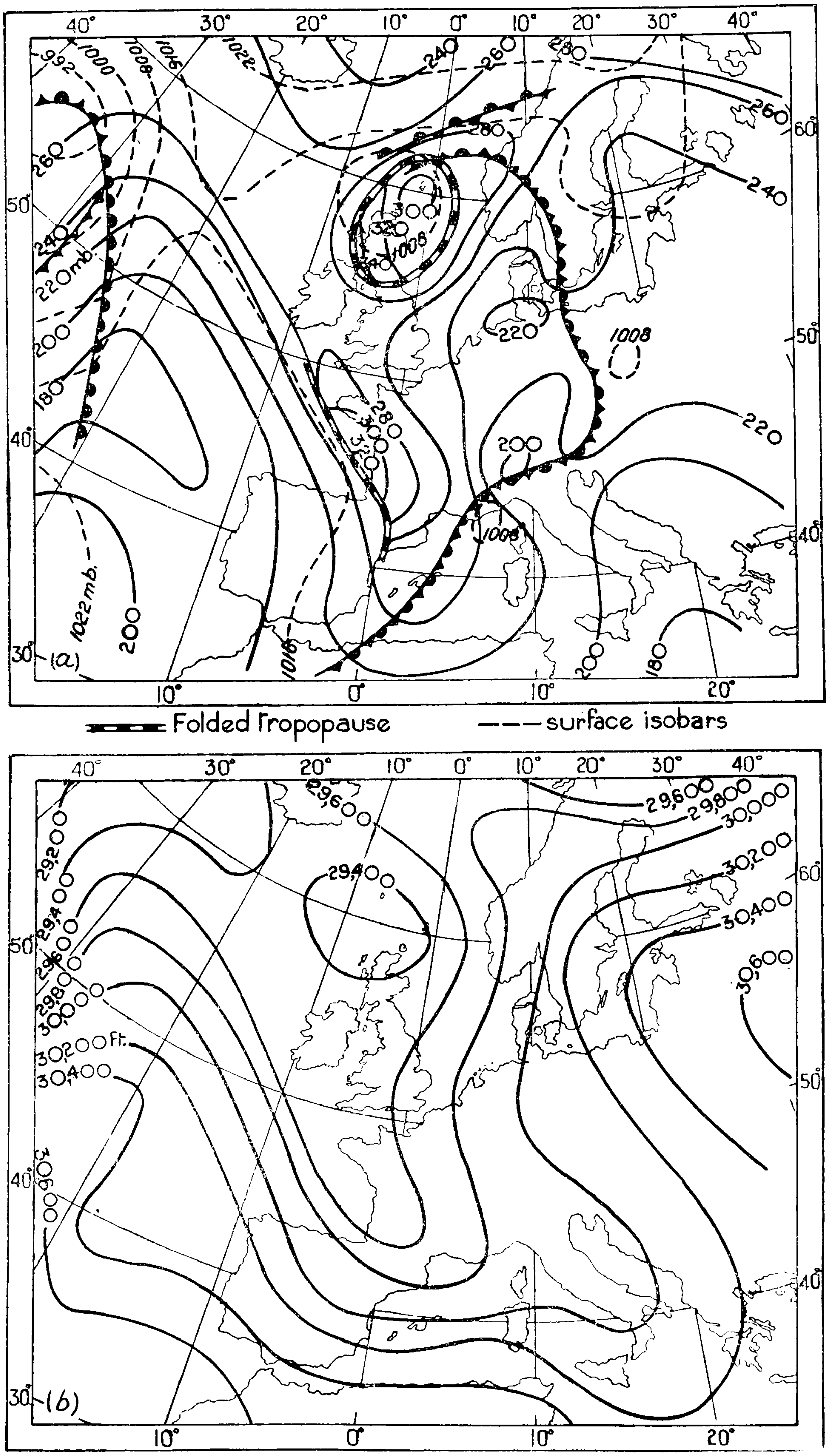

FIG. 25—0300, MAY 19, 1949; (*a*) SURFACE CHART AND ISOBARS ON THE TROPOPAUSE AND (*b*) CONTOURS OF THE 300-MB. SURFACE

together with charts of the 300-mb. contours. Surface isobars and fronts are superimposed on the tropopause charts. This example was selected because it was well observed over the British Isles, but the 300-mb. trough is not as clearly defined in the early stages as in many examples.

The sequence of soundings from Larkhill in Fig. 26 presents typical soundings in various regions of a tropopause funnel. The arrows indicate the positions of the tropopause and the discontinuity in lapse in the upper troposphere. Continuous arrows have been used to indicate the level which has been accepted as the tropopause in the construction of contour charts.

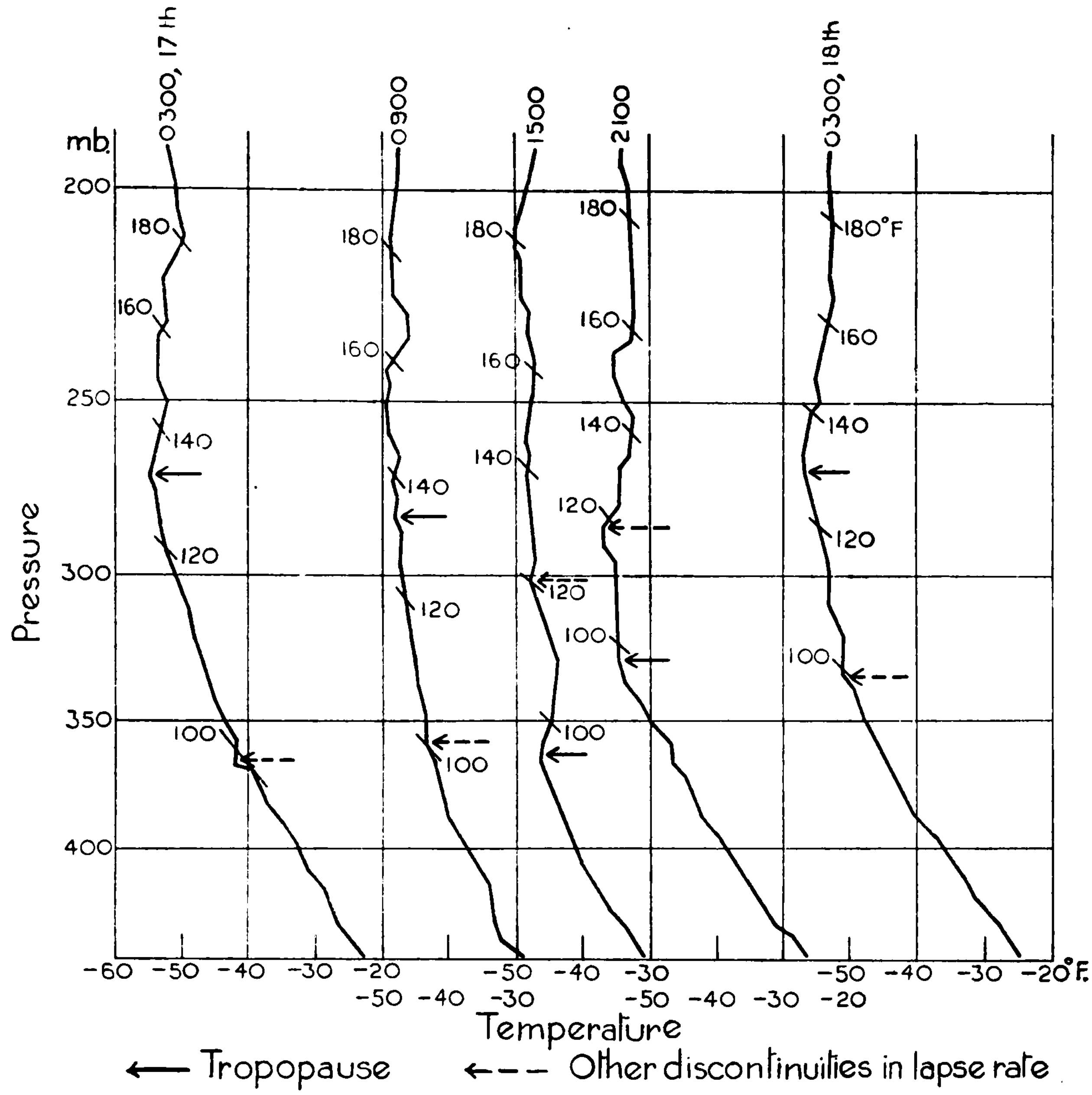

FIG. 26—TEMPERATURE SOUNDINGS, LARKHILL, 0300, MAY 17 TO 0300, MAY 18, 1949

Short sloping lines are segments of dry adiabatics at potential temperatures indicated

Two cross-sections through this funnel in perpendicular directions are shown in Fig. 27 and illustrate the structure. The isokinetics, lines of equal normal wind speed, have been based on both geostrophic measurements and observations ; they show a jet stream to the north and east of the tropopause funnel and a less well defined maximum of wind to the south and west.

The overrunning of a tropopause funnel is also illustrated in Fig. 25, over the west coast of France where a funnel, which has moved in from the Atlantic, is collapsing beneath the high tropopause encroaching in association with the Atlantic frontal system. There is insufficient evidence to indicate whether a typical central core existed in the tropopause funnel over western France.

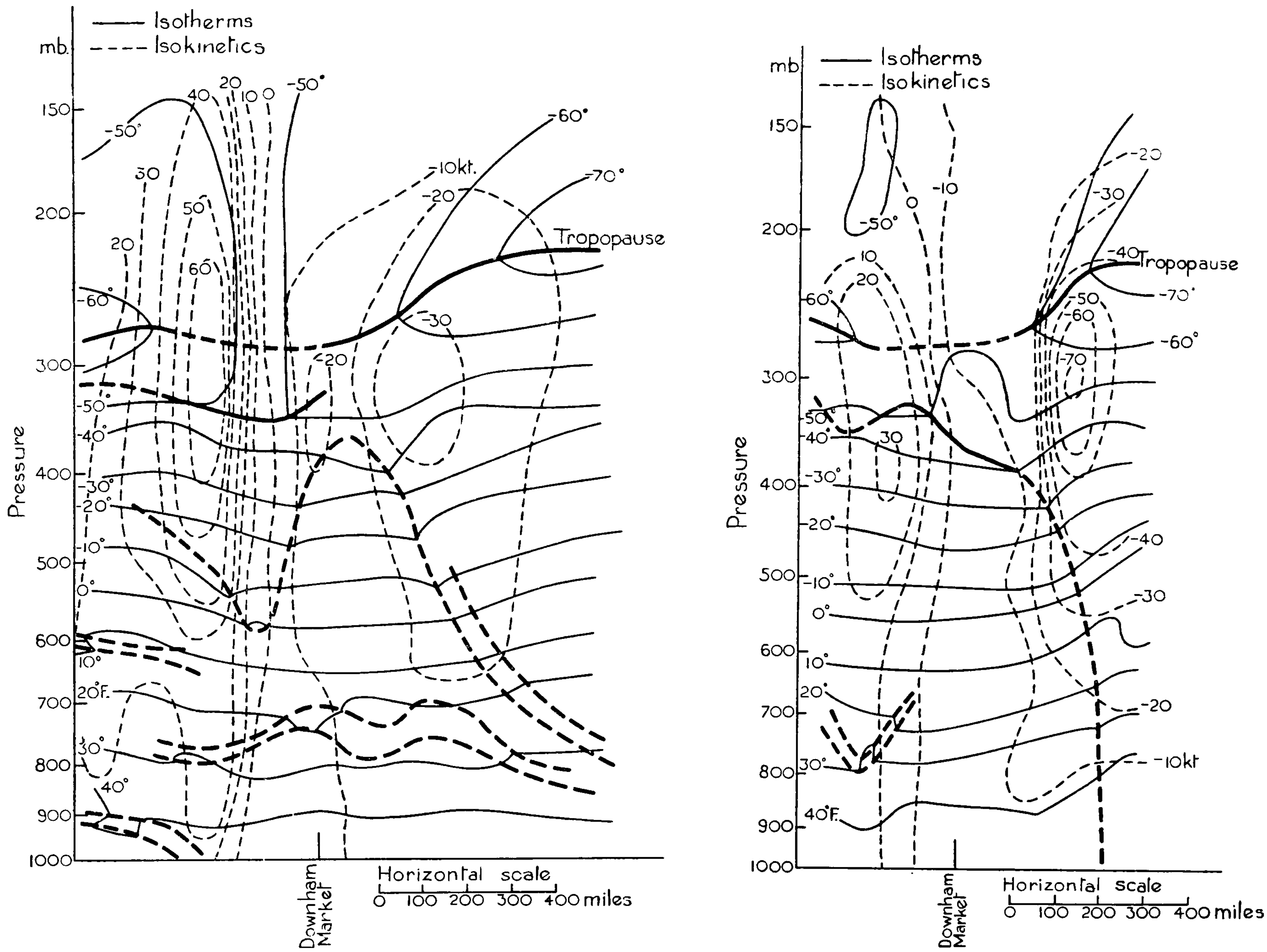

FIG. 27—CROSS-SECTIONS THROUGH THE TROPOPAUSE FUNNEL, 0300 MAY 18, 1949

Heavy continuous lines indicate the tropopause and heavy broken lines indicate other significant changes in lapse rate

Re-formation of the tropopause at a new level.—On the tropopause charts for May 1949 there are several situations in which the tropopause appears to have been replaced simultaneously over a fairly wide area by a new tropopause at a different level.

There were five occasions on which the tropopause over the British Isles appears to have been displaced downward in this manner, and one rather doubtful occasion on which it appears to have been transferred upward. This excludes developments in association with folded tropopauses or tropopause funnels as described in the preceding subsections, and also some cases which depended on the interpretation of a single sounding and may be attributable to instrumental error. The selection of the cases was made from the air trajectories at tropopause level, and every occasion on which the tropopause potential temperature appeared to change by 10° F. or more following the trajectory was examined.

The change in tropopause level was usually not large; 20–40 mb. seems common with a corresponding change of potential temperature of 10–20° F. (smaller changes would have been eliminated by the method of selection). It is difficult to prove whether the change of tropopause level is continuous or discontinuous, but comparison of soundings along a trajectory suggests in most cases that a discontinuity of lapse rate develops at a new level and subsequently becomes the dominant discontinuity, the potential temperature at both levels being approximately conserved meanwhile. This was also found by Palmén[20].

The surface synoptic chart shows no features which could be connected directly with these developments ; several of the cases occurred on the fringes of anticyclonic areas. If the process is a quasi-adiabatic one, considerable horizontal divergence would have been required between the old and the new tropopause levels in order to transfer the tropopause downward as observed. In most of the examples the original tropopause, which was replaced, covered only a limited area 300–500 miles in width, and its elimination resulted in an essentially simpler tropopause distribution, and probably the flow pattern was also simplified. A dynamical cause is therefore possible.

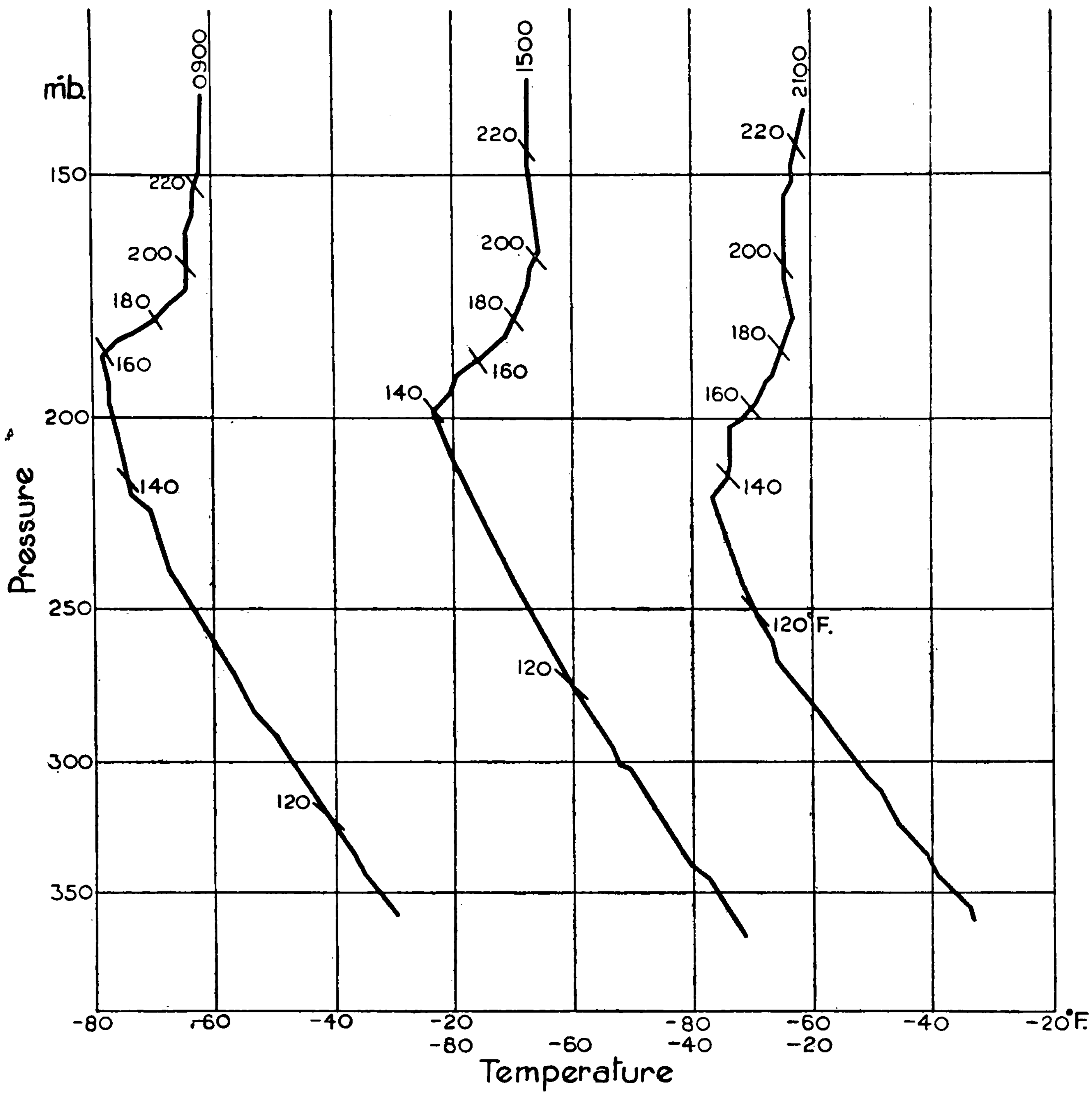

FIG. 28—TEMPERATURE SOUNDINGS, LARKHILL, 0900 TO 2100, MAY 21, 1949

Short sloping lines are segments of dry adiabatics at potential temperatures indicated

An example is given by three successive soundings at Larkhill from 0900 to 2100, May 21, 1949 (Fig. 28). The winds were light at the tropopause level and the soundings can be regarded as representing essentially the same air column. That advection was unimportant is also brought out by the existence of similar simultaneous changes at Liverpool and Downham Market. The original high-level tropopause disappeared after the first sounding, but was continuous with a high tropopause previously identified at Camborne. The new lower-level tropopause is indicated on the first sounding, and appeared to rise during the process while air at higher levels subsided. The synoptic situation is illustrated in Fig. 29 together with the topography of the tropopause.

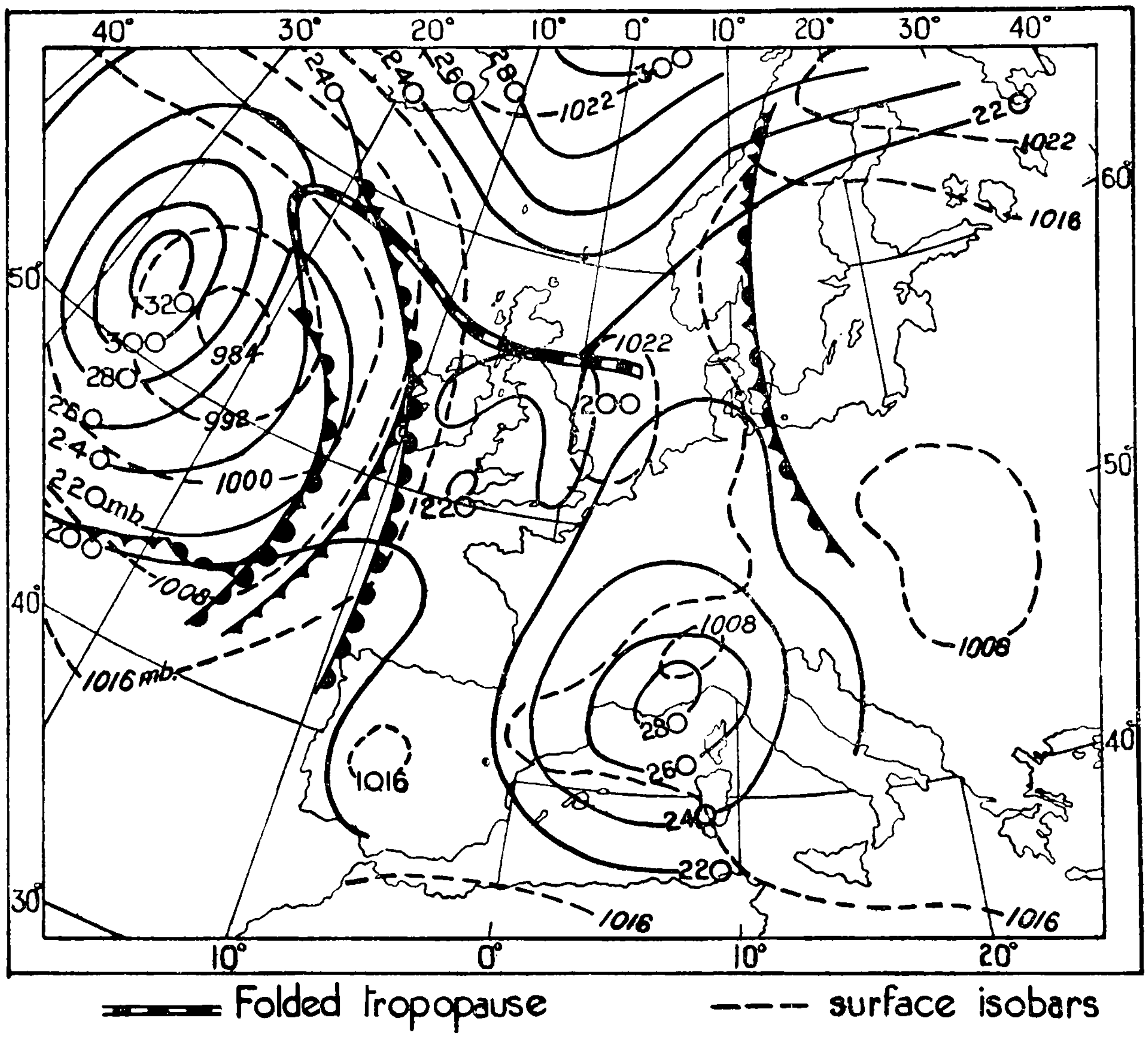

FIG. 29—1500, MAY 21, 1949; SURFACE CHART AND ISOBARS ON THE TROPOPAUSE

Minor discontinuities of the tropopause.—Several of the charts of the tropopause show minor discontinuities of the tropopause at which the pressure level of the tropopause changed by about 20-mb. and the potential temperature by some 10° or 15° F. Such discontinuities are recognized by Bjerknes and Palmén[26] in their diagrams of laminated tropopause. These discontinuities are persistent and can be traced on the tropopause charts over periods of one or two days at least. The discontinuous nature of the change is suggested by the frequent observation of double tropopause near the boundary.

An example of such a discontinuity appears on the tropopause chart for 0300, May 5 (Fig. 15) preceding the advance of a folded tropopause from the west. On this occasion the change in tropopause level seems to have been associated with a change in the source of the air at that level; on the 4th the air over southern England had approached from the south-east over France, but on the 5th this was replaced by a westerly current from the Atlantic. The existence of a frontogenetic col at the 200- and 300-mb. levels is clear from the 300-mb. contour chart for 0300, May 5 (Fig. 15).

The successive soundings at Larkhill from 2100 on the 4th to 0900 on the 5th are reproduced in Fig. 30. The changes in this example are somewhat obscured by the general descent of the air at tropopause level which was taking place, but the original tropopause can still be identified on the last sounding at Larkhill, having descended from 225 to 267 mb. but changing in potential

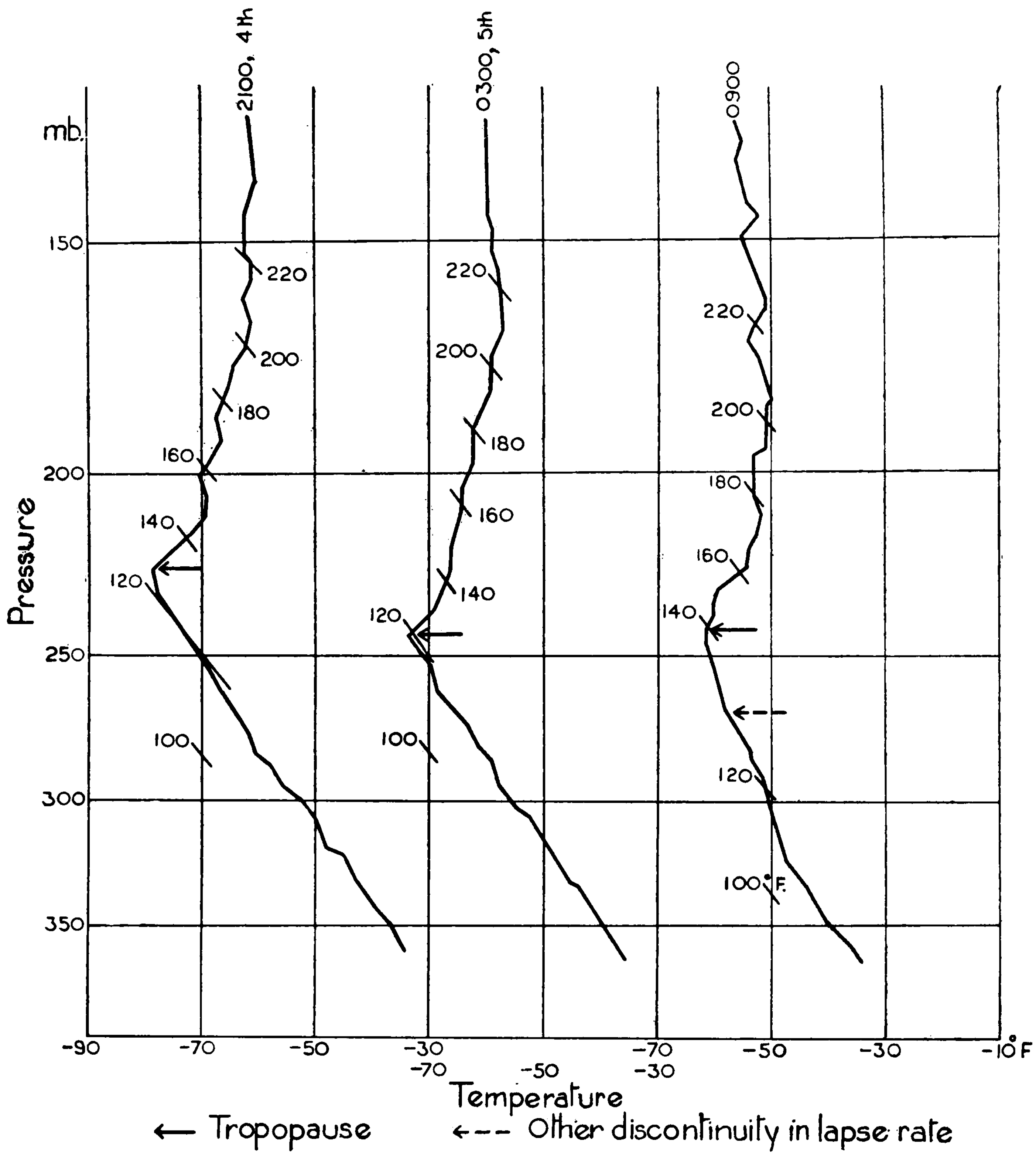

FIG. 30—TEMPERATURE SOUNDINGS, LARKHILL, 2100, MAY 4 TO 0900, MAY 5, 1949

Short sloping lines are segments of dry adiabatics at potential temperatures indicated

temperature only from 123° to 127° F. The occasion is interesting because an ascent by a Meteorological Research Flight aircraft was made at Farnborough using a frost-point hygrometer (Fig. 32). It is noteworthy that the original lower tropopause is the more striking feature of the temperature curve at Farnborough although the upper new tropopause is also indicated by a small irregularity. On the frost-point curve the upper new tropopause is marked by a rapid decrease in frost point upward (Fig. 31).

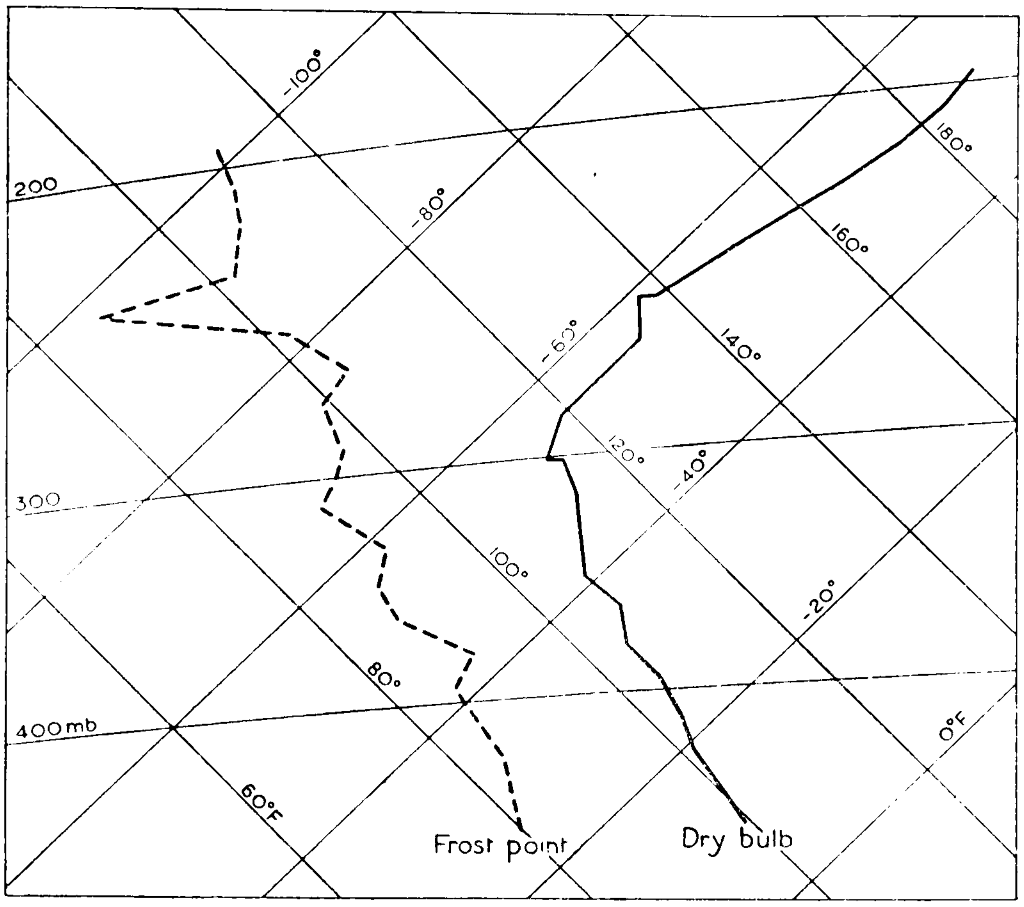

FIG. 31—SECTION OF TEPHIGRAM OF ASCENT OVER SOUTH FARNBOROUGH, 0920 TO 1100, MAY 5, 1949

§ 8—RESULTS OF THE PRESENT INVESTIGATION IN RELATION TO THE STRUCTURE OF THE TROPOPAUSE

The results described in § 4 indicate that at most times the tropopause may be regarded as a material surface moving with the air, but that at infrequent intervals the tropopause dissipates at one level and re-forms at another. During the investigation no indication was found of steady motion of the tropopause upward or downward relative to the air, and usually the tropopause is found to retain its potential temperature within the limits of measurement over 24 hr. Thus over such periods behaviour of the air near the tropopause level may be treated as adiabatic. The results of the trajectory analysis also indicate that vertical motion of the air at the tropopause level is of similar importance to horizontal advection in producing the changes of tropopause level at a given point.

Although the tropopause moves with the air as a material surface it is not continuous, but the discontinuities do not appear to be as numerous as some of the analyses by Palmén would suggest. On the tropopause charts drawn in the present investigation, there seems to be no strong evidence that the potential temperature is strictly uniform along a single tropopause sheet, and the use of this convention seems to have caused Palmén to depict an unnecessarily complex tropopause structure. Some of the discontinuities in the tropopause arise by a process of folding over, but other processes may also be operative. In particular the tropopause structure in subtropical latitudes and the connexion between the tropopause in the equatorial belt and in the temperate regions requires further investigation.

It is possible to recognize certain characteristic disturbances of the tropopause. These lead to the transfer of air both from troposphere to stratosphere (in the occluding of high tropopause) and from stratosphere to troposphere (in the collapse of tropopause funnels).

The investigation gives no direct answer to the problem of the reason for the existence of the tropopause, but it does draw attention to the fact that the tropopause is maintained as a distinct feature during complicated distortions and displacements which might have been expected to destroy it. Moreover it acts as a material surface during the process. It therefore seems likely that some factor is operative which tends to maintain the discontinuity in lapse rate at the tropopause in association with particular material layers of air. The different radiation from moist and dry air seems a possible factor, although different dust content might also affect radiation and have a similar, but much smaller, influence. The occurrence of anomalous occasions, when the humidity discontinuity and tropopause appear to be at different levels may perhaps be accounted for by complex structure, as described in § 7 and Fig. 32 or by the displacement of the tropopause from the level of minimum temperature during the course of dynamical developments such as described in other paragraphs of § 7.

§ 9—PRACTICAL APPLICATION OF THE PRESENT RESULTS

It appears to be possible to prepare a self-consistent analysis of the tropopause in which the tropopause is treated as a material surface embedded in the atmosphere and moving with it. It is necessary to admit the existence of discontinuities in the surface and of occasions when it re-forms at a new level. It is considered that these should be incorporated in any system of tropopause analysis. It does not appear likely that any definition of the tropopause can be formulated which will permit it to be determined unambiguously on every individual temperature sounding, but if in fact the existence of the tropopause is associated with a change in radiative properties of the air, it would be desirable to give considerable weight to the abruptness of the change of lapse rate.

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