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K. R. POSTMA

THE FORMATION AND THE DEVELOPMENT OF OCCLUDING CYCLONES
A STUDY OF SURFACE-WEATHER MAPS

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CONTENTS

ERRATA

pg. 11: c 1st line: read for ideals: ideas.

pg. 11: e 7th line: add after currents: in the same direction.

pg. 14: read formulae as follows:

$$l v_{grad} = \frac{\text{pressure gradient}}{\varrho} - \frac{v^2{}_{grad}}{r}$$

giving

$$v_{grad} = -\tfrac{1}{2} r l \pm \sqrt{\tfrac{1}{4} r^2 l^2 + \frac{r}{\varrho} \frac{\partial p}{\partial r}}$$

pg. 14: last paragr.: only the solution with the + sign has a meteorological sense; indeed the — sign would......

pg. 18: read in fig. 21 for mbar: mbar/unit of time.

pg. 24: 2nd paragr.: read for 27*a*, 28*a* and 29*a* resp.: 28*a*, 29*a* and 30*a*.

pg. 25: 2nd, 3rd, 4th, 5th and 6th paragr.; pg. 26: 1st paragr.: read for 40, 41, 42, 43, 44, 45 and 46 resp.: 39, 40, 41, 42, 43, 44 and 45.

INTRODUCTION

Synoptic meteorology is still in a stage of rapid development. The beginning of an important phase of this development, which commenced about 1920 with the work of a few Norwegian meteorologists, was hardly noticed in Holland. Later on, however, the modern Norwegian theories too, were accepted also in our country to an ever growing-extend.

In the meantime modified methods for weather-analysis were being developed elsewhere as well. The Mid-European synoptici were, among others, prominent by their work, in which more attention was paid to the currents in the higher layers of air than was usually done by the Norwegians (see, for example, the thesis of RODEWALD [1]).

During the latest war Dutch meteorologists were for some years in a position to study critically the relevant literature, with the result that a few publications were issued. Foremost among these is the "Leerboek der Meteorologie" [2], Volume I of which contains a comprehensive survey for the Dutch reader of the fundaments of modern meteorology. For a detailed list of literature the reader is referred to appendix A of this book. It is quite on a level with any of the textbooks of synoptic meteorology, published in practically all languages, of which we mention here only the book by PETTERSSEN [3].

Most of the figures, referring to the development of frontal cyclones in the Leerboek der Meteorologie (L. d. M.) mentioned, and likewise the analysed weather maps reproduced in it, have been drawn by the author of the present publication. From certain investigations, carried out after it was published, it appeared that some parts of the Norwegian methods of analysis were open to objection. This became clear in particular from a preliminary statistical investigation of the nature of frontpassages over Holland, carried out with the help of the extensive synoptic and climatological data available in this country.

The Norwegian methods were not the only ones to give rise to difficulties, the same is true of those applied by the Mid-European meteorologists. The latest literature so far received in Holland since the war and mostly arriving from America, does not yet solve these difficulties. The American synoptici use mainly the same methods of analysis for surface-weather maps as those used up to the present in Europe. They pay, moreover, much attention to the development of theories concerning the currents in the upper air, in which respect however, the Mid-European meteorologists had set the example already before the war.

In the present publication directional lines are profferred, along which a few of the difficulties met with in analysing synoptic weather maps in the Norwegian way, can be solved. This solution forms, at the same time, a modest contribution to the synthesis of the more or less divergent views of the various schools.

The considerations here put down are not complete in themselves; various points will have to be discussed more fully later on. As far as practical meteorology is concerned however, they can be of immediate use. The slightly modified method of analysis, given in the present publication, will make it necessary to alter many of the figures, published in the literature of recent years, of cyclones and of the frontal systems connected with them, and also many analyses, drawn on the daily weather maps of the meteorological services.

In conclusion I want to thank most sincerely all those, who have kindly assisted me in the preparation and completion of this publication.

CHAPTER I. SURVEY OF THE USUAL METHODS OF ANALYSIS

A. General

Meteorologists are used to starting their study of the processes going on in the atmosphere by the examination of synoptic weather maps prepared with high regularity from the observational data, obtained by mutual exchange along internationally accepted lines. These weather maps are subjected to thorough physical as well as isobaric and kinematic analysis.

The first of these yields the distribution over the earth's surface of the various air-masses (tropical, polar, arctic air) and the dividing-lines between the various air-masses called fronts (cold front, warm front, occlusion etc. [1]).

The isobaric analysis furnishes the distribution of the pressure of the air over the earth's surface, that means the relative positions of the various regions of high and low pressure, the furrows and troughs of low pressure, the wedges and ridges of high pressure and the saddle regions.

Finally, the kinematic analysis enables one to form an idea of the movements of the various systems.

Apart from these analyses, which refer all of them to surface-weather maps, analyses of the upper air can also be carried out by means of aerological observational data. According as the available data grow more and more extensive, these aerological analyses are performed by the various meteorological services on an ever-increasing scale. They serve to study the currents in the higher layers of air and the positions and motions of the various frontal surfaces in the atmosphere.

B. The Norwegian method

From about 1920 on the Norwegian meteorologists concentrated their activities at first completely on the physical, isobaric and kinematic analysis of the surface-weather maps. Later on they applied also the aerological analysis, though only to a fairly limited extent and mainly with a view to confronting the positions of the fronts found on the surface-weather maps with the observed aerological data.

According to the Norwegian conceptions a great number of cyclones develop as wave-like disturbances in the frontal surfaces. For the theoretical founding of these ideas, they start from an undisturbed state to which a slight perturbation is applied. Under certain conditions this will give rise to the formation of a wave in the frontal surface.

At the earth's surface such a wave will manifest itself as a wave in the front.

The Norwegian authors have, as yet, not succeeded in establishing a wholly satisfactory theory of the origin of these waves. Experience taught them, however, that waves originate mostly in those regions, in which the fronts are straight or only slightly curved. The waves once being formed, the Norwegian methods of analysis are quite capable of describing their subsequent development.

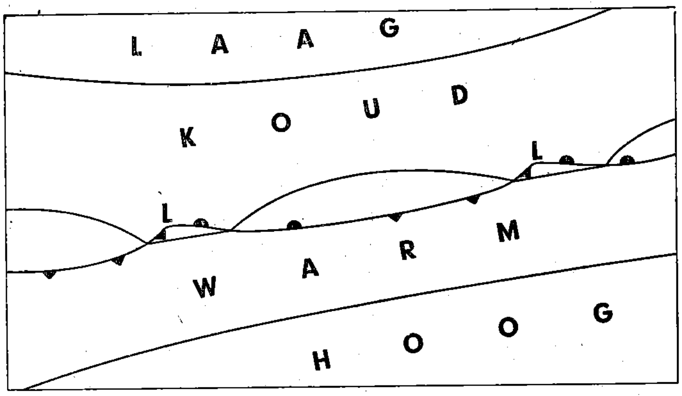

Fig. 1. [2]

Small stable wave-like disturbances in an initially stationnary front.

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[1] In the various figures in this publication the symbols used for the fronts and the other weather elements will be those, internationally agreed upon, in 1948.

[2] We are greatly indebted to the firm W. J. THIEME and Cie at Zutphen for placing the blocks of the figures 1 to 10 at our disposal.

In the Dutch "Leerboek der Meteorologie" the formation of these waves is related to the occurrence of changes in the inclination of the frontal surfaces, like those that can, for example, take place when a frontal zone approaches a quasi-stationary front (see also [7]).

The wave-shaped disturbances are propagated along the fronts and frontal surfaces. If the region of relatively low pressure, thereby formed, is only of slight importance and does not increase in depth, the wave is called stable. Fig. 1 (≡ fig. 121 L. d. M.) shows small stable wave-like disturbances of this nature, which have developed in an initially stationary front. For the rest, such stable waves are only seldom found on the weather maps.

The development of the waves to extensive areas of low pressure is much more frequently observed. The waves are then termed unstable. Fig. 2 (≡ fig. 122 L. d. M.) gives a schematic representation of a series of unstable waves, which have developed in an originally stationary front.

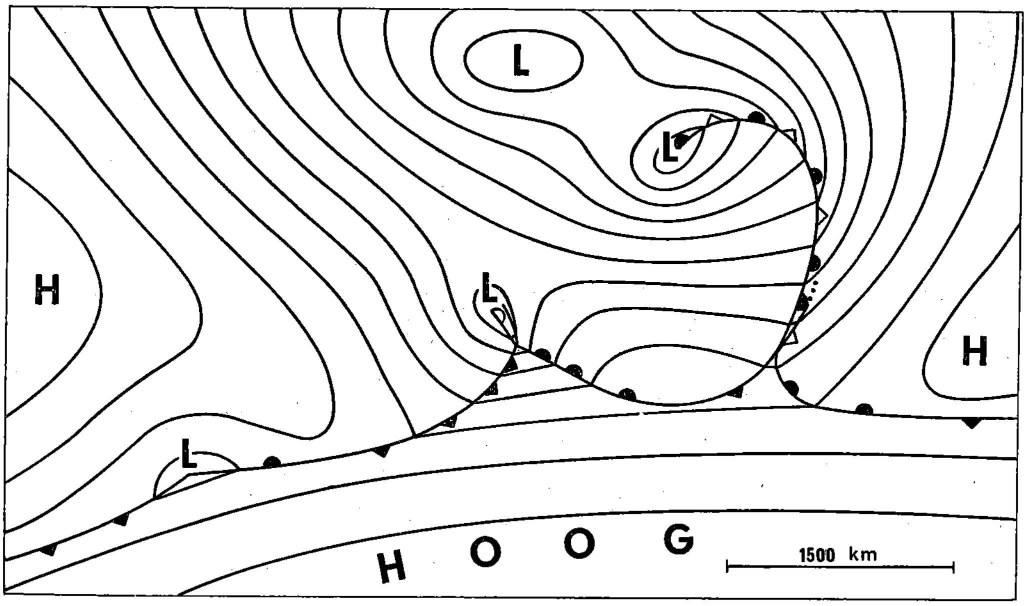


Fig. 2. Large unstable wave-like disturbances in an initially stationnary front.

In the case of stable waves the relatively lowest pressure is found in the point where warm- and cold front meet, at the so-called top of the wave; this is also true for unstable waves, so long as the wave is not yet occluded. The process of occlusion once started, the relatively lowest pressure is practically always found at the end of the occlusion (see, for example, in fig. 2 the wave of which the development is most advanced).

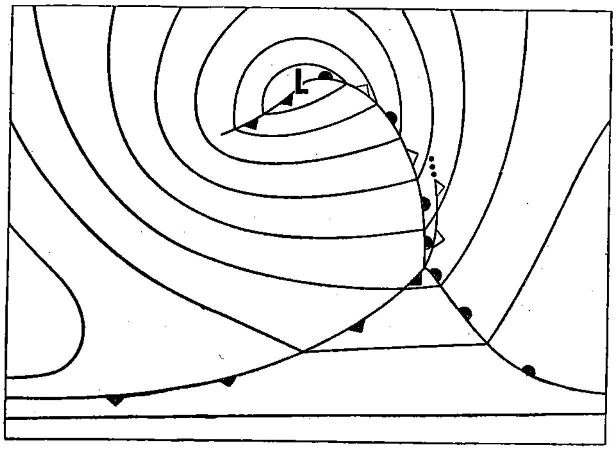


Fig. 3. Showing the bent-back occlusion.

Now and then it happens, that a depression, already occluded to a fairly large extent, suffers in the vicinity of the point of occlusion such a strong deepening, that the centre of low pressure begins to displace itself along the occlusion. In that case a so-called "bent-back" occlusion is formed, as shown in outline in fig. 3 (≡ fig. 143 L. d. M.).

In some very old depressions the occlusion near the centre of the region of low pressure can often hardly be traced; the occlusion is then broken off outside the centre, as occurred with the cyclone over the British Isles, represented in fig. 4 (= fig. 157 L. d. M.).

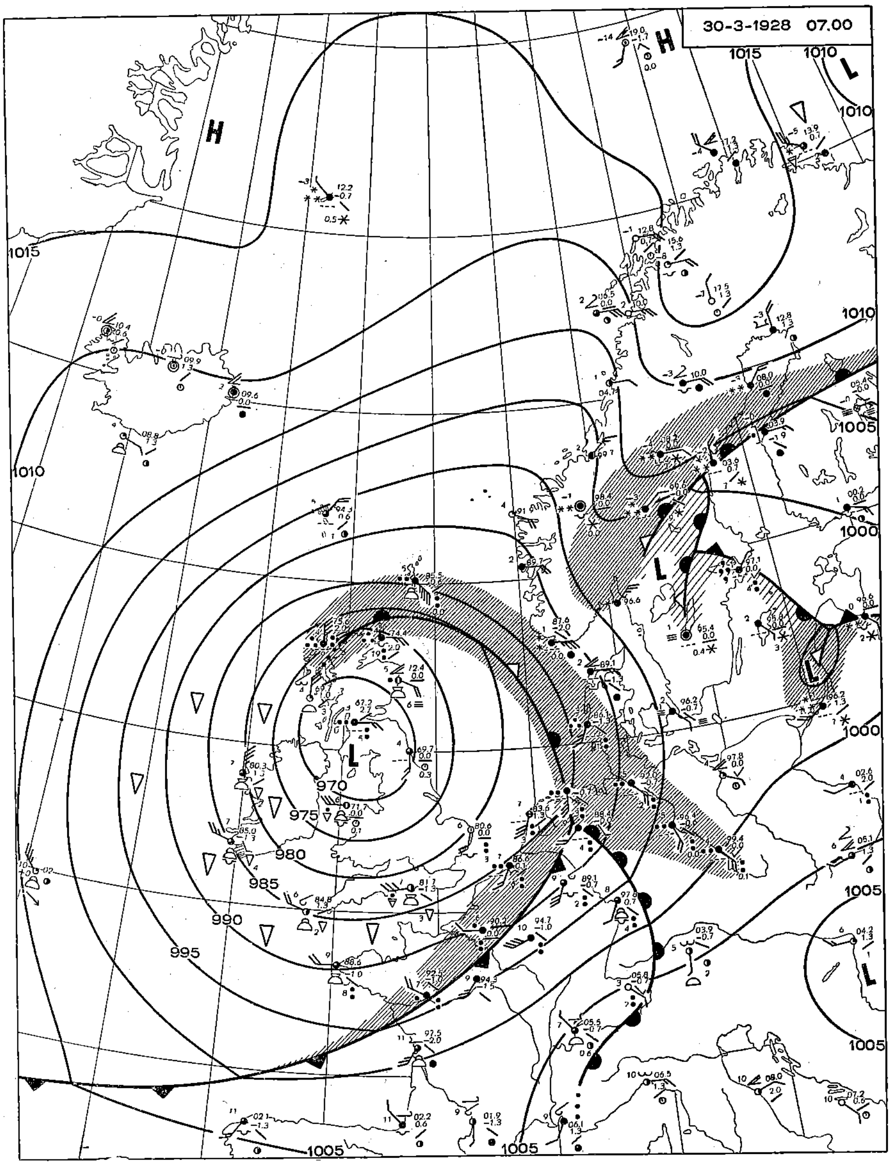
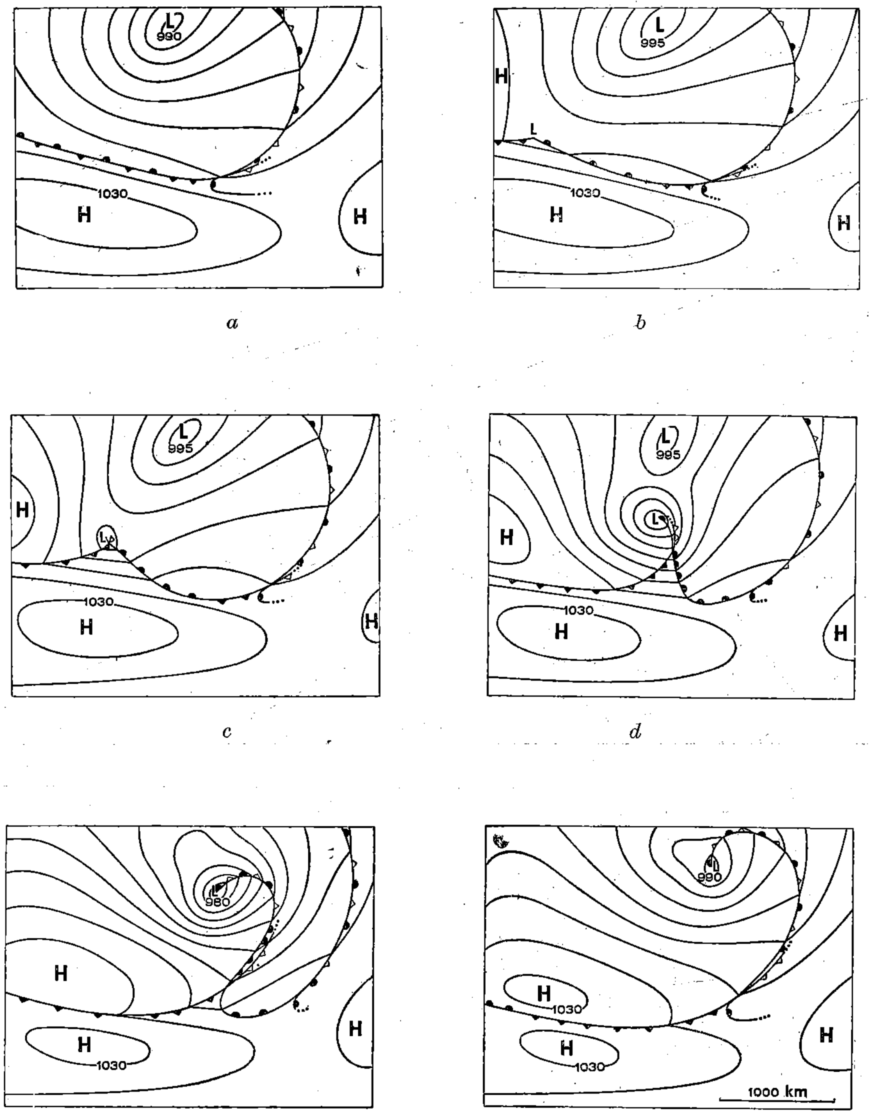


Fig. 4.

Weather map of March 30th 1938, 0700 G.M.T. (re-analysed from Bjerknes and Palmén, Btr. Ph. fr. Atm. 21, p. 54).

For "historical" reasons such old occlusions are traced by those meteorologists, who use the Norwegian analysis, as far as the innermost part of the centre, even though the weather maps furnish only very few and weak indications of its position. The Mid-European meteorologists are, generally speaking, much sooner inclined to give up drawing a front, when a direct indication of its existence is no longer to be found. On the other hand they frequently draw one or more secondary coldfronts ("gestaffelte Kaltlufteinbrüche") at the so-called back of the cyclones. French synoptici, too, often draw many such secondary fronts, the existence of which, after a careful re-analysing of the weather maps, appears to be open to serious doubt.

The life of an unstable wave can best be elucidated by means of a series of figures (fig. 5 ≡ fig. 132 L. d. M.).



a *b*

c *d*

e *f*

Fig. 5. The development of an unstable wave.

In an originally isobar-parallel front a wave is formed, which gradually develops into a deep depression, this process being accompanied by a continual decrease of the warm sector, a lengthening of the occlusion, a more and more deepening of the centre and a steady increase of the pressure-gradients (states *b*, *c*, *d* and *e*). Finally, when the warm sector has shrivelled up considerably, the depression begins to fill (state *f*). If the state, shown in *a*, is restored, the process may start afresh.

An example of such a wave development is shown in the fig. 6, 7, 8, 9 and 10, which the present author analysed at the time for the "Leerboek der Meteorologie".

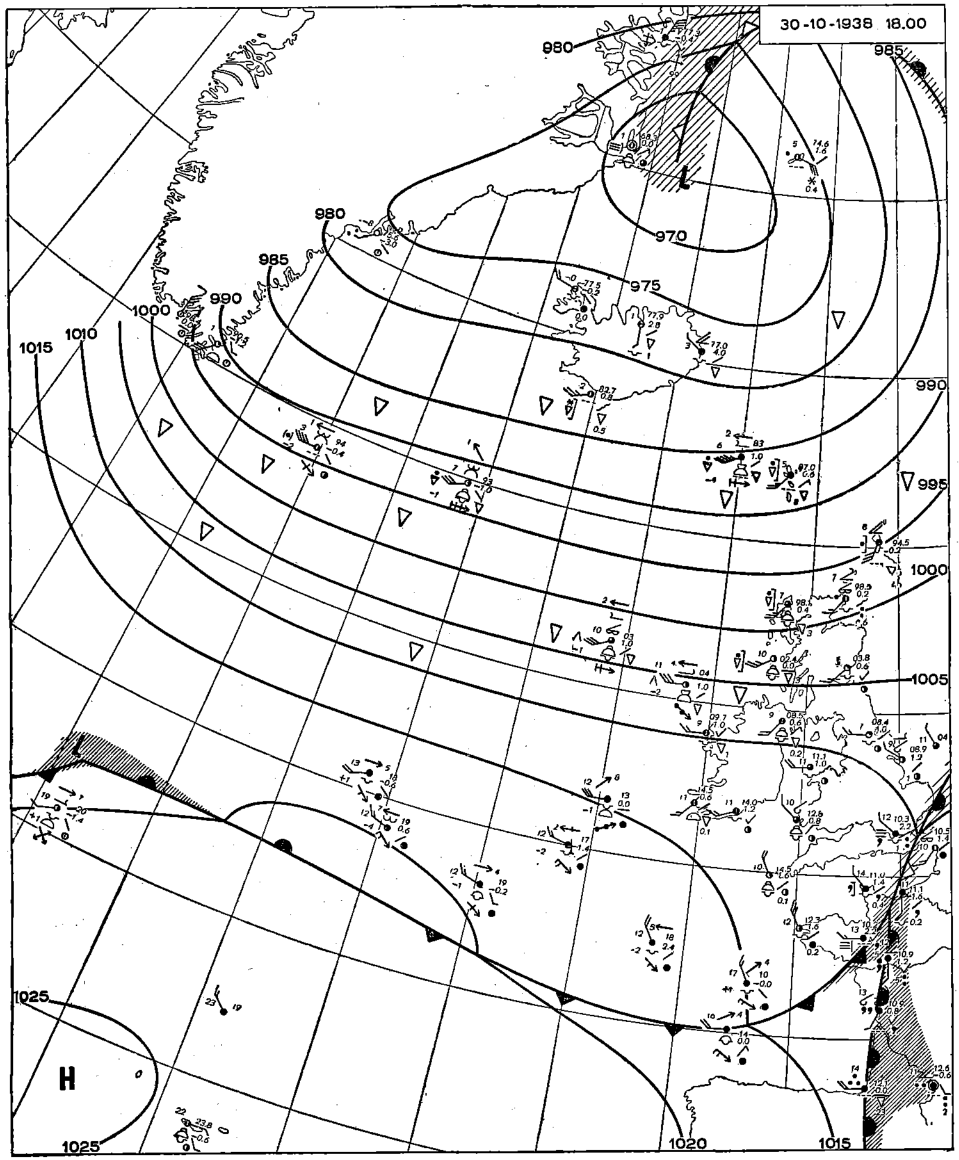


Fig. 6. Weather map of October 30th 1938, 1800 G.M.T.

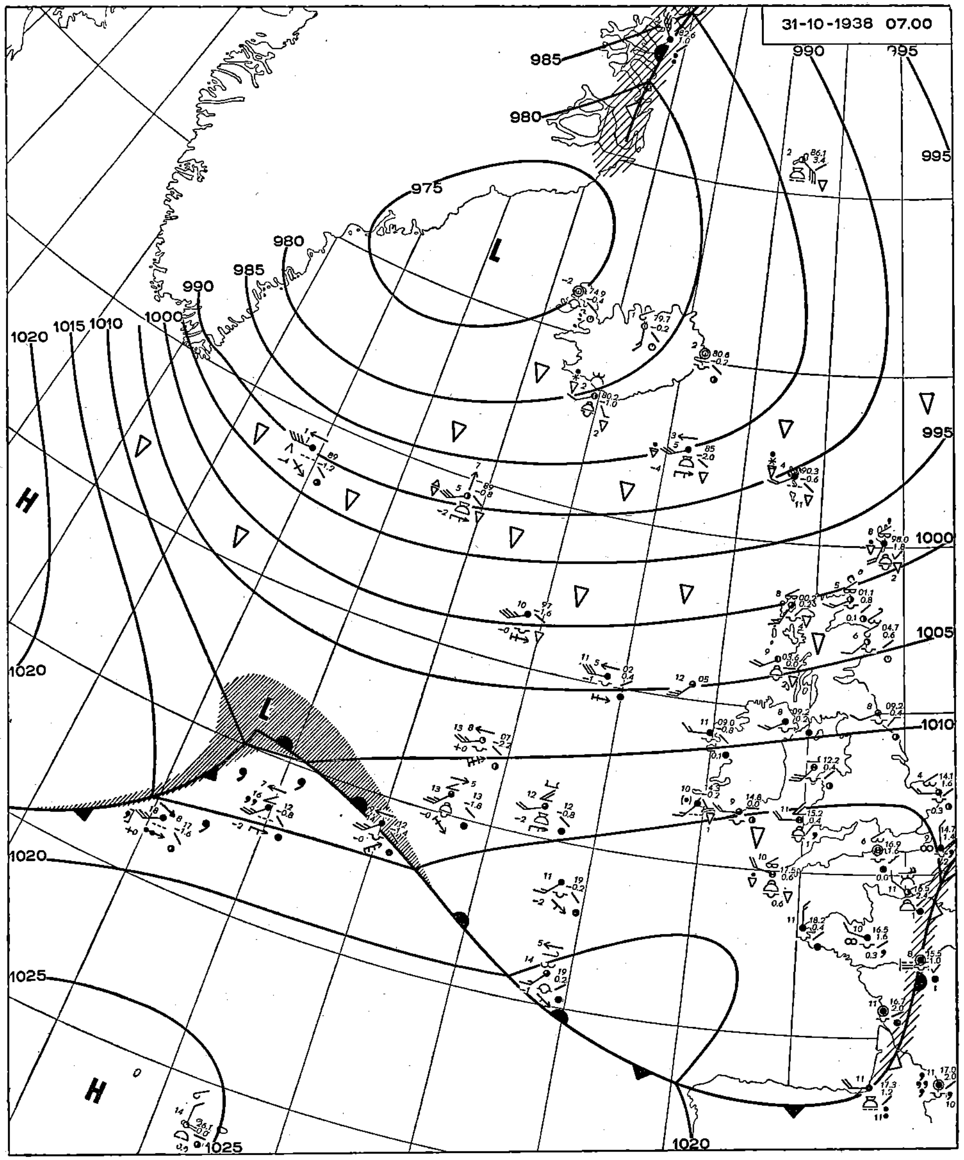


Fig. 7. Weather map of October 31st 1938, 0700 G.M.T.

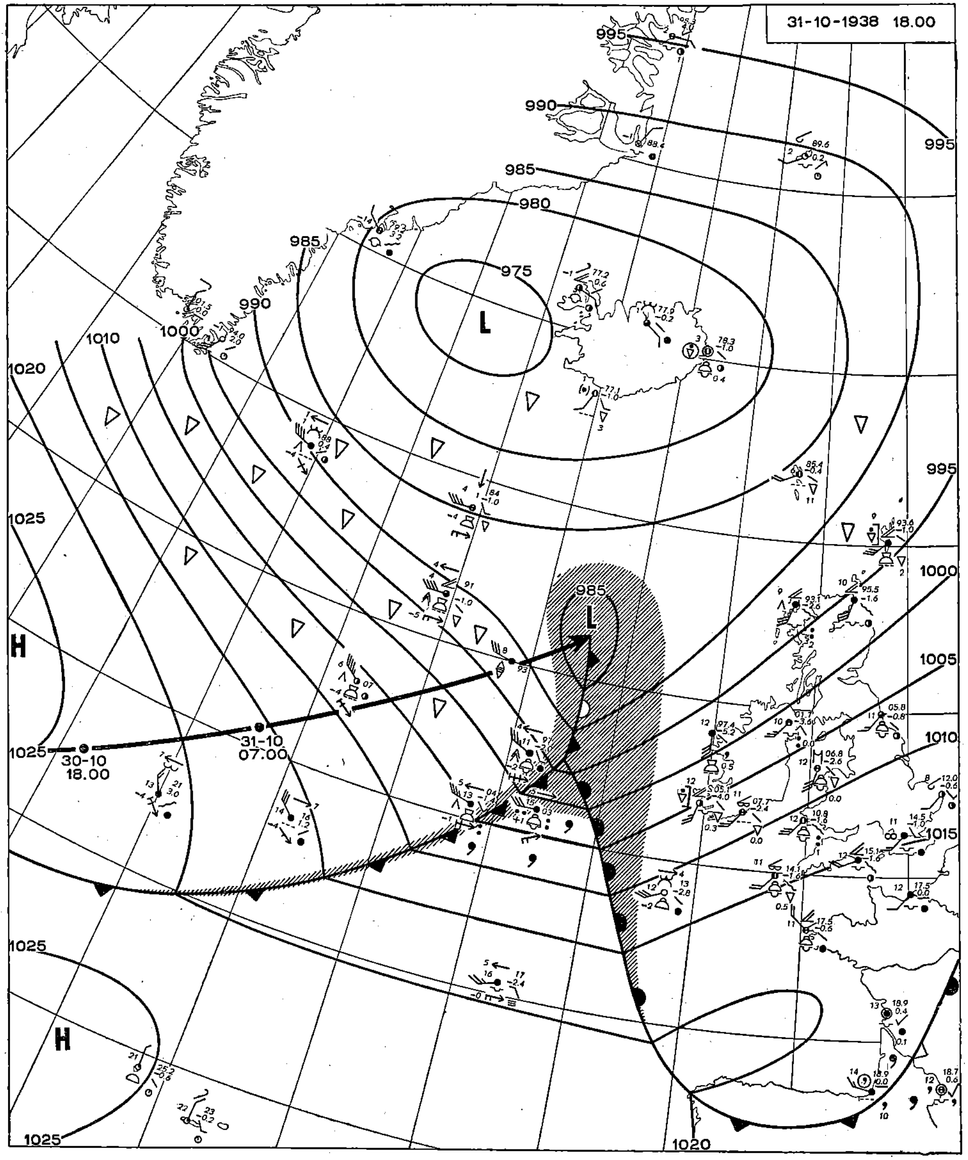


Fig. 8. Weather map of October 31st 1938, 1800 G.M.T.

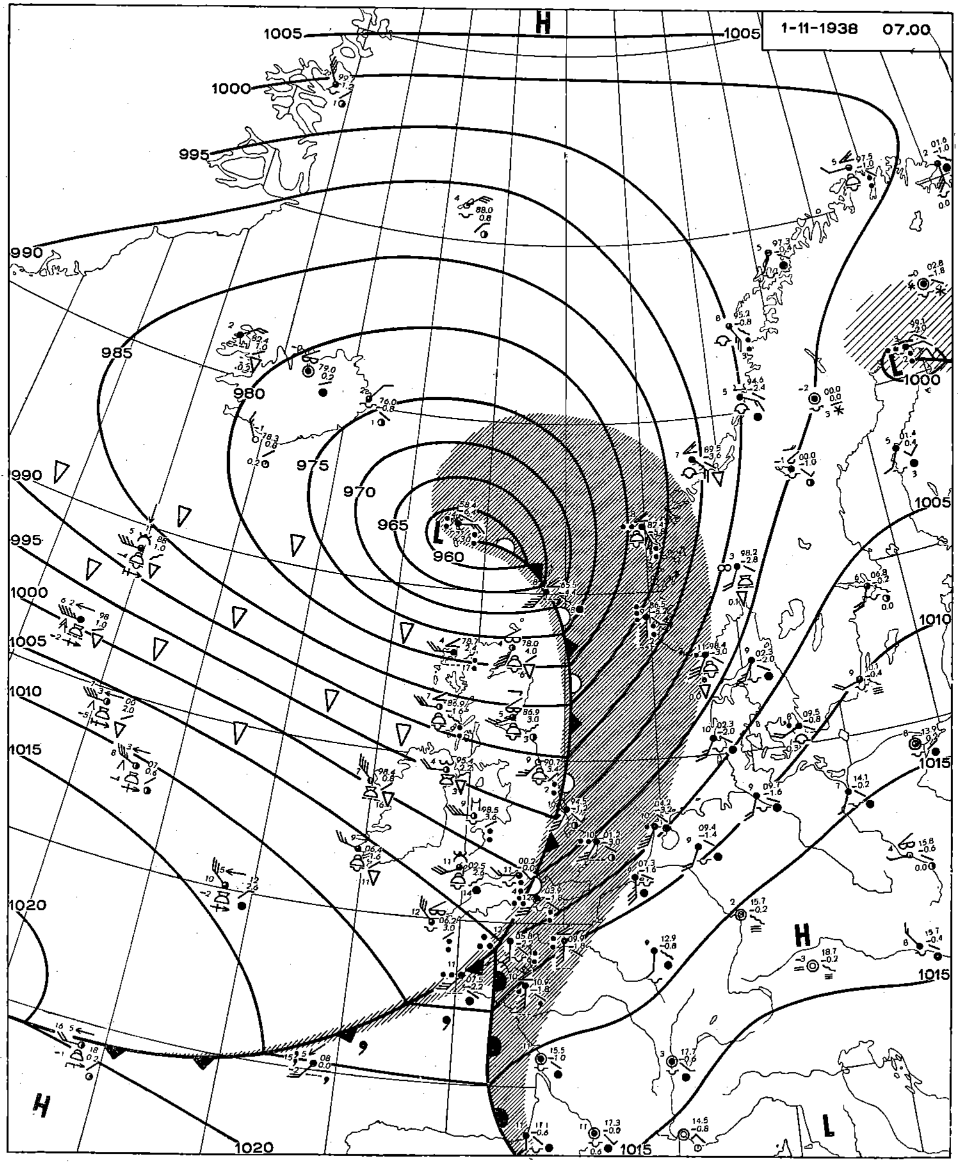


Fig. 9. Weather map of November 1st 1938, 0700 G.M.T.

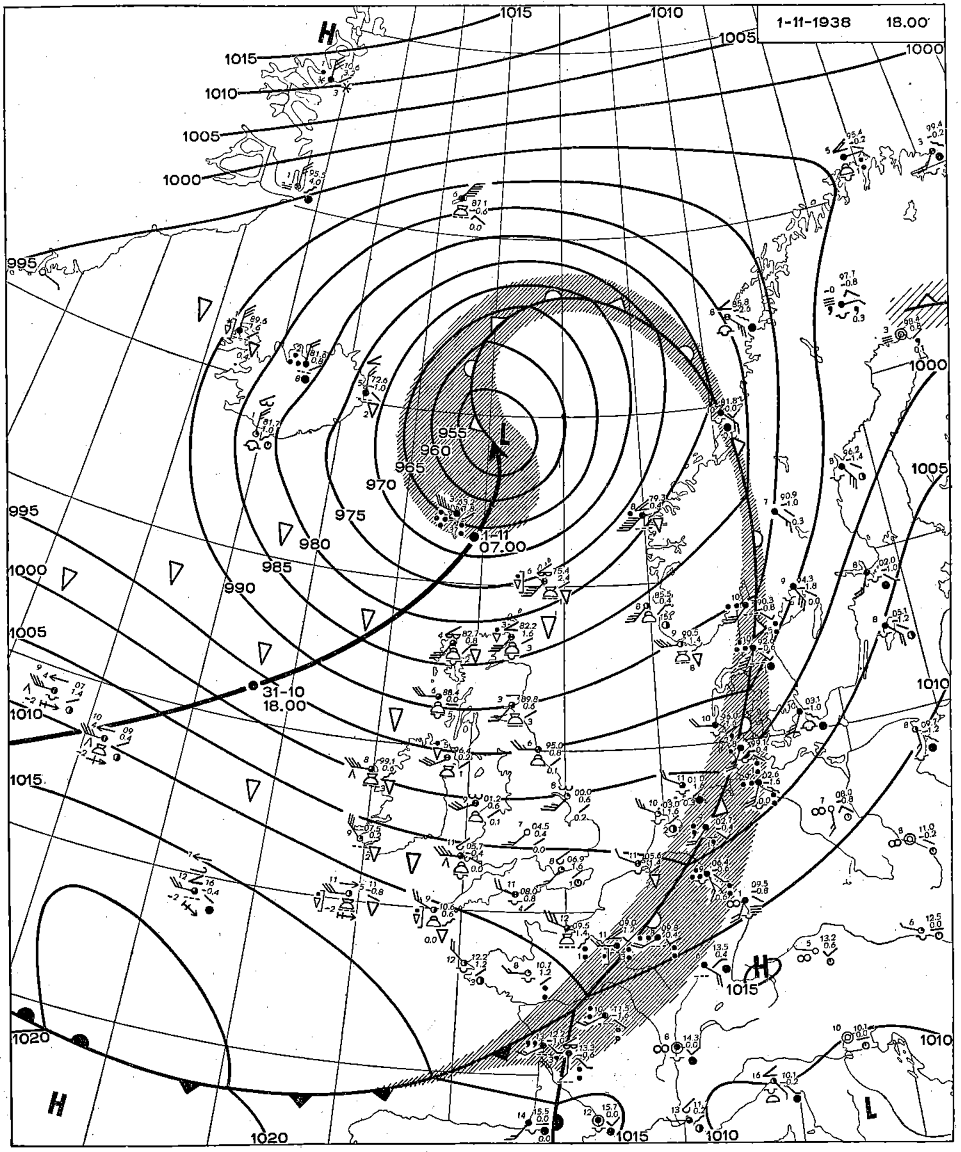


Fig. 10. Weather map of November 1st 1938, 1800 G.M.T.

When these weather maps are examined attentively, one is struck by the impossiblity to gain from any of the published maps a satisfactory proof, based on the observations that the actual development of the wave in question must necessarily have been such as is drawn here according to the Norwegian method. It is more in particular on the ocean in the most important areas, namely in the vicinity of the top of the wave drawn, that the observations, which must serve to prove the correctness of the analysis, are wanting.

A closer study of the various cases dealt with in the literature with a view to proving that the actual disturbances behave indeed in the same way as the one described here for a practically ideal case, makes it clear, that almost invariably the observational material is too scanty to make a rigorous proof possible. From the same observations other constructions could be deduced, which might be successfully defended. Simply putting the daily weather maps issued by the various meteorological services next to each other, suffices to draw the conclusion that the observations can evidently be interpreted in many different ways.

In Chapter II we shall develop the objections which can be raised against the Norwegian methods, briefly described above.

C. Other methods

Mid-European meteorologists are used to drawing, apart from surface-weather maps, also very detailed maps of the higher layers of air. Thanks to this completion, they have been more successful than the Norwegians in making the atmosphere as a whole the subject of their considerations.

Their analysing methods of the surface-weather maps are, however, about the same as those of the Norwegians. A complete description of the German analysis-methods is given in a war edition of the Reichsamt für Wetterdienst [4]. The objections, which can be raised against the Norwegian method, will therefore also apply for the greater part against their methods. The Mid-European meteorologists carry out also physical and isobaric analyses of the surface-weather maps, but instead of the kinematic analysis, as applied by the Norwegians, they give extensive considerations concerning the steering ("Steuerung") of the pressure- and isallobaric systems. This steering is largely judged with the aid of the upper-air maps, which in their opinion allow them to form a much better mental picture of the movements of the pressure-systems; in this picture the state of the whole of the atmosphere is then characterised by the isohypses of the 500 millibar level. The topography of this level is drawn partly with the aid of aerological data, partly by applying exprapolation methods to the data of the surface-weather maps. Of the extensive literature concerning these questions we mention here only an article by Baur, "Die Bedeutung der Stratosphäre für die Groszwetterlage" [5].

From the study of a great many weather situations a number of Mid-European synoptici came to the conclusion that the wave-motion of fronts and frontal surfaces is not the primary cause of the formation and development of cyclones, but that their origin and deepening are very closely connected with areas of divergent currents in the upper air while the formation and development of travelling anticyclones bear a close relation to convergent currents in these higher layers. These areas of divergence and convergence occur mostly in connection with frontal zones.

Rodewald [1] in his publication already mentioned gives a more detailed exposition of these theories. Schmidt has developed a theoretical foundation of such divergences and convergences [6]. In a book, published after the war, Raethjen [7] has attempted to synthesize the various existing theories concerning the origin and development of areas of low pressure.

In the practical checking of these theories, which require also the use of upper-air maps, the lack of observational data is still felt, just as with the surface-weather maps. Many of these maps might easily have been drawn in a different way and the detailed working out of them is here as in the case of analysing the surface-weather maps, still partly a matter of the personal insight of the analyser.

CHAPTER II. OBJECTIONS TO THE NORWEGIAN ANALYSING-METHODS

From preliminaries for an investigation into the character of front passages over Holland during the pre-war period (April 1938—September 1939) in which in Holland the Norwegian methods were applied in analysing weather maps, it appeared that among the many fronts, which according to the Norwegian (Bergen) as well as to the German (Seewarte) as to our own weather maps, had passed over our country, only part of them could be clearly identified from the registrations of the various meteorological elements and from the observations of the Dutch weather stations. This was the first occasion to give rise to doubt as to the complete correctness of the analysing methods applied.

How was it, that only part of the fronts could be clearly identified? Could this mean, that more fronts were drawn in the weather maps than existed in reality? Was it possible that in order to be able to adhere to the familiar construction-model, certain fronts, mostly occlusions, were drawn through regions, which a slightly different interpretation of the synoptic informations would have left free from fronts?

These questions led to the decision to carry out a thorough investigation of a certain number of cases, with the aid of the whole of the relevant observational material of Western Europe. It was, more in particular, the drawing of the isochrones of the fronts and centres which proved, in this connection, to yield valuable results. The consistent application of the Norwegian analysing methods to some old depressions appeared to give rise to a few difficulties and this in itself, was a sufficient reason to make the whole of the modern methods once again the subject of a critical discussion. This discussion can be divided into the following 6 parts:

a. The first difficulty arising from the application of the Norwegian method is most clearly explained with the aid of a figure (fig. 11). In this figure the full and the broken lines represent respectively two successive states of the isobaric field and the front connected with it as frequently drawn in this connection. The —. line represents the path of the centre from the first (full line) to the second (broken line) state. What will happen, for example, to the direction of the wind in a station *P*, on the assumption that this construction is correct?

In the full-line situation the front has just passed the point *P* in the direction of the general cyclonic motion round the centre, with the result that a veering of the wind has occurred. Shortly afterwards a backing of the wind will set in in *P* since the centre moves on the —. track. This backing continues until the broken-line state is reached. In this state *P* appears to lie once again at the other side of the front, and, as the front is always drawn right to the centre most point of the depression, this can only have taken place by a front passage, which therefore has this time been accompanied by a continual backing of the wind. Now this does not agree with theory, which requires a continual veering of the wind to take place during a front passage, provided strong isallobaric effects are absent and the friction against the earth's surface is neglected. Only in the case of large deviations from the gradient wind (so that strong isallobaric effects are indeed present) can a front passage be accompanied by a backing wind. Owing to the prevailing field of pressure, however, this will,

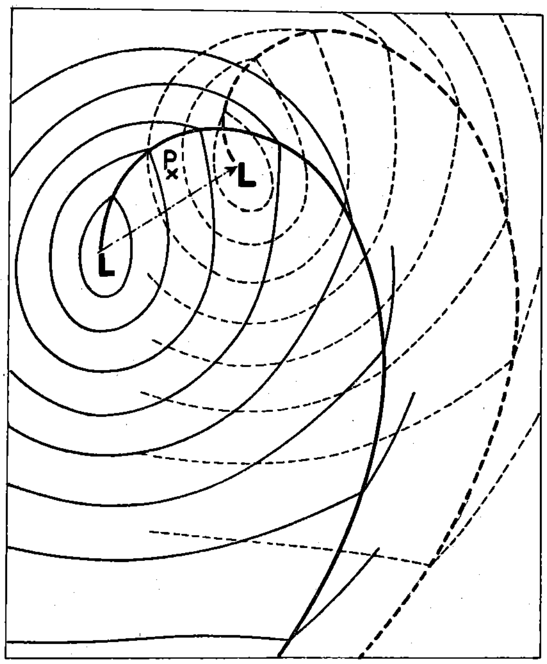


Fig. 11. Full and broken lines two successive states of the isobaric field; —. line path of centre.

generally speaking, not occur near the centre of a depression. It is, moreover, allowed to neglect the friction, as the same argument holds for a level above the friction-layer.

In analysing surface-weather maps in this way, one is evidently too much inclined to consider the motion of the centre and of the front as rigidly coupled together. Even if one should make the front describe a spiral round the centre, the difficulty would still exist that the centremost particle, which constitutes the end of the front, would have to move with the speed of the centre along the — . line. A closer study of the paths described by the various particles in a moving depression will make it clear that this is wrong. The several phenomena observed in the most-central parts of a depression can equally well be explained in other ways.

b. If it should indeed be wrong to draw a front in this way right to the centre of a depression, the construction of the bent-back occlusion, described in fig. 3, will also be open to serious doubt. In fact, the phenomena which lead one to draw such a bent-back occlusion, do allow of a different explanation, for example, by means of convergence in a moving trough. Some of the Norwegian synoptici have themselves already pointed out that many of the bent-back occlusions are not genuine fronts (comp. [3], page 338). This can often easily be proved by considering that the velocity of the trough, in which the bent-back occlusion is led, is less than the wind-component at right angles to the axis of the trough, which is the speed required by a moving front present in that axis.

c. Meteorologists adherent to the Norwegian ideals have nowhere in the relevant literature proved convincingly that the relatively lowest pressure in the case of a stable wave or of a not yet occluded unstable wave must invariably be found at the top of the warm sector. When, however, the observations make it at times necessary to draw the relatively lowest pressure of a still developing depression no longer at the top of the warm sector, one feels bound to find a way out of this difficulty by assuming that in the meantime the wave has occluded, so that one can draw the centre at the end of the occlusion. This centre is then supposed to be due to processes in the higher layers of air, without taking duly into account that in the initial state, before the occlusion, such processes were already at work just as well. It is true that the Mid-European meteorologists have been aware of this fact, but so far, not one of them has drawn the conclusion from it, that the relatively lowest pressure may possibly be found not at the top of a newly originated wave, but a few hundred kilometers away and that the wave is then not necessarily already occluded.

Very occasionally one finds in the literature an analysis to which a method slightly different from the usual Norwegian one has been applied, see for example Brunt [9], page 362.

d. In many cases meteorologists analysing in the Norwegian way draw the only newly-formed wave with a rather sharp bend at the top (cf. for example fig. 6 and 7). A rigorous proof of the actual existence of such a bend is, however, not given anywhere. In these cases one would be perfectly justified, as far as the observations are concerned, in drawing a smoother curve for the front, and this is what is actually done by a few meteorologists (for example in England; see also the figure in Brunt, page 362).

e. One of the chief difficulties met with in applying the Norwegian methods, and making itself also felt already during the writing of the "Leerboek der Meteorologie", arises, when an attempt is made to explain the process of occlusion. From an examination of the maps issued by the several meteorological services or of certain series of weather maps in various publications the way to set about appears to be the following: On one of the maps (cf. fig. 7) the wave is drawn as yet without occlusion and without a closed centre (we are here chiefly concerned with the formation of new depressions in the case of parallel currents on both sides of the original front). On the next map, however, one must with the aid of the observations draw a separate new centre, of which the lowest pressure must lie completely outside the warm sector. To this end it is simply assumed that the wave has in the meantime occluded and an occlusion is therefore drawn right to the innermost part of the newly formed centre, although the actual warm sector has not, or not yet, materially altered its first shape, the only difference being that in a completely unexplained way an occlusion is added as an accretion. Most authors do, in fact, not enter at all into the question how the transition from the non-occluded state takes place. In the publication by Raethjen, already mentioned (comp. [7], pages 93—94), the process of occlusion is explained theoretically, without however being corroborated by analysed weather maps.

f. Finally a few words may be said here concerning an objection, which has already been raised in various parts, viz. is one indeed justified in using the term wave-motion? Those, who are familiar with the daily weather service of the various meteorological institutes know quite well, that one of the most characteristic features of a genuine wave-motion, namely the perfectly periodical repetition of certain processes, is not often observed to take place in this large-scale atmospheric motion. And, likewise, the ideal depression family (drawn in fig. 2) outlined by the Norwegians does occur much less frequently than a study of their literature would suggest. Many meteorologists have, therefore, already abandoned the theory of pure wave-motion, though the term „waves" for the disturbances is still used. In order to arrive at a more satisfactory explanation of the development of depressions an attempt should be made to synthesize the various existing theories. In his "Kurzer Abrisz der Meteorologie, Teil I" Raethjen has already ventured on such a synthesis (comp. [7] page 79 and following pages).

CHAPTER III. SOME CONSIDERATIONS CONCERNING THE MOTIONS OF PARCELS OF AIR IN TRAVELLING DEPRESSIONS

The motions of parcels of air in the atmosphere have been investigated by various authors, for example by Koschmieder, who gives in his "Dynamische Meteorologie" [10], (page 207) a figure, showing the paths of a number of such parcels (A, B, C, D and E), when a rotation is superposed on a translation (see fig. 12).

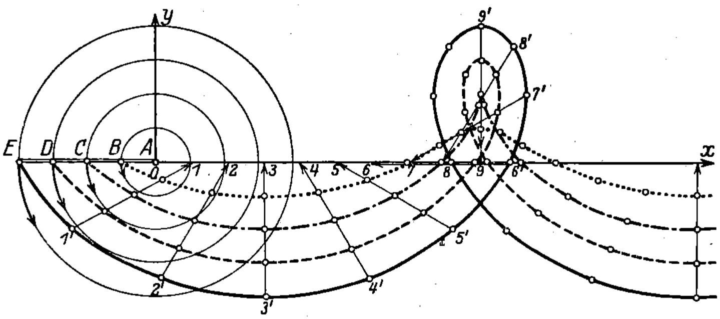


Fig. 12. Showing the paths of the parcels A, B, C, D and E, when a rotation is superposed on a translation (after Koschmieder).

In a system of coordinates moving with the vortex, the paths are the circles; relatively to a system of coordinates at rest, they are represented by the full, broken and dotted lines.

These trajectories, which are partly cycloidal, resemble closely those described by parcels of air round areas of low pressure. Figure 13 shows the trajectories in the case of the depression passing over England from 10 to 11 September 1903. This figure is reproduced from Koschmieder's book, its original is to be found in the well-known treatise by Shaw and Lemfert on this subject [11]. Here the full lines are described by the parcels, the broken line by the centre, and the numbers added represent the corresponding times.

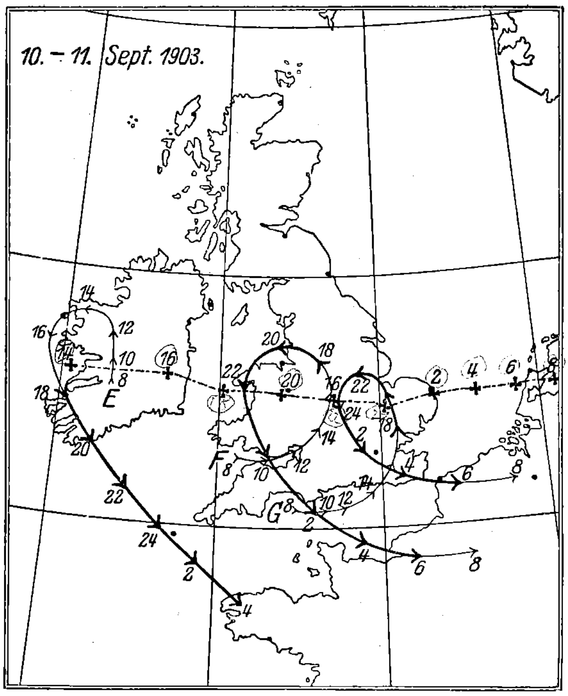


Fig. 13. Showing the trajectories in the case of the depression from 10—11 September 1903 (after Shaw and Lemfert).

If the paths are computed in Koschmieder's way, a parcel in the centre of the vortex (A in fig. 12) will have the velocity of the translation. When dealing with motions of the air in the atmosphere, however, one must take into account that the motions of the parcels are influenced by the continually changing field of pressure. The central parcels of the travelling depression, for example, cannot have the same speed as the centre itself since at the heart of the centre the pressure-gradient is zero, and because, moreover, the strength of the isallobaric wind is small compared with the velocity of the centre. The centremost part of a depression is, therefore, windless or practically windless, which is in perfect agreement with observations (the eye of a tropical cyclone!).

For the present publication Ryd's "Travelling Cyclones" [12] is highly important as a method is there described for the construction of trajectories of particles of air (as a matter of course many other authors have also given methods for this same purpose, cf., for example Petterssen ([3] pp. 221—227). However, Ryd's method and the figures drawn by him do not give a clear idea of the problems connected with the motions of *fronts* in travelling depressions. That is why the problem of the trajectories of parcels of air in depressions will be treated in this chapter with a view to its practical application to moving fronts in travelling cyclones. This treatment will not be rigorously mathematical; for the greater part it will be given in outline only, as it is not meant to yield mathematically correct results, but merely an approximation for use in synoptic meteorology. The influence of friction has, therefore, been consistently neglected, while only horizontal motions in the Northern hemisphere are studied.

To begin with, we shall consider a circular depression, travelling at uniform speed along the *x*-axis (the positive *x*-axis is supposed to be directed towards the East, the positive *y*-axis towards the North, so that the isobaric field will bear a rather close resemblance to the general West-circulation in the temperate zone of the Northern hemisphere. We assume for this depression a pressure-profile, more or less like the profiles occurring in reality. In fig. 14 it is represented by the heavy full line. From this profile the course of the pressure-gradients can be computed, as is shown in fig. 14 by the thin full line. The travelling velocity of the centre is supposed to be 60 km/h.

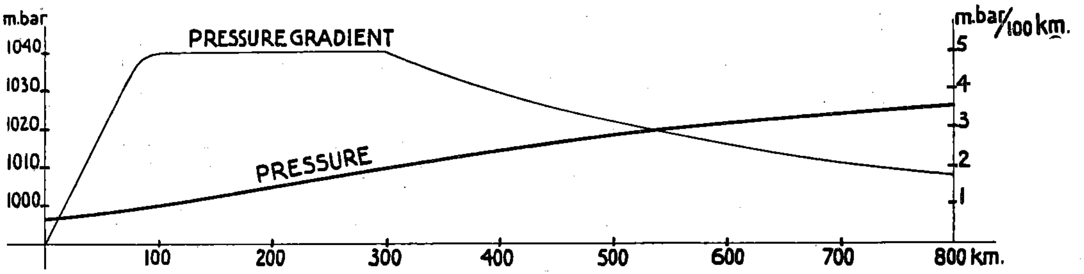


Fig. 14. Pressure and pressure-gradient.

Considering that our problem is made to bear more in particular on the motion of fronts in depressions, we shall first construct the trajectories of a number of parcels of air, lying on a straight line from the centre towards the South (A_0 - - - G_0). This construction is shown in fig. 15.

lv_{grad} = pressure gradient

v_{grad} =

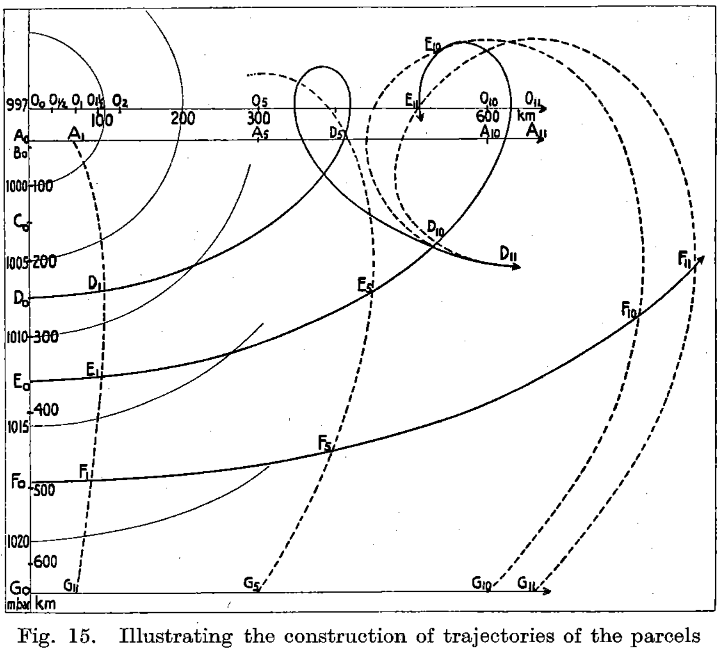


Fig. 15. Illustrating the construction of trajectories of the parcels of air. Thin full lines: isobars. Heavy full lines: trajectories of the parcels. Broken lines: successive positions of the imaginary front.

For the computation of the velocity of the parcels of air, we start from the equation for the gradient-wind in the case of cyclonic motion:

$$lv_{grad} = G + \frac{v^2{}_{grad}}{r} = -\frac{1\,\partial\, r}{\varrho\,\partial\, p} + \frac{v^2{}_{grad}}{r}$$

giving $v_{grad} = \frac{1}{2}\,rl \pm \sqrt{\frac{1}{4}\,r^2\,l^2 + \frac{r}{\varrho}\,\frac{\partial p}{\partial r}}$

($l = 2\,\omega \sin\varphi$; ω = angular velocity of the earth; φ = geographical latitude; ϱ = density of the air; p = pressure of the air; r = radius of curvature of the trajectory).

Only the solution with the +-sign has a meteorological sense; indeed, the $\mp$ sign would for straight isobars ($r = \infty$, after developing the $\sqrt{\ }$ give $v_{grad} = \infty$. Considering that at the start the radii of curvature of the trajectories are not known, the velocities of the parcels of air cannot be computed directly, although the instantaneous field of pressure is given for each moment. We can, however, easily find two parcels having the same speed as the centre, namely those parcels straight to the south of the centre, for which the geostrophic wind velocity, computed from the equation $v_{geostr} = \frac{1}{\varrho l} \frac{\partial p}{\partial n}$, is equal to that of the centre, that is in our case equal to 60 km/h. From our arbitrary profile, it follows that this is the case with the parcels A_0 and G_0, lying respectively at 40 and 640 kilometer from the centre. The other parcels south of the centre will, in a first approximation, move on trajectories of which the curvature is less than that of the isobars; their velocity will lie between those of the geostrophic- and the gradient-wind, which for these parcels can be computed by assuming them to move on the circular isobars. The velocities of the geostrophic wind for the parcels B_0, C_0, D_0, E_0 and F_0 are respectively 72, 120, 120, 100 and 80 km/h; on the assumption that their motion is along the isobars on which they lie, their gradient-wind velocities would be respectively 31, 61, 72, 70 and 63 km/h. Now in order to introduce, for a first approximation, a set of velocities for the parcels (as the system is supposed to be already in motion) an estimate of the radii of curvature must be made. These radii will be large for parcels in the vicinity of A_0 and G_0 (as these move in straight lines). This has led us to assume for B_0 and F_0, in a first approximation, 70 and 75 km/h and for the remaining parcels C_0, D_0, and E_0 respectively 90, 100 and 90 km/h, which are more or less the average velocities between their geostrophic- and gradient-wind velocity.

With the aid of these velocities the construction of the trajectories has then been carried out as follows:

in order to find the position of a parcel at the moment t_{i+1}, the centre of the moving depression is assumed to remain at rest during the whole unit of time (here, therefore, 1 hour) in the position $O_{i+\frac{1}{2}}$. Round this centre a circular arc is drawn with a radius, equal to the distance between $O_{i+\frac{1}{2}}$ and the position at t_i of the parcel at the time t_i (in fig. 15, for example, D_1 is found by measuring on the circular arc with radius $D_0O_{\frac{1}{2}}$ round $O_{\frac{1}{2}}$ a length of 100 km in the direction of the velocity of D_0). In this way a succession of approximate positions is found for each parcel. Of course, an error is introduced by measuring the velocity on the arc, as in reality the parcel does not move along this arc. Generally speaking, however, this error will be small. By drawing lines through the successive positions of the parcels a first approximation of the trajectories is obtained. From these trajectories a first estimate of their radii of curvature can be made and by means of these radii corrections can be applied to the first-drawn trajectories because now more accurate values of the velocities are available. Fig. 16 shows a corrected trajectory of this kind for parcel D_0, which is cycloidal in shape (the error in the initially assumed velocity of D_0 turned out to be about 10 %, as the parcel must cover a distance of 110 km in the first unit of time, instead of 100 km).

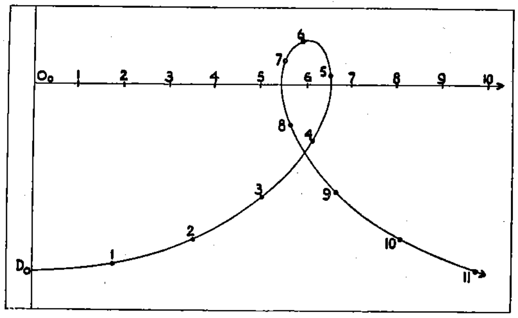


Fig. 16.

Corrected trajectory of the parcel D_0 from fig. 15.

The above construction cannot be performed on the present scale for parcels in the immediate neighbourhood of the centre. As, however, these very parcels are particularly important we shall presently refer to them again.

It has appeared that by those, who have attained a certain skill in the practice of this construction an estimate of the radii of curvature can readily be made. To this end the trajectory under consideration must always be drawn so as to include the last point and some simple reasoning suffices then mostly to make out what the next part will be like. A set of concentric circles, drawn on transparent paper aids greatly to a quick determination of the radii of curvature. In order to facilitate the construction still further, a set of auxiliary graphs was prepared, giving the relation between the pressure-gradient in mbar/100 km, the velocity of the wind in m/sec. and the radii of curvature; in these graphs we used $\varphi = 53°$ and $\varrho = 1.231 \times 10^{-3}\, g/cm^3$ (at 1000 mbar and 10° C). When, now smooth curves are drawn through the simultaneous positions of the various parcels, a fair idea can be formed of the successive positions of an imaginary front, initially lying along the y-axis (A_0 — G_0). The broken lines in fig. 15 represent a few of such fronts. The originally straight line has been deformed into a shape, like that is often actually shown by parts of fronts on weather maps.

In order to investigate the paths of the parcels of air near the centre more in detail, this centre is drawn once again on a much larger scale (in fig. 17).

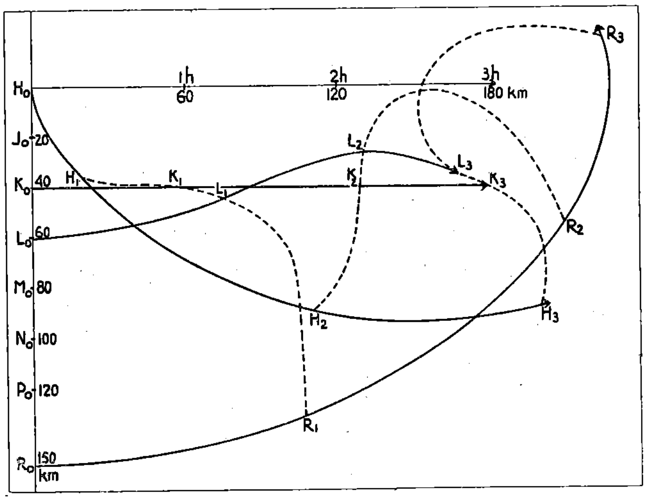


Fig. 17. Illustrating the construction of trajectories of parcels of air near the centre. Full lines: trajectories of the parcels of air. Broken lines: successive positions of the line-element H_0R_0.

For greater accuracy a time-unit of 10 minutes is now introduced instead of 1 hour. The construction is performed in a way analogous to the one just dealt with, starting again from a row of parcels on a straight line from the centre towards the South (H_0---R_0). The parcel K_0 (corresponding to A_0 in fig. 15) at 40 km from the centre moves with the same speed as the latter and in the same direction, as already explained above. The broken lines represent the positions of the line-element H_0R_0 after 1 hour, 2 hours and 10 minutes, and 3 hours. Obviously an element of this kind is subject to considerable deformations but besides, it is clear that already after a short time it has loosened itself from the centre. *In a moving depression a front can never permanently extend right to the centre.*

Not a single parcel of air, which at a certain moment occupies exactly the centre of a moving depression can remain there and the parcels near the centre describe paths of various shapes, among which in the immediate vicinity of the centre in an isobaric field of strong cyclonic curvature even trajectories of anticyclonic curvature occur. This leads us to the general conclusion *that in the centremost part of a travelling depression the air will be subjected to a vorticity too strong to make an identification of the fronts possible.*

Examining once again fig. 15, we observe that all the paths of the parcels of air North of the centre (we have still in mind a purely West-East motion) are strongly curved and more or less squeezed together. This can also clearly be seen from the broken lines, representing the imaginary front.

If, therefore, one wishes to break off the front in a moving depression, this is best done north of the centre as is shown in fig. 4. If one should prefer an other procedure, one must make the front describe a wide spiral round the centre, while the parcel having the same speed as the centre at a certain distance from it acts as the "apparent centre". Such a construction, however, is not advisable and is, indeed, never seen on a weather map. It will also be clear from the above, that the construction of a bent-back occlusion, as drawn in fig. 4 must be rejected in the case of a moving depression. When nevertheless such occlusions are drawn on the weather maps, this must be due to an erroneous interpretation of the observations. Mostly one will in reality have to deal here with troughs, which are mistaken for fronts, or with "caught" fronts, which then, however, will not be capable either of extending permanently in the centre of a moving depression.

The fact that in the immediate neighbourhood of such a centre straight trajectories or even trajectories of anticyclonic curvature can occur warns us to be very cautious in using the geostrophic windscale for computing wind velocities as there is always a tendency to take the radii of curvature of the isobars for those of the trajectories and this may lead to large errors for parcels close to the centre of a depression.

CHAPTER IV. SOME CONSIDERATIONS CONCERNING THE DEVELOPMENT OF FRONTAL DISTURBANCES

As already remarked in Chapter I, sub *c*, a number of meteorologists are of opinion, that cyclones develop preferably at places, where in the upper air areas with strong divergence occur (c.f. Rodewald [1]).

Schmidt has treated various of these problems theoretically in his publication "On the causes of pressure variations at the ground" [6].

It also appears, that areas with strong divergence in the higher layers are mostly found directly in connection with transitional zones in these layers. It is easily seen that these transitional zones in the upper air will chiefly occur on the "cold" side of the boundary at the earth's surface between the warm and cold air (comp. for instance Rodewald [1], pp. 7 and 8) and we may remark here that the strongest upper current of the transitional zones will be found in the warm air above the frontal surface and in the region of transition between the warm and cold air. A quasi-stationary front at the surface of the earth can, therefore, be accompanied by an upper current in the 500 mbar level of a shape shown in fig. 18.

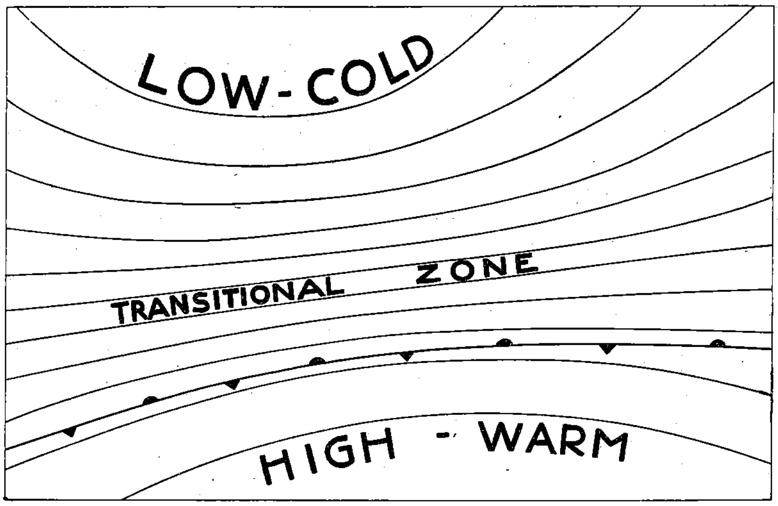


Fig. 18. Upper current in 500 mbar level; quasi-stationnary front at the surface of the earth.

In any case there will always be found divergence on the one side of a transitional zone and convergence on the other side, while the structure of the whole of the field of flow depends on the more or less accidentally developed state of the atmosphere in the area in question.

According to Schmidt the following rules hold for the occurrence of falls and rises in the pressure, in the case of divergent and convergent upper currents (c.f. [6] pag. 22).

a. "If the high level isobars diverge uniformly, surface pressure falls (rises) if the largest gradients lie on the high (low) pressure side.

b. If the high level isobars converge uniformly, surface pressure rises (falls) if the largest gradients lie on the high (low) pressure side".

These rules are an improvement on the simple empirical rules of Scherhag.

Now the frontal upper current will mostly show the largest gradients on the "cold" side of the front at the earth's surface. A region with decreasing gradients will be found towards the side of the high pressure as well as of the low pressure. In applying the above rules, the actually observed pressure-falls and -rises are easily explained. The area with decreasing gradients on the low pressure-side, which in the case of divergence is accompanied by pressure-falls, lies consequently still somewhat further on the "cold" side of the front at the earth's surface than the region with the largest gradients. In the following we shall confine ourselves to the study of pressure-falls only, and shall not include the rises in pressure in our discussion.

It follows from the above that, when one states the occurrence of pressure-falls one can expect in many cases that during the further development of a frontal disturbance accompanying them, the largest falls will not be found to lie at the front at the surface of the earth, but a few hundred kilometer on the "cold" side of the boundary between warm and cold air at the earth's surface. This is in excellent accordance with what the weather maps show. We shall not consider here the question of the primary cause of the falls.

In order to obtain a better insight in the motions of fronts in depressions, we must first enter into more detail about the pressure-fields which can arise, when a pressure fall, supposed to last for some time (an isallobaric minimum), is superposed on a given pressure-field.

For the initial state with a quasi-stationary front two principal types of the surface pressure-field can be distinguished:

a. on both sides of the front the flow has the same direction (fig. 19);

b. the front lies in a furrow of low pressure, so that the flow on both sides of it is in opposite directions (fig. 20).

The case sub a is of frequent occurrence, for example when new disturbances are formed on the Atlantic Ocean.

When, now, a depression begins to develop, an isallobaric minimum will superpose itself on this linear field. This minimum can be approximately represented by a set of concentric circles. The profile of this isallobaric minimum and the structure of the original linear field determine together the new pressure-field. In general such an isallobaric minimum will vary with time; its profile will be sine-like as drawn, for example, in fig. 21.

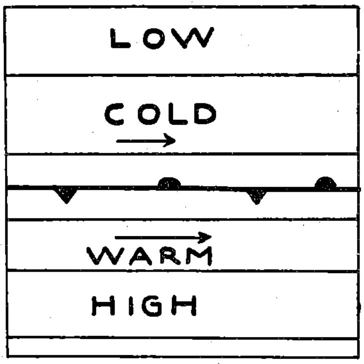


Fig. 19.

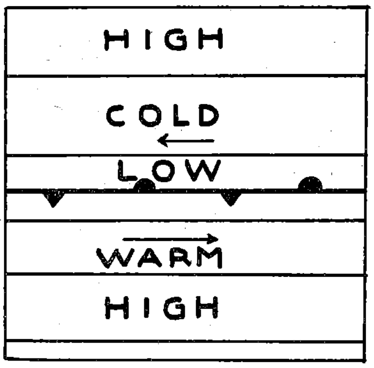


Fig. 20.

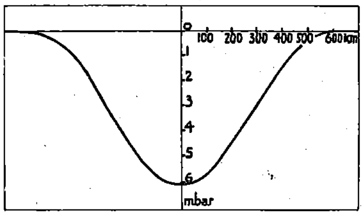


Fig. 21.
The isallobaric minimum.

Now to find out whether the superposition of an isallobaric minimum of this kind on an originally linear field will lead to the formation of a centre of low pressure and where this will take place, it suffices to consider the result of such a superposition in a direction at right angles to the front. If in this cross-section a point is found with higher pressure on both its sides, this means that in the whole field a centre of low pressure has been formed, as we have a circular structure with a finite boundary for the isallobaric minimum.

Two cases can be distinguished:

a. The less probable case (in view of the above considerations in this chapter) that the centre of the isallobaric minimum lies exactly on the front. We assume now a linear field on the „warm" side of the front with a gradient of 2 mbar per 100 km. (*OP* in fig. 22).

On the „cold" side we assume, on the contrary, various gradients (*OA*, *OB*, *OC*, *OD* and *OE*) on these fields we superpose an isallobaric minimum of the shape indicated in fig. 22 by *QRA*. As a result we obtain the pressure fields *PRA*, *PRB*, *PRC*, *PRD*, *PRE*. From this result *the possibility appears that, even on the assumption that the centre of the isallobaric minimum lies exactly on the front, provided certain relations exist between the undisturbed field and the superposed minimum, centres of low pressure may form with centres at a few hundred kilometer on the „cold" side of the front.*

We need not explain in any further detail that in this case, when the front lies in a furrow of low pressure the super-position always leads to the formation of an area of low pressure with its centre on the front.

b. The more probable case, that the centre of the isallobaric minimum lies a few hundred kilometer on the „cold“ side of the front, say, for example 300 kilometer. There are then various possibilities as shown in fig. 23.

(Original profile on the „warm“ side $O'P'_3$ on the „cold"side $O'A'$, $O'B'$, $O'C'$, $O'D'$ and $O'E'$; profile of isallobaric minimum $Q'R'C'$, after superposition profiles, at right angles to the front: $P'R'A'$, $P'R'B'$, $P'R'C'$, $P'R'D'$ and $P'R'E'$). There is no essential difference between this figure and fig. 22. In this case too, when certain relations exist between the original field and the isallobaric minimum, superposition of the latter will give rise to centres of low pressure lying a few hundred kilometer on the „cold“ side of the front, also when initially the front lies in a furrow of low pressure (see $P'R'B'$).

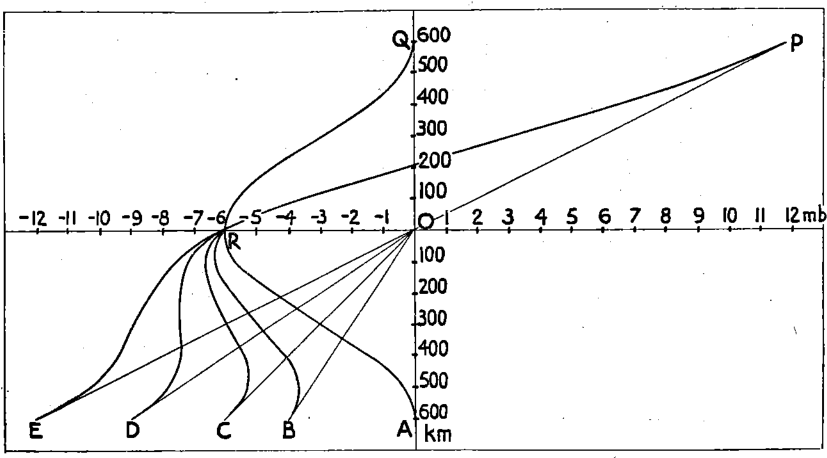


Fig. 22. Illustrating the superposition of an isallobaric minimum with centre on the front on different linear fields of pressure

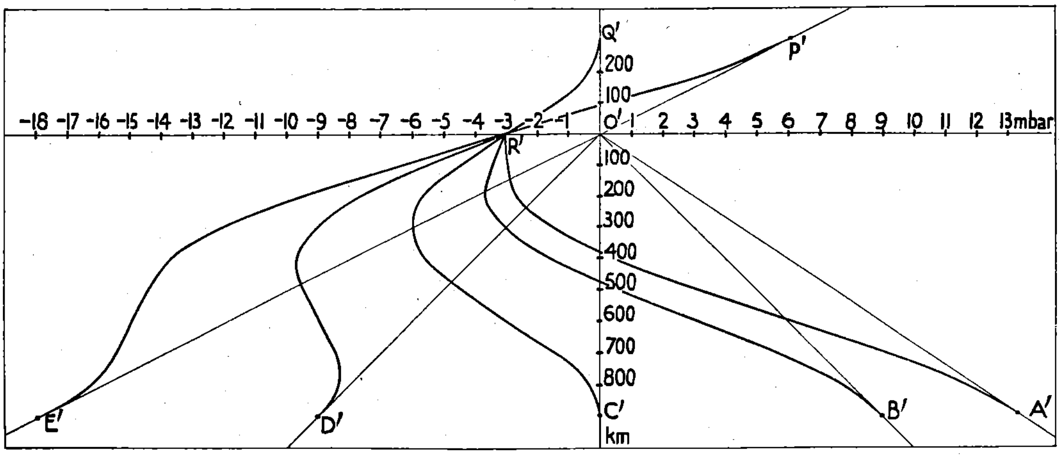


Fig. 23. Illustrating the superposition of an isallobaric minimum with centre 300 kilometer beside the front on different linear fields of pressure

In the above we have assumed the front not to alter its position during the interaction with the isallobaric minimum, which, naturally, is not actually the case.

In the beginning of this chapter, we have explained that in many cases the largest pressure-falls accompanying frontal disturbances, will occur a few hundred kilometer on the „cold“ side of the front at the earth's surface. *In certain cases, this may cause the formation of low pressure centres beside the front.* In view of the considerations in Chapter III, it is improbable that the deformations of the pressure-field at the earth's surface, will cause the front to move at once in such a way as to make it immediately extend up to the centre of the newly formed depression.

If the original front lies in a furrow of low pressure and the centre of the isallobaric minimum is very close to the front, a situation will arise, wherein for some time the front will either extend across the centre or so close to it, that one cannot make out whether it lies in or just outside the centre of the depression. Frictional processes, changes in the inclination of the frontal surfaces and isallobaric effects can in such cases also cause the front to remain for some time in the immediate vicinity of the centre. Examples of situations of this kind are, among others, the formation of depressions in which arctic fronts come into play.

We shall now proceed to prove that in a situation, in which a centre is formed on the „cold“ side of the front, the formation of an area of low pressure in an originally straight front will cause it to assume a shape resembling a wave all the same.

As an approach to this problem, we refer once more to our circular depression, introduced in Chapter III, of which fig. 14 shows the pressure profile and the course of the pressure gradient. Instead, however, of examining the behaviour of a line at right angles to the isobars extending to the centre, we shall now examine the deformations of a line initially parallel to the trajectory of the centre. Our model has the same properties as that in Chapter III, so that the construction of the various successive positions can be quickly carried out. The construction in question is shown in fig. 24.

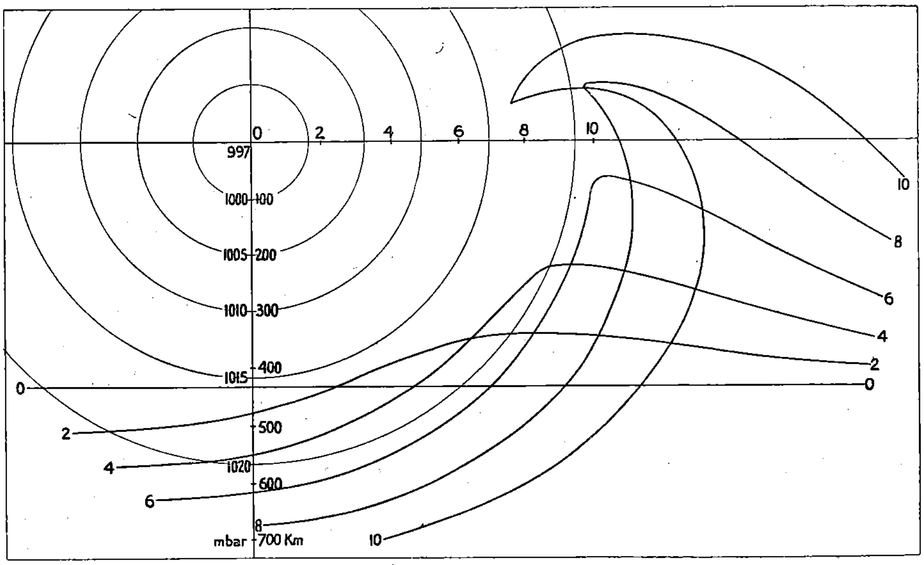


Fig. 24. Showing the development of the sweep in an imaginary front initially parallel to the trajectory of the centre of the depression
Thin full lines: isobars in initial stage. Heavy full lines: successive positions of the front.

As appears from this figure the shape of the successive stages of this „front“ bear a close resemblance to that of a developing wave as is yielded by the Norwegian analysing methods. In the „sweep“ which deforms the front a slight bend appears, which grows gradually sharper.

This model did not permit the construction of still more stages, as the speed of the centre was chosen so as to make it enter, in due course, into the „warm“ sector. In reality the upper current will change during the developing-process of the depression and the deformations of the front and the centre will, therefore, also alter its trajectory.

It must be observed here, that in applying this construction, which invariably operates with gradient wind, the formation of an occlusion can never be explained. The various parcels can never „catch each other up“, so that the warm sector, though indeed subject to deformations, cannot entirely „fall together“. In the last stage, drawn in fig. 24 the warm sector in the vicinity of the centre has already become very narrow so that the remaining step towards occlusion is a very small one.

We can summarise the above in the following conclusion:

If wave-motion in the front is not considered to be a primary cause, but the forming of a low pressure centre is ascribed to other processes of any kind whatsoever, a deformation in the front will nevertheless occur, which resembles a wave motion.

After the investigation of this case an attempt was made to obtain a better approximation to the development of depressions, as they occur in reality on the weather maps, by a set of models instead of by one model of a circular depression moving at uniform speed along a straight line and of constant depth. To this end an isallobaric minimum with a depth increasing with time, was superposed on a linear field, while the centre of the isallobaric minimum was made to describe a certain curve with variable speed. This investigation, however, did not lead to any new points of view, and the simple set of drawing rules furnished by the circular depression turned out to be completely adequate for these constructions.

For the development of an "unstable wave" a modified set of figures can be designed analogous to fig. 6. This development is given in outline in fig. 25.

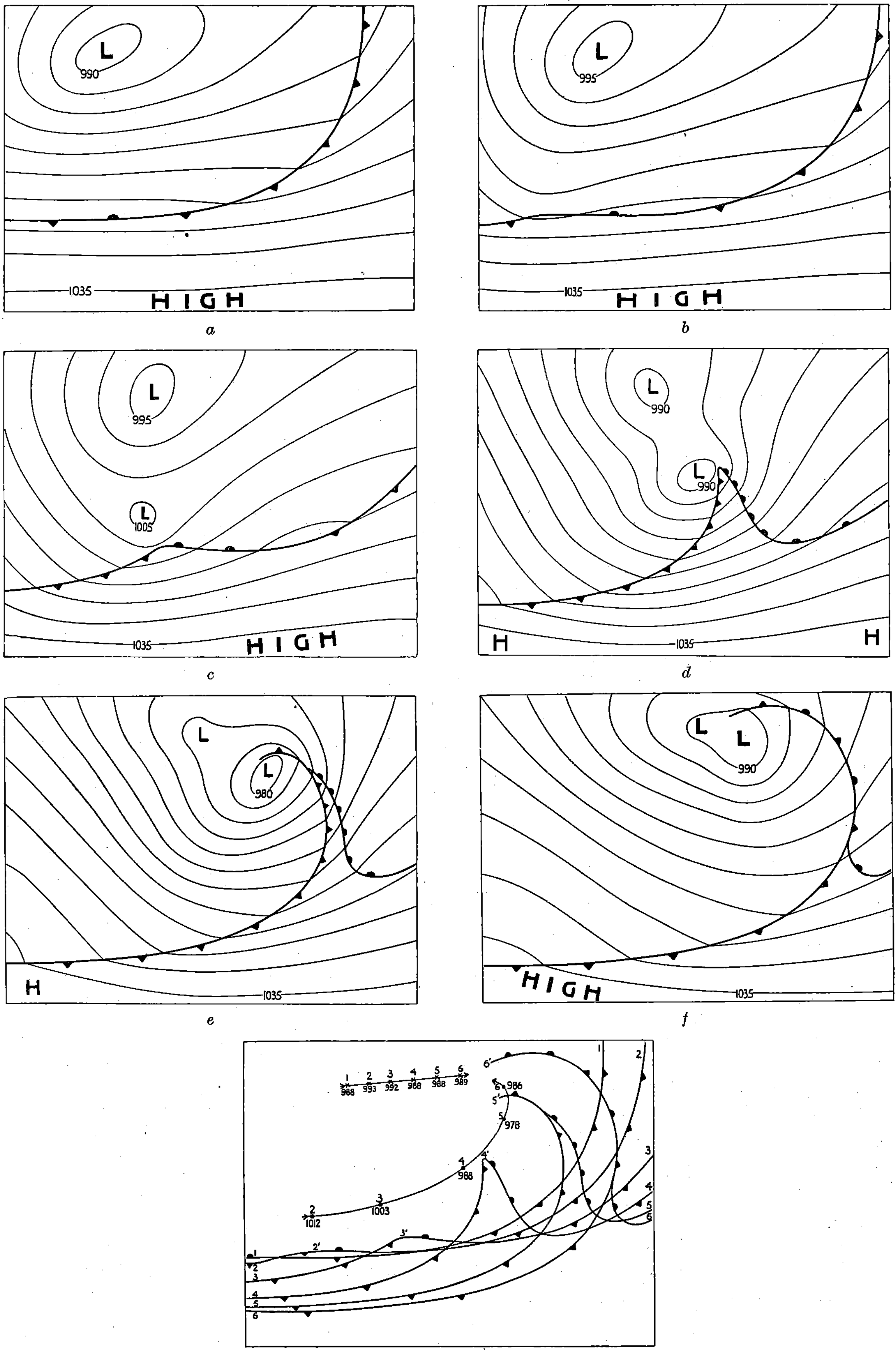
Stage *a* shows the original undisturbed state of affairs. To begin with, we have, therefore, the case (frequently occurring on the Atlantic Ocean) of a front in a general West-East flow. In stage *b* the occurrence of pressure-falls has caused a slight cyclonic bulging of the isobars, which has given rise to a feeble sweep in the front, while a new centre begins to form. In stage *c* the new centre has grown independent and the sweep begins to develop strongly. Here the majority of the synoptici, analysing in the Norwegian way, would certainly draw an occlusion from the top of the "wave" to the innermost part of the newly formed centre. The stages *d*, *e* and *f* show the further deepening, the occluding and finally the dying down. In stage *g* of fig. 25 the isochrones are drawn of the two centres and the fronts; the figures added designate the phases, corresponding to each other.

We must now for a few moments consider the question whether in stage *c* the observed meteorological phenomena do or do not make it necessary to draw an occlusion from the top of the "wave" to the centre. For, in the region between the top of the sweep and the centre, one will indeed often find certain characteristic differences in these phenomena, in the direction and strength of the wind and, at times, in the temperature and other elements. These differences can, however, always be explained without assuming that a front passes through that region. Above this region passes a gully in the frontal surface so that certain characteristic changes in weather phenomena will result, which will depend on the masses of air entering into the processes in question. The passing of the trough of low pressure connected with them, will cause changes in the direction and strength of the wind, and these, in their turn, can be the cause of changes in temperature and other elements, apart from the possibility that precipitation does or does not occur so that the lower layers of air, by evaporation thereof, are or are not cooled down to the wet-bulb temperature.

The rate of development of the "sweep" in the case of the circular model depends not only on the profile of the depression but also on the speed of the centre on its trajectory. When this speed becomes sufficiently high the developing sweep will not have an opportunity to swing round the centre and none of the parcels lying in the imaginary front will describe a complete cycloid. In this case, there originates, so to speak, a *stable wave.* One can, therefore, form an idea of the creation of such a wave by imagining that a swiftly moving isallobaric minimum, caused by a prevailing irregular state somewhere in the atmosphere, induces a sweep in a front.

Application of the developed drawing rules will remove the objections in Chapter II to the Norwegian analysing methods.

a. Considering that it is not necessary to extend the front right up to the centre of a depression the difficulty in Chapter II, sub *a*, is solved, namely that, owing to the extension, just mentioned, in certain places, this front would have to pass twice.



a *b* *c* *d* *e* *f* *g*

Fig. 25. Illustrating the development of an „unstable wave”.

b. With moving depressions bent-back occlusions like those drawn in fig. 3 do not occur.

c. The centre of a developing depression can originate free from the front.

d. The wave can develop as a "sweep" in the front, which starts as a slight bend, while later on the "warm" sector becomes more and more pointed.

e. The drawing of the occlusion-process gives no longer rise to any difficulties. One is not obliged to draw the occlusion right up to the innermost part of the centre.

In the case of a West-East motion one should preferably break off the occlusion north of the centre.

f. The considerations in this publication do not allow us to draw any definite conclusions as to which of the various theories concerning the origin of frontal disturbances is correct. It is shown, however, that by approaching the problem along another line, satisfactory results can be obtained and certain difficulties can be solved.

Finally we can also explain away the discrepancy that from the registrations furnished by the Dutch weather stations the number of identifiable fronts was less than according to the weather maps must have actually passed. Indeed, in the vicinity of the centres there are less fronts than are usually drawn when the original Norwegian methods are applied, although a few genuine fronts can be so slightly pronounced, that they can hardly or not at all be identified from the registrations.

In Chapter V an attempt will be made to illustrate the practicability of the drawing rules designed in the present publication.

CHAPTER V. EXAMPLES

I. **Development of the weather from 13—19 Nov. 1938** (International week for swell observations in the North Atlantic Ocean)

Some years ago the synoptic weather maps of the International week for swell observations held from 14 to 19 November 1938, were analysed by the present writer according to the Norwegian methods, then in use at the K.N.M.I. To do so for the various synoptic situations on the Atlantic Ocean was not an easy matter, although more than the usual number of observations was available. Finally, however, a satisfactory solution could be found for all cases. The fig. 26*a*, 27*a*, 28*a*, 29*a*, 30*a*, 31*a* en 32*a* ¹) show the weather maps from 13 to 19 November 1938, 1200 G.M.T. (scale 1:30 000 000) ²) already reproduced in communication 126 of the K.N.M.I. [13].

On closer inspection of this set of maps a remarkable inconsistancy is noticed in the transition from the analysis of fig. 27*a* (15 November) to that of fig. 28*a* (16 November), the introduction, namely, of a secondary cold front, which had to be introduced, however, for a satisfactory explanation of the centre of low pressure at 46° N and 41° W, shown in fig. 29*a*. It involved the assumption of frontogenesis, which is not an elegant solution in this case. On the other hand the available observations made it perfectly clear that the top of the warm sector of the "wave" in the front further south could not possibly extend to within the centre of this new depression, moreover, the "wave" was still so "young", that it would have been decidedly premature, to draw at this stage, already an occlusion from the top of the wave to within that centre. The actual presence of the latter, in the position mentioned above, was, however, put beyond any doubt by the observations, so that the only possible solution with the methods, in use at the time, was the introduction of a secondary front.

This once introduced, the further weather maps could be analysed fairly easily, though the constructions are admittedly not very elegant and occasionally make a rather clumsy and forced impression. Besides, it appeared from a closer study of the observations, that the secondary cold front, mentioned above, could hardly be identified and that the observed weather phenomena could be explained at least equally well by a, for the rest, also still fairly weak trough.

Now, by applying the considerations, developed in the foregoing chapters, to these situations the satisfactory analysis of the maps is made decidedly simpler, because it is now no longer necessary to make the fronts, connected with the development of new depressions, always extend to the centre. Fig. 26*b*, 27*b*, 28*b*, 29*b*, 30*b*, 31*b* and 32*b* show the modified analyses of the maps. For elucidation a few observations have been added.

The better to follow the development of the depression from 17 to 18 November sections of the maps of 17 November 0000 and 0600 G.M.T. (fig. 29*c* and 29*d*) and of 17 November 1800 and 18 November 0000 and 0600 G.M.T. (fig. 30*c*, 30*d* and 30*e*) are inserted. On comparing the analyses according to the modified and according to the "old" method, it is seen at once that the former gives the simpler, more flexible and less angular constructions.

The development of the unstable wave, described in Chapter I, can also be better constructed in the modified way (cf. fig. 6 to 10). It turned out, moreover, that some observations, which in the unmodified way could hardly be explained or not at all, and which, for that reason, were neglected, could now be satisfactory accounted for after all. ³)

Besides, some of the maps lent themselves very well to the carrying-out of a construction analogous to the one described in Chapter IV for an imaginary front in a circular isobar-

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¹) The figures of this chapter are reproduced separately in the appendix.

²) The observations on board the ships were, in 1938, generally made at 0000, 0600, 1200 and 1800 G.M.T., those on land at 0100, 0700, 1300 and 1800 G.M.T. On the maps the former ones are retained.

³) This emphasizes once more, how cautious one must be in neglecting observations, although in analysing weather maps, it will presumably be unavoidable to reject a small number of observations as unreliable.

field, while, this time, the various pressure-gradients actually determined from the weather maps, were used, whereas friction and other disturbing influences were not taken into account. (We observe here, once again, that only horizontal motions are considered.)

To begin with, we take a section from the weather map of 17 November 0000 G.M.T. The isobaric field is idealized and the front on the Ocean is made exactly parallel to the isobars, by which simplifications our front deviates slightly from the real one (see fig. 33) (in the fig. 33 to 38 all on the scale 1 : 30 000 000 the thin lines represent the isobars, the thick line the computed front, the broken line the position of the front as drawn on the original corresponding map, while the dash-dot lines in the fig. 33 and 38 represent the computed trajectories, covered between 17 November 0000 and 18 November 0600 G.M.T. by the parcels of air, occupying initially the positions 1—7). Now we assume that the field of cyclonic isobars connected with the small centre, present on 17 November 0000 G.M.T. at 42° N and 54° W expands to beyond the isobar-parallel front, so that this begins to move in accordance with the circulation of the air, resulting from the prevailing pressure-field. The interaction between the isallobaric minimum and the already present frontal zone leads then to the development of a very deep depression causing the front to move in a way, analogous to the one, described in Chapter IV for the developing "sweep" in the circular field of isobars. The successive positions of the front on the various weather maps are each time determined by constructing first the positions of a number of parcels of air and by then drawing a line, running evenly between these newly-found positions. For carrying out these constructions the field of isobars was assumed to remain unaltered for a period of 6 hours. To be exact, these periods are too long, but in 1938 the number of observations made on the Atlantic Ocean was still insufficient to allow the introduction of a shorter period, say for example of 3 hours.

The map for the time h represents, therefore, so to speak, an average state of affairs for the period from $h - 3$ hours to $h + 3$ hours. If, now, we compare the changes in the successive computed fronts and those in the fronts actually found, we notice deviations, more in particular on those weather maps, on which high speeds occur. The computed position is, as it were, 3 hours in advance of the real one. This gain on the real front is made still more pronounced by our neglecting the friction, as this friction will cause a further lag of the front at the earth's surface. Fig. 34 to 38 show clearly, that the shape of the wave computed in this way, differs but slightly from the real one, drawn on the weather maps.

In passing, we may draw here attention to the paths, described by the various parcels of air in the period from 17 November 0000 to 18 November 0600 (see fig. 33 and 38) from which it appears that the air, immediately behind the cold front, arrives at all parts from relatively southern latitudes (cf. for example parcel 4, which for the moment lies exactly at the top of the "wave"). By its flowing over the warm water in southern latitudes, this cold air will have experienced a considerable rise in temperature. According as later on, the air is gradually supplied along more northern trajectories, the temperatures will suffer a fall, which, however, is not necessarily accompanied by the occurrence of a secondary front. This is in perfect agreement with the observed phenomena when Atlantic depressions of this kind pass; the temperature of the polar air at the earth's surface immediately after the passing on the cold front is then indeed often found to be remarkably high. A further and occasionally fairly quick fall in temperature, also not necessarily accompanied by the passage of a front, often takes place when a trough, formed in the polar air passes, whereupon cold air is supplied along a path lying further north. It appears also from these constructed trajectories, that parcels initially only a few hundred kilometer apart, can be separated already after a rather short time by thousands of kilometers. (See, for example, the parcels 1 and 2, of which the first one, under the influence of the developing area of high pressure, begins to move in a western direction, while the second one is carried away farther and farther by the eastward current.)

II. Development of the weather from 3 to 4 Februari 1948

Considering that the material for the week of swell observations was still rather lacunar, though not to such an extent as is usually the case with the ordinary daily weather maps of the Atlantic Ocean, we searched the series of weather maps for an example of a disturbance, mainly taking place over the continent of West-Europe, where the weather stations are numerous and not far apart. This turned out to be very difficult to find, because most of the depressions have already developed considerably and are already occluded before reaching the shores of Europe. A typical case occurred however from 3 to 4 February 1948. It is represented in fig. 39, 40, 41, 42, 43, 44 and 45, respectively sections from the synoptic weather maps of 3 February 0000, 0600, 1200 and 1800 and of 4 February 0000, 0300, 0600 G.M.T.

On the first of these maps (fig. 40) there is a faint indication, that NNE of the Azores, due south of an area in which the isobars of a deep depression near Iceland have a rather strong cyclonic curvature, a "sweep" in the front of this depression begins to develop. This development is the more remarkable because, before then, this front formed the warm front of an old depression further west. The trough further north on the ocean, moving from West to East, induces however the "splitting off" from the warm front. The cold front of this new "sweep" lies obviously between the two most western weather stations of the Azores. The position of the remaining part of the front cannot be satisfactorily gathered from the observations and is mostly drawn on the basis of "historical" considerations.

The next map (fig. 41) gives already stronger indications of the presence of the new disturbance.

The Dutch weathership at 47° N. and 15° W. reported continuous light rain, with a rather low dew-point and a negative difference between the temperatures of air and water, which means that it was surrounded by cold air, while the observations made on a ship, further south, showed that the front must lie between the position of this ship and the positions, where a number of still further southern observations were made. Following the disturbance, we see as early as on the map of 3 February 1200 G.M.T. (fig. 42) that especially over Western France the pressure falls markedly, with the result that the field of isobars over South-England and in the ocean region of the coast is, as it were, pulled apart causing a rapid decrease of the prevailing strong winds.

The following map (fig. 43) shows more clearly than the previous one the difference between the warm sector air and the cold air, as now, owing to the daily variation above land, the temperatures in the warm sector have risen considerably, after the removal of the cold surface-layer caused by the nightly radiation. These differences are still more accentuated by the cooling of the cold air in those regions, where rain is continually falling. In the cold air, too, differences in temperature occur, as in those places where there is no precipitation and the sky is not wholly overcast, the solar heat can raise the remperature. In the meantime the sweep has now so far developed, that in the pressure-field over our country, lying entirely in the cold air, practically no pressure gradients occur, and the originally rather steep isobaric field has disappeared in a short time. The stand of the barometer at Gilze-Rijen (1005,5 mbar) was already slightly less than the one at de Bilt (1005,9 mbar) and at Valkenburg (1005,8 mbar).

The next map (fig. 44) shows already a separate new centre of low pressure of 998,5 mbar over North Germany, while it is clear from observations further south that the top of the warm sector does not extend further north than just north of Neurenberg. Not one of the observations in the region of the flat depression centre gives an indication that an occlusion should extend to within the centre. Besides, the shape of the "wave" is still so open, that the formation of an occlusion is, as yet, impossible.

This can, indeed, only occur after a considerable narrowing down of the top of the warm sector. Moreover, the speed of the small centre is much higher than the velocities of the wind, reported by the stations in its neighbourhood, so that an occlusion front cannot possibly move together with that small centre.

This small new centre lies practically 400 kilometer north of the top of the warm sector, which agrees fairly well with the superposition of an isallobaric minimum on an originally linear field as represented in fig. 22 by *PRD*. Although during the further development of this "sweep", the new depression appears still to increase in depth, the separate small centre does not grow much larger (see fig. 45 and 46, maps of 4 February 0300 and 0600 G.M.T.). The positions of the successive fronts over central-Europe cannot be seen clearly, owing to disturbances caused by mountains while, moreover, the air in the lower layers of the warm sector has cooled down again considerably through the radiation during the night.

It is clear from these weather maps, that a centre of low pressure can quite well develop without being necessarily accompanied by a front extending to the heart of the depression formed.

The development of a depression can be briefly described as follows:

Examining the daily weather maps several small disturbances are noticed moving in accordance with the circulation generally prevailing in the atmosphere. These disturbances are steered by the large centres of action, the anticyclones and cyclones, extending to great heights in the atmosphere and moving at low speeds. Many of these disturbances move quietly along, now deepening to a certain extent and then filling again. When, however, they happen to come in the neighbourhood of frontal zones, interaction becomes possible and this may result in the formation of deep depressions, in particular when the current in the upper air is then strongly divergent. BRUNT in his "Physical and Dynamical Meteorology" [9], pag. 361, where he describes a certain way of development of depressions, has already advanced a suggestion in this direction: "In this case we have a weak cyclonic circulation strengthened by the interaction with a front, and it is possible that this represents the initial stages of all depressions, which form at polar fronts". GENTRY [14] in investigating the development of a fairly large number of depressions in the years 1936 and 1937 arrives at analogous conclusions.

One must then conceive the "waves" in the fronts as not being real waves, but bends, originating and developing according as the changes in the pressure-field take place. The waves are then not themselves the primary cause, but the effect of the interaction of disturbances, already present in the general circulation and an already present front or frontal zone. Whether the development of the "sweep" will be stable or unstable depends entirely on the general constitution of the atmosphere.

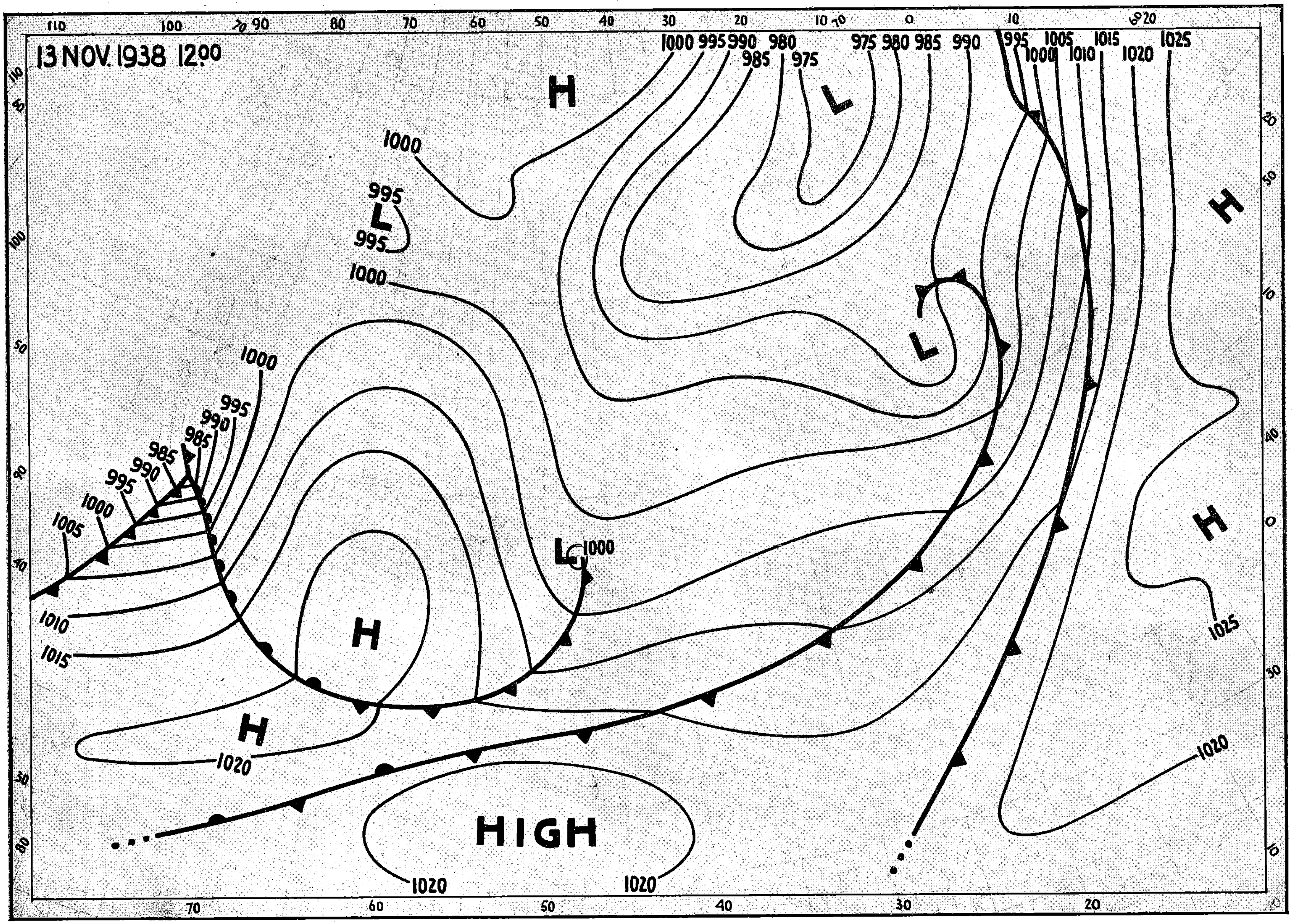
Further investigations are needed to throw more light on these problems.

REFERENCES

1. M. Rodewald. Das Dreimasseneck als zyklogenetischer Ort dargestellt an den Sturmtiefbildungen bei Kap Hatteras. Aus dem Archiv der Deutschen Seewarte und des Marine Obs. Bd. 59, n°. 10, 1939.
2. W. Bleeker. Leerboek der Meteorologie. Zutphen 1942.
3. S. Petterssen. Weather Analysis and Forecasting. New York and London 1940.
4. G. Schinze und R. Siegel. Die Luftmassenmäszige Arbeitsweise. Reichsamt für Wetterdienst, wissenschaftliche Abhandlungen. Sonderband. Leipzig 1943.
5. F. Baur. Die Bedeutung der Stratosphäre für die Grosswetterlage. Met. Zeitschrift, Bd. 53, 1936.
6. F. H. Schmidt. On the Causes of Pressure Variations at the Ground. Med. en Verh. K.N.M.I., Serie B, deel I, n°. 4, 1946.
7. P. Raethjen. Kurzer Abrisz der Meteorologie. Teil I, Hannover, 1947.
8. Headquarters U.S. Army. Air Forces Weather Service: Historical Weather Maps Northern Hemisphere Sea level and 500 mbar.
9. D. Brunt. Physical and Dynamical Meteorology, Cambridge 1939.
10. H. Koschmieder. Dynamische Meteorologie, Leipzig 1941.
11. W. N. Shaw and R. K. G. Lemfert. The Life History of Surface Air currents: A study of the surface trajectories of moving air. Meteor. Office, London 1906.
12. V. H. Ryd. Meteorological Problems. I Travelling cyclones. Publikationer fra det Danske Meteorologiske Institut. Meddeleser nr. 5, 1923.
13. Kon. Ned. Met. Instituut. N°. 126. Results of the International Observations of Swell in the North Atlantic Ocean, November 14—19, 1938. Ships' Observations, Den Haag 1946.
14. R. C. Gentry. Formation of New Moving Centers South of Deep Lows (Preliminary Report). Research Papers n°. 7. U. S. Departement of Commerce, Weather Bureau, Washington 1944.

FIGURES REFERRING TO CHAPTER V

Fig. 26*a*. Weather map of November 13th 1938, 1200 G.M.T.



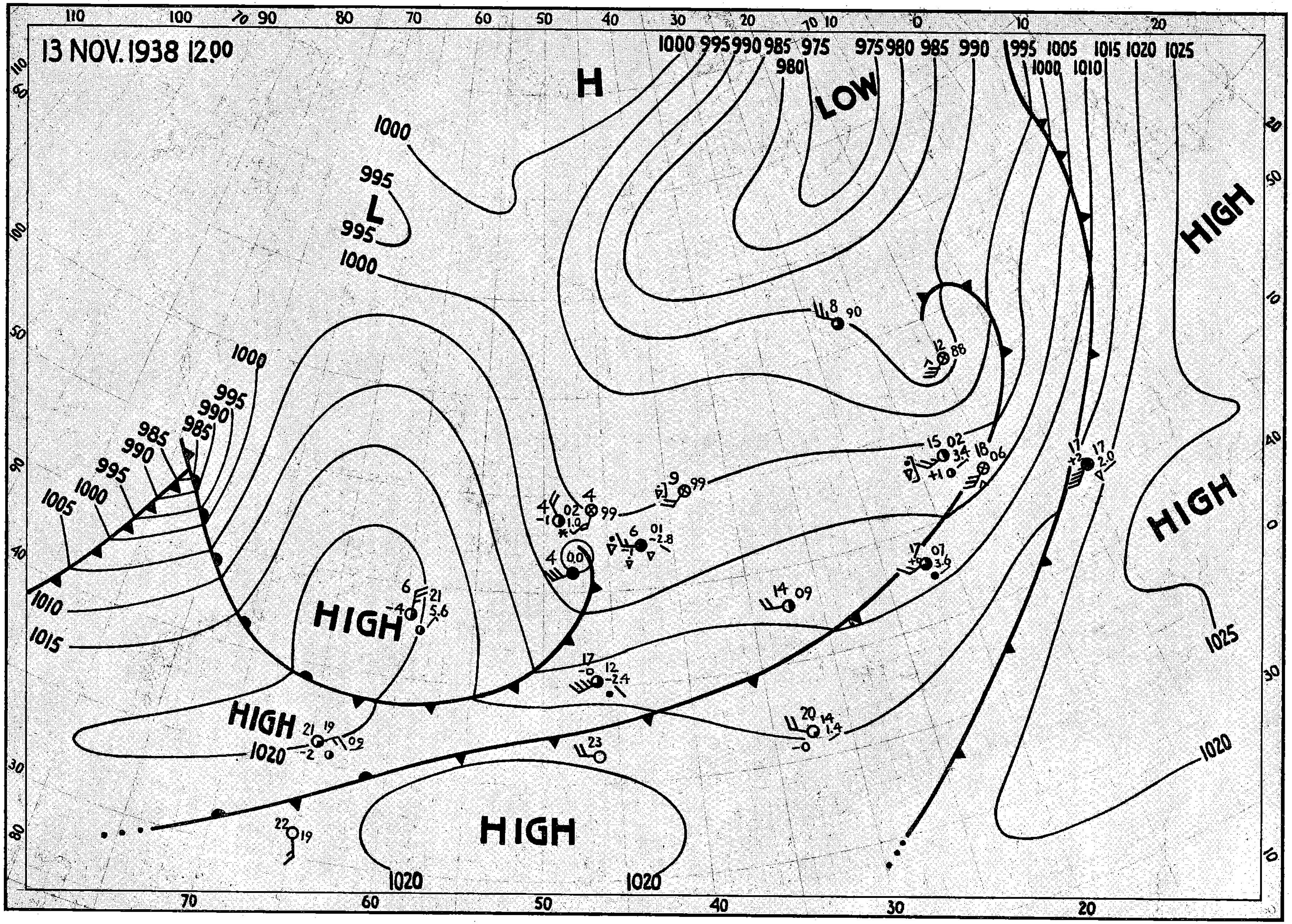
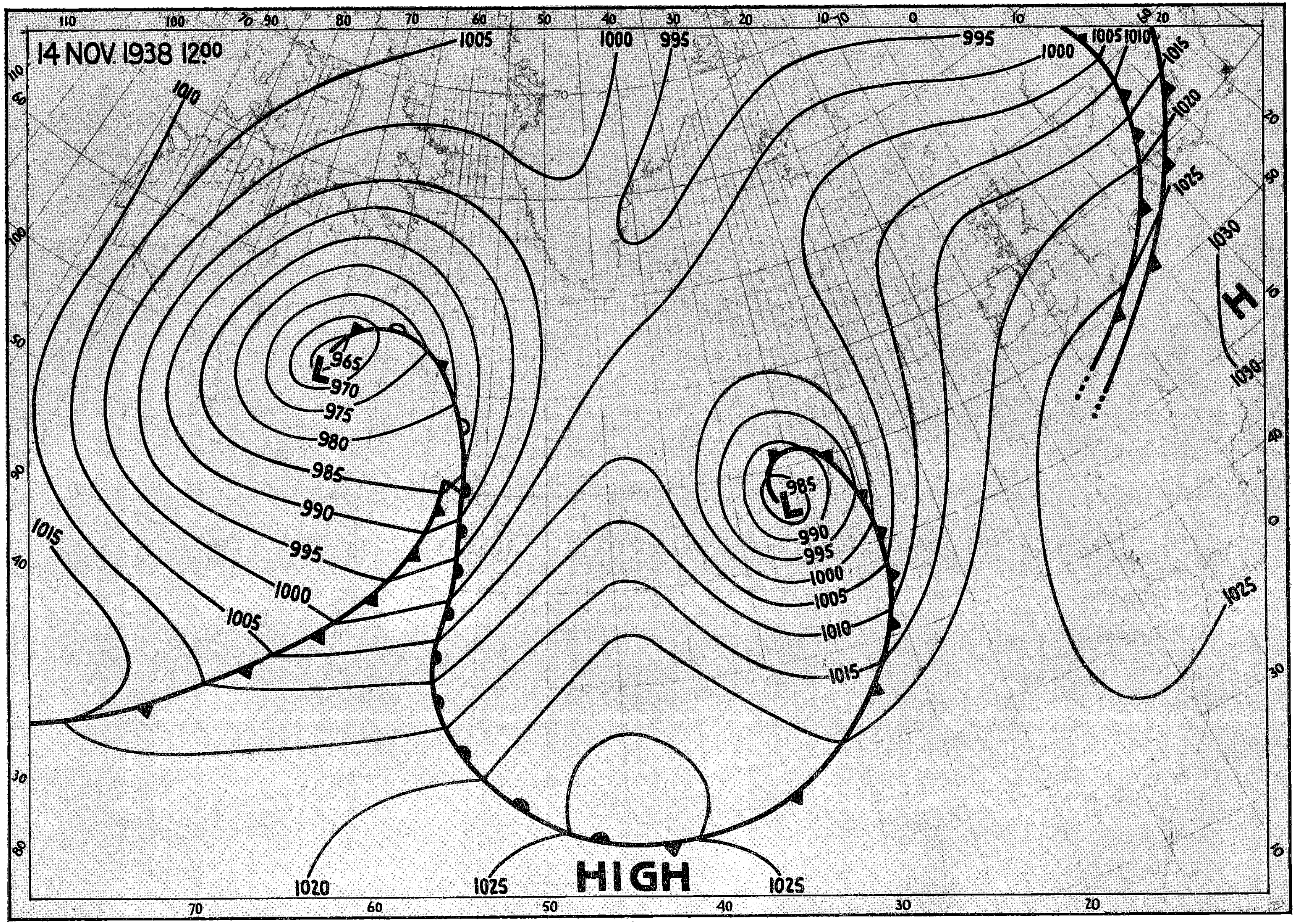


Fig. 26*b*. Re-analysed weather map of November 13th 1938, 1200 G.M.T.

Fig. 27*a*. Weather map of November 14th 1938, 1200 G.M.T.



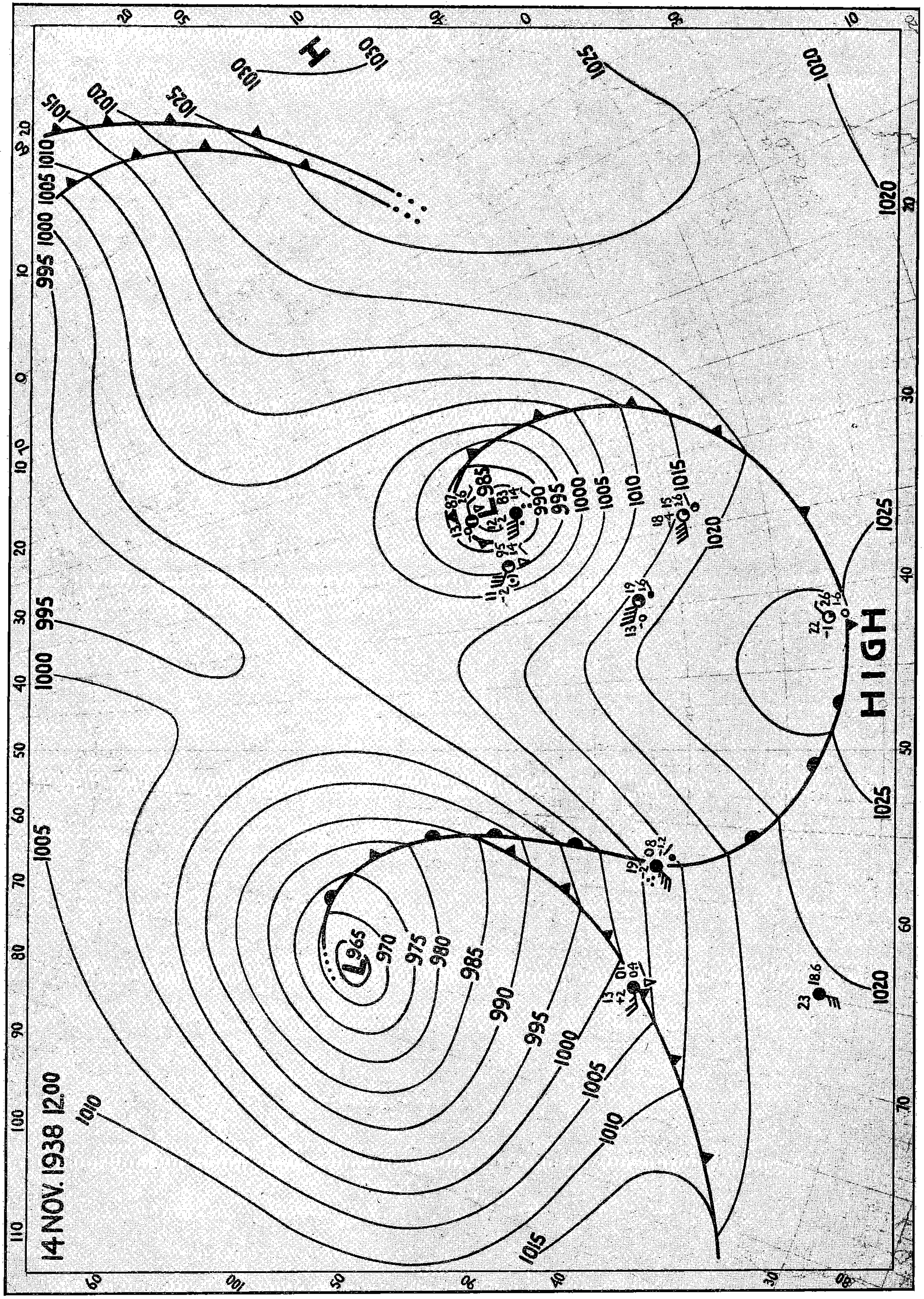
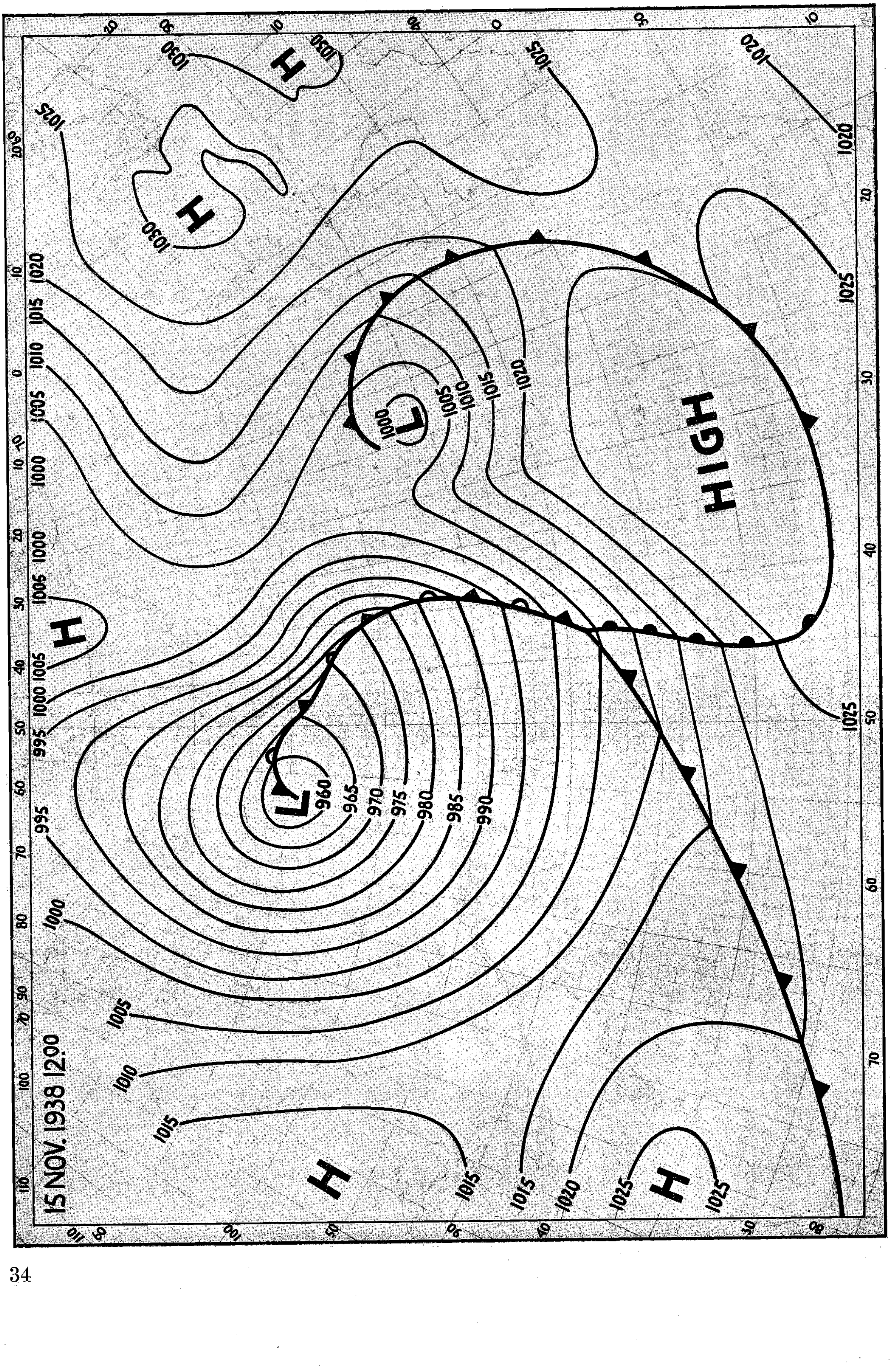


Fig. 27b. Re-analysed weather map of November 14th 1938, 1200 G.M.T.

Fig. 28*a*. Weather map of November 15th 1938, 1200 G.M.T.



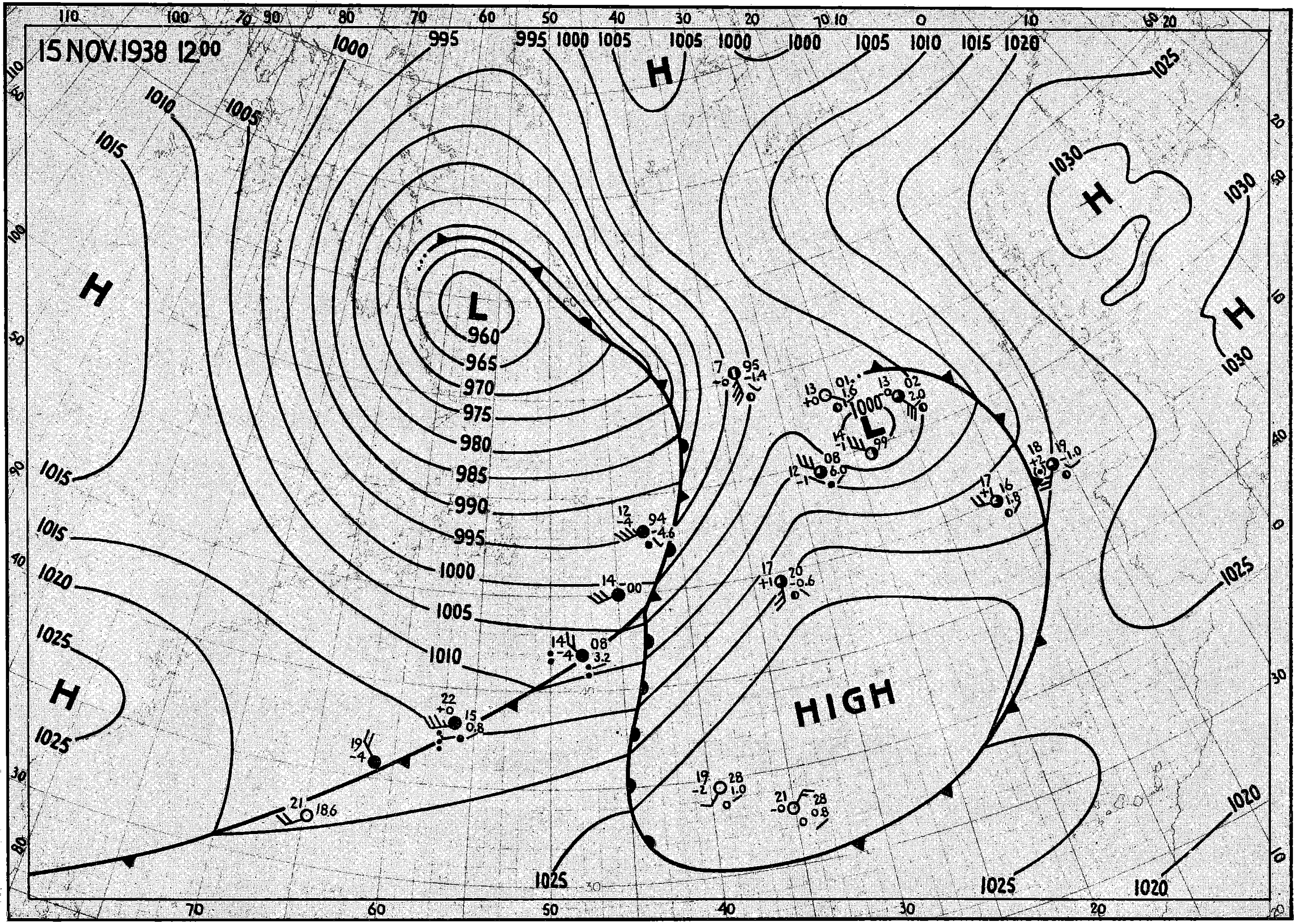
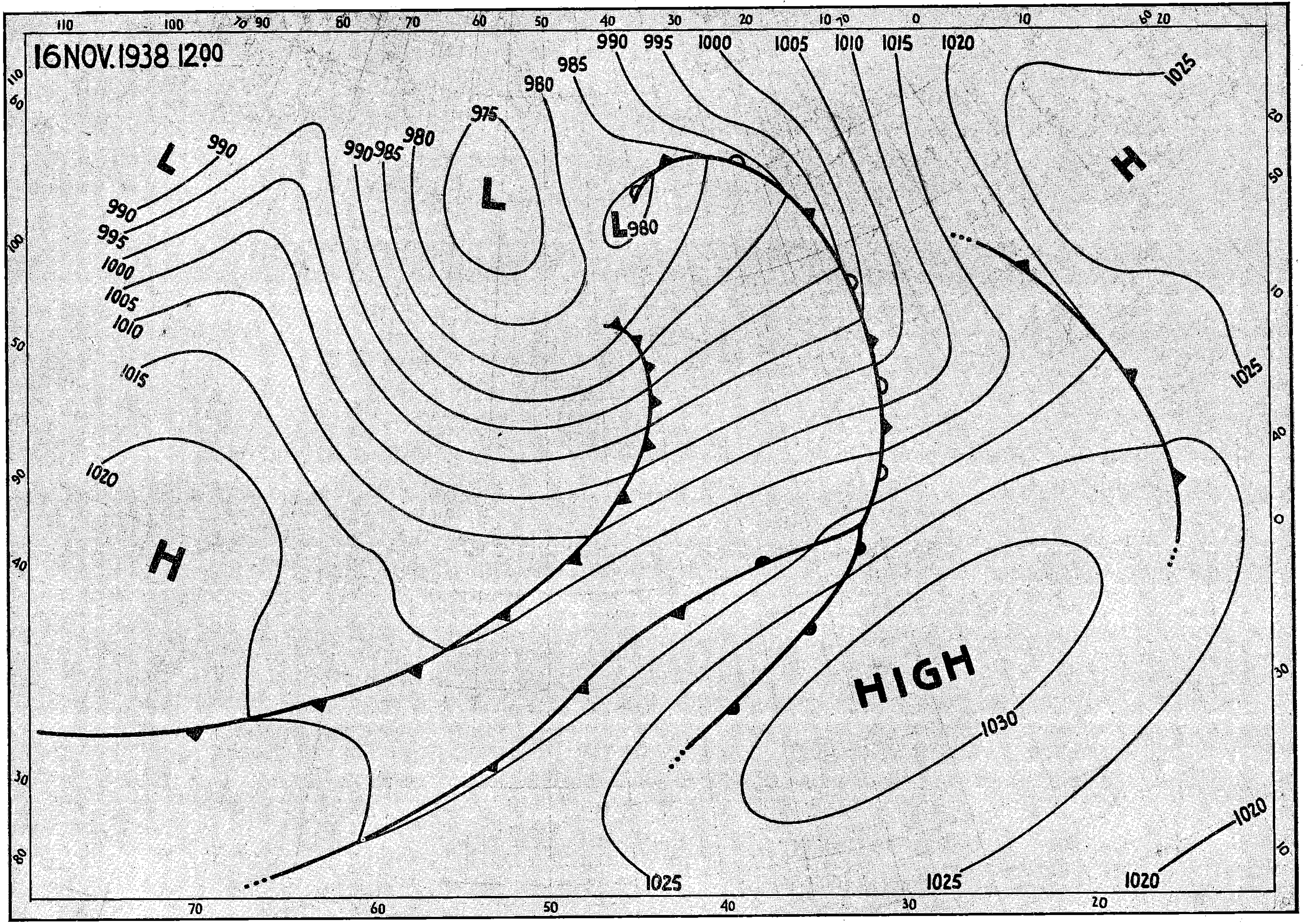


Fig. 28*b*. Re-analysed weather map of November 15th 1938, 1200 G.M.T.

Fig. 29*a*. Weather map of November 16th 1938, 1200 G.M.T.



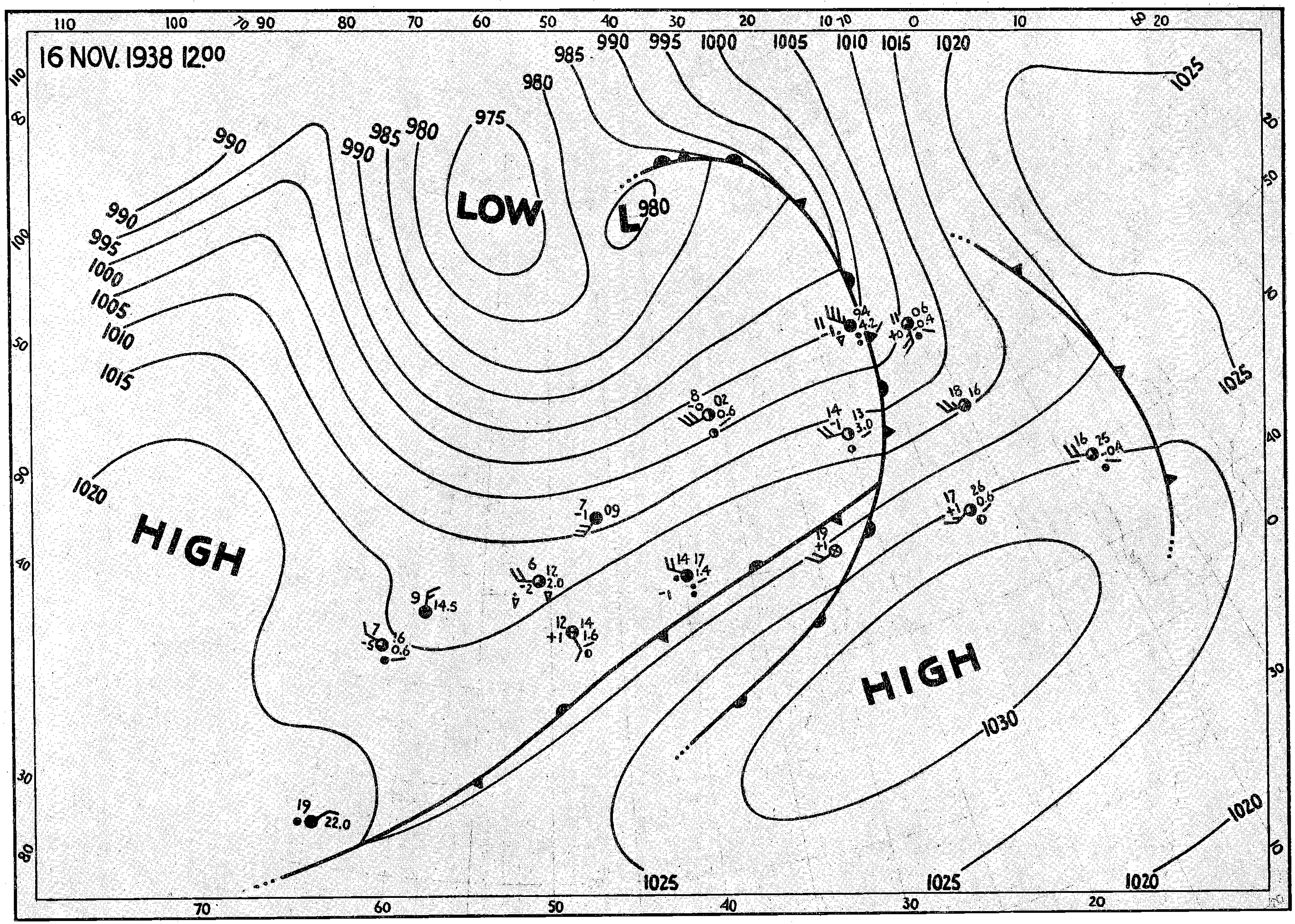


Fig. 29*b*. Re-analysed weather map of November 16th 1938, 1200 G.M.T.

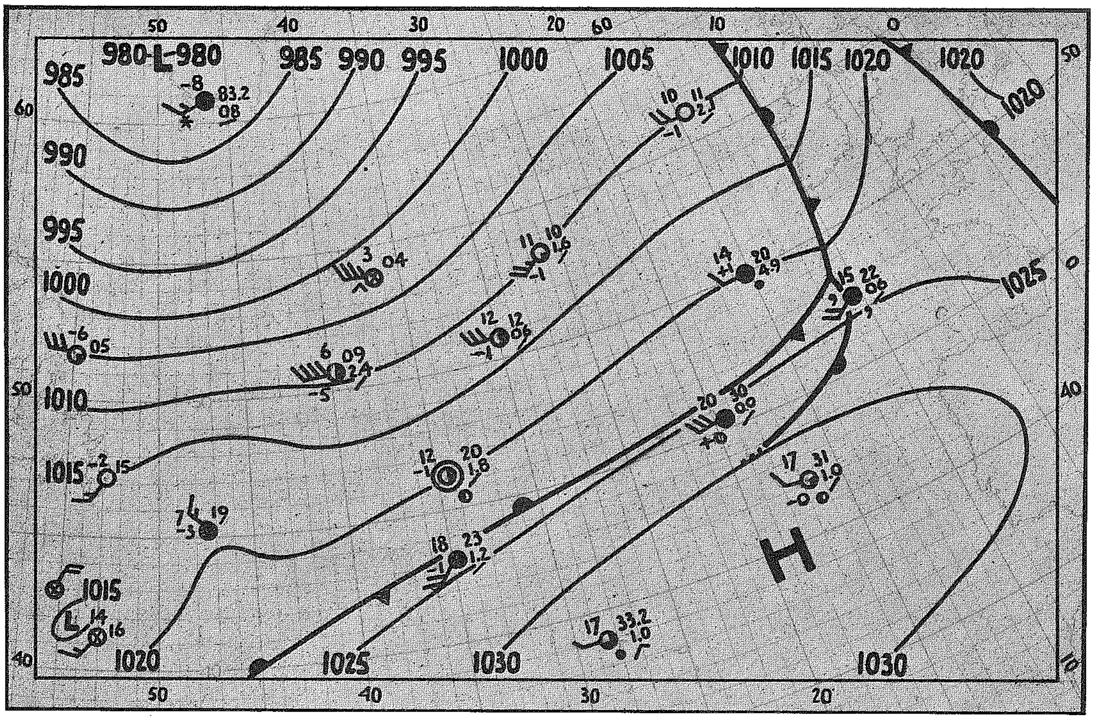


Fig. 29c. Re-analysed weather map of November 17th 1938, 0000 G.M.T.

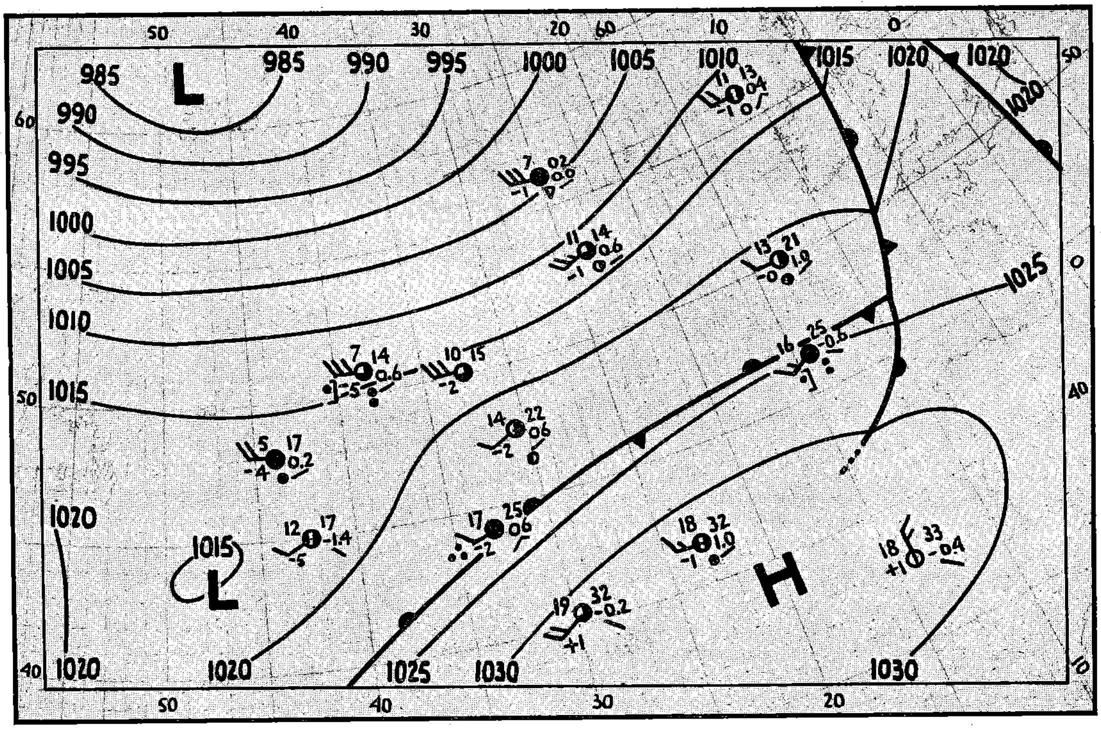
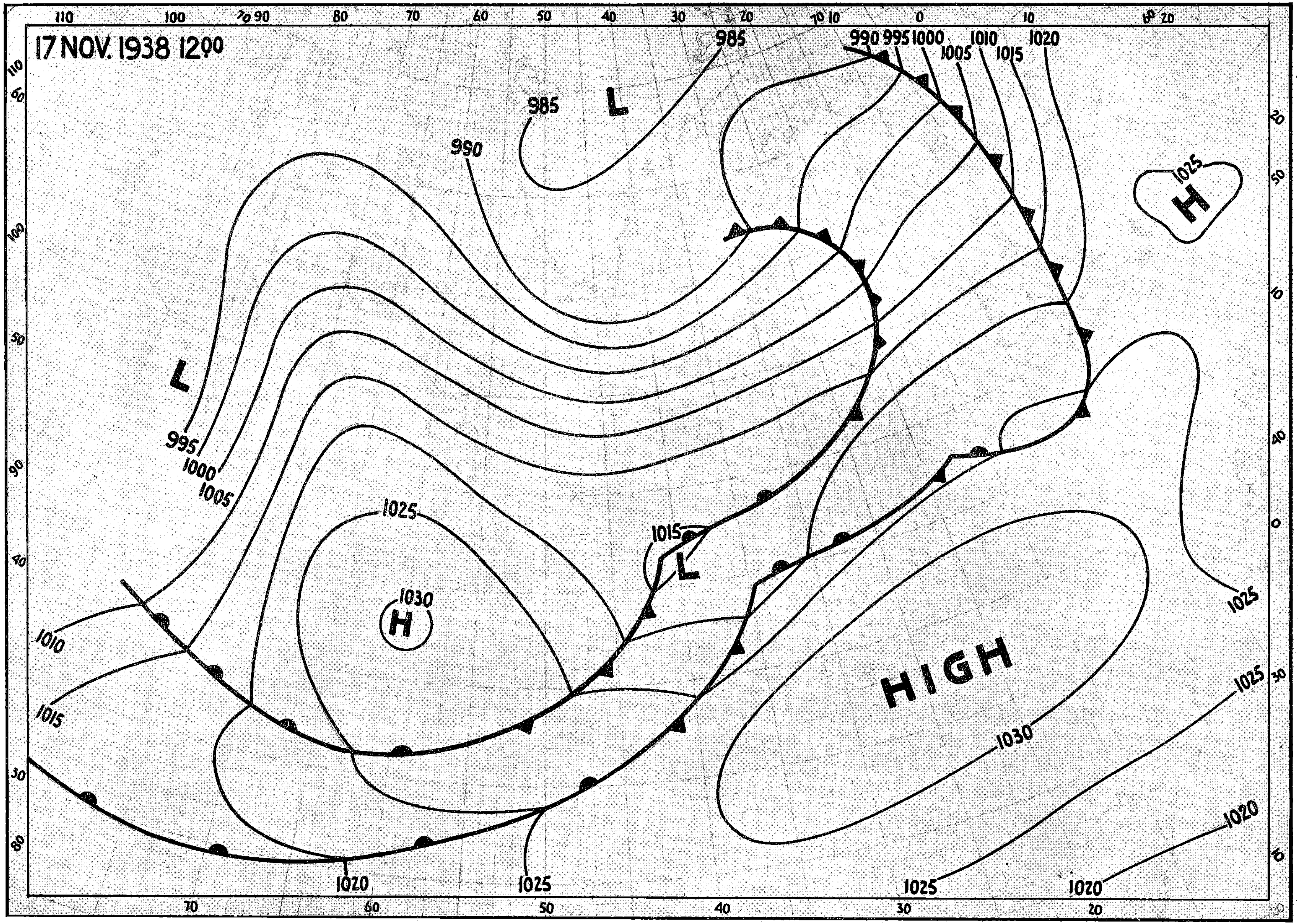


Fig. 29*d*. Re-analysed weather map of November 17th 1938, 0600 G.M.T.

Fig. 30*a*. Weather map of November 17th 1938, 1200 G.M.T.



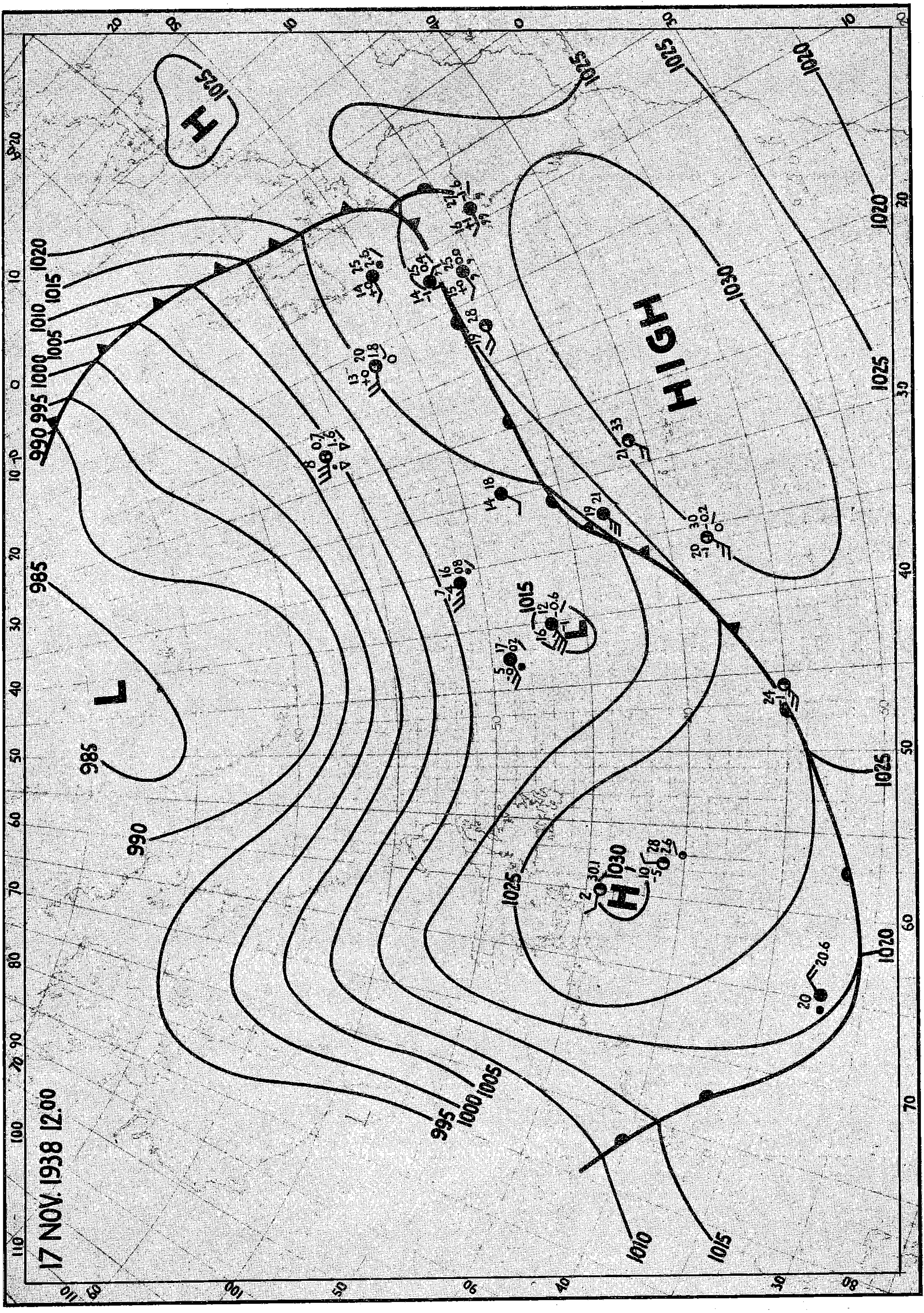


Fig. 30*b*. Re-analysed weather map of November 17th 1938, 1200 G.M.T.

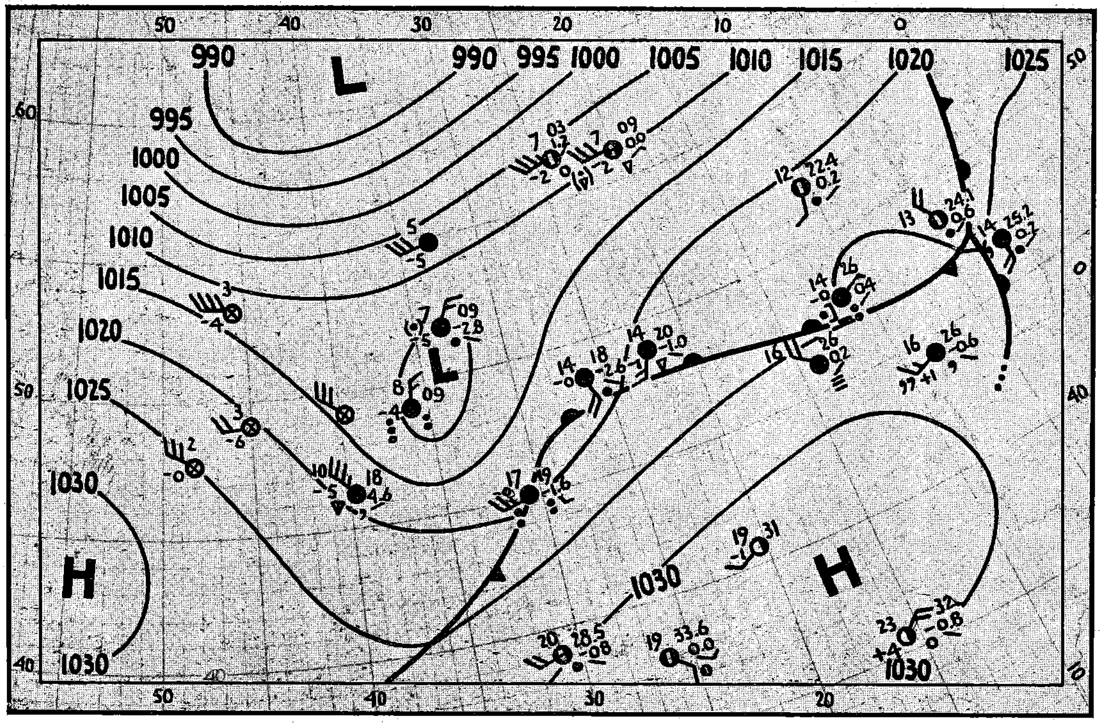


Fig. 30*c*. Re-analysed weather map of November 17th 1938, 1800 G.M.T.

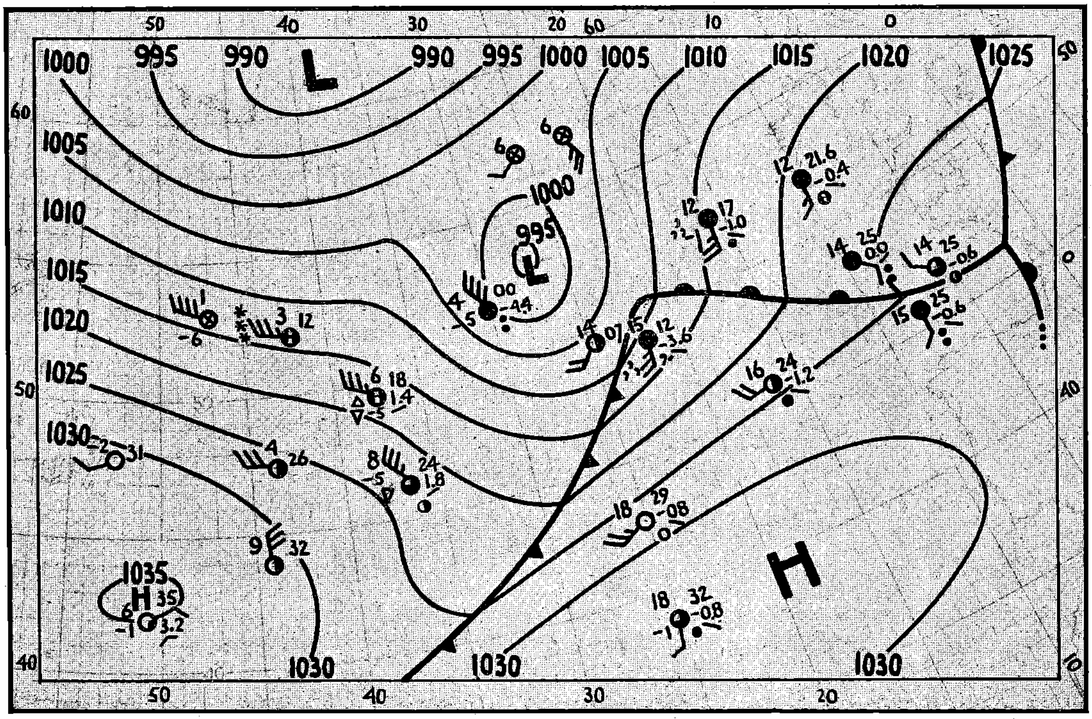


Fig. 30*d*. Re-analysed weather map of November 18th 1938, 0000 G.M.T.

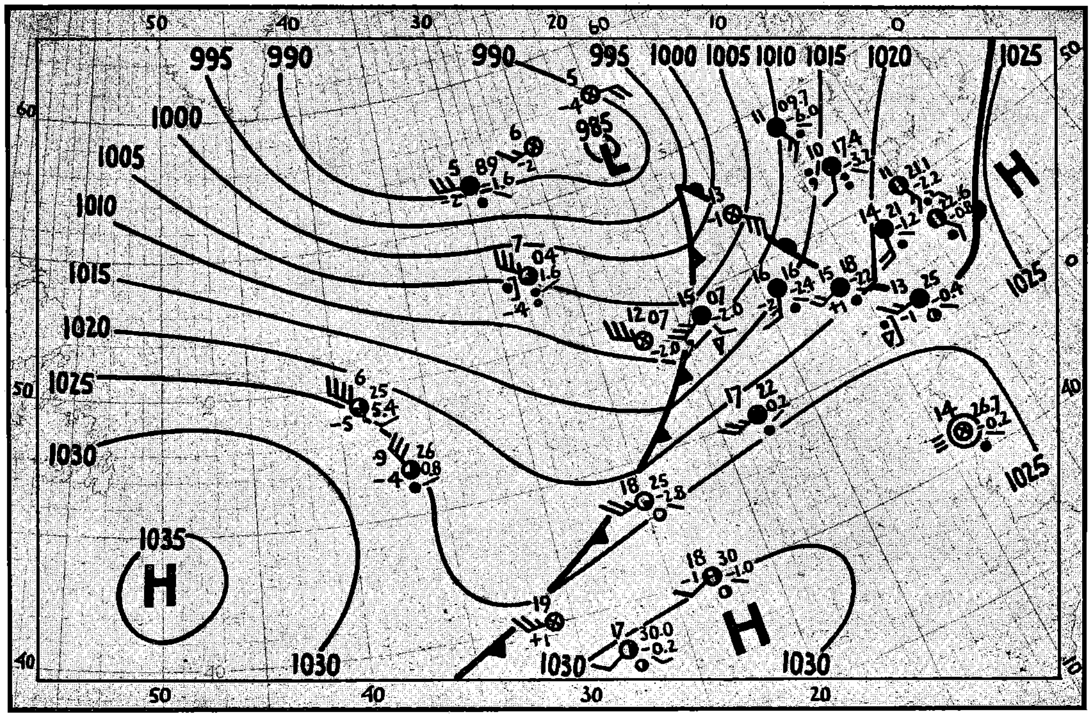
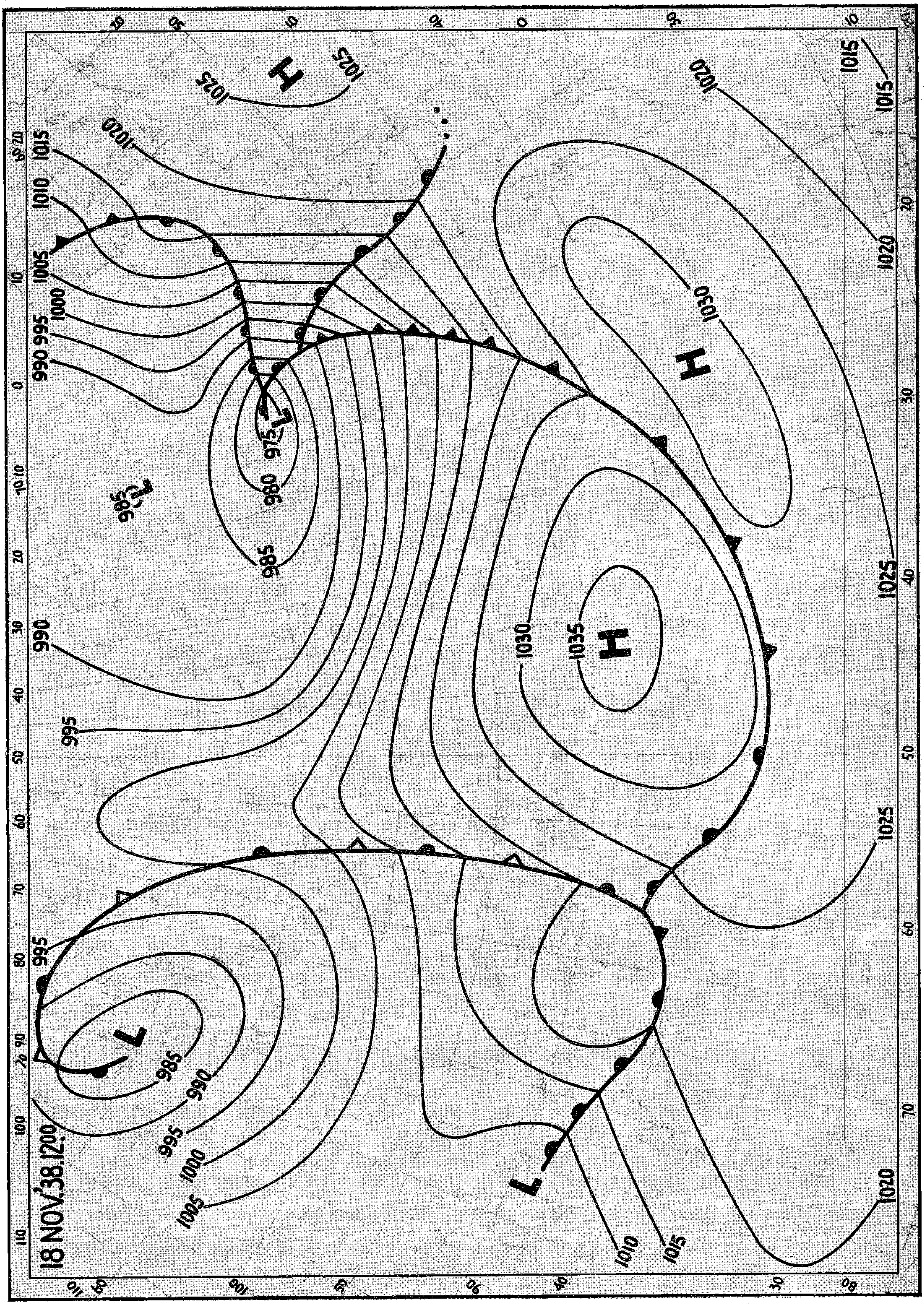


Fig. 30*e*. Re-analysed weather map of November 18th 1938, 0600 G.M.T.

Fig. 31*a*. Weather map of November 18th 1938, 1200 G.M.T.



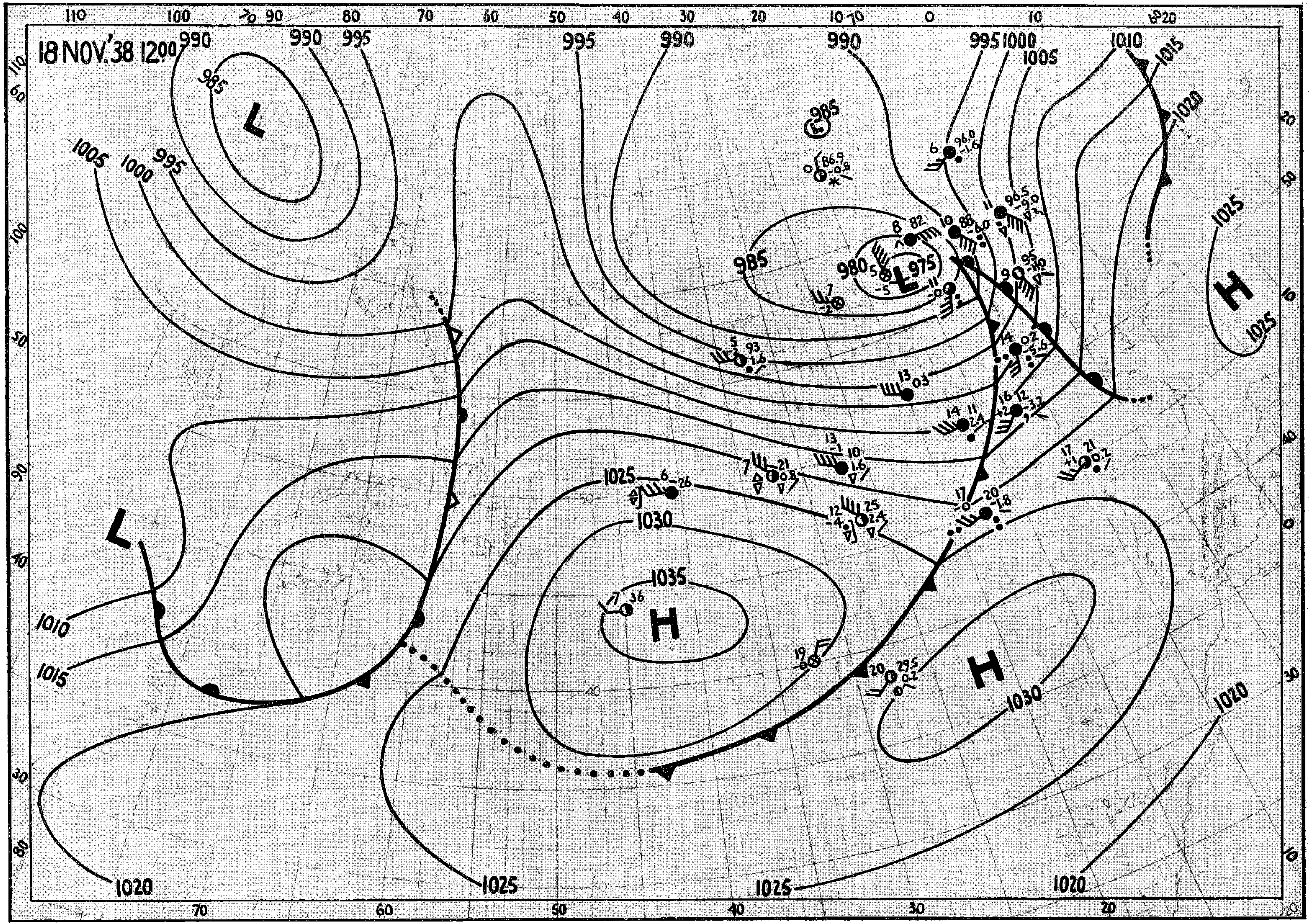
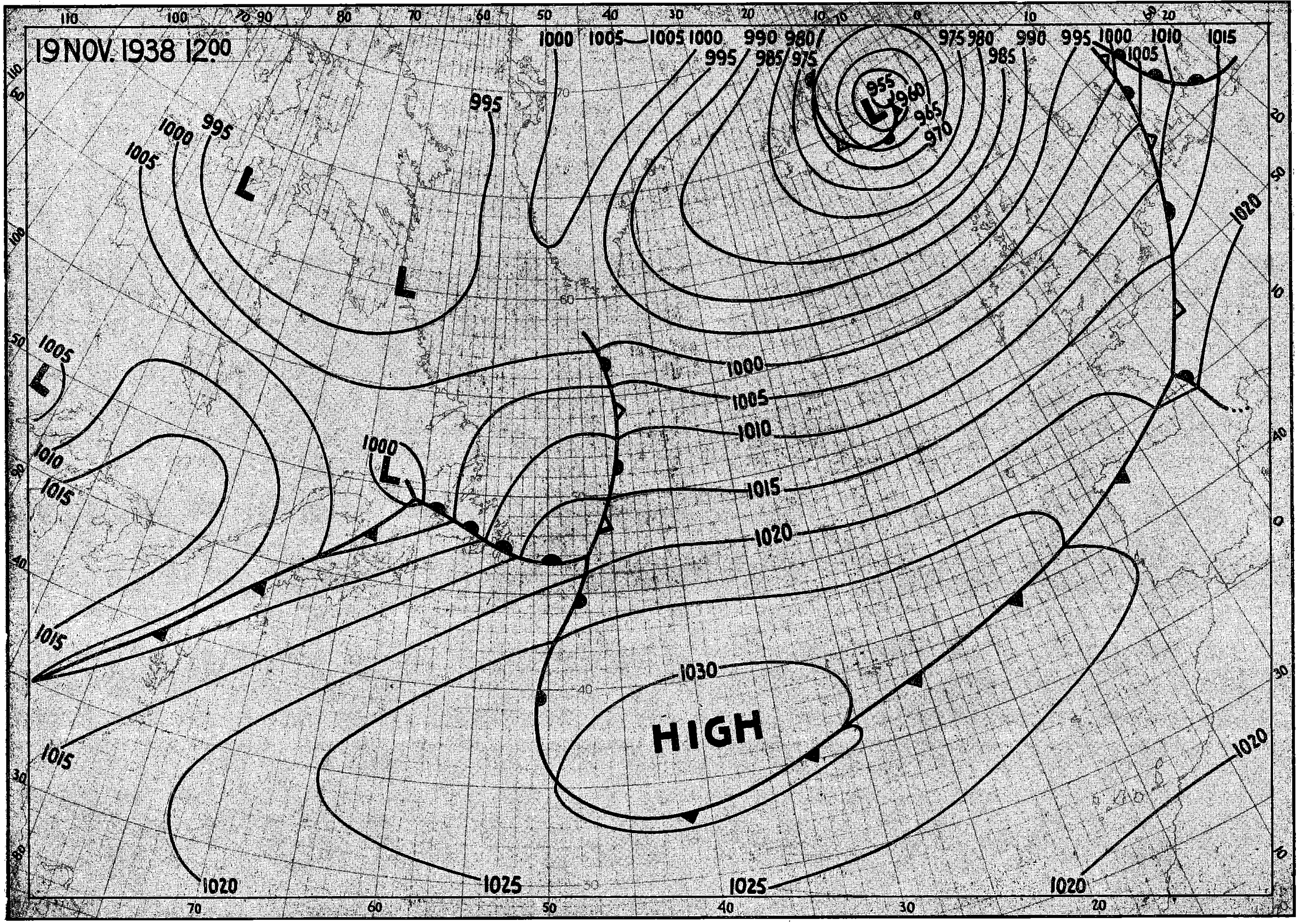


Fig. 31b. Re-analysed weather map of November 18th 1938, 1200 G.M.T.

Fig. 32*a*. Weather map of November 19th 1938, 1200 G.M.T.



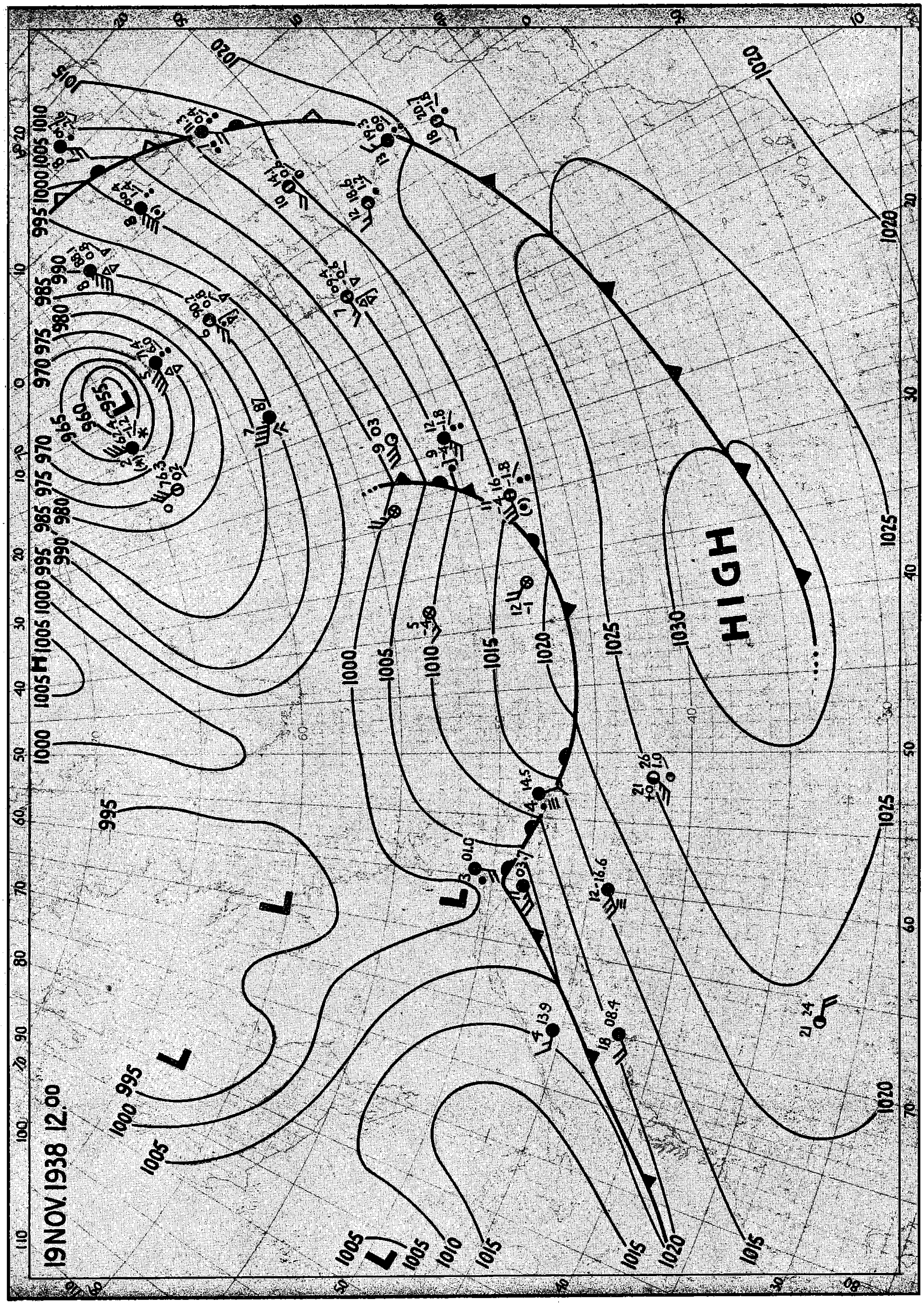


Fig. 32*b*. Re-analysed weather map of November 19th 1938, 1200 G.M.T.

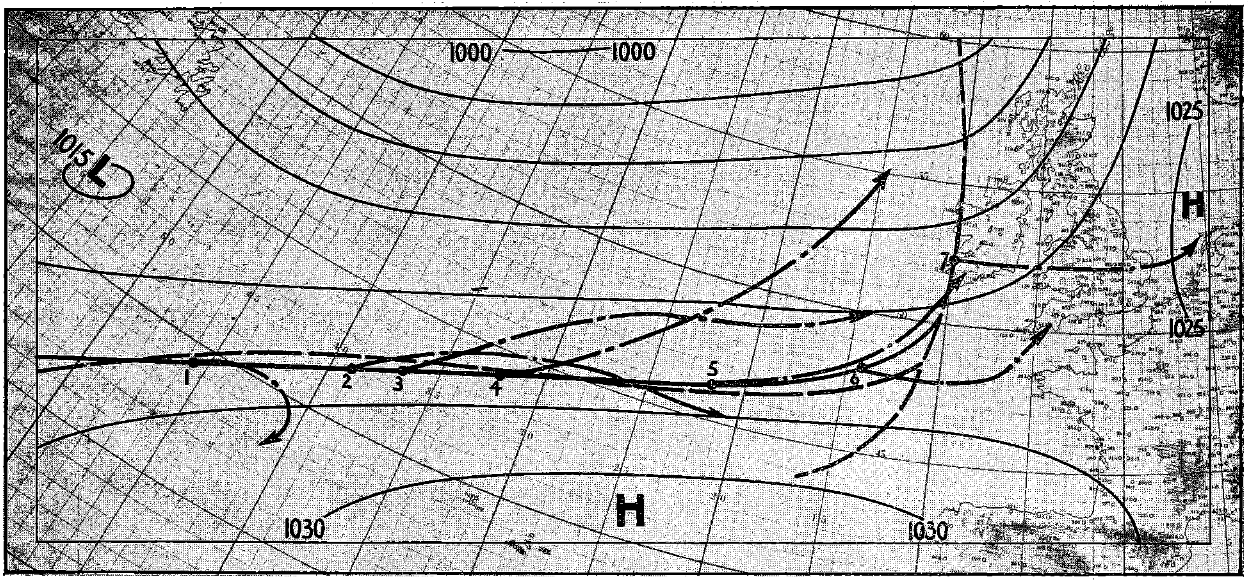


Fig. 33. Idealized weather map of November 17th 1938, 0000 G.M.T. showing the initial stage of the construction of the development of the „sweep" in the front.

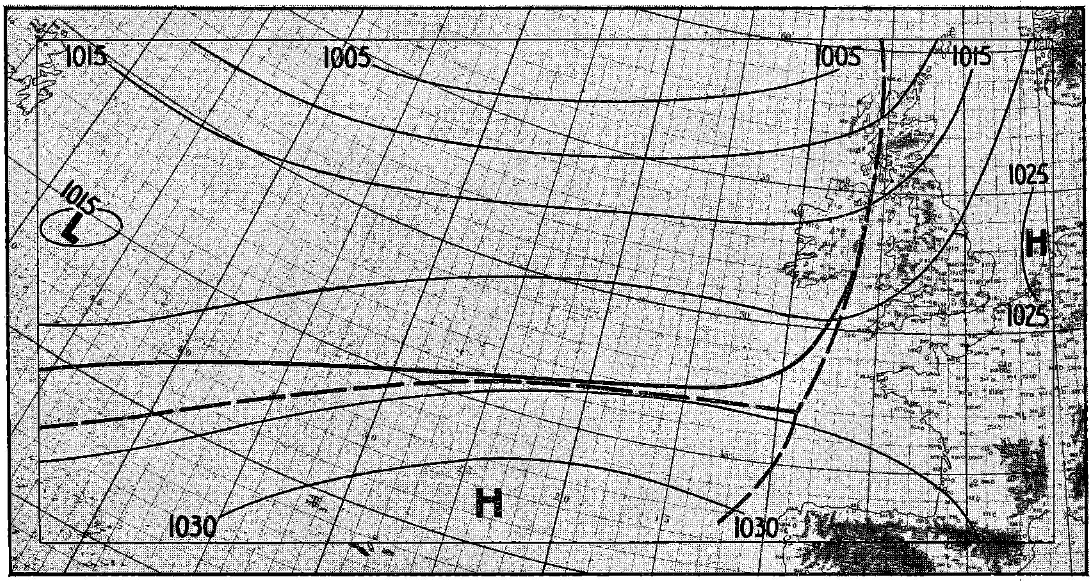


Fig. 34. The development of the sweep; positions on November 17th 1938, 0600 G.M.T.

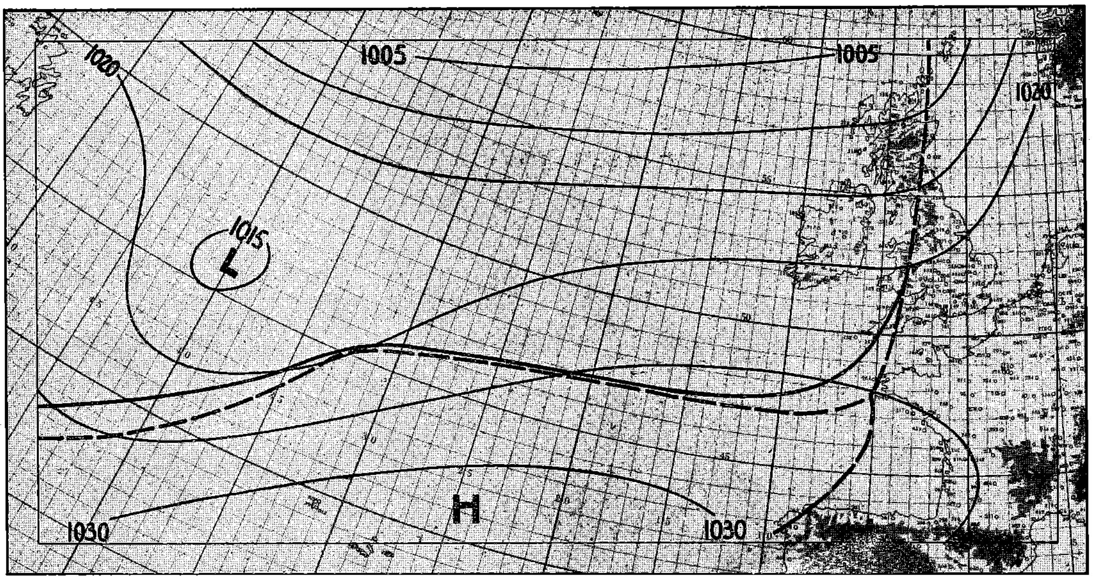


Fig. 35. The development of the sweep; positions on November 17th 1938, 1200 G.M.T.

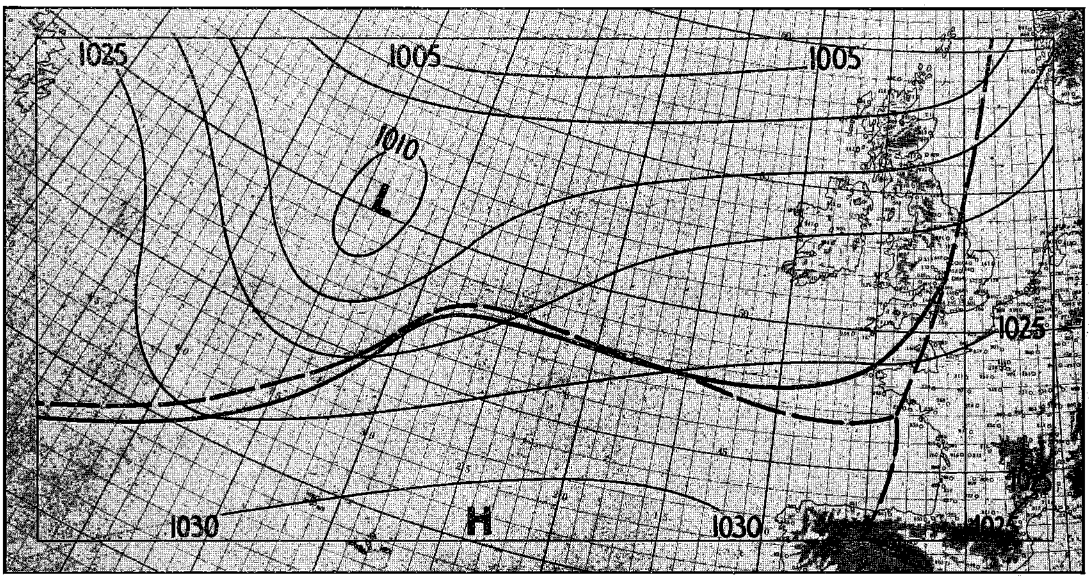


Fig. 36. The development of the sweep; positions on November 17th 1938, 1800 G.M.T.

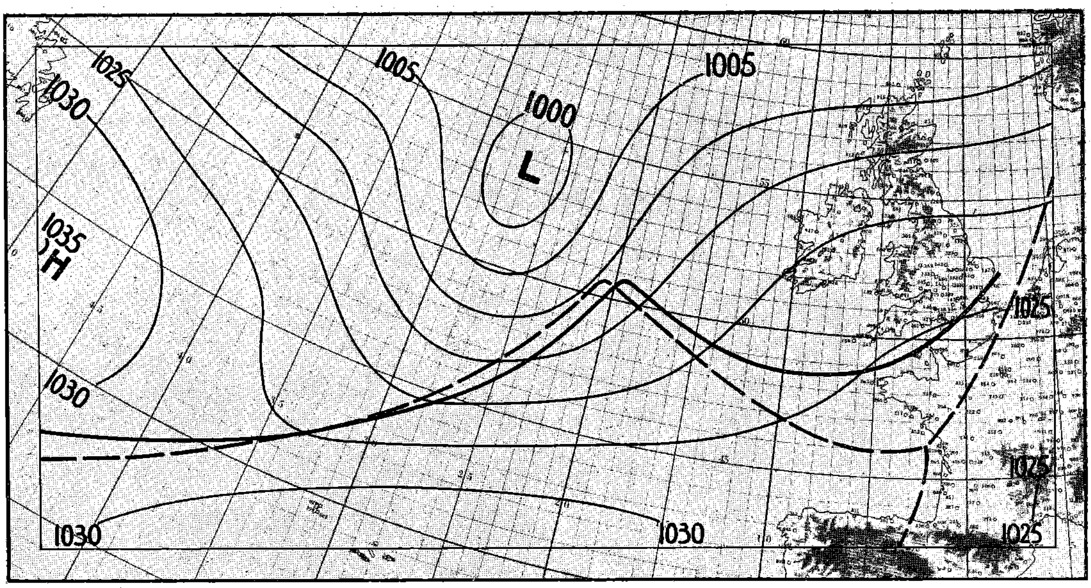


Fig. 37. The development of the sweep; positions on November 18th 1938, 0000 G.M.T.

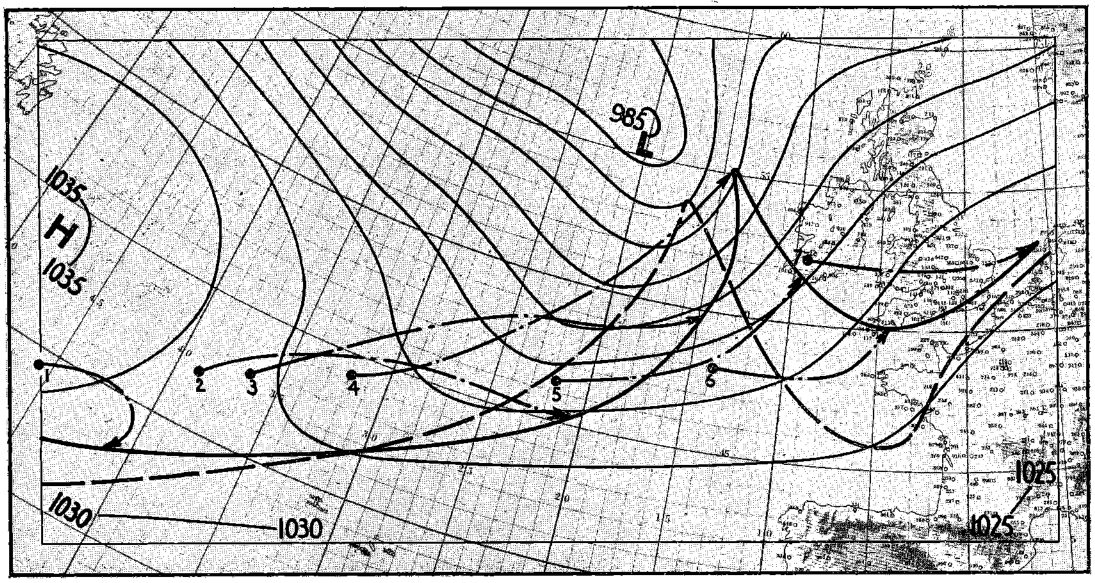


Fig. 38. The development of the sweep; positions on November 18th, 0600 G.M.T.

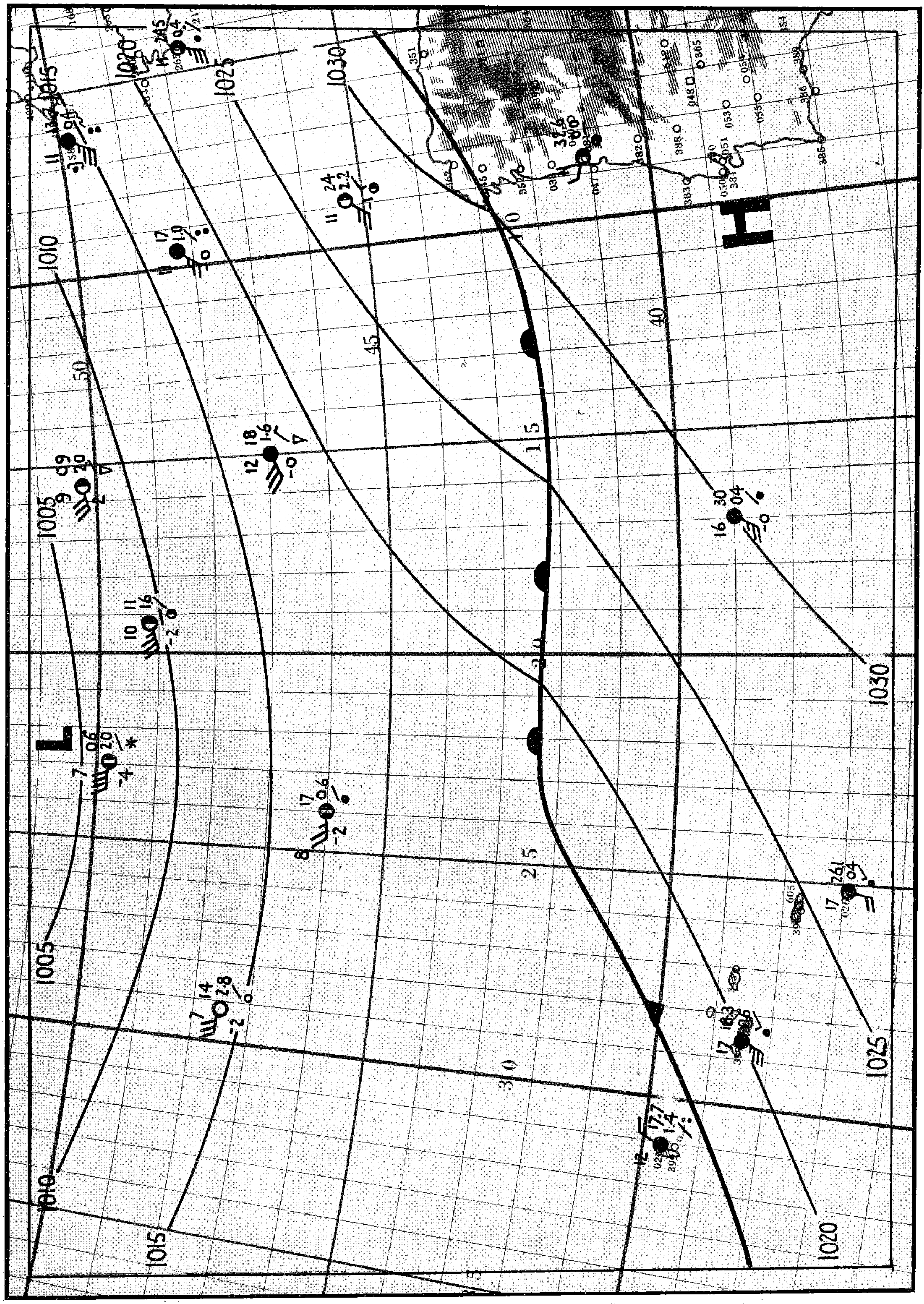
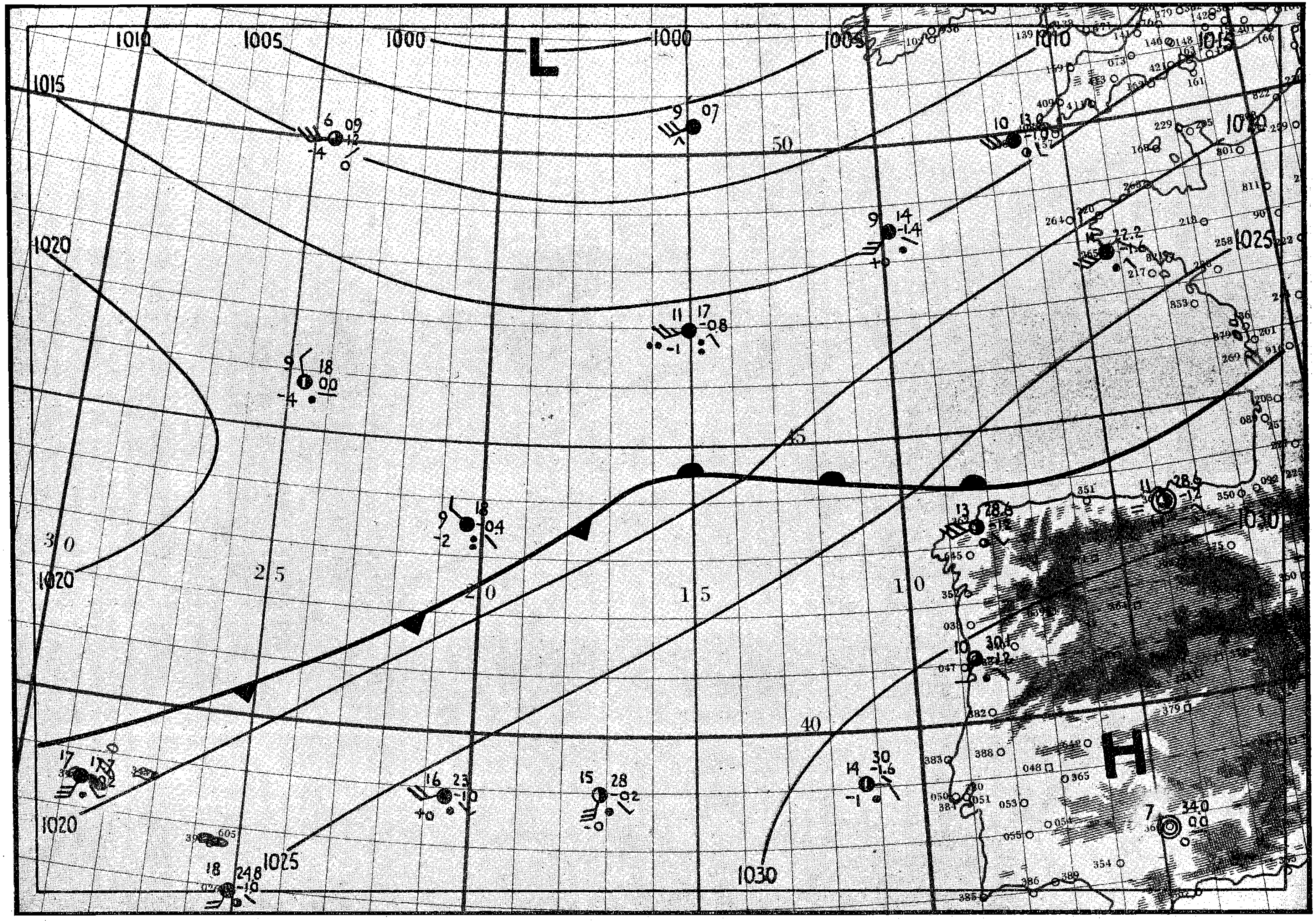


Fig. 39. Weather map of February 3rd 1948, 0000 G.M.T.

Fig. 40. Weather map of February 3rd 1948, 0600 G.M.T.



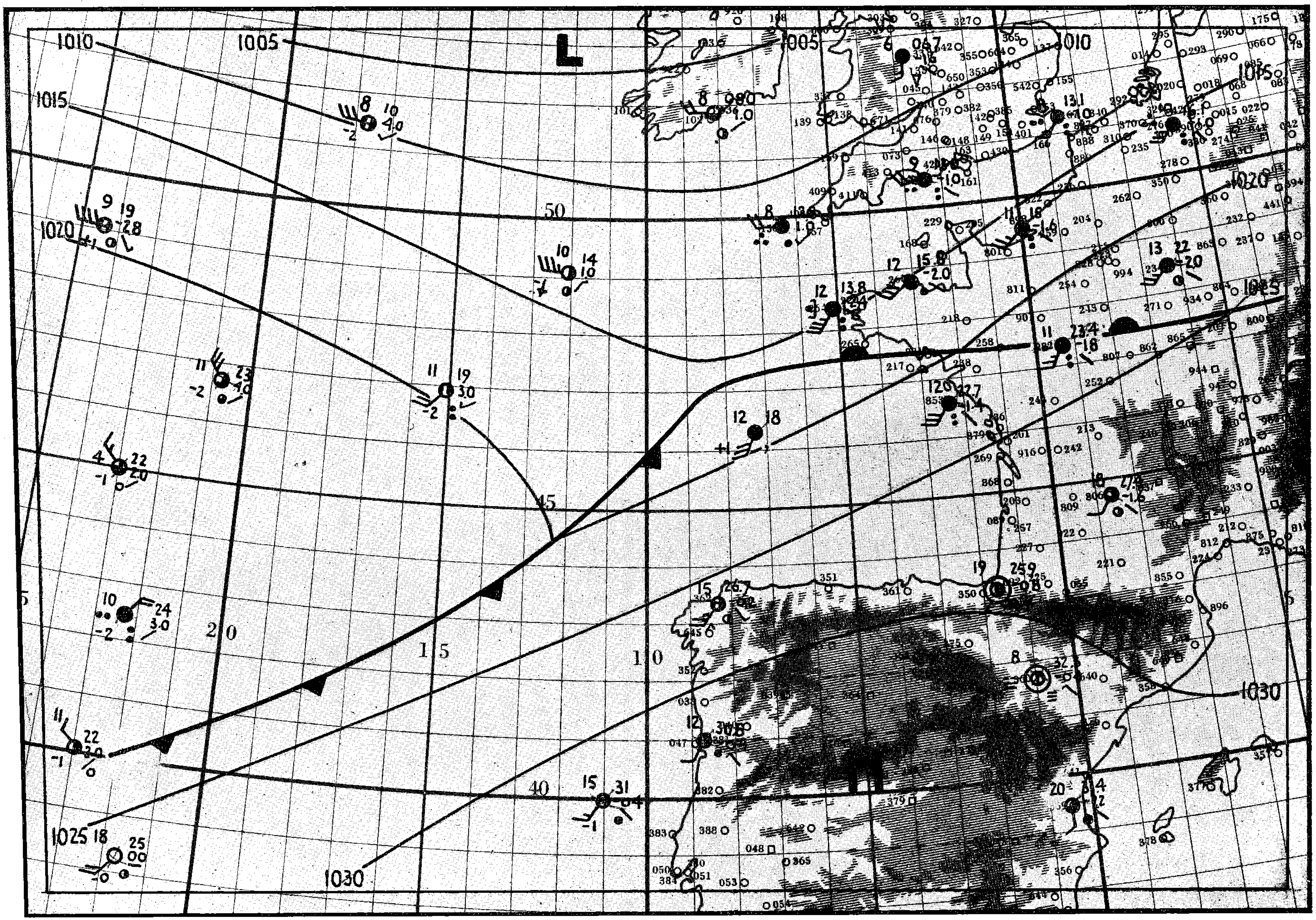


Fig. 41. Weather map of February 3rd 1948, 1200 G.M.T.

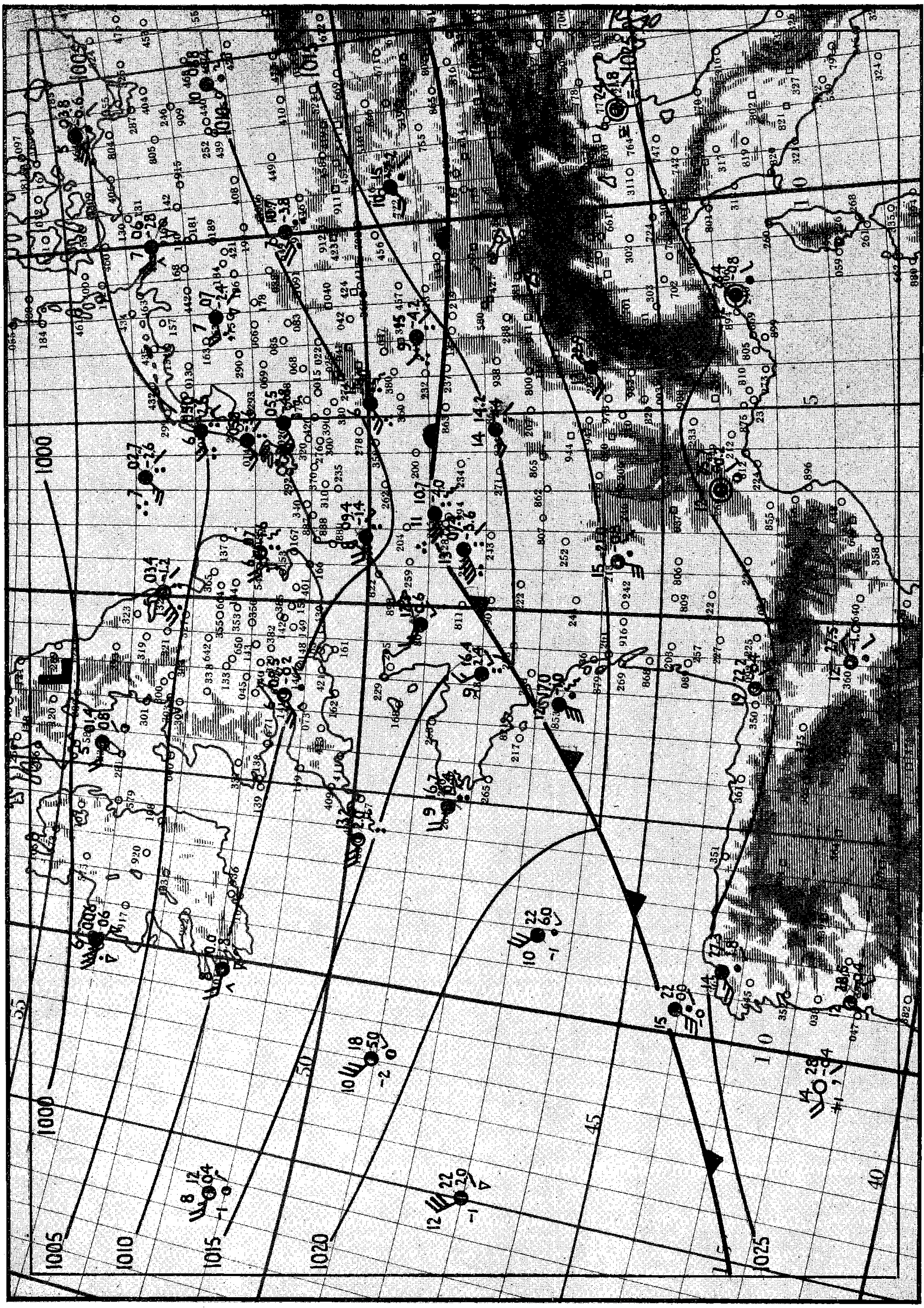


Fig. 42. Weather map of February 3rd 1948, 1800 G.M.T.

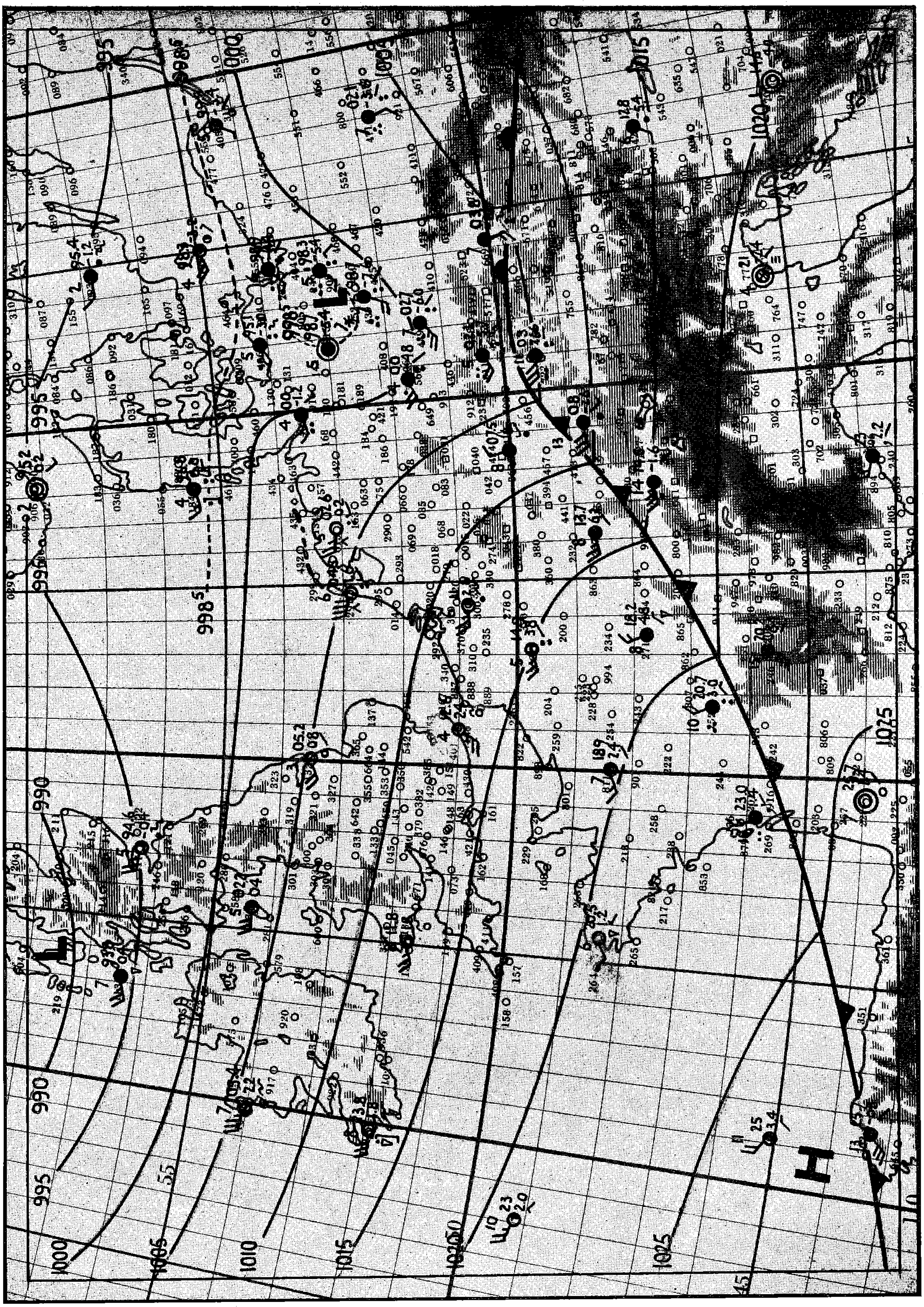


Fig. 43. Weather map of February 4th 1948, 0000 G.M.T.

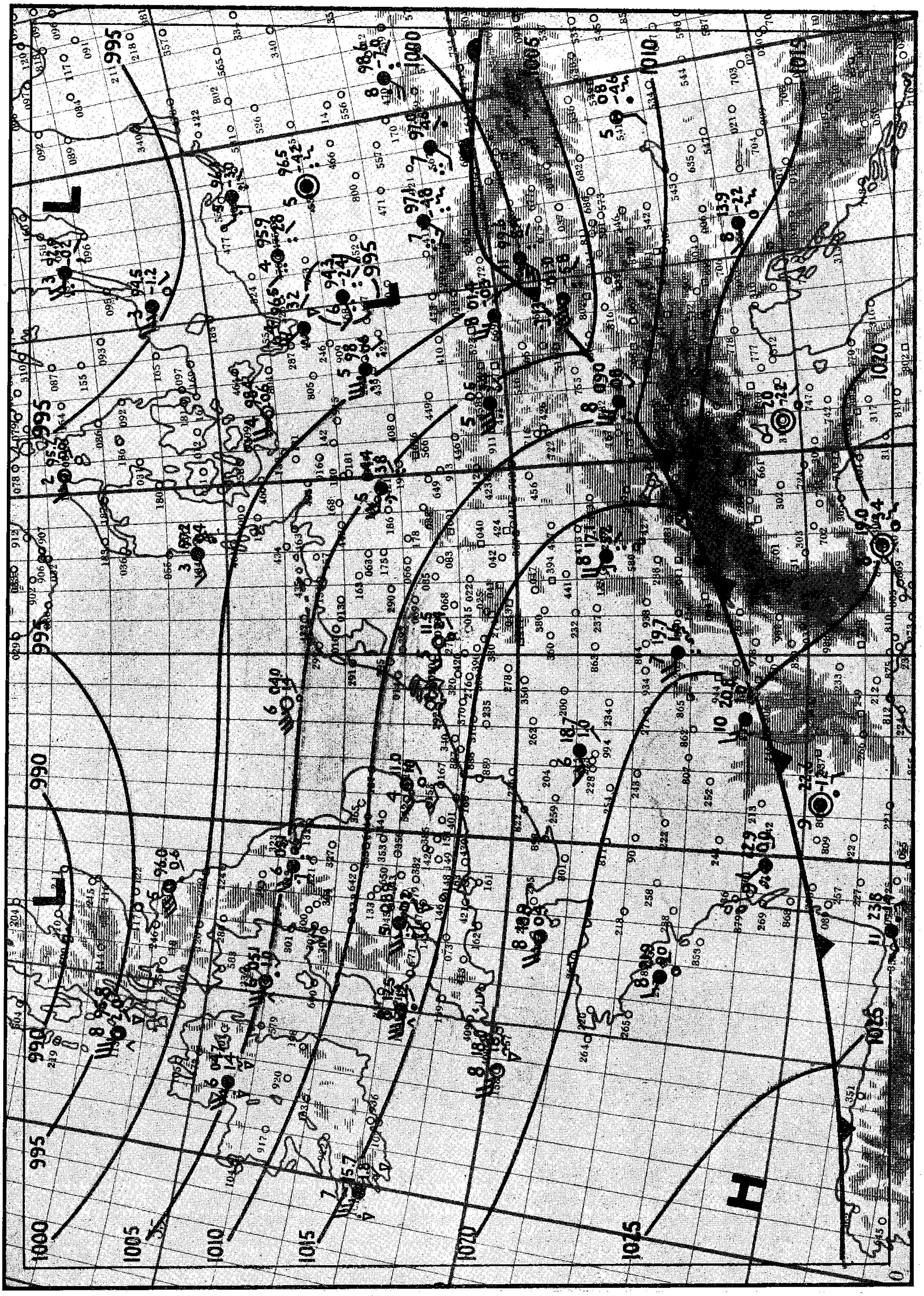


Fig. 44. Weather map of February 4th 1948, 0300 G.M.T.

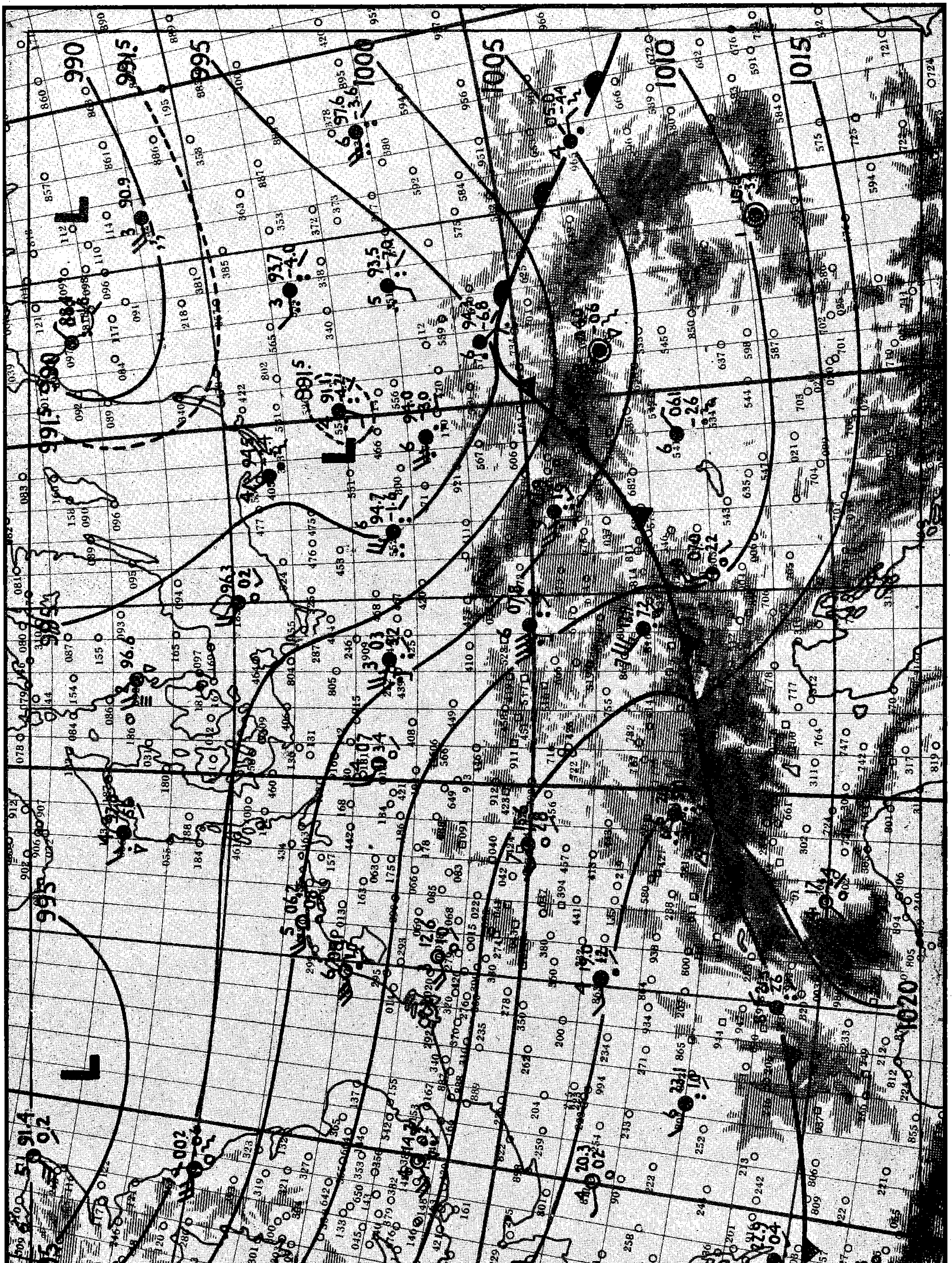


Fig. 45. Weather map of February 4th 1948, 0600 G.M.T.