

METEOROLOGICAL CONDITIONS FOR THE FORMATION OF RAIN.

BY

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The laws of physics show that clouds form when cooling of atmospheric air condensates the moisture content. Further physical investigations show that the condensed water drops fall out as rain as soon as they grow large enough to attain a falling velocity greater than the ascending velocity usually occurring in the clouds.

These physical results being given, the meteorological problem of rain formation is to determine the conditions under which larger air masses are cooled sufficiently to provoke condensation and rain. Cooling of atmospheric air may be caused by radiation, by contact with cold bodies or by mixing with colder air masses, further by adiabatic cooling due to expansion of the air. Considerations on the order of magnitude of these cooling influences in the atmosphere show that the last one, the adiabatic cooling by expansion, is the most effective cooling process at least for larger airmasses. Expansion of atmospheric air will again mainly be due to ascending motion, which rapidly brings the air from layers of high pressure to layers of lower pressure. Horizontal motion may certainly also bring air from high to low pressure, but the resulting expansion will be much smaller than that attained by vertical displacement. The effect of pressure changes in a horizontal current can thus only in exceptional cases cause rain.

The predominating influence of ascending air motion reduces the meteorological side of the problem of rain formation to the following principal one: What are the conditions for development of strong ascending motion? The solution of this problem gives the explanation for the cause of the greatest part of occurring rainfall. Others of the above mentioned cooling processes shall only be regarded in special cases.

An attempt will be made in this paper to classify all rain occurring in Norway according to the mode of formation, and to present some specimens illustrating the different types. The results set forth are based upon the detailed material of observations provided daily for the Norwegian Weather Service in the latest years. For the readers to whom topographical nomenclature and names of meteorological stations in Norway are not wellknown, a map with all local names occurring in this paper is given on Plate I.

The application of Norwegian material for the analysis of rainfall has advantages as well as disadvantages. The position of Norway, bordering as it does on the Atlantic Ocean, causes the frequent occurrence of rainfall, especially in autumn and winter seasons, from oceanic depressions. On the other hand, the Scandinavian peninsula is large enough considered as a »continent« to give conditions for the formation of continental summer rain. All seasonal rain-types of the temperate zones are thus represented in typical form offering a splendid opportunity for examination and study. A certain difficulty, however,

is encountered resulting from the influence of the Norwegian mountains on the phenomena of the free atmosphere. The influence of mountains on rain phenomena must therefore be closely examined before conclusions of general validity may be drawn from investigations carried out with Norwegian material. Correspondingly the pure influence of mountains on rain formation must, if possible, be examined in absence of all moving rain areas formed in the free atmosphere.

Rain Due to Ascension of Air Blowing against Mountains. Orographical Rain.

Figs. 1 a, b, c represent three successive weather maps in a situation, which may be expected to give rain due to air ascending upwards against the western slope of the

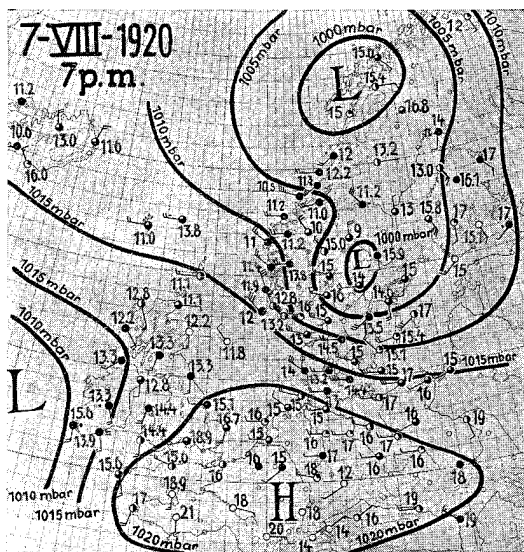


Fig. 1 a.

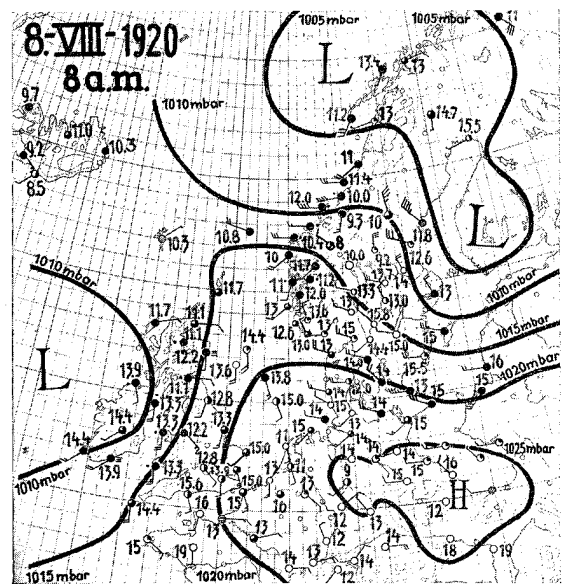


Fig. 1 b.

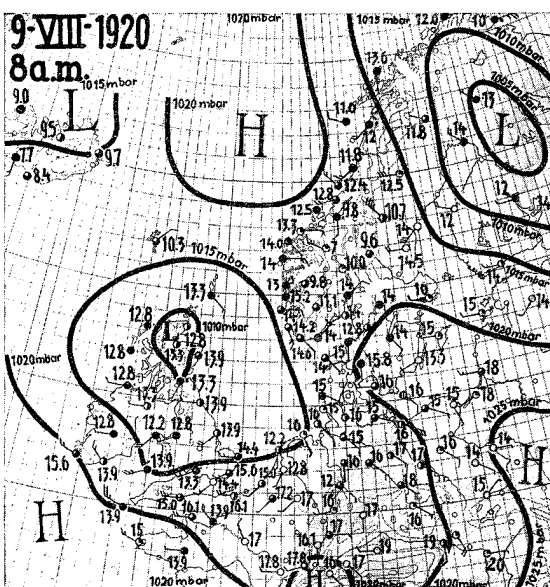


Fig. 1 c.

Norwegian mountains. In the evening of August 7, 1920, a North-Westerly to Westerly current was prevailing over the whole coast from the southernmost point up towards Lofoten. The next morning, the wind was backing on the southern part of the coast, but still persisting as a strong Westerly further north. The backing of the wind spread slowly northwards till the morning of the 9th, so that finally Westerly winds were blowing only along the coast north of Trondhjem. The rain due to the depression over Scotland until the morning of the 9th, had not yet reached the Norwegian coast.

Fig. 2 a gives a detailed map for the evening of the 7th. Among the stations introduced on this map, only some few make

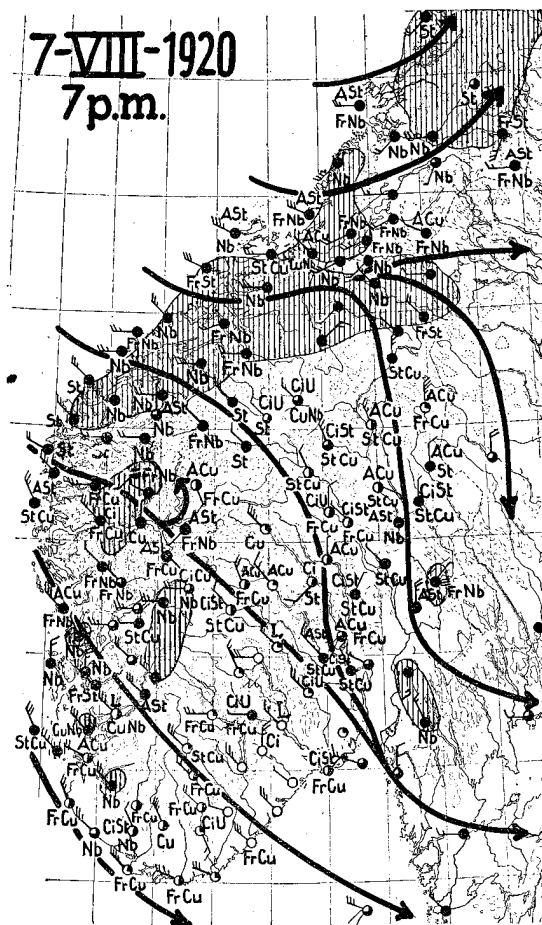


Fig. 2 a.

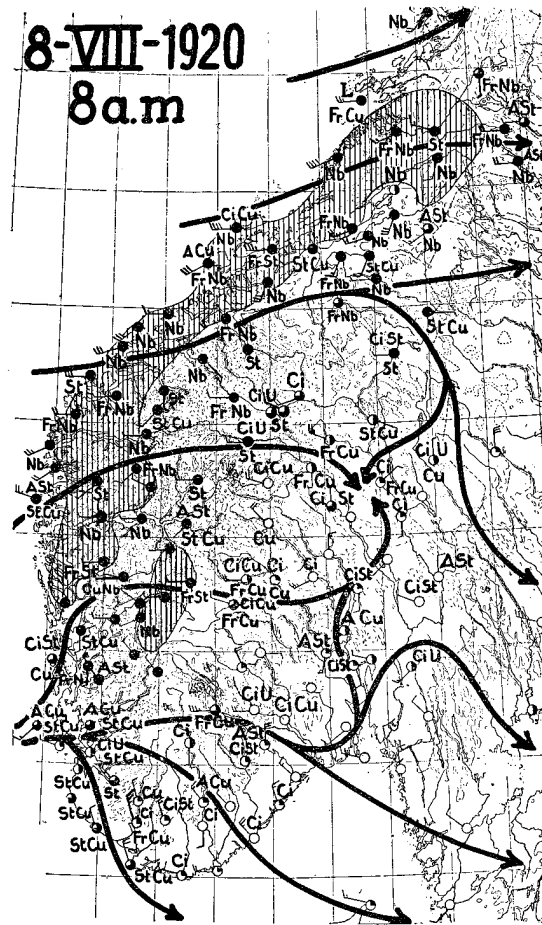


Fig. 2 b.

barometric readings. The isobars, which accordingly do not bring new details, are omitted. On the base of the numerous wind observations, lines of flow are drawn representing the instantaneous motion of the air along the ground. These lines of flow are of course not to be considered complete, as many wind observations are not reliable, and often locally influenced. The lines of flow are, however, rather useful as they facilitate the survey of a detailed meteorological map.

The shaded areas indicate where rain is falling at the time of observation. These areas do not cover perfectly the entire western slope of the mountains, several stations, especially on the coastal islands, not reporting rain. An overcast sky, however, prevails over nearly the whole western slope, whereas the eastern slope is marked by fine weather. In the south-eastern part of the country, near the Swedish frontier, some rain is again reported, being the last remainders of a secondary depression passing away over Sweden (see Fig. 1 a).

The morning of August 8 (Fig. 2 b) finds the secondary cyclone already far away, and it does not interfere with the characteristic weather-distribution of the Westerly type, — overcast and rainy on the western, and fair weather on the eastern slope of mountains.

Fig. 3 gives a representation of the amounts of rainfall during the night of the 7th to the 8th of August.

As only rather few stations measure precipitation three times a day, this map over the 13*) hours night rainfall cannot give many details. Isohyets for 5 and 10 mm

*) From 7 p. m. to 8 a. m.

are sketched on the base of available measurements. The outer limit of the whole area where rain has fallen (the isohyet 0), is, however, determined from the weather-characteristic at about 400 rainfall stations.

Aside from the last scattered showers due to the cyclone in Sweden, rainfall has occurred in Norway only on the western slope of the mountains. At some places, the rain has reached the highest ridge, and some slight showers have even passed it. At other places, however, it has not been able to penetrate so far. This is especially striking in the innermost part of the Sognefjord districts, where a big area to the west of the highest ridge has escaped from rainfall all the night. The explanation of this phenomenon lies

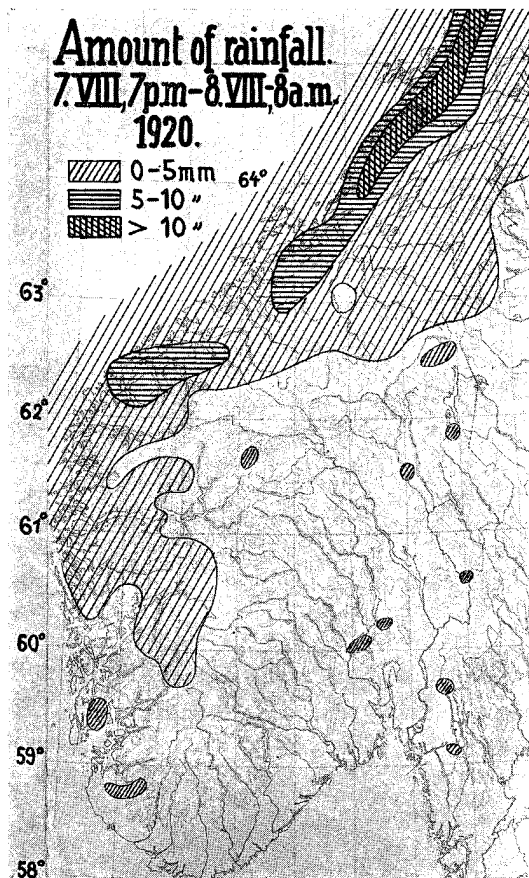


Fig. 3.

difference is due to rain drifting in the Westerly current over the sea independently of all orographic influences. In the actual case, this assumption may be directly proved. The steamer »Ranenfjord« reports rain showers between 3 and 5 o'clock in the night, at a time when it was situated about half-way between the Farøe Islands and Norway. On the Shetland Islands (Lerwick), however, no rain has occurred. The Westerly current has thus conveyed showers to the northern part of the Norwegian coast and not to the southern part. Only as regards the section south of the 61st parallel, we may assume that the rainfall has been of exclusively orographical origin. This difference has apparently influenced the amounts of rainfall; on the northern part of the coast, amounts up to 14,5 mm. have occurred, to the south of the 61st parallel, the biggest amount is only 2,0 mm.

Fig. 4 gives a representation of the precipitation which had fallen during the following 24 hours, August 8, 8 a. m. to August 9, 8 a. m. The entire eastern slope of the mountains has been perfectly free from rain. The distribution of rainfall on the

certainly in the influence of the big glacier Jostedalsbræen on the air current passing it. Jostedalsbræen forms a ridge, about 1800 m. high, just across the way of the North-West current. The air ascending upwards over the glacier will not only be cooled adiabatically, but also by direct contact with the ice and snow masses, whereby much of its moisture will condensate as rain or dew on the glacier and adjacent regions. Arriving further in to the lee of the glacier, the air is unable to give any more rain, even when it ascends towards the water-shed between western and eastern Norway.

The greatest amounts of rainfall are recorded along a stripe about 30 kilometres from the coast, decreasing landwards as well as towards the sea. This distribution of rainfall is a general feature reproducing itself so often, that it even appears on the maps of annual rainfall, the maximum amounts of rainfall being found there, arranged along a narrow zone 30 or 40 km. from the sea.

To the north of the latitude 61°, all rain-gauges, even on the outmost islands, have recorded precipitation, to the south of it, however, a coastal stripe has escaped rainfall. We are inclined to believe that this

western slope is nearly the same as in the previous 13 hours period. As the wind has backed during the period, relatively smaller amounts of precipitation have fallen, especially in the southern part where the backing began earlier than further north. The great number of stations allow us in this case to draw isohyets with more detail than in the 13 hours period. Among the numerous interesting details of local importance, we will only emphasize the characteristic shape of the zone of maximum precipitation in the northern part of the map. Just at the mouth of the Trondhjemsfjord, the zone of high amounts of rainfall is interrupted, and the highest amounts are to be found further inland. Apparently, the air has been able to enter horizontally along the Trondhjemsfjord and starts its ascending motion first at the eastern end of the fjord. Similar effects may often be observed in other fjords of sufficient dimensions. Even the maps of annual rainfall are influenced in this way, that the maximum zone is less accentuated in the bigger fjords.

Also in the 24 hours period, a coastal stripe has escaped from rain, this time nearly up to the latitude 62° . Only to the south of this parallel, we may thus with certainty classify the rainfall as pure orographical rain. The highest amount in this region is 4.9 mm.

As a general experience from orographical rain in western Norway in the years 1918 to 1921, we may give the following rough values. Pure orographical rain in western Norway seldom exceeds 5 mm. in 24 hours, even in the zone of maximum amounts. A Westerly current containing showers also over the sea may, however, in the same zone cause rain up to 30 mm. in 24 hours. The difference of amounts is thus much greater than the amount of precipitation given by the showers on sea or even on the coastal islands.

There are two essential causes for this effect.

1) The showers will retard their motion passing over the obstacles at the coast, and further inland move with smaller velocity or even stop. A series of showers moving with great mutual distances over the sea will thus give showers over land of longer duration, or even continuous rain. The amount of precipitation from each shower will of course be higher where they move slowly, and thus the showers may add to the orographic precipitation more than they can give alone on the sea, provided that they have not meanwhile decreased considerably in intensity. The zone of maximum amounts of precipitation is just a place where showers by topographical reasons are forced to move slowly and still have not decreased in intensity. Beyond this region, the intensity of the rain decreases, probably as the air has lost too much moisture in the zone of maximum precipitation.

2) Stable and unstable air currents will behave differently, when they shall pass a mountain range. Air masses of a stable current being forced to ascend against the moun-

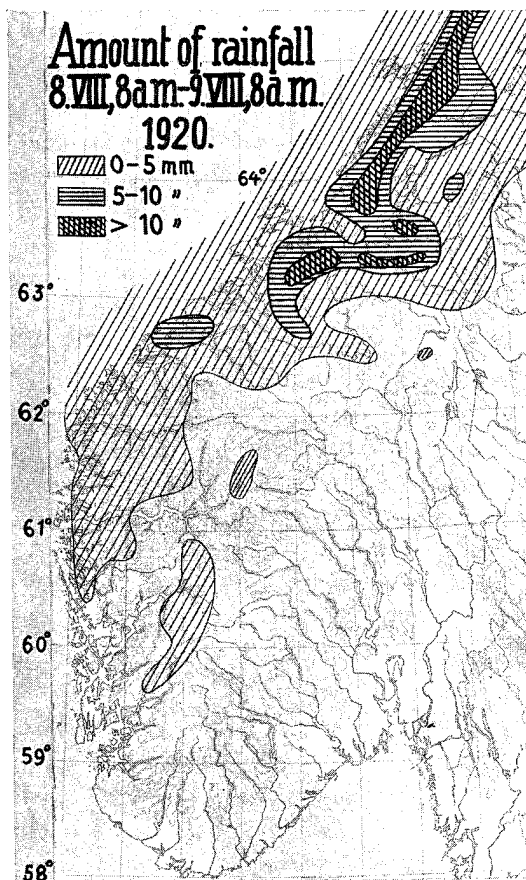


Fig. 4.

tains, will become colder and thus heavier than the surrounding air at the same level, and will resist further vertical displacement. In unstable currents, the opposite will be the case; ascending air masses will become lighter than the surrounding air, and will favour the initiated motion. Accordingly, a stable air current will as far as possible avoid the vertical motion due to the traversing of mountains by curving round the obstacle horizontally, whereas an unstable current will pass more directly across it. The amount of orographical precipitation will of course be greater in the latter case, when an unstable current passes directly across the mountains.

The unstable currents will mainly be those which originate from cold regions and afterwards are warmed from below. Thereby the thermal stratification may easily become unstable, and strong local ascending and descending currents will start. Over the ascending currents cumulo-nimbus clouds form, giving showers, which, according to their formation, may be called instability showers.

In all seasons Northerly currents are most likely to get unstable stratification, as they bring air from colder to warmer parts of the earth. Unstable air currents may, however, arrive from any direction, even from the south; but they are then always branches of originally cold currents following curved tracks.*)

Instability showers form over the continents almost exclusively in the warm part of the year, when the strong insolation renders much heat to the layers nearest the ground. (Continental summer rain, see page 38). Instability showers formed over the sea are experienced in all seasons, but most frequently and typically in winter, when the temperature difference sea \div air has its greatest value. This sort of showers often reach stations near the coast when the wind blows from sea to land, i. e., in situations when also orographical rain may be expected to form. These circumstances have often led to the erroneous conclusion that instability showers should be an effect of orographical conditions. The fact that instability showers occur over the entire sea proves, however, that their formation is perfectly independent of orographical conditions.

In our case, the northern part of the Westerly current is originating from regions of ice or cold water to the north of Iceland, and arrives afterwards over the warmer water of the Gulfstream region. The produced instability is probably the cause of the showers reported from the ship »Ranenfjord«. The instability of the air may have facilitated the traversing of the mountain range, and has, together with the corresponding instability showers, shared in the abundant precipitation on the northern part of the Norwegian coast, whereas the southern part of it only has had pure orographical rain.

Air currents originating from warmer parts of the earth will be cooled from below when they reach colder regions. Thereby their thermal stratification will become stable and there will be no tendency to the formation of showers. In such currents, however, the cooling of lower layers by the ground may lead to condensation which creates fog or even slight drizzle. Such phenomena often occur in winter, for instance, when warm and moist SW currents pass over the relatively cold water in the Skagerak. The precipitation from the fog-drizzle will under circumstances also be added to that of the pure orographical rain, but will by far not influence so much the amounts as the instability showers do.

As a rule, most air currents are stable, at least in the mean for thicker layers, and it will therefore be a very common thing to observe currents curving round the mountains in order to avoid vertical displacement. The orographical rainfall in such cases is usually rather small, often only a slight drizzle. Specimens of stable currents dividing and curving round obstacles occur, for instance, on the maps Figs. 28, 29 and 42, 45, pp. 42—44 and 56—59.

Corresponding to the tendency of stable air currents to curve round obstacles, strong winds will blow round the terminus of the mountain range, and it seems even as if the

*) C. K. M. Douglas: »Temperature Variations in the Lowest Four Kilometres«, London, Q. J. R. Meteor. Soc., Vol. 47, 1921.

convergence of air passing round the corner itself, must lead to a sort of orographical precipitation. This effect has especially been observed in easterly currents passing round the southern corner of Norway, giving there strong local gales often accompanied by slight rain or snowfall without any relation to cyclones or their secondaries. Also in South-Westerly currents round the mountainous north-western corner Statt, similar formations of rain have been observed.

Also other sorts of orographical rain formation may under special circumstances come into consideration.

An air current passing from the sea to a flat country, will not directly be forced to ascend enough to produce condensation and precipitation, but the greater friction over land relative to that over sea will retard the lower parts of the current so that following air masses must climb the retarded ones. This ascension might be expected to cause a sort of orographical rain.

We have examined several situations of that kind, especially on the flat countries Denmark and southern Sweden, but have not found a single case of rainfall merely due to retardation of air currents by friction. This result could also be anticipated, as the influence of friction from the ground does not usually reach higher than about 500 metres, and its effects thus may already be compensated at the level of condensation. It seems, however, as if passing rain or showers give greater amounts of precipitation where the influence of friction co-operates with other influences in causing ascending motion. Otherwise the local maxima of annual precipitation on slowly inclined slopes in generally flat country could not be explained. (For instance on the Danish and Swedish western coasts).

Embodying the results concerning orographical precipitation in Scandinavia, it may be said that *pure orographical rain, which necessarily forms as well in stable as in unstable currents, occurs only in connection with mountains at least 1000 metres high. Showers due to instability may in particular cases add considerable amounts to that of the pure orographical rain and make even orographical rain possible in connection with smaller obstacles. The effects of orographical rain are strongly restricted by the tendency of all stable air currents to curve round the mountains horizontally.* This effect makes also orographical rain occur only in situations where the air currents have sufficient energy to render the work implied with the traversing of mountains, thus especially in periods with brisk activity of cyclones. Therefore also the greater part of the orographical rain will occur simultaneously with rainfall of other origin. The resulting combined cyclonic and orographical rain, which will be treated further on (see pages 17, 21 and 34), causes much more abundant rain than the simple orographical rain in homogeneous currents.

Conditions for Rain-giving Ascending Motion in the Free Atmosphere.

The places where strong ascending motion occurs in the lower parts of the free atmosphere (without influence of mountains) will be characterized by vectorial convergence of surface winds. It is a general experience from investigations with a close network of stations, that regions of strong convergence are arranged along narrow stripes corresponding to lines of convergence in the field of horizontal motion. The simplest form of a line of convergence is that of Fig. 5 a*), where lines of flow pass symmetrically from both sides towards a central line of flow. This type which is a rather special one does not often occur in nature. A more general line of convergence is obtained when a vector field of constant translation (Fig. 5 b) is added to the field of a symmetrical line of convergence (Fig. 5 a), resulting in a field of flow of the type represented by Fig. 5 c. The former line of convergence is drawn as a dotted line and is no longer a line of flow; it is only a line through the places having wind-shift just at the time to which the map in question

*) Treated in V. Bjerknes: Dynamical Meteorology and Hydrography. Part II. Kinematics. Section 37.

refers. It thus corresponds simply to a more or less accentuated trough-line in the field of pressure.

The new shape of the wind field implies, however, no change in the field of vertical motion. This field being constructed by aid of the equation of continuity will be just the same for Fig. 5 a and Fig. 5 c, in both cases showing a narrow belt of rapidly ascending motion along the line of convergence (Fig. 5 a), respectively the wind-shift line (Fig. 5 c).

The ascending motion at the wind-shift lines is much greater than that occurring in simple homogeneous currents without discontinuous changes of wind direction and velocity.

Very often a wind-shift line coincides with a boundary line between warm and cold air, marking the front of an invasion of a new air mass. Such discontinuities of temperature will originally appear where air masses from warm and cold regions are brought together, and may then on account of the slowness of mixing processes persist for days or weeks. The most striking discontinuities of temperature are found when the two air masses flow in opposite directions parallel to their mutual boundary (V-shaped trough). Then the two air masses have just up to date had perfectly different »life histories«, which have resulted in very different temperatures. When the air, however, flows in nearly the same direction on both sides of the boundary (slight sinuosity in isobars), the life histories of the two air masses have in the last stage been rather similar. Then also the external thermal influences have had time to smoothen the originally existing differences of temperature. We use in this paper the word boundary line also in cases when smoothing effects have made it more diffuse. The evidence for the existence of such boundaries is usually derived from observations of the same boundary in earlier, more distinct state.

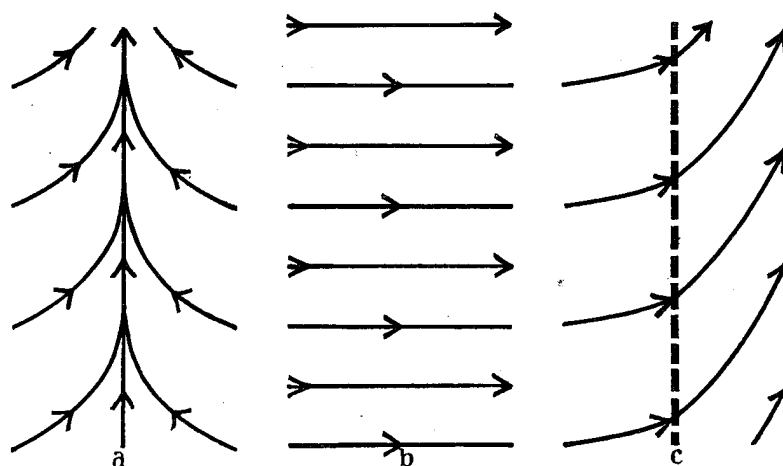


Fig. 5.

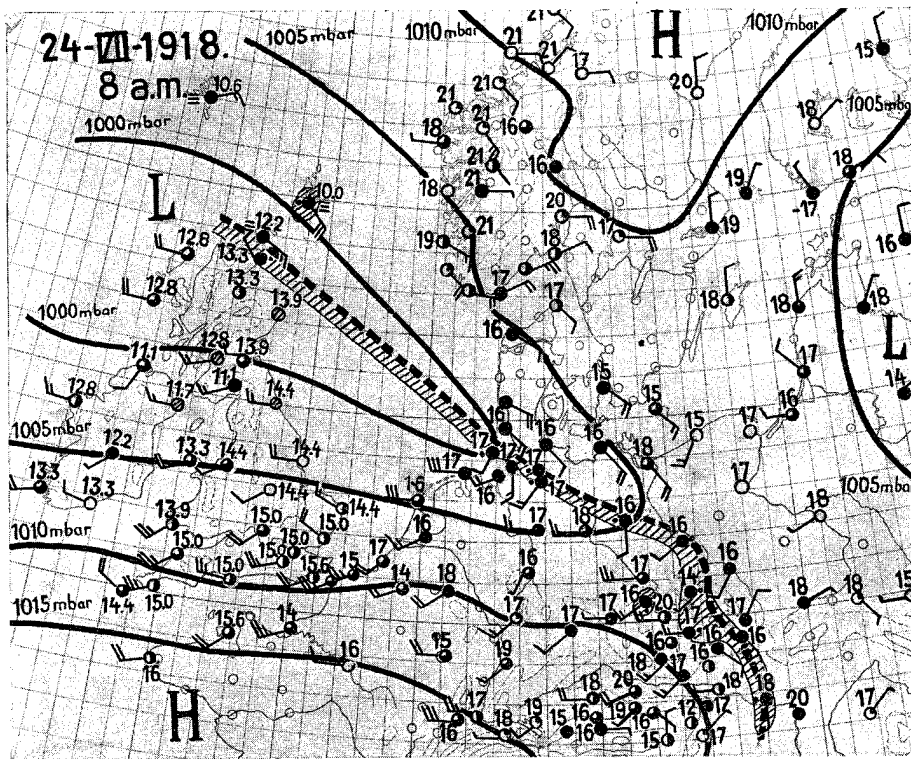
- a. Field of Flow in a Stationary Line of Convergence.
 b. Additional Field of Translation.
 c. Resulting Field of Flow in a Moving Line of Convergence.

A thermal boundary line at the ground is the line of intersection between a thermal boundary surface in the free atmosphere and the surface of the earth. This boundary surface will incline towards the cold side so that the cold air forms a flat wedge resting on the ground underneath the warmer air. The tendency of the cold air to spread along the ground displacing the warmer air may be balanced by the deviating force of the earth's rotation, so that the inclined surface of discontinuity by certain distribution of winds has a position of equilibrium. The mathematical conditions for this equilibrium is given by the wellknown formula of Margules*), or in a more complete form by the formulae and tables of V. Bjerknes**). These theoretical formulae applied on real meteorological situations give boundary inclinations of the order of magnitude 1/100.

Non-fulfillment of the equilibrium condition leads to motion and deformation of the

*) *M. Margules*: Über Temperaturschichtung in stationär bewegter und in ruhender Luft, Hann Band der Met. Zeitschrift. 1906, also in *F. M. Exner*: Dynamische Meteorologie, p. 155.

***) *V. Bjerknes*: On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmospheric Vortex and Wave Motions. Geofysiske Publikationer Vol. 2, No. 4, Section 26.



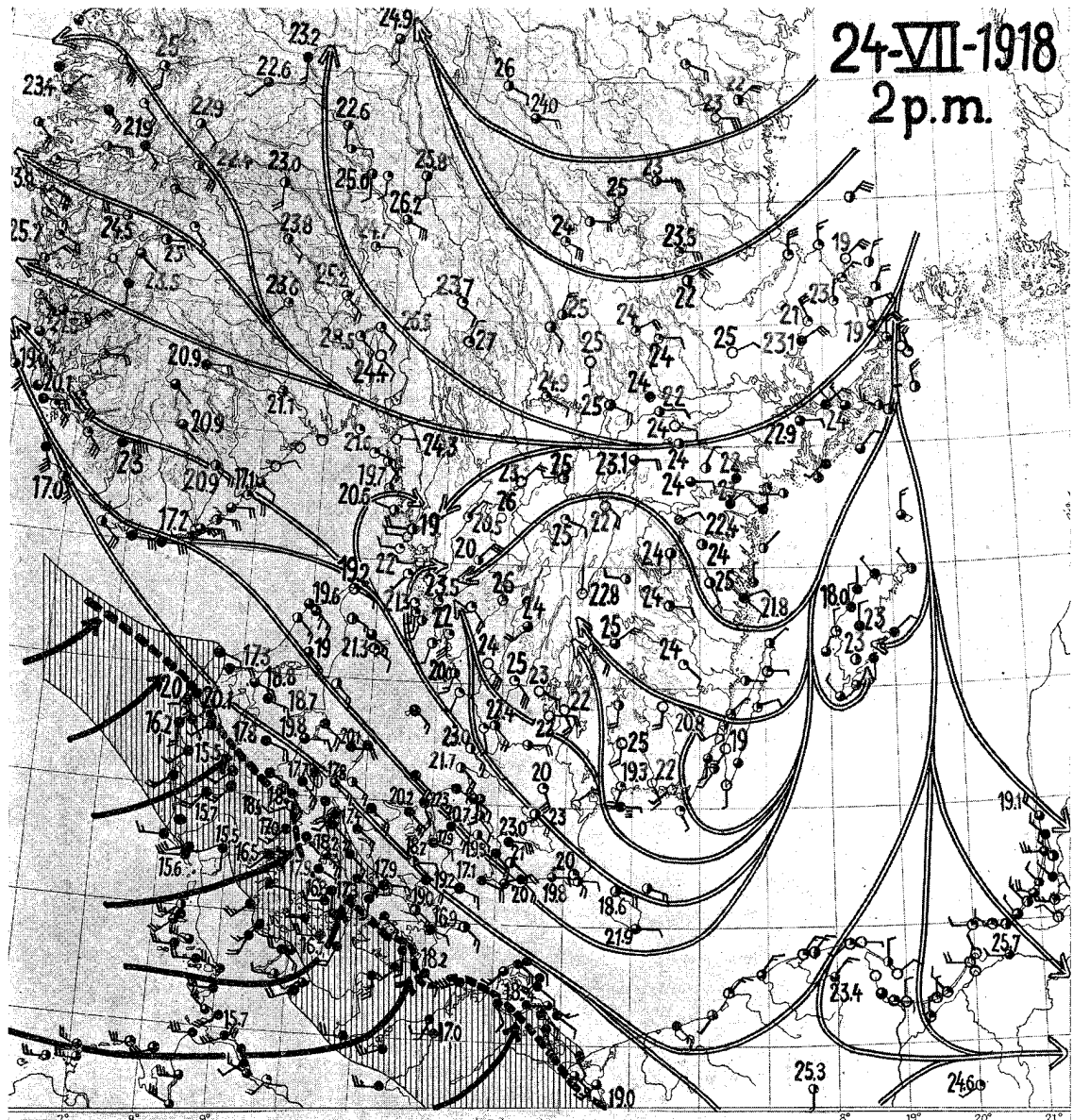


Fig. 7 a.

surface of discontinuity. This motion may either bring a spreading of the cold air over the region previously occupied by the warm air, or, vice versa, an invasion of warm air over the region previously occupied by the cold air. In the first case, the boundary line at the ground will be the front of advancing cold air, or, to introduce a shorter expression, a »cold front«. In the latter case, the boundary line will be the front of advancing warm air, or simply a »warm front«.

Moving cold fronts and warm fronts are usually accompanied by ascending motion which produces large rain zones extending along the fronts. Discussion of some specimens of such rain formation follows.

Rain Due to Ascension of Warm Air Displaced by a Propagating Wedge of Cold Air. Cold Front Rain.

Figs. 6 a and b show the weather situation on July 24, 1918, morning and evening. A well defined trough-line (dotted line on the maps) runs towards south-east.

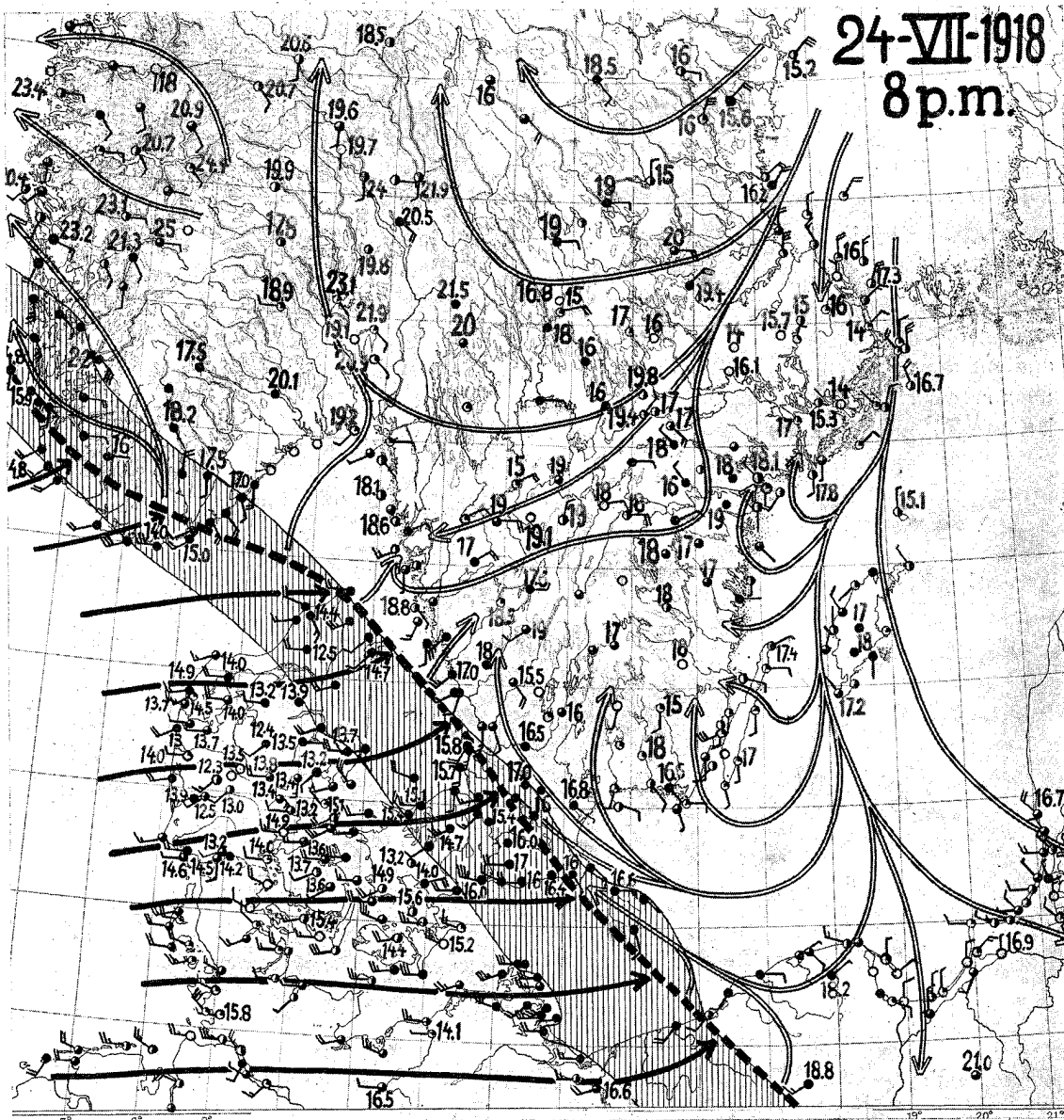


Fig. 7 b.

from a centre of low pressure at Scotland. The trough-line is moving towards north-east and enters south-western Scandinavia in the course of the day. Figs. 7 a and b give a detailed representation of that part of the trough-line, which is situated over the close net-work of Scandinavian stations, at noon and in the evening of the same day.

On the noon as well as on the evening map, a distinct line of discontinuity is to be seen in the lines of flow, corresponding to the trough-line on the isobaric charts.

At some distance north of the line of discontinuity, the ordinary summer situation prevails with clear summer weather and correspondingly very high temperatures (on the noon chart up to 28 degrees centigrade). Southern Sweden is invaded by light sea breeze from the Baltic, Kattegat and Skagerak, which still persists in the evening just in front of the line of discontinuity. In Norway the weather is also generally fair and warm before the arrival of the line of discontinuity. In towards this calm warm mass, a relatively cold westerly wind with temperatures about 15 degrees is advancing from the west. The nearest part of the warm mass is forced to ascend and gives rise to the formation

of a rain band all along the line of discontinuity. Behind this rain band, the sky is again gradually clearing, temperatures, however, remaining lower than in front of the rain.

The marked contrasts of temperature indicate that the line of discontinuity in the wind field also forms the boundary line between two different air masses. The corresponding boundary surface in the free atmosphere is inclined to the rear, the cold air forming a flat wedge under the warm.

It may thus be expected, that the boundary surface will be reached by aerological ascents, starting in the region of cold air. The boundary surface ought to produce an inversion of temperature or, when more diffuse, at least a slight decrease of normal lapse-rate of temperature. Fig. 8 gives the temperature height diagrams from all stations behind the line of discontinuity where ascents have been made about the time of morning- and noon-observation. The continuous lines refer to morning ascents and dotted lines to noon ascents. At the stations Montreuil, Brugelette, Hardoncelle, Montmedy, and Friedrichshafen, all being situated between 500 and 650 km. behind the line of discontinuity, the

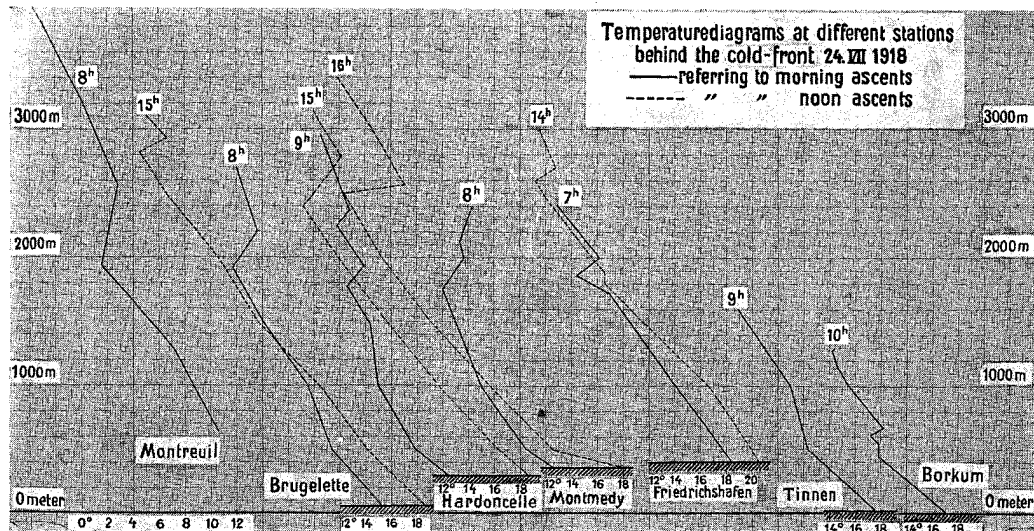


Fig. 8.

corresponding surface of discontinuity is reached somewhat below a height of 2000 m. At Tinnen, about 200 km. behind the line, the inversion cannot easily be recognized on account of the missing information of curve details, but a sheet with small lapse-rate, perhaps involving an inversion, is to be seen between the heights of 500 m. and 1000 m. At Borkum, about 150 km. behind the line, the cold air has only reached the height of 440 m.

Although the mentioned aerological stations are not favourably situated to give a representation of the topography of the surface of discontinuity, an attempt has been made to sketch it. The heights of beginning disturbance of usual lapse-rate representing the upper limit of the cold air are plotted on the little map Fig. 9. Instrumental errors and deviations from synoptic time of observation make irregularities, but on the whole a continuously sloping plane (inclination about $\frac{1}{275}$) is clearly shown, cutting the ground along the line of discontinuity.

The sloping surface characterized by inversion of temperature, can certainly be identified with the upper limit of the cold wave. It will, when propagating towards north-east, gradually appear in higher position above the fixed stations. The noon diagrams (dotted lines) really also show an elevation of the inversion from the morning,

amounting to 6--900 m. In the evening, the inversion is only reached in two ascents from Saarwaldhof in Lorraine, still at slowly increasing height.

It may seem curious, that rain only is formed in such a narrow zone along the line of discontinuity, whereas the propagating cold wedge continues to displace warm air far behind it, without any condensation effects. The warm air, however, avoids ascending motion when moving horizontally as fast as or faster than the cold wedge. In reality, winds up above the boundary surface are westerly and mostly a little stronger than the winds below. The warm air in this part has therefore no ascending motion, but probably even a small descending component. This descending motion is also indicated by the very low relative humidities occurring above the surface of discontinuity.

Rain will only be formed where the warm air does not escape horizontally, in this case only along the foremost front of the cold wedge where the warm air is generally moving from SE along the ground.

This SE wind seems to be limited to lower layers. Stations placed on coastal mountains in western Norway observe in the evening winds between S and SW also before the arrival of the rain. The lines of flow running from SE are in this region drawn only according to observations from lower stations.

In the years 1918--21, a great number of rain lines of the described type have passed Norway. The passage of these lines has always been accompanied by a characteristic succession of cloud forms, which makes the identification of cold front rain possible without any synoptical charts, provided that no lower clouds of other origin interfere with the free view. The following description may be given corresponding to the most common type.

Usually, the first clouds arriving are of the form A.-Cu. (or Ci.-Cu.), often arranged in oblong lenticular systems having their longitudinal axis parallel to the approaching rain front. These cloud systems move with a component perpendicular to their own longitudinal direction and also towards the right when facing the approaching cloud bank. Frequently, it may directly be observed that the cloudlets of A.-Cu. dissolve or even completely disappear during their travel across the sky. New A.-Cu. masses are, however, constantly arriving from the horizon and replace the dissolved ones. Thus the sky is gradually covered by A.-Cu., the scratches of which become always narrower and finally close together. Having reached this stage, the cloud sheet has become a sort of A.-St. Underneath this A.-St., a great compact mass of Nb. appears, soon bringing heavy rain.

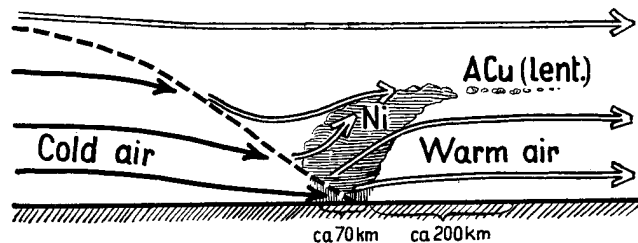


Fig. 10. Vertical Section through a Cold Front.

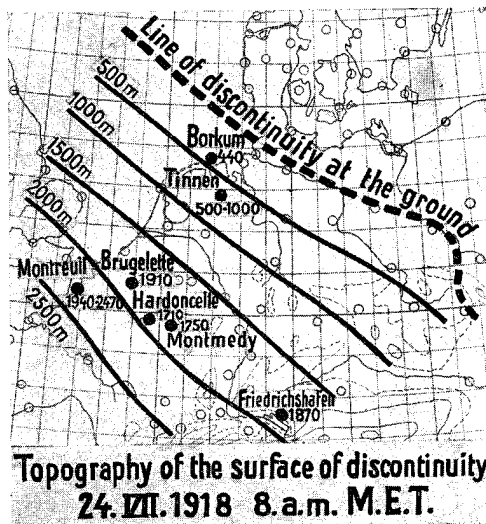


Fig. 9.

The time between the appearance of the first A.-Cu. clouds and the beginning of the rain seldom exceeds three or four hours. Often these types of rain may come with still shorter warning. The rain usually lasts some few hours. After the cessation of the rain, the layer of Nb. is split into F.-Cu., which

gradually become smaller and finally disappear. During the clearing, no higher clouds are to be seen.

This experience from a fixed point combined with the study of detailed maps of cold front rain, leads to the scheme of Fig. 10. This figure represents a vertical section through the atmosphere across the line of discontinuity. The compact mass of Nb. is formed in the rapidly ascending warm air at the front of the cold wedge, and extends on account of the strong ascending motion up to a height of 4 km. or even more. The upper parts of it will then come up into air layers moving forwards with greater velocity than the cold wedge, which has caused the ascension. The top of the cloud mass will then be carried forwards forming a cloud shield, which gives overcast weather some distance in front of the rain. These cloud masses will, when moving away from the ascending current, dissolve into cloudlets of A.-Cu. type. During the continued dissolution, parts of the A.-Cu. sheet completely disappear, and the remainders form lenticular shaped systems arriving as the first signs of rain.

The performance observed at a fixed place is just this process of dissolution running the opposite way. The fact that A.-Cu. clouds are drifting forwards in front of the rain-stripe is a second indication, that the upper parts of the warm air move faster than the cold wedge, thus avoiding ascending motion on the higher part of its slope.

The maintenance of the ascending motion along the rain stripe will always depend upon the differences of temperature between the front and rear. As big adjacent air masses mix very slowly, their differences of temperature may persist for days or weeks. Greater smoothing influences in this case are to be expected through the heating from the ground acting with the same intensity upon both masses of air. The cold wedge flowing over the continent in clear summer weather will be heated from below, and finally, become as warm as the air which is to be displaced and lifted by it. Then the system has lost its energy and all motion, vertical as well as horizontal, will die away.

This process is already initiated in our case. On the temperature height diagrams Fig. 8, it will be seen on all stations having two ascents, that a heating from below has acted effectively in the intermediate time, although not yet reaching the upper limit of the cold wedge.

A cold front of the described type is known in meteorological literature as the V-shaped depression. Cold fronts met with in nature are not always accompanied by such characteristic and accentuated formations in field of flow and field of pressure. They may belong to all different types between the accentuated V-shaped depression and the slight »ill-defined secondaries«. In the latter type, the warm and cold air border along a slight trough in the isobars of a greater system, and both air masses move consequently in nearly the same direction. Only those parts of the warm mass, which do not move fast enough to escape horizontally, will then be forced to ascend above the cold wedge. That will often merely be the lower parts of the warm mass which are retarded by friction at the ground, thus moving with smaller velocity than the cold wedge which advances nearly with the velocity of upper winds within itself. In such a case, evidently only small masses of air will take part in ascending motion, and condensation effects will be correspondingly slight. Cold fronts of this type therefore give rather little or even no precipitation.

Conditions are, however, different when mountains hinder the warm air from flowing away from the cold wedge. This fact appears clearly from the effects of cold fronts in western Norway.

A cold front surface with front direction SW—NE (Fig. 11 a) will together with the mountain range form a triangular shaped cul-de-sac into which the warm air enters. Under the continued advance of the cold front, this warm mass will be forced to ascend, and

heavy continuous rainfall develops even far in front of the boundary line between cold and warm air. This combined cold front and orographical rain may last up to 12 hours at any one station on the mountain slope, even when the proper cold front rain would last only 1 hour. Such prefrontal rain cannot be of merely orographical origin, as in absence of the cold front the warm air would have curved around the mountains northwards and southwards, and thereby avoided ascending motion.

The same sort of prefrontal cold front rain develops even when the front direction is parallel to that of the mountain range (Fig. 11 b). The warm current flowing along the

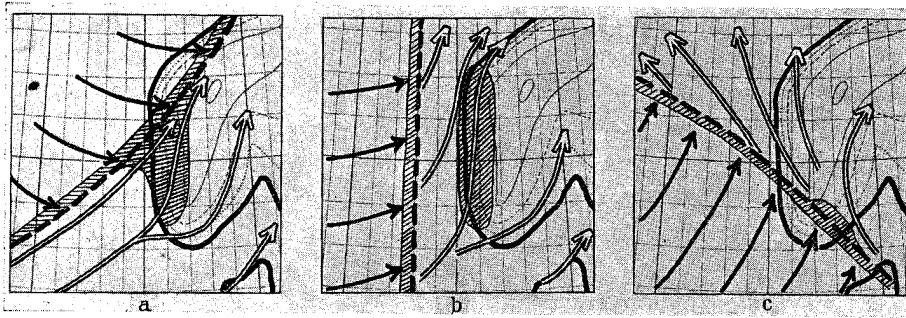


Fig. 11. Combined Cold Front and Orographical Rain.

channel between the mountains and the cold wedge will be pressed together on a stripe which gradually becomes narrower. The first effect of this process will be an increase of wind velocity in the warm current, which tends to maintain unaltered transport of air. The continued advance of the cold front makes it impossible for all warm air to be brought away horizontally, and parts of it must begin to escape vertically. From this moment, formation of prefrontal rain begins along the mountain slopes (indicated by the shaded zone on Fig. 11 b) and persists till all warm air is completely driven away over the mountain ridge. Also this sort of rain may last several hours and render considerable amounts of precipitation.

A cold front with front direction SE—NW (Fig. 11 c) gives rain of about the same duration and intensity in western Norway as it would do in plain country. No prefrontal rain develops on the western coast in that case.

The phenomenon described above is found in a more or less accentuated form also in other regions of analogous topography.

Rain Due to Ascension of Warm Air above a Retreating Wedge of Cold Air. Warm Front Rain.

Fig. 12 shows the diagrams from thermograph and self-recording rain gauge at Bergen during the passage of a marked line of a discontinuity of warm front type, January 21, 1921. Just after 2 o'clock p. m. on the 21st, the temperature curve shows a sudden rise of $4^{\circ},5$, in overcast weather without sunshine. The only explanation of this sudden rise of temperature must be the arrival of new warm air with a distinct limit against the cold air. (Föhn effect is impossible on account of the wind direction S—W). A period of heavy continuous sleet and rainfall from 8 a. m. to 4 p. m. corresponds

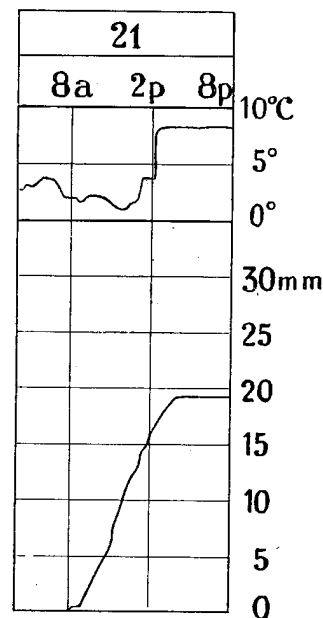


Fig. 12.

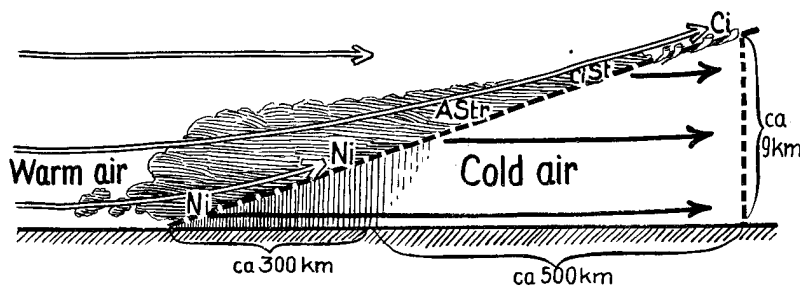


Fig. 13. Vertical Section through a Warm Front.

the rain has been formed in the warm air climbing the retreating wedge of cold air and falls over a large area on the cold side of the line of discontinuity (Fig. 13). This type of rain may be called warm front rain.

If we examine the weather situation closer, which brought the warm front rain of January 21, 1921, we find, on the morning of that day, a depression centered at the

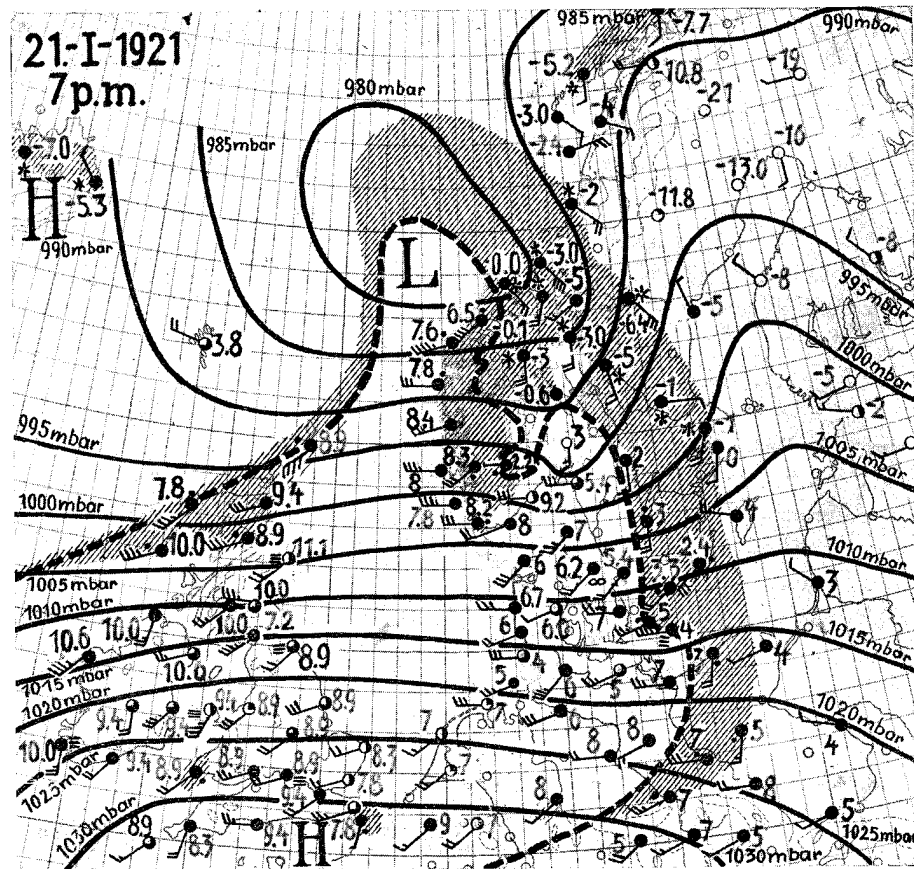


Fig. 14.

Farøe Island, and in the evening of the same day just outside the Norwegian coast (Fig. 14). The rain having passed Bergen between 8 a. m. and 4 p. m. is seen to belong to a long rain band extending in the evening from the centre of the cyclone across Scandinavia down to Germany (shaded area). Detailed maps of southern Norway are given for the time of noon and evening observations on the Figs. 15 a and b. Temperatures are on

*) The first rise of temperature at about 1 p. m. is caused by the transition from sleet to rain. The two rises together amount to $6^{\circ},5$ in the course of one hour and a half.

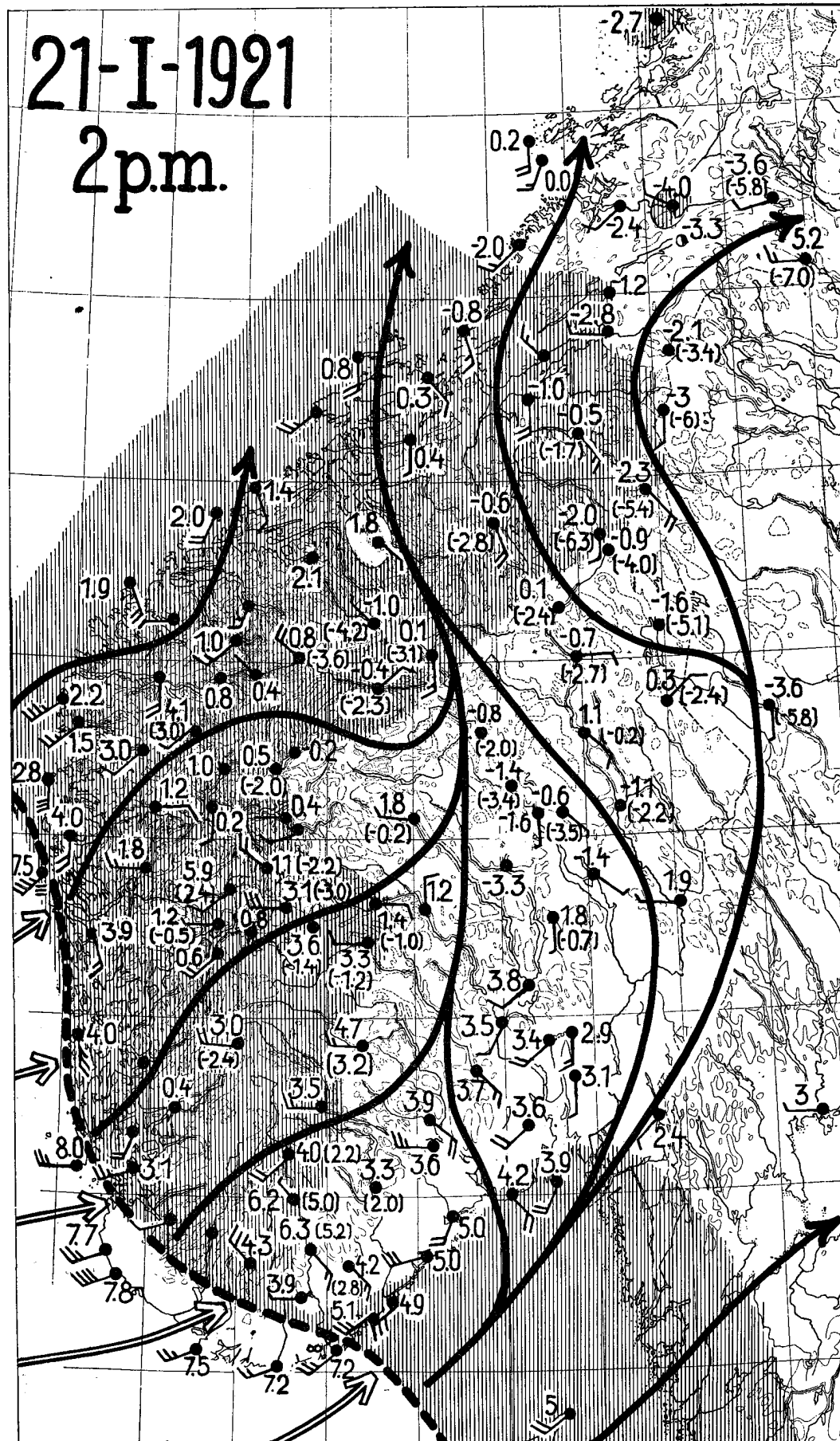


Fig. 15 a.

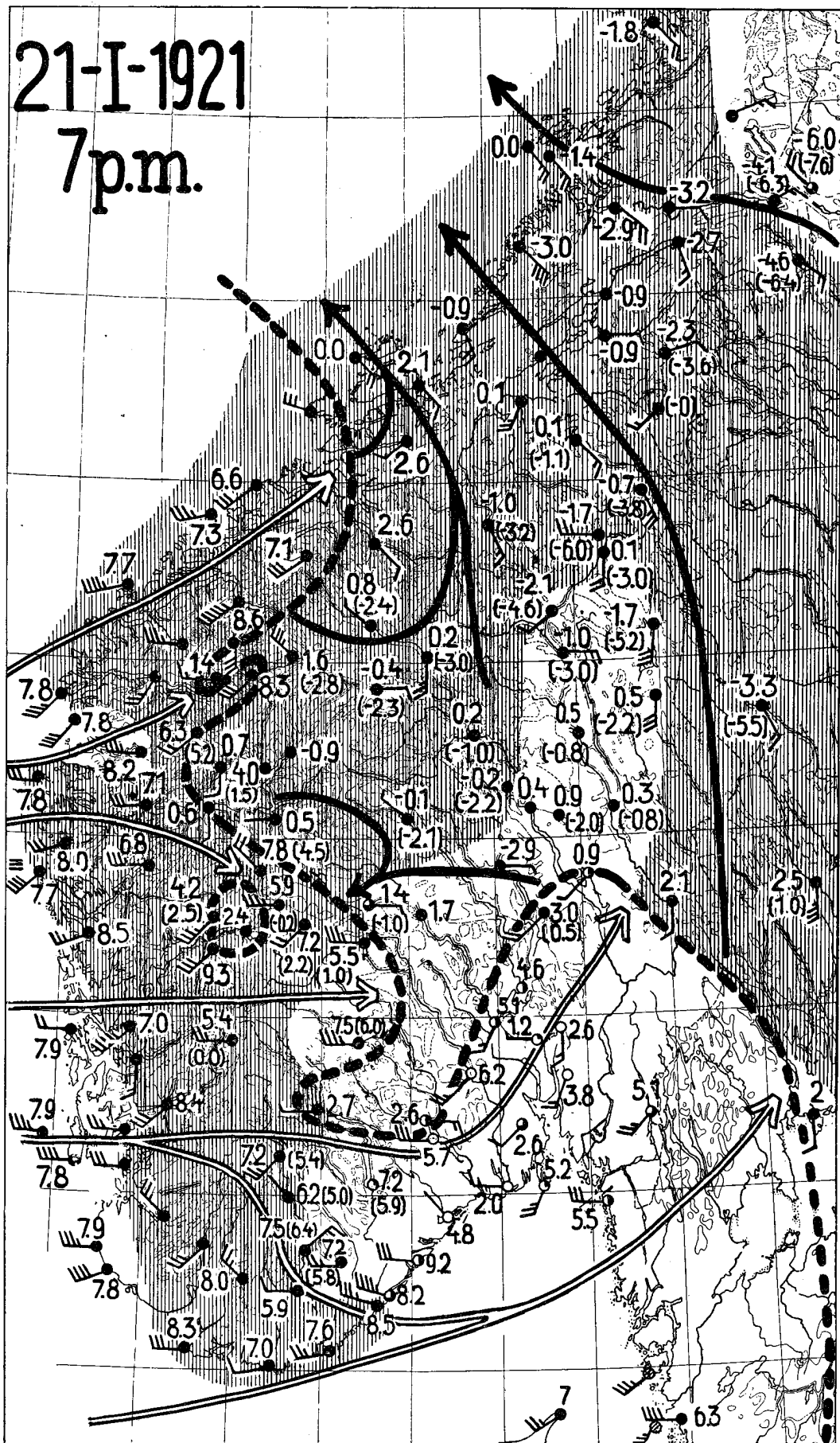


Fig. 15 b.

all stations reduced to sea level with $0^{\circ},5$ pro 100 m. Where the reduction term exceeds $1^{\circ},0$, also the observed temperature is plotted in parenthesis.

Corresponding to the sudden rise of temperature at Bergen just after 2 o'clock p. m. we may expect to find a marked line of discontinuity passing quite near that place on the noon map (Fig. 15 a). Till the time of observation, the warm air has really reached the stations Hellisö $7^{\circ},5$, Skudenes $8^{\circ},0$, Obrestad $7^{\circ},7$, Kvasshheim $7^{\circ},8$, Lister $7^{\circ},5^{\circ}$, Mandal $7^{\circ},2$, and Oksö $7^{\circ},2$. (Note the small differences of temperature between these stations indicating a great uniformity of the warm air). In front of the dotted line, temperatures are several degrees lower than behind it. The discontinuity of temperature is most marked between Hellisö $7^{\circ},5$ and Bulandet $2^{\circ},8$, less accentuated on the Skagerak coast between Oksö $7^{\circ},2$ and Grimstad $5^{\circ},1$.

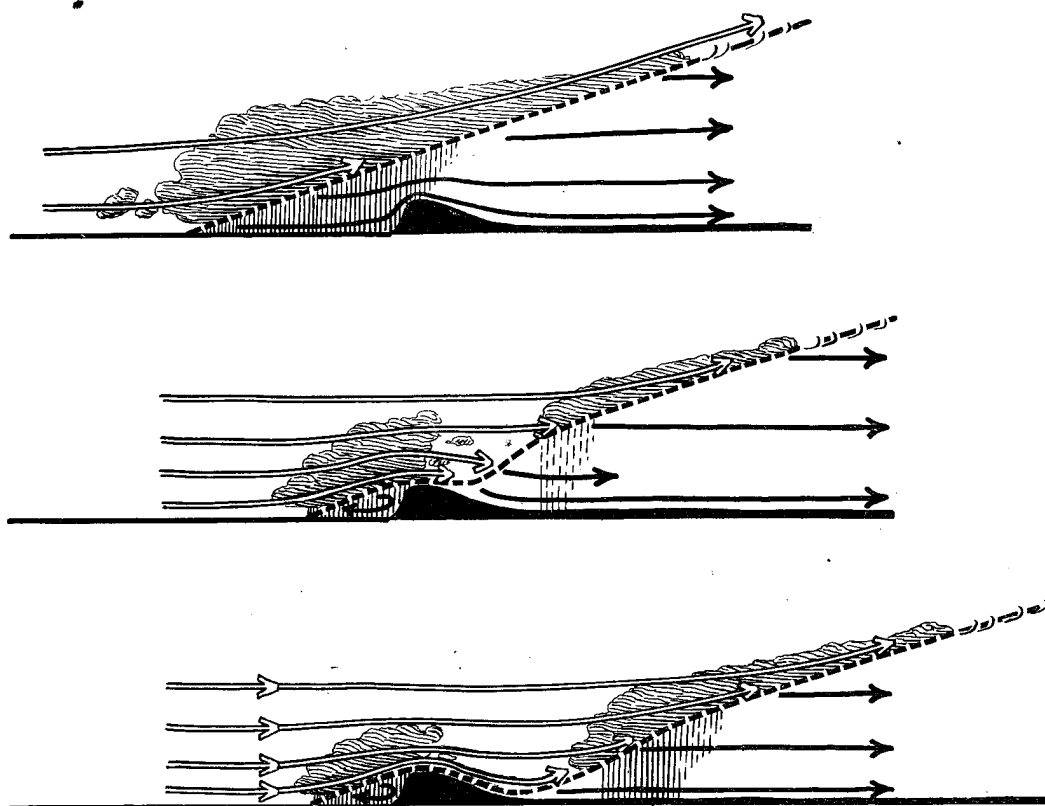


Fig. 16. A Warm Front Passing a Mountain Ridge.

Before proceeding further in the examination of the map Fig. 15 b, we shall consider the effects of the mountains on the warm front system.

The schematic Fig. 16 represents a vertical section through a warm front surface passing a mountain range. The section through the mountains is imagined as following a fjord of western Norway, then through a mountain pass and down a valley in eastern Norway.

The warm front surface, which has usually a smaller inclination than that of the mountain slope, will reach the ridge and its passes while still a part of the cold air is lying below the slope. This cold mass will have no opportunity to escape as the way over the mountain ridge is already blocked by the overlying warm air. The lower part of the warm front surface will accordingly become stationary, supported by the mountains, and the corresponding rain zone will persist at the same place for a long time. The upper part of the moving warm front surface with appertinent upper clouds will, however, pass over the mountain range without any hindrance. The lee side of the mountains may

consequently receive rain from clouds lying high enough to pass over the ridge. Frequently even this rain is prevented by the descending motion induced on the lee side of the mountains. This descending motion which first develops in the cold mass, may also suck down the warm air so that the cloud cover in that air must dissolve. Arriving afterwards over plain country the descending motion ceases, and the cloud system of the warm front regenerates.

This phenomenon is seen already on the noon map (Fig. 15 a), where the rain zone having passed western Norway, is interrupted on the eastern mountain slope. On the evening map (Fig. 15 b), we see it recover again over the flat country in Sweden.

Bearing in mind the above mentioned effect of mountains on the warm front surface, we may now on the evening map, (Fig. 15 b) examine the course of the front of invading warm air.

Beginning on the northwestern coast, we may easily detect the position of a well marked line of discontinuity in the wind field between the neighbouring stations Titran and Strömskag, Titran having SE 4 and Strömskag WNW 6. The nimbus clouds over the station Titran are already drifting from SW indicating that the windshift has reached farther in the height than on the ground. These clouds obviously belong to the warm mass, and their appearance over the cold region proves the forwards inclination of the boundary surface, at least in lower layers. The discontinuities in the wind field corresponds to a distinct discontinuity also in temperature. Titran in front of the discontinuity has $0,0^{\circ}$, whereas the nearest thermometer station behind it (Hustad) reports $6^{\circ},6$. From the northwest coast the line of discontinuity may be followed by aid of the temperatures southwards through the mountainous country. It runs between Sundalen $2^{\circ},6$ and Aandalsnes $7^{\circ},1$, and between Stryn $1^{\circ},4$, and Hellesylt $8^{\circ},6$, all stations near sea level. Just to the east of Stryn, the station Opstryn, at a height of 200 m., has the warm air already (temp. red. to sea level $8^{\circ},3$). All lower stations in the innermost Sognefjord district have temperatures about zero, whereas Kirkebö just outside has already $7^{\circ},1$. The station Lyster Sanatorium, at a height of 500 m., reports $1^{\circ},5$ (red. to sea level $4^{\circ},0$) and rain, whereas the station Forthun, quite near at sea level, has $-0^{\circ},9$ and heavy snowfall. Obviously the warm air has, in the level of 500 m., already reached the innermost parts of the Sogn district, whereas the cold air still persists in the bottom of the valley. Further south, the warm front has already crossed the mountain ridge (Finse, 1226 m., temp. red. to sea level $5^{\circ},9$), whereas a small cold mass has been left back in the innermost part of the Hardangerfjord. (Note the temperatures Eidfjord $2^{\circ},4$ and Lofthus $9^{\circ},3$). The warm air has thus arrived earlier to the pass station Finse than to the fjord station Eidfjord farther west. This fact may serve as a further proof for the forwards inclination of the warm front surface.

On the eastern slope of the mountains the course of the boundary line becomes uncertain, especially where the sky has cleared over the warm air, and the surface layers are exposed to cooling by radiation. We may, however, still indicate the most probable boundary between the two masses. It curves round a little cold mass, which is left back in Telemarken and passes from there to the north of Kristiania towards the Swedish frontier.

The fastest propagation of the warm front has taken place along the north-west coast and along the Skagerak coast, where no obstacles can retard it. But even there it has not moved as fast as the velocity of wind in the warm mass itself. This involves the necessity of the warm air moving over the receding cold wedge in the intermediate period. Along the north-west coast, for instance, the warm front has moved approximately with a velocity of 45 km. an hour or 12,5 m. a second. The surface wind in the warm air along the coast is estimated by the observers to about 7 Beaufort or 14 m/sec. corre-

sponding to a velocity of at least 20 m/sec. in the free atmosphere. The difference between this velocity 20 m/sec. and the velocity of the warm front 12,5 m/sec., thus 7,5 m/sec., represents the component of the warm air upwards along the cold wedge. If this wedge has an inclination of 1/100, the vertical component of the warm air would be 7,5 cm/sec. Supposing a lapse-rate of 0°,7 pro 100 m. and a constant relative humidity of 96 per cent, as observed at the ground, up to the height of 4 km. in the air behind the warm front, we may calculate how much water will condensate by adiabatic cooling during the flow of the warm current upwards the warm front surface. Assuming further that all water condensated below the height of 4 km. reaches the ground, we would in the actual case get 21,3 mm. precipitation on each station passed by the warm front rain. This amount represents under the given conditions a maximum, as much water will evaporate before reaching the ground. The actual amounts are therefore smaller, in Bergen for instance, 18,9 mm. were recorded, and on the north-west coast where the rain falls through a dry South East current blowing down from the mountains, only amounts of 5 mm. have resulted.

This rough calculation shows, however, that an ascending motion of the warm current up the cold wedge of air will give amounts of precipitation of the same order of magnitude as those actually observed. Further, the small inclination of the warm front surface (about 1/100) explains the great breadth obtained by the rain band. If rain falls from the entire part of the cloud mass lying below 4 km., the rain zone will have the breadth of 400 km. actually observed in our case.

In plain country the rain stops immediately after the passage of the warm front. On the western coast of Norway, however, orographical rain forms behind the warm front in the strong and moist Westerly current ascending the mountains. It has, however, according to the great stability in the warm current, the character of slight drizzle, which gives only small amounts of precipitation. In Bergen, for instance, no measurable precipitation fell during 4½ hours after the passage of the proper warm front rain. Such slight orographical rain is characteristic for the stable air currents, which are warmer than the sea (see page 8). In comparison with the great amounts of precipitation of the heavy continuous warm front rain, the slight orographical rain in the warm current is almost negligible.

A warm front, as described above, is always accompanied by a characteristic succession of cloud forms, which makes it easy to determine the type of rain only by observing the sky at a fixed point.

The first sign of the approaching rain will be the cirrus clouds, in most cases of the typical form »cirrus en houpe« or tufted cirrus. They usually consist of a long straight narrow cloud-stripe, which is curved upwards in the end directed forwards relatively to the motion of the cloud. Sometimes, they appear quite isolated on the blue sky, more often, however, many are congregated with the tufts arranged in straight-lined fronts (tracto-cirrus vertebratus). After a short time, a thin veil of cirro-stratus begins to cover the sky, giving it a pale milky colour, and producing halo phenomena around sun and moon. This thin veil is gradually thickening to a grey uniform cover of alto-stratus, the sun or moon appearing only like pale diffuse disks. Further along in the development, the alto-stratus becomes so thick that neither sun nor moon are visible. The daylight diminishes considerably, and the sky has a gloomy aspect. Often, the alto-stratus just before the beginning of rain, adopts the form mammato-stratus and simultaneously stripes of falling evaporating precipitation may be seen underneath the cloud cover. The first rainfall reaching the ground, having fallen through the cloudless layer of at least 3 km. thickness, is usually rather slight. Gradually the rain increases in intensity coincident with a continued lowering of the nimbus clouds. During the rainfall, which may persist

for a whole day, detached fracto-nimbus clouds form underneath the real strato-nimbus. Just before the cessation of the rainfall, the nimbus clouds become very low and compact. In typical cases, these low cloud masses disappear soon after the cessation of the rainfall, only detached fracto-stratus clouds remaining.

Although not all cloud forms belonging to the warm front system can be seen simultaneously, we may still imagine it as a huge continuous cloud mass, as represented in Fig. 13, page 18. In the most typical cases, no distinct limit can be discovered between the successive cloud forms, cirro stratus, alto-stratus, and strato-nimbus. The inferior limit of the cloud shield then forms an inclined plane running continuously from the lowest nimbus up to the thin veil of cirro-stratus.

This inclined inferior surface of the cloud mass must certainly coincide or nearly coincide with the warm front surface. As to this point, we may refer to C. K. M. Douglas*), who summarises his results in the following way:

»The cause of the other type of cyclonic rain, the pushing of the warm over the cold air in front of the cyclone, was also verified by the Berck observations. On entering the alto-stratus in front of the rain, there was usually a marked decrease in the lapse-rate of temperature, at least for two or three thousand feet, and occasionally a slight inversion . . . «. The investigations of Douglas thus have brought evidence for the existence of the warm front surface, although usually such of a more diffuse type. We are inclined to believe that corresponding investigations nearer to the centres of depressions would give more marked surfaces of discontinuity than in France, where usually only the extreme diffuse ends of the cyclonic discontinuities pass. Such investigations in more northern countries, Scotland or Scandinavia, would be of great importance for the understanding of cyclones and corresponding formation of rain.

Cold Front and Warm Front Rain as Constituents of the Cyclonic Rain.

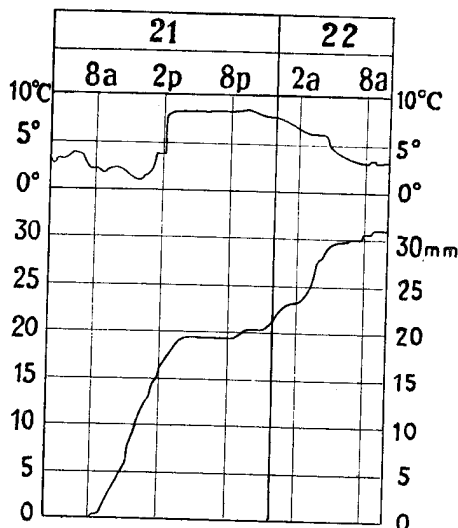


Fig. 17. Registration of Temperature and Precipitation at Bergen during the Passage of the Cyclone January 21 and 22, 1921.

The warm front described above was soon followed by a cold front (see Fig. 17 giving temperature and rain record for January 21 and 22, 1921). The temperature of the 22nd, fell slightly till about 5 o'clock in the morning, reaching its maximum at about 10 o'clock in the evening of the 21st, then a sudden fall set in, indicating the passage of a line of discontinuity, the »cold front«. The slight fall of temperature during the night is due to the cooling effect of the heavy prefrontal cold front rain (see page 17), which began at 9 o'clock in the evening. The proper cold front rain ceased one hour after the sudden fall of temperature. Afterwards, the cold instable air blowing against the mountains gave conditions for formation of instability showers, which can be seen at the right end of the rain record curve.

The cold front, passing Bergen at 5 o'clock in the morning of the 22nd, was in the evening of the 21st (Fig. 14, page 18) lying somewhere between the Shetland Islands and the Farøe Islands. The 5 degrees temperature difference between these two places indicates the existence of a thermal boundary line of cold front type between them.

*) l. c., p. 37.

The two thermal boundary lines*), the warm front and the cold front, lead towards the centre of cyclone, and are there connected. They form together an unbroken line of discontinuity dividing the cyclone in a cold and a warm part.

Within the warm part, the »warm sector« of the cyclone, temperatures are generally conspicuously high for the time of year. Most of the stations within the warm sector have higher temperatures than that of the sea. At some places, the cooling from the sea surface has produced fog and thereby lowered the air temperature in lower layers making it equal to that of the sea. The high temperature in the warm sector shows that the air in this part of the cyclone must have been conveyed from parts of the ocean, which are warmer than the sea bordering northwestern Europe. Probably, the warm air originates from the latitudes of the Azoric Highs.

In the cold part of the cyclone, over Iceland, the Farøe Islands, and northern Norway, temperatures are considerably lower than those of the sea. The air over this region must therefore originate from colder parts of the earth, — from polar regions or from cold northern continents. Farther from the centre, over the Baltic and eastern Germany, we find air belonging to the rear of the foregoing cyclone. This air is consequently also of cold origin, but has had time to absorb heat in lower layers when passing over warmer regions. Anyway, it is still a little colder than the air of the warm sector.

The well defined discontinuities in the Bergen thermogram (Fig. 17) and on the detailed Norwegian maps show that the mixing process between warm and cold air has had very small effect. The thermal boundary line may, at least in the part nearest the centre of cyclone, be considered practically as a real line of discontinuity. Farther from the centre, temperature contrasts are less accentuated, but nevertheless the position of the warm front may easily be determined even down in Germany.

All precipitation of greater importance is found along the thermal boundary line of the cyclone, either in the warm front rain across Scandinavia and Germany, or in the cold front rain over Shetland and the Hebrides. In the cold part of the cyclone the weather is generally fair outside the big rain and snow areas, however with local instability showers. In the warm sector, we find only the orographical rain of western Norway and some occasional drizzle, fog, and mist, otherwise cloudy to fair weather.

We may embody the principal features of this cyclone in the idealized scheme of Fig. 18.**) The line of discontinuity is drawn through the cyclone without the deformations generally produced by the Norwegian mountains, and the figure represents thus an idealized cyclone on perfectly flat ground. The shaded area indicates the region of precipitation at the moment of observation. It consists of the warm front rain, extending as a broad curved zone in front of the warm tongue of air, and the narrow cold front rain stripe behind the warm tongue. All smaller squalls are for convenience omitted; usually they can be accounted for when considering the orographical conditions of the different stations or stability conditions of the air constituting the cyclone.

*) In a previous paper: »On the Structure of Moving Cyclones«, Vol. I, No. 2 of this publication, the two thermal boundary lines of the cyclone were called »steering-line« and »squall-line«. Especially the first of these names may, however, give rise to objections and even mistakes, as the »steering-line« has only nearest to the centre that direction tangential to the track of the cyclone to which the name should allude. We have therefore in the present paper introduced the names »warm front« and »cold front«, which directly define the character of the boundary line in question.

**) The same scheme is outlined in: »On the Structure of Moving Cyclones«, Vol. I, No. 2 of this publication.

Previous to this, nearly the same structure of cyclones has been indicated by *Sir Napier Shaw* in: »Forecasting Weather«, Fig. 96, p. 212, based upon the investigations of Shaw and Lempfert in »The Life History of Surface Air Currents«.

Beneath on the same figure, a vertical section is sketched through the cyclone to the south of the centre. It gives from right to left the succession of weather to the south of the passing cyclone. First, the passage of typical warm front rain preceded by a huge shield of cirrus, cirro-stratus, and alto-stratus clouds. Then, a rainfree, relatively warm spell of weather during which the cloud shield of alto-cumulus appears, announcing the approaching cold front rain. After the passage of the cold front rain, cool and, under certain circumstances, showery weather persists till the final clearing.

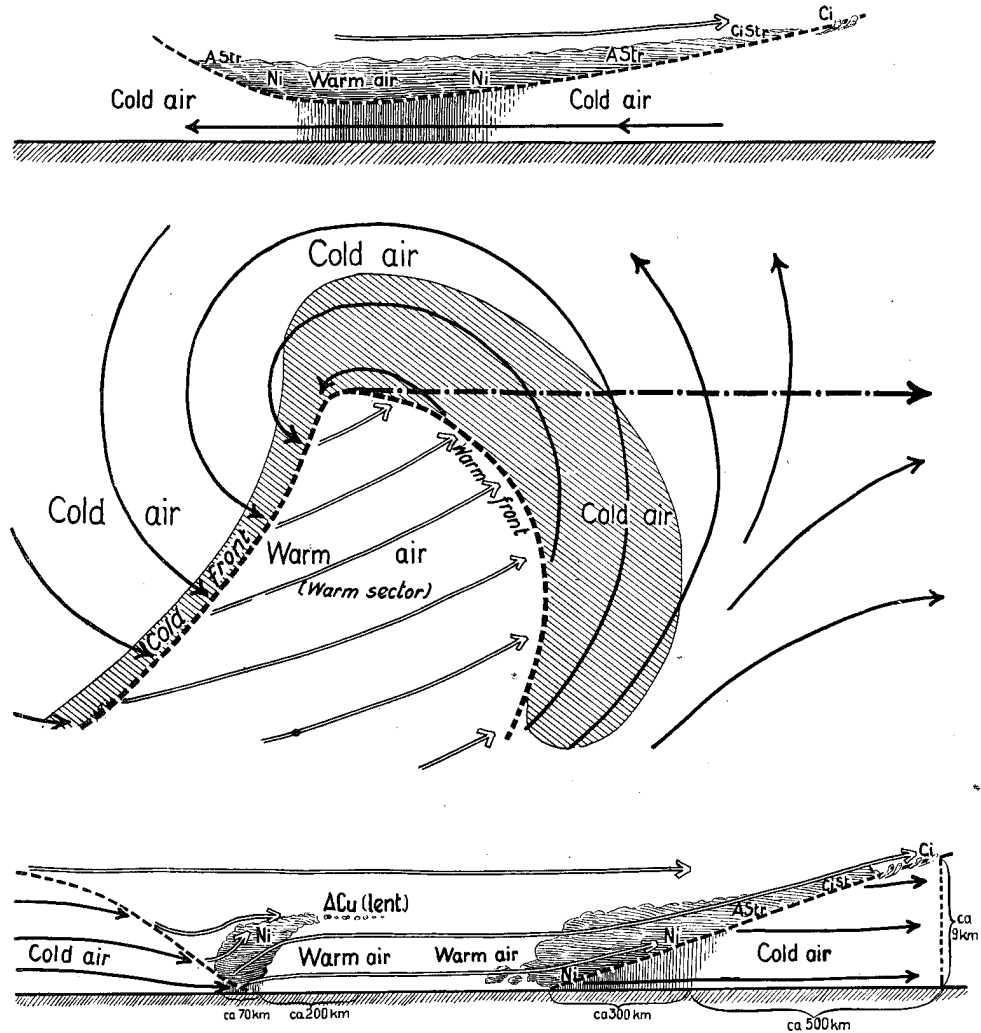


Fig. 18. Idealized Cyclone.

The upper part of the same figure represents a vertical section through the cyclone to the north of the centre giving from right to left the succession of weather to the north of the passing cyclone. Such a section cuts the rain area only once, corresponding, thus, to a single rainfall of duration according to relative distances from the centre. This rainfall is of the warm front rain type, and is preceded by the same sorts of clouds. The warm front itself does not, however, pass the observer at the ground. The rain ceases by and by simultaneously with a gradual elevation of the cloud cover.

How high up in the atmosphere the boundary surface of a cyclone may reach can not be stated with certainty at the present stage of aerological investigation. Provisionally we may only bring the following indirect indices for the upper continuation of the boundary surfaces, known from lower parts of the cyclone.

All the clouds preceding the warm front rain, cirro stratus, alto-stratus, and mammato-stratus, are typical sheet clouds, and their close mutual connection makes it probable that they belong to the same inclining boundary surface, which can be observed in lower atmosphere. Even the tufted cirrus is a sign for the existence of a surface of discontinuity at that height. The tufted cirrus must consist of ice crystals falling from the tufts through a well defined surface of discontinuity into a layer with different velocity from that of the tufts. The ice crystals will there form a long tail in the direction of the vectorial difference of winds above and below the surface of discontinuity. As tufted cirrus always move nearly in their own longitudinal direction, the tufts being directed forwards, it may be concluded that the velocity up above the surface of discontinuity has stronger component forwards than the velocity below. We get thus the picture of a strong upper current penetrating forwards and probably a little upwards in front of the cyclonic continuous cloud masses. It is not improbable that we here observe the uppermost part of the warm current above the warm front surface. Also the small cirro-cumulus undulatus clouds, often forming in front of the veil of cirro-stratus, seem to indicate the existence of the same surface of discontinuity.

These questions, however, must be closer examined before definite opinions can be stated.

As regards the cold front surface, we have no high clouds to show its upper continuation, but we may in this connection again refer to the results of captain C. K. M. Douglas from his observations in north-eastern France.*) He concludes, partly from the successive veering of wind upwards in the free atmosphere behind a squall line (cold front), partly from the following development of high reaching cumulo-nimbus clouds in the cold mass, that the polar air currents in the rear of cyclones often extend through the whole troposphere.

In northern regions, this will be the more true as the cold outbreaks will reach greater heights nearer the source of polar air than they have after a spreading to lower latitudes.

As cold front surface and warm front surface are parts of the same connected boundary surface, separating »polar air« from the »tropical air« of the warm sector, they must both continue in more or less accentuated form in all heights where polar air is found to be colder than tropical air. In all probability this will be the case through the greater part of the troposphere.

Application to Summer Cyclones.

Experience shows, that even rather slight summer cyclones have the same characteristic rain zones, known from winter cyclones as warm front rain and cold front rain, and likewise a relatively rainfree »warm sector«. In summer, however, the discontinuities, once existing in the cyclone over the sea, will become rather indistinct at the ground, when arriving over the continent.

The air in front of the cyclone, namely if it has been exposed to sunshine heating over the continent, will be even warmer than the warm sector arriving from the sea. And likewise, surface temperatures in the fair weather behind the cold front may often be higher than in the warm sector. Nevertheless, this does not imply that the contrasts of temperature vanish higher up in the atmosphere. Above the foggy cooled surface layers of the warm sector, and above the reach of sunshine heating, the warm sector still must be the warmest part of the cyclone.

We believe, we therefore are entitled to apply the same theory for the formation

*) l. c., p. 35.

of rain in summer cyclones, even when temperatures at the ground do not bring such good evidence for it as in the described winter cyclones. Aerological investigations in the future shall prove if the supposition is right.

As an example of summer cyclones we will take that of August 27 to 28, 1919 (Figs. 19 a, b, c), moving from the North Sea northeastwards along the western coast of Norway. The corresponding detailed maps over southern Scandinavia for the 27th, 8 a. m., 2 p. m., 7 p. m., and the 28th, 8 a. m., are given on Figs. 20 a, b, c, d respectively. In Norway cloud forms are plotted, the observation of which was introduced in the Norwegian Weather Service in the summer 1919.

On the first of the detailed maps (Fig. 19 a), a large rain zone, the warm front rain, extends from the German coast across the southern Baltic, southern Sweden and southern Norway.

On the following maps, this rain zone moves slowly northwards, and is on the morning of the 28th to be found over a somewhat smaller area across central Sweden, and parts of eastern Norway. On the two last maps, a new rain band, the cold front rain, enters from south-west and advances rapidly northeastwards across southern Scandinavia.

The corresponding boundaries (dotted lines) will lie: the warm front at the rear of the first rain area, and the cold front at the front of the second rain area. Both boundary lines are in a rather diffuse state, and the contrasts of temperature are evidently dependent on the time of day. So, for instance, on the morning of the 27th (Fig. 20 a), temperatures are only very little warmer behind than in front of the dotted line, but at noon of the same day, temperatures are considerably higher in the fair weather of the warm sector than in the rain area in front of it. Surface temperatures are accordingly in this case difficult to use in the analysis of the structure of the cyclone.

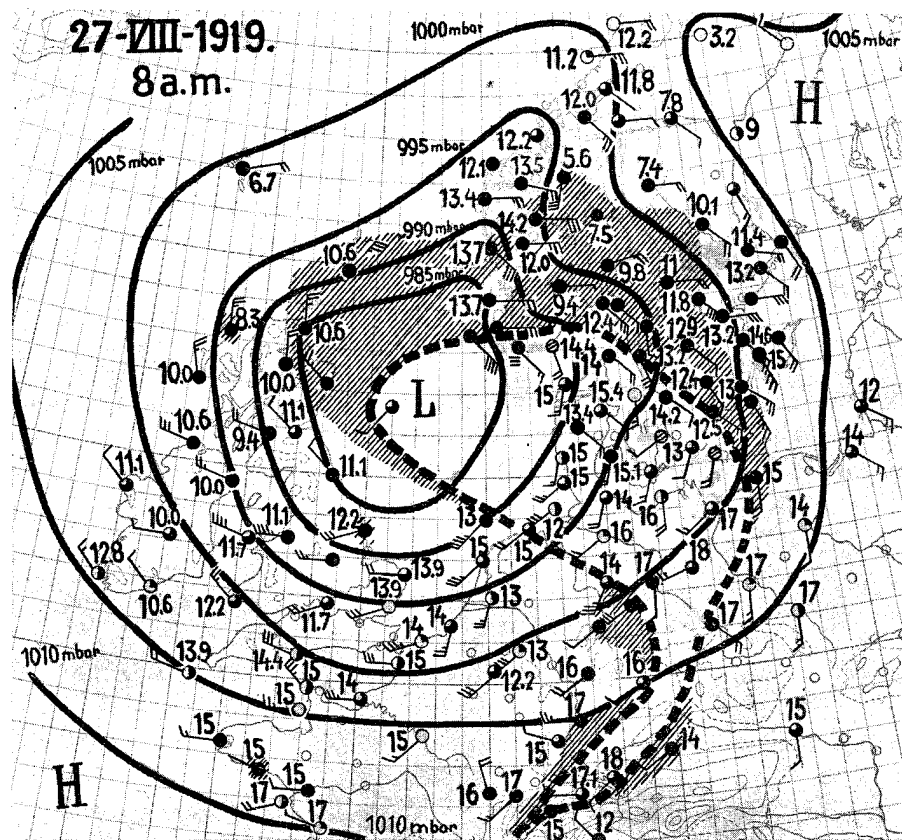


Fig. 19 a.

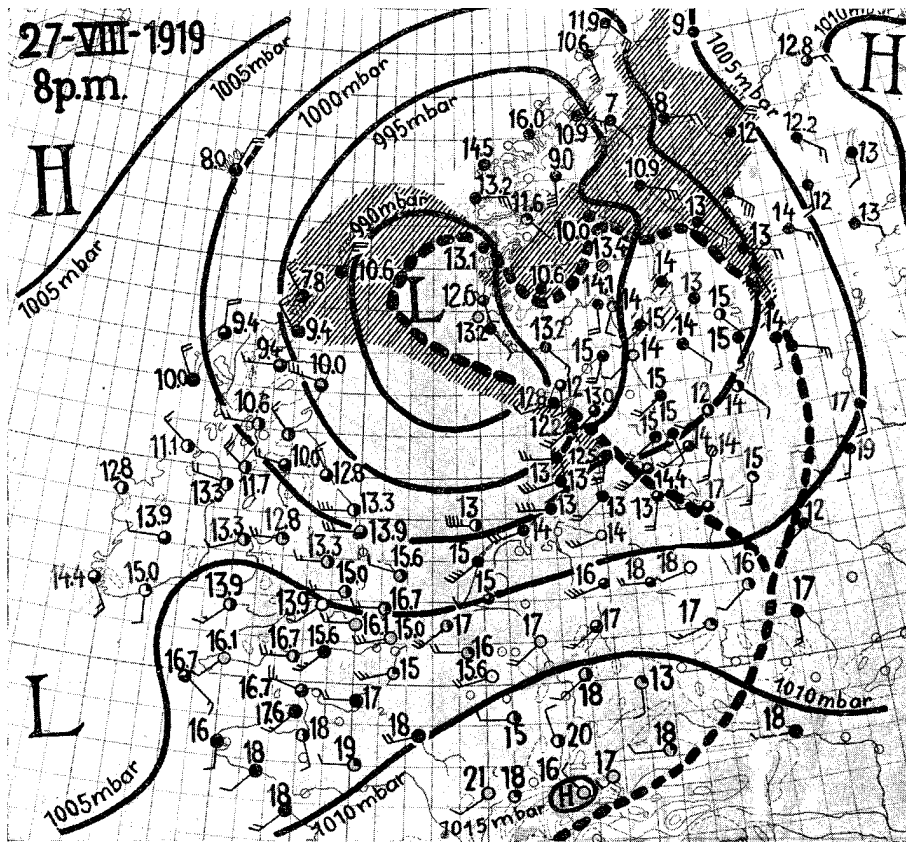


Fig. 19 b.

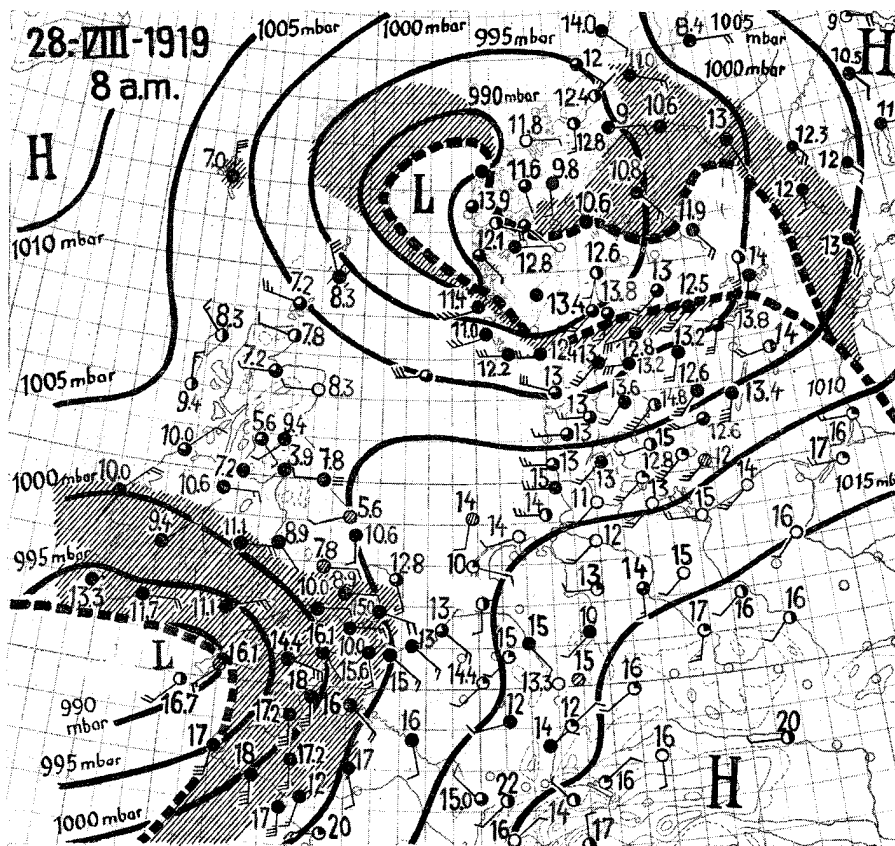


Fig. 19 c.

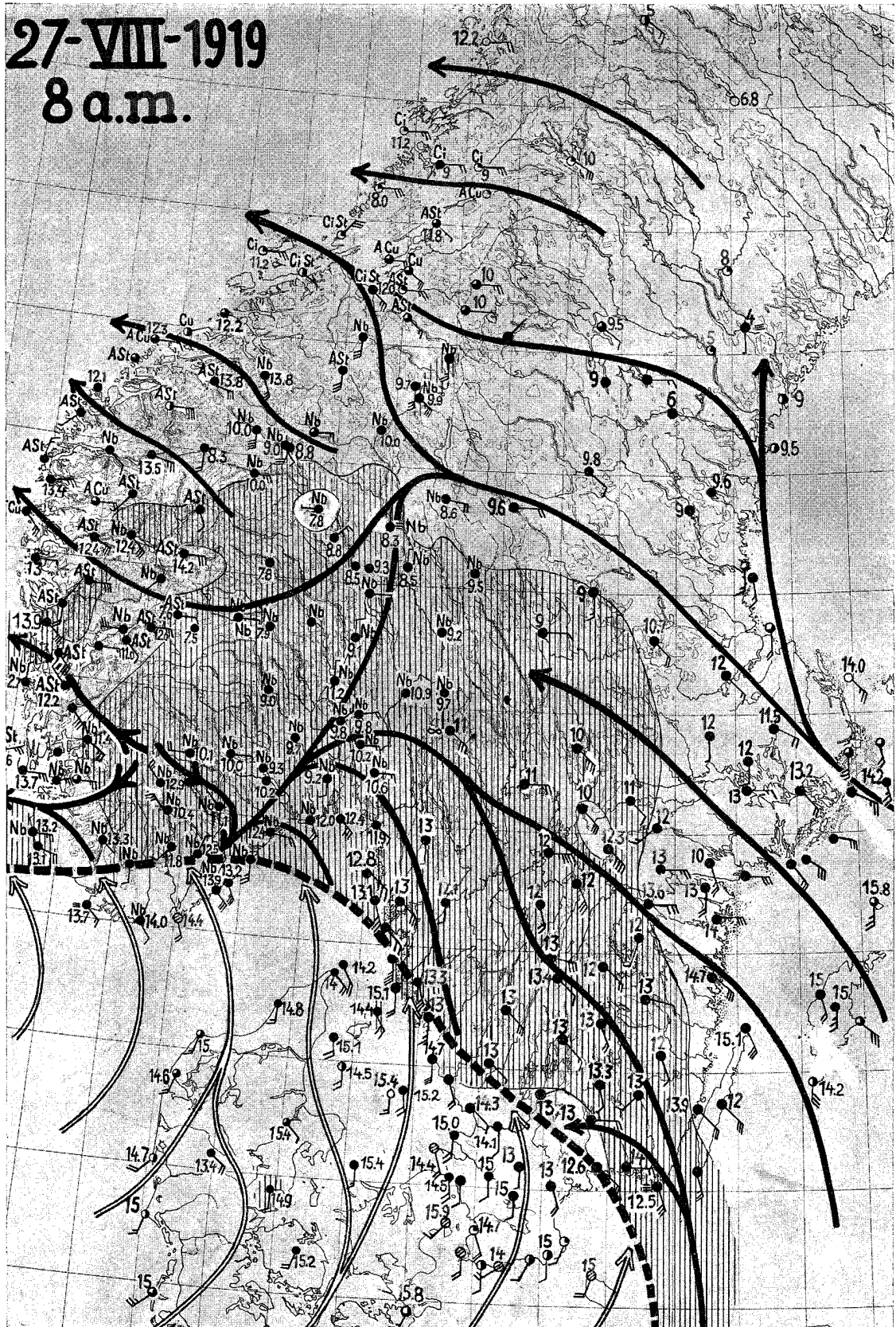


Fig. 20 a.

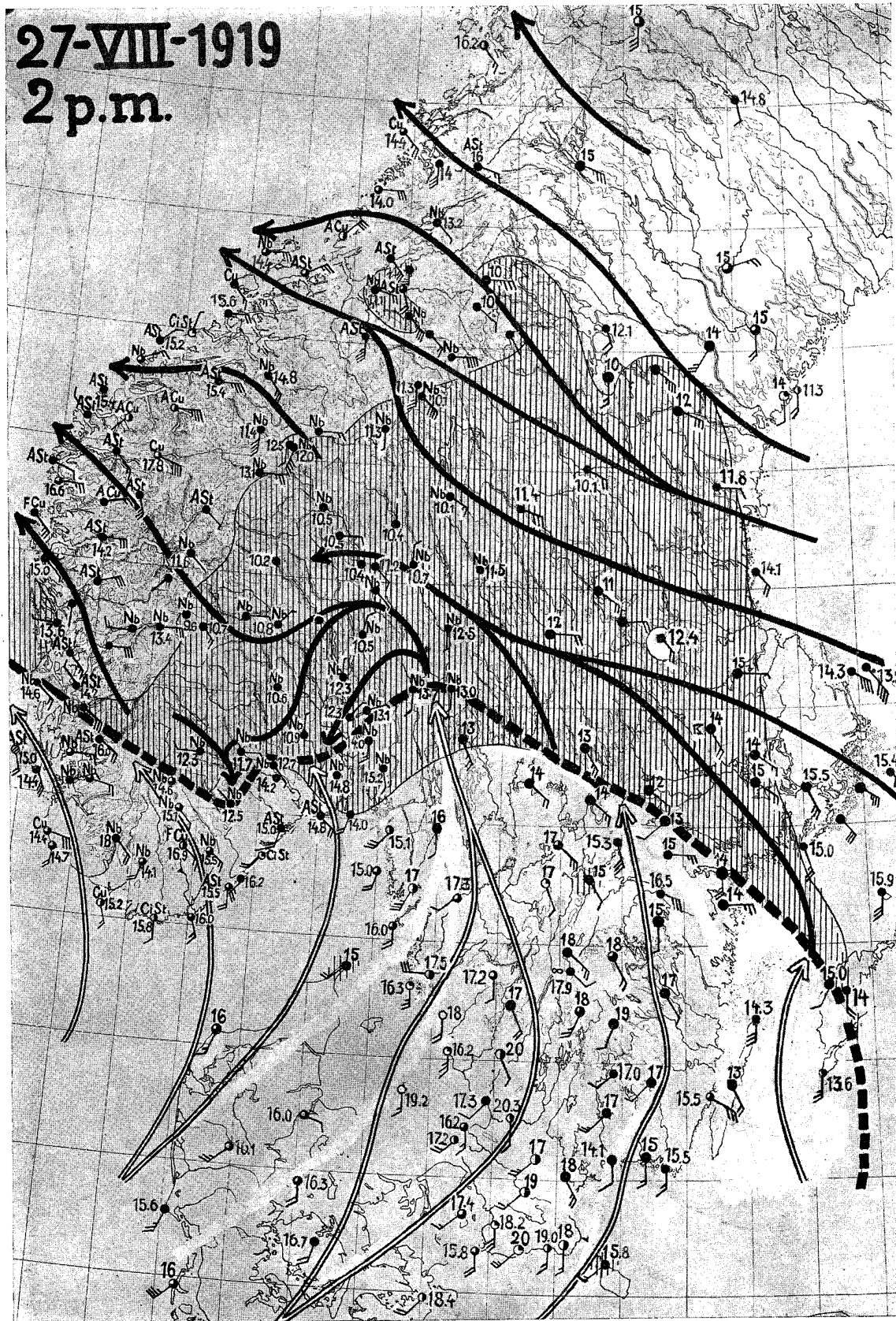


Fig. 20 b.

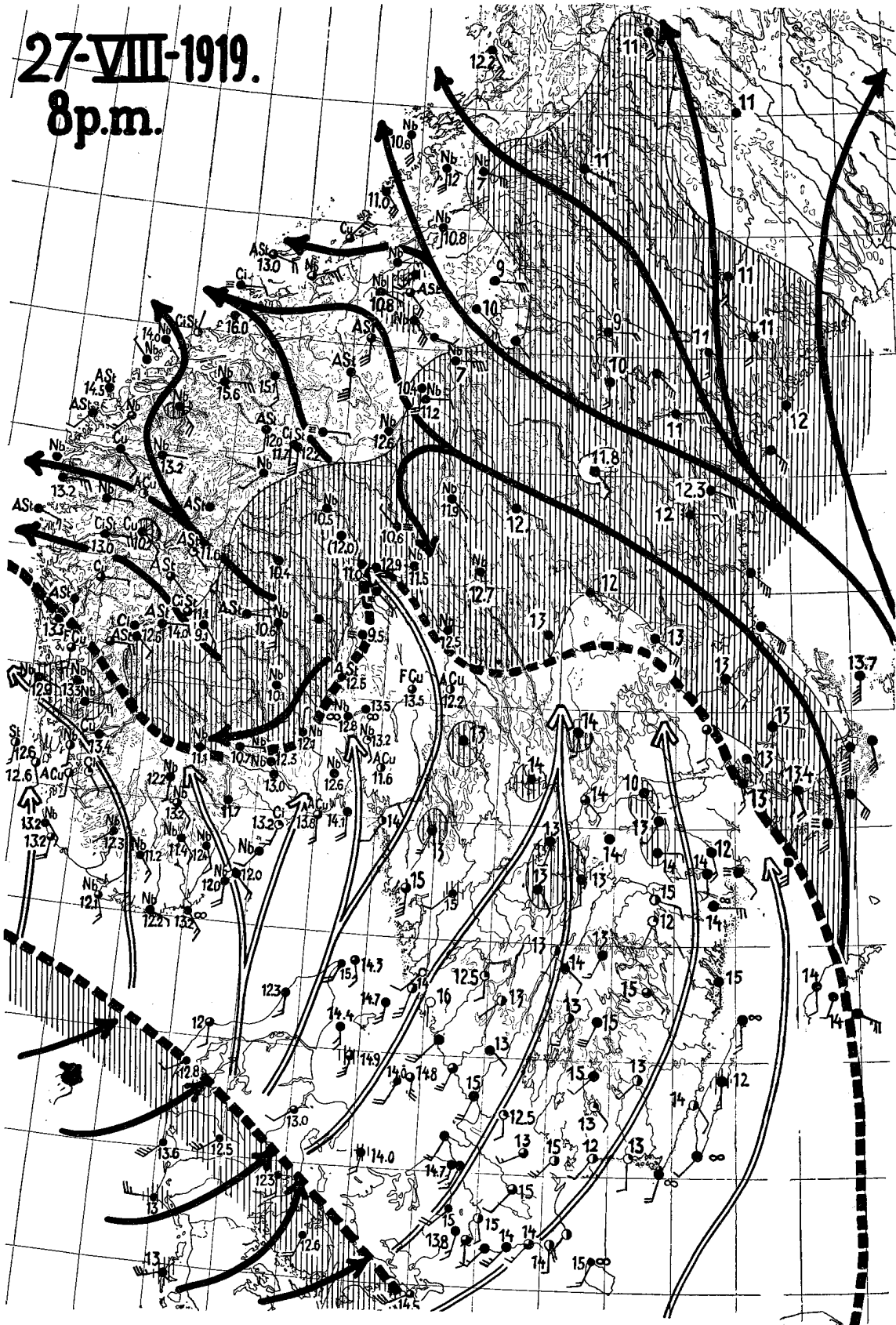


Fig. 20 c.

The cloud forms observed at the Norwegian stations give a better survey of the structure of the cyclone. On the morning of the 27th (Fig. 20 a), the cloud form nimbus is observed over a zone up to 400 km. ahead of the warm front. Then a zone of about 100 km. breadth follows mainly with alto-stratus clouds, and finally cirro-stratus and cirrus are observed on the stations at the northern frame of the map, 600 to 700 km. away from the warm front at the ground. Also the typical clouds of the cold front can be found on the morning of the 28th (Fig. 20 d). Besides the cloud form nimbus, remarkably many stations in southern Norway report alto-cumulus, which drift forwards in front of the cold front rain (see page 15). The alto-cumulus masses arrived at 11 o'clock also over Kristiania.

This perfect conformity of cloud distribution in the slight summer cyclone with that of the typical winter cyclones shows that the processes going on are in both cases the same, probably only with a difference of intensity. The summer cyclones have smaller contrasts of density from which they can derive their kinetic energy, so that velocities, horizontal as well as vertical, become slighter. The high absolute humidity in summer cyclones and their slow propagation make, however, the resulting amount of precipitation during the passage as big as or bigger than that of winter cyclones.

The four maps Figs. 20 a, b, c, d render also good specimens of the influence of mountains on the rain zones of cyclones.

On the western side of the Norwegian mountain range, the cold air flows down the slope and causes, after having been heated and dried, strong Easterly Föhn wind in the fjords. Under these circumstances, the precipitation which is formed above the warm front surface, will evaporate in the dry Föhn air and fail to reach the ground or reach it only as slight rain. The western slope of the mountains accordingly receives in this situation only slight and intermittant rain. Even the continuous cover of clouds may at times break up on the lee side of the mountains, when the descending motion of the cold air also forces the overlying warm air to descend. This descending motion makes the cloud masses in the warm air dissolve and adopt the characteristic form of Föhn clouds, or alto-stratus lenticularis.

On the eastern side of the mountains, however, the formation of clouds and rain is favoured by the inclination of the ground. The cold air is already moist on account of the forced ascension towards the mountain ridge, and the precipitation formed above, falls without considerable evaporation. In this situation, the rain will accordingly begin earlier on the eastern slope of the mountains than on the western slope, and even relatively earlier than on the plain country in Sweden. In this way the great breadth of the rain zone on the eastern slope of the mountains is to be explained.

The influence of the Norwegian mountains is also seen on the propagation of the two boundary lines. They are both propagating slower over the rough surface of the mountains than over the sea and the plains. Rather interesting is the deformation produced in the course of the warm front on the south-eastern slope of the Norwegian mountains. In this region, the South Easterly current of cold air flows against the mountains and tries to curve round the obstacle. The way to the south of the mountains is still open on the morning of the 27th, but is afterwards blocked by the warm air. From that moment the cold current runs into a cul-de-sac, bordered on the west and the north by the mountains, and on the south and upwards by the warm front surface. Only the lowest passages towards the north-west are still open and let parts of the cold mass pass. The greater part of it will, however, keep on the south-eastern slope, and thus stop the advance of the warm front. The warm air current will all the time push upwards above the cold air, and the rain accordingly continues wherever the cold air remains. In the upper valleys of eastern Norway this combined warm front and orographical rain lasts more

than 24 hours. This rain falls all the time through the same cold mass of air, and makes it finally so wet that on some stations real fog develops.

The centre of the depression has continuously been situated outside the detailed maps, and we must return to Figs. 19 a, b, c to see the structure of the entire cyclone. On these figures, the rain zone and the lines of discontinuity over Scandinavia are traced on the base of the detailed maps. To a certain extent, the boundary lines may also be traced further down in Germany in spite of the scanty material of observations. The construction of them, however, is very uncertain for the continent, where the heating of the sunshine, acting on cold as well as on warm masses, nearly causes the disappearance of the contrasts of temperature near the ground. In such cases the rain itself is the best indicator of the position of »warm front« and »cold front«. On Fig. 19 a, the warm front runs from Scandinavia over Germany down to Switzerland; the cold front, which at that time has not yet entered the region of the detailed maps, can nevertheless be traced also on the great map. Its characteristic features, the differences of temperature and a marked increase of wind force make it possible to determine its position in a great curve from the North Sea over western Germany towards Switzerland.

The cold as well as the warm front lead towards the centre of the depression, and are there connected with each other. Between the warm and the cold front, we have the practically rainfree «warm sector», even the ship nearest the centre reports $\frac{3}{4}$ of the sky covered with clouds, and no rain.

Considering the three consecutive maps of the cyclone, the 27th, 8 a. m. 7 p. m. and the 28th 8 a. m. (Figs. 19 a, b, c), we see that the area covered by the warm sector decreases from map to map. On the first map it had an area of 580 000 square kilometres, on the second 490 000 square kilometres, and on the third 290 000 square kilometres. This diminishing of the warm sector is a necessary effect of the ascension of warm air masses upwards over the cold barriers, mainly the warm front surface. The rapid decrease of the warm sector area between the 2nd and the 3rd map, in comparison with that between the 1st and the 2nd map, is certainly an effect of the Norwegian mountains, which retard the advance of the warm front. The warm air which ascends from the ground will spread in higher strata, whereas cold air replaces it along the ground. This development leads finally to the perfect disappearance of the warm sector at the ground. Having arrived to this stage, the cyclone has lost the energy due to asymmetric distribution of temperature, and dies gradually. The cyclone really filled up the following day in the region of the Farøe Islands, and was absorbed by the next cyclone, arriving from south-west.

Cyclones in the dying stage consist of the same cold air mass on all sides, and nowhere in the cyclonic area contrasts of density exist which are able to provoke ascension of larger air masses. Consequently, no bigger rain areas due to atmospheric surfaces of discontinuity can be formed, and precipitation falls only in irregularly dispersed showers. These showers are usually instability showers, formed under the influence of surface heating.

Rather many of the European cyclones are far developed towards the dying stage, when arriving from the Atlantic, and show only rudimental remainders of warm front and cold front rain.

The weather situations described above (July 24, 1918, January 21 to 22, 1921, and August 27 to 28, 1919) bring only some few specimens of the two different types of rain: warm front rain and cold front rain. *All moving rain areas of bigger dimensions (not of squall type) occurring in any situation may be classified as belonging to one of these types. They may, however, either exhibit the accentuated typical shape, or they may be dissolving remnants of previously typical formations.*

Rain zones of bigger dimensions never form in homogeneous currents which do not contain thermal boundary surfaces. Buoyancy forces are there too small to produce rain-giving ascending motion.

Local Showers.

We have treated before (page 8) the instability showers formed under the influence of heating from the ground, especially from warm sea surfaces. A similar sort of showers develop as an effect of insolation over land. The detailed topography of land surfaces makes such rain fall in »local showers«, a name which is generally adopted in meteorological literature.

The local ascending currents (convective currents) giving rise to local showers, will start where air masses have become warmer than their surroundings in the same level. The topography and natural disposition of the ground for receiving sunshine heat will thus contribute to the determination of the starting places for these currents. As to the further maintenance of convective air currents, the stability of the air is of decisive importance. In stable atmosphere, ascending air masses become colder than their surroundings in the same level, and resist further motion upwards. In unstable atmosphere, ascending currents are favoured by the distribution of densities, and tend to push upwards until they reach stable layers.

Finally, as to the effects of convective currents, their content of moisture must be considered. The greater the content of moisture, the greater the resulting amounts of precipitation will be.

Our investigations on the subject of local showers are mostly carried out with Norwegian material of observations, and the results can therefore not directly be generalized for flat countries, and for other latitudes. Otherwise, the marked topography of Norway gives the phenomena of local showers a sort of simple regularity which makes it easy to detect laws of general validity.

The mountainous country of southern Norway, surrounded on three sides by the open sea, produces a sort of monsoon wind, in winter blowing towards the sea, in summer towards the land. When atmospheric disturbances pass, the monsoon is overcompensated and cannot be seen, but, whenever the atmosphere is relatively calm and cloudless, the system of monsoons is established again.

In winter, the monsoon is connected with a descending motion over land, and accordingly no opportunity is given for the formation of local showers in that season. In spring, when the cover of snow melts away, insolation may begin to act upon air motion and produce convective currents. The melting of snow takes place in early spring (March) in the coast district, and some months later in the inner parts of the country. As long as the coast districts only are free from snow, the convective currents develop there, producing a range of cumulus clouds along the coast. These formations, however, do not often attain sufficient strength to produce showers. Over the inner parts of the country, the weather keeps generally clear in the spring season, no convective currents being possible as long as the high plains are covered with snow. As, moreover, cyclones are rare too in the spring season, Norway may then get a distinct dry period.

Not before the snow has melted away from the greater parts of the inner mountain regions, the summer monsoon accompanied by corresponding ascending currents over land and descending currents over the sea may begin. This system of motion produces showers over the inner part of the country, and clear weather over the sea and coast districts. This type of weather may occasionally be disturbed by moving summer cyclones, but as

soon as they have passed, and the atmosphere is again generally calm, the same type is established anew. First when the bigger autumn cyclones have begun, and insolation is less intensive, the summer monsoon has no longer opportunity to develop.

The summer monsoon system gives a general ascending tendency of the inland air. Certain parts of the inland regions, due to the topography, will be especially fitted as starting places for stronger ascending currents. Such places are mainly the dominating mountain blocks. Provided, that the mountains are not covered with snow, the air will be heated stronger at the mountain slopes than in the free atmosphere at the same level. This heating effect produces an additional ascending tendency over the higher parts of the country and a descending tendency over the lower regions. The result will be that the general ascending motion due to the summer monsoon system will concentrate above the relatively higher parts of the country, over adjacent plains and valleys even descending currents may develop.

The stability of the air taking part in the monsoon system will decide how high up the local convective currents will extend. As no soundings of temperature are carried out in Norway, we are obliged to use other indices in order to judge the state of stability for the air masses in question. Air masses arriving from the south or east will in summer generally have rather stable stratification. The surface layers of such air have during their travel from warmer to colder regions of the earth lost heat, whereas the upper layers only very slowly change their temperature. The thermal stratification will thus be stable and will disfavour the formation of strong convective currents. Air masses arriving from the north or west will in summer generally have rather unstable stratification. Their surface layers will, flowing from colder to warmer regions, be warmed, whereas the upper temperatures remain unchanged, till convective currents have brought the heat upwards. Such air will consequently be unstable and will favour all vertical revolutions.

Conditions for formation of strong convective currents are thus rather favourable after the passage of cold fronts, when the sky has cleared. The convective currents will, however, only be able to ascend to the upper boundary of the new cold air, and will stop against potentially warmer and more stable air masses. A certain thickness of the cold layers, at least 3 km., will thus be necessary for the free development of perfect cumulonimbus clouds, giving local showers.

The precipitation resulting from convective currents is dependent upon the supply of moisture. Air which is conveyed from far south usually has a great absolute humidity in all layers, the mentioned great stability of such air is, however, still a hindrance for the formation of local showers. Air which is conveyed from far north, for instance from polar regions, will have small absolute humidity, and consequently showers formed in such air may give small amounts of precipitation, in spite of the instability favouring the convective currents. The best conditions for formation of strong local showers occur in polar air, which has been supplied with sufficient moisture. This moisture can only to a small extent be supplied over inland regions, where evaporation takes place merely from lakes and rivers and to a small extent from soil and vegetation. For a stronger developed formation of local showers supply of moisture from the sea is indispensable. When no general wind maintains such transport from the sea, the moisture can only gradually be brought into the country by aid of the sea breeze. »Polar air«, resting over the sea, will under the vivid turbulence due to its unstable stratification soon have absorbed considerable amounts of water vapour which spread rather rapidly also to higher layers. The sea breeze accordingly consists of air which is nearly saturated at the temperature of the sea surface. When this air enters the country, its relative humidity decreases, due to the heating, and it may arrive as a rather dry air in the innermost regions. This exsiccating effect will be greater, the greater the difference of temperature between sea and inland.

The most effective supply of moisture will therefore take place from relatively warm parts of the sea, thus in the case of Norway mainly from the Skagerak and the southern North Sea.

The invasion of the sea breeze into the warm country is analogous to the cold front phenomenon as far as cold air displaces warmer air. The sea air will accordingly during its propagation form a sloping wedge undermining the warmer inland air, and the ascending warm air will usually in the height flow towards the sea with a direction opposite to that of the sea breeze. The thickness of the sea breeze will be greater, the higher the shore of the country, and is thus of great depth in Norway; but nevertheless the cold wedge is shallower than in usual moving cold fronts, and the accompanying vertical motion does not necessarily reach the level of condensation. The fact, that cold and moist displaces warm and dry air, is also unfavourable for direct formation of rain, as only the dry air will ascend. Not before the sea air is warmed enough to be able to take part in the ascending motion will there be any possibility for the formation of rain. This will usually not be fulfilled the first day of sea breeze activity, as the sea air which must be warmed, starts with a rather low temperature when entering the coast.

In the night, the sea air again retires towards the coast. This backwards motion of the monsoon system, which lasts only during the short summer night of northern latitudes, cannot by far carry away all the sea air brought in by the sea breeze of the foregoing day. The sea breeze of the second day has consequently sea air brought in the previous day in front of it, and forces this air to ascend. Conditions for formation of local showers are thus more favourable the second day than the first, still more favourable the third day, and so on.

The first place where local showers develop, will usually be the mountains lying within reach of the sea breeze of the first couple of days. As the velocity of the sea breeze is rather small, the regions farther away from the coast in the central part of the country will first be reached by the sea air after some days. But if the calm weather type persists, the whole country will as an effect of the monsoon system finally everywhere be reached by air which has previously been over the sea. When that stage is reached, the great moisture content permits local showers to develop over the whole country wherever strong convective currents are rising. We have then the typical continental summer rain type which under favourable circumstances may persist for weeks. The cessation of the type is usually brought on by the arrival of atmospheric disturbances. Then the overcast sky allows no strong insolation to reach the ground, stability and humidity conditions are altered by general ascending or descending motion, and all existing local showers are swept away by the strong winds.

The strong ascending current leading to the formation of a cumulo-nimbus, will always be accompanied by descending currents beneath in the cloudless space. In unstable atmosphere, this current will reach the ground with lower temperature than the air surrounding. Further cold air will be formed by the falling rain under the cloud and will join the cold descending air. The entire cold mass thus formed will tend to spread underneath the neighbouring air forcing it to ascend. In this ascending air new cloud-masses form amalgamating with the existing cumulo-nimbus increasing the cloud growth. On flat ground and in the absence of upper winds the cold air would spread symmetrically in all directions and likewise make the cumulo-nimbus cloud grow symmetrically. This case which is of course very improbable and perhaps even unrealizable will have no practical importance. In reality either the shape of the ground or upper winds will make the cloud grow asymmetrically and determine the direction of propagation.

On sloping ground the cold air produced under the shower will tend to flow downwards in the direction of greatest inclination. Later, when the cold mass has attained some velocity, the deviating force of the earth's rotation will also act upon it and give it a

tendency to move to the right (northern hemisphere) of the steepest gradient of the ground. During its propagation the cold air will displace all warm air lying in its way forcing it to ascend and share in the growth of the cumulo-nimbus cloud. The energy for the maintenance of the moving shower may in this case partly be derived from the potential energy of the initial stage of cold and heavy air stored on the top of a slope. Under such conditions, the unstable stratification of the atmosphere which is necessary for the maintenance of showers in flat country, may be dispensed with. So, for instance, showers may develop strongly over the mountains and maintain their strength during their movement down the mountain slopes, but then dissolve as soon as they reach flat regions.

The upper wind which alone determines the propagation of showers in flat country, also influences showers formed over mountains. A shower formed over a mountain peak or isolated block will have opportunity to choose any direction favoured by the upper wind, and moves therefore downwards on the lee side of the mountain. Showers formed over salient heights on the slope of bigger mountains cannot choose all directions of propagation. If the upper wind blows towards the higher mountains, the showers will have difficulties to follow up the slopes, and the conflict of forces then usually leads to the destruction of the shower. It is thus a general rule that no local showers form on the eastern slope of the Norwegian mountains, when the upper wind blows from the east, and, vice versa, no showers occur on the western slopes, when upper winds are Westerly.

On the other hand, showers develop easily on the lee side of mountains. Special favourable conditions have such showers which by the upper winds are blown towards the coast and there profit by the convergence in front of the sea breeze. Also in flat country the most favourable place of formation of local showers is along the coast where upper winds blow from land towards the sea.

These upper winds are usually limited to the layers above the height of the mountain range. If they reach down to the ground they will produce orographical cloud covers or even orographical rain on the weather side of the mountains, and Föhn phenomena on the lee side. In such situations, no local showers have opportunity to develop, on the weather side on account of the lacking sunshine and the conflict of propelling forces for local showers, on the lee side on account of the dry descending Föhn air, which permits no formation of rain.

A weather map in a period of typical development of local showers presents a rather confusing aspect. Winds are slight, all directions occur, and the weather changes from clear sky to heavy thunderstorm. A very close network of stations is necessary to give a survey of the situation. Even the networks used in the Norwegian Weather Service in the latest years is not sufficient if all occurring local showers shall be detected and explained. A detailed investigation of the records from about 400 rain-gauge stations has therefore been made for several periods of local showers. These rain-gauge stations give the amount of rain during 24 hours measured 8 o'clock each morning. Further indications are given about the time of day, forenoon, afternoon or night, when rain has fallen; some stations give even exact time of beginning and end of rain. This material proved to be very useful. The regions where local showers had occurred could be determined with considerable certainty, and within these areas the places could be pointed out, where showers had developed before noon, and where they first arrived in the afternoon or even in the night. Thereby also some indications were given about the place of formation and dissolution of showers and the approximate routes of the moving shower systems.

Development from Dry to Showery Summer Weather.

Figs. 21—26 give a series of maps from a period of local showers in the summer of 1918, from July 29 to August 3. The general situation changed rather slowly during

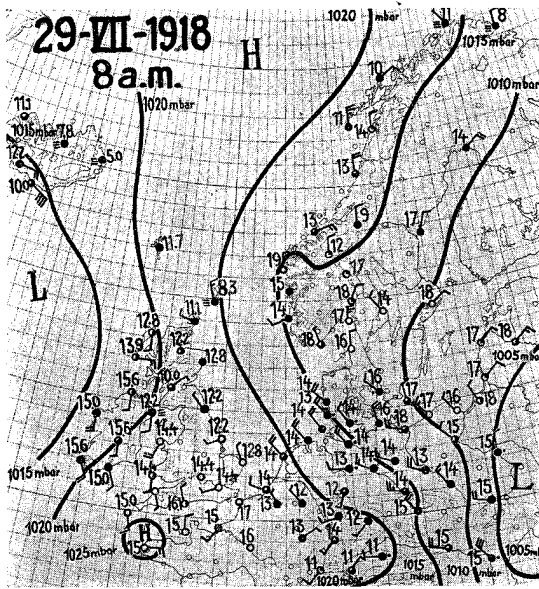


Fig. 21.

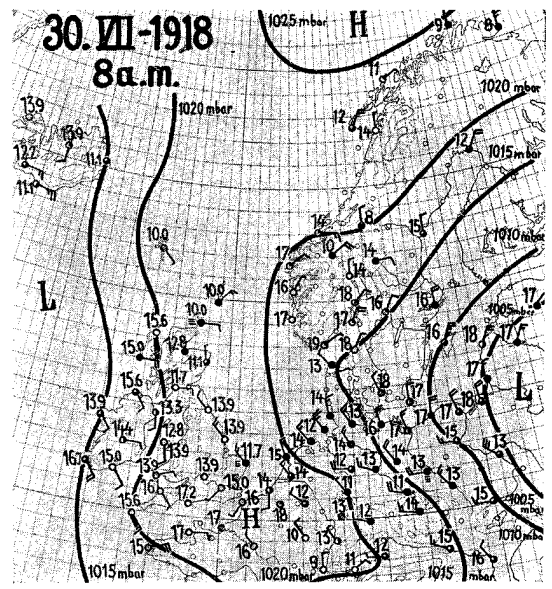


Fig. 22.

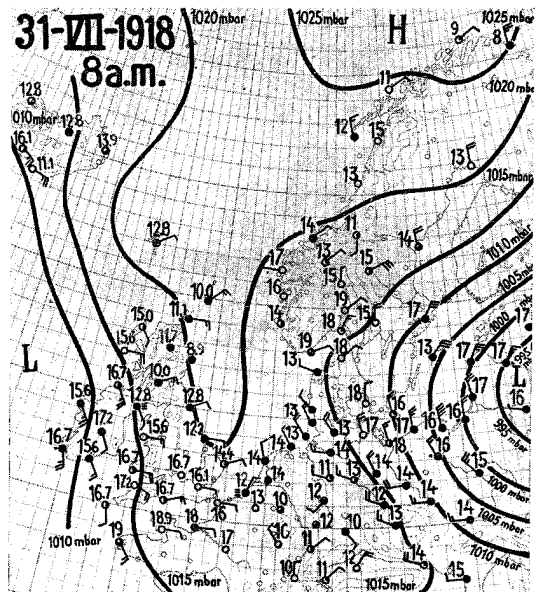


Fig. 23.

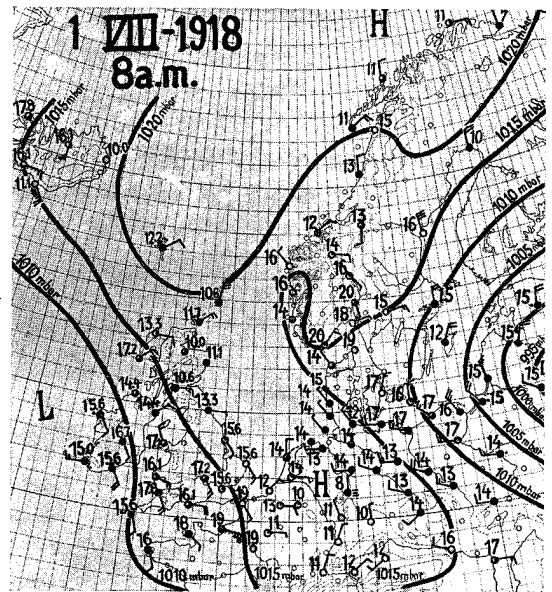


Fig. 24.

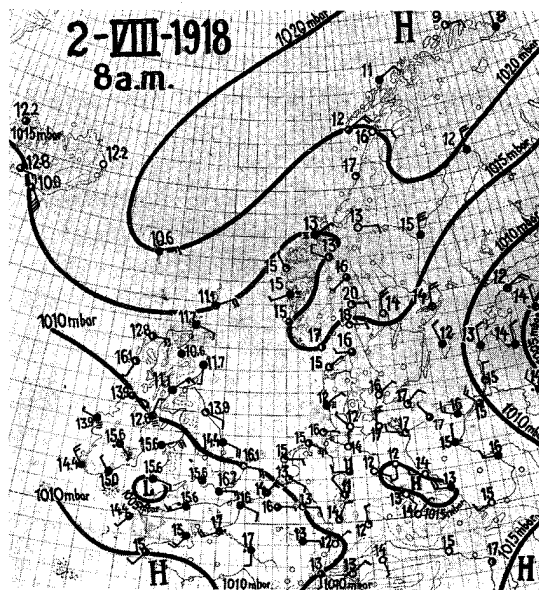


Fig. 25.

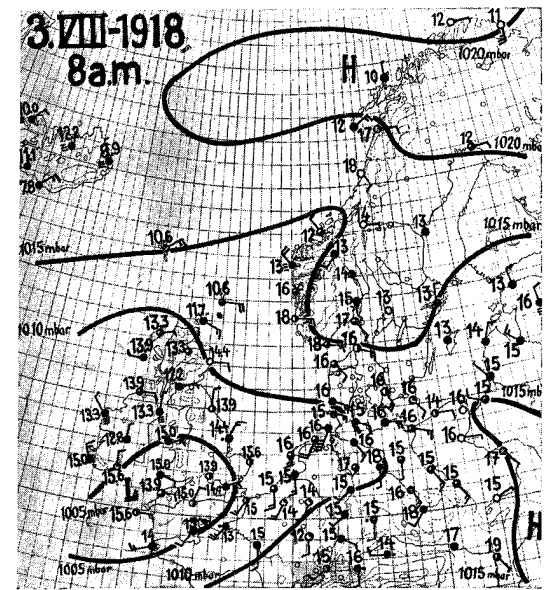


Fig. 26.

that period. From July 29 to August 1 low pressure existed over the Atlantic and over Russia, and a ridge of high pressure extended from the Norwegian Sea through the North Sea to France. On the 2nd and 3rd of August, the eastern low pressure withdrew eastwards and the western low entered over England.

For the part of southern Norway, this series of days brought a slight Northerly, later Easterly, current of air; the first days of the series conveying air directly from polar regions, later from northern Russia. It is therefore likely that the air over Norway during the whole series of days on account of its cold origin easily could be made unstable by the daily insolation. Conditions should therefore seem rather favourable for the development of local showers, provided that also sufficient moisture can be supplied to the originally very dry polar current.

The diagrams on Fig. 27 show the variations of absolute humidity derived from the readings three times daily, on some selected Norwegian stations. On the station Rena, the beginning of the Northerly current had brought a sudden fall of absolute humidity from 11,7 mm. to 7,4 mm. in the night between July 28 and 29. Then the humidity remained low with small fluctuations till August 3, when a distinct rise set in again. The station Granheim records frequent changes between dry and moist air. After a dry period from the morning of the 29th till the forenoon of the 30th, the noon and evening readings of the 30th show the presence of moist air. On the 31st the air is again rather dry; but during the night to August 1 again moist air has arrived and stays till the afternoon of the same day. After some later fluctuations on August 2, the moist air finally conquers the place on August 3. At Mykland, farther south, the humidity was high, however with several smaller variations. The last day of the series an abrupt fall of humidity set in. The curve from Oksø exhibits nearly the same character, humidity being constantly high until the night between August 2 and 3.

Although the weather maps show no special incidents of greater dimensions in the weather situation, there has in Norway been a vivid struggle between dry and moist air masses. The result of this struggle proved to be of deciding importance for the occurrence or non-occurrence of local showers. An attempt is made below to follow the development of the situation in detail in Norway, making thereby use of all available records of humidity for determining the mutual limit between moist and dry air masses. In the regions of moist air the lines of flow are drawn with double lines, in the dry air with single black lines.

Figs. 28 a, b, c show the situation at 8 a. m., 2 p. m. and 8 p. m. on July 29, 1918. The Northerly current enters through Trøndelagen and flows across the whole country. Absolute humidities are plotted reduced to sea level*). There may be seen a rather

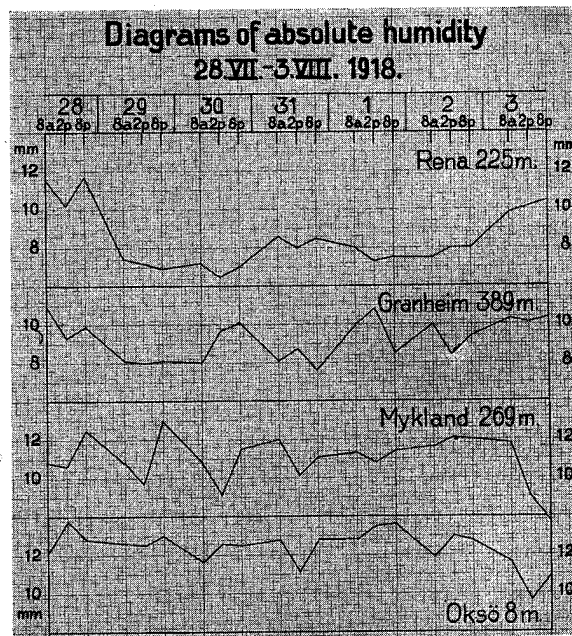


Fig. 27.

*) According to the formula: $\log e_0 = \log e_h + \frac{h}{6300}$ (v. Hann: Lehrbuch der Meteorologie, 1915, p. 230).

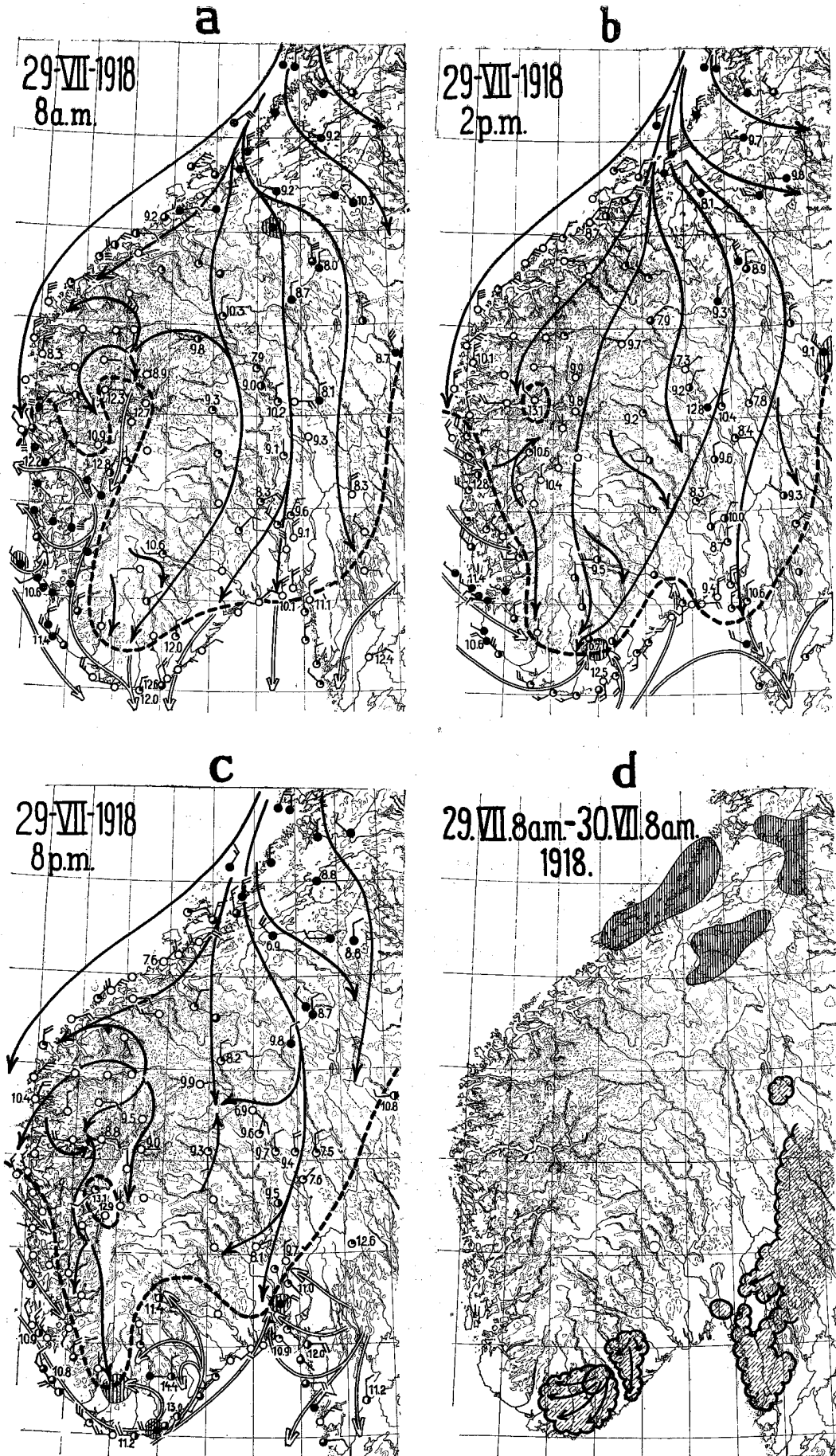


Fig. 28.

distinct limit between moist and dry air along the dotted line on all three maps. The passage of this limit had just caused the sudden fall of humidity, which is to be seen on the diagrams (Fig. 27) for Rena, and (although slighter) on Granheim. On the morning, the limit is still moving southwards following the Northerly current. At noon, however, the Northerly current on the entire coast section from the Kristianiafjord to the Sognefjord has been replaced by the sea breeze, which stops the further invasion of dry air from the north. In the evening, the sea air has reached farther inland bringing moist air just up to Telemarken (Dalen).

On Fig. 28 d, the regions are indicated where rain has fallen during the same day. The greater part of the country has had fair summer weather without any precipitation. In Trøndelagen, on the northern slope of the mountains, some slight orographical rain has occurred. Along the Swedish frontier where the moist air has not yet been driven away, local showers have developed. Some of them have even drifted down to the Kristianiafjord.

The strongest shower have formed in the southernmost part of the country inside the two small shaded areas. The sea breeze has there, on account of the shape of the coast, converged towards a centre near Evje in Sætersdalen. In the region of this centre, convective currents concentrate, and heavy showers with thunder are formed. The arrows within the shaded areas indicate the direction of propagation of the single showers deduced from the time of beginning and end of rainfall. In the northeastern corner of the western shower area rain has begun already before noon. This place corresponds just to the position of the wind centre about noon, i. e., it lies just within reach of the moist air supply through the sea breeze. Likewise, the small shower area beneath lies within the region occupied by the moist air.

In both areas the showers have travelled south or southwestwards following the upper wind as well as the sloping ground.

Also within the dry air, convection has certainly occurred, for instance around the wind centre visible in the evening in eastern Jotunheimen, but it has not resulted in any formation of rain.

The following night, the land breeze dominates and persists till the morning of the 30th (Figs. 29 a, b, c). In the morning however, there is still great humidity on all coast stations, and even farther inland on Mykland, Kristiania, and Aas moist air remains. The land breeze, thus, has not been able to bring back again all moist air brought into the country by the sea breeze of the previous day.

Otherwise, the situation is almost exactly the same as the foregoing morning, slight Northerly winds with clear weather except on the northern slope of the mountains.

The monsoon system of this day brings the moist air considerably farther into the country. The most rapid invasion of moist air has taken place towards the Jotun mountains where the station Granheim records a sudden increase of humidity from morning to noon and evening (see Fig. 27). Obviously, the sea air which entered the country the day before, has advanced farther following the monsoon circulation and has reached the central mountain block. The effect of this invasion immediately appears (Fig. 29 d) in the formation of showers over the area occupied by the invading tongue of moist air.

The showers have everywhere developed first over the dominating mountain regions, and from there travelled downwards to lower parts of the country.

The precipitation area is divided in several sections arranged around the centres of shower formation. We recognize the same two shower centres from the previous day just at the place where they occurred the day before. The new shower centres are all situated on the dominating parts of the mountains. Especially well developed is the shower centre over the high Gausta mountain where showers developed already before noon. Many of

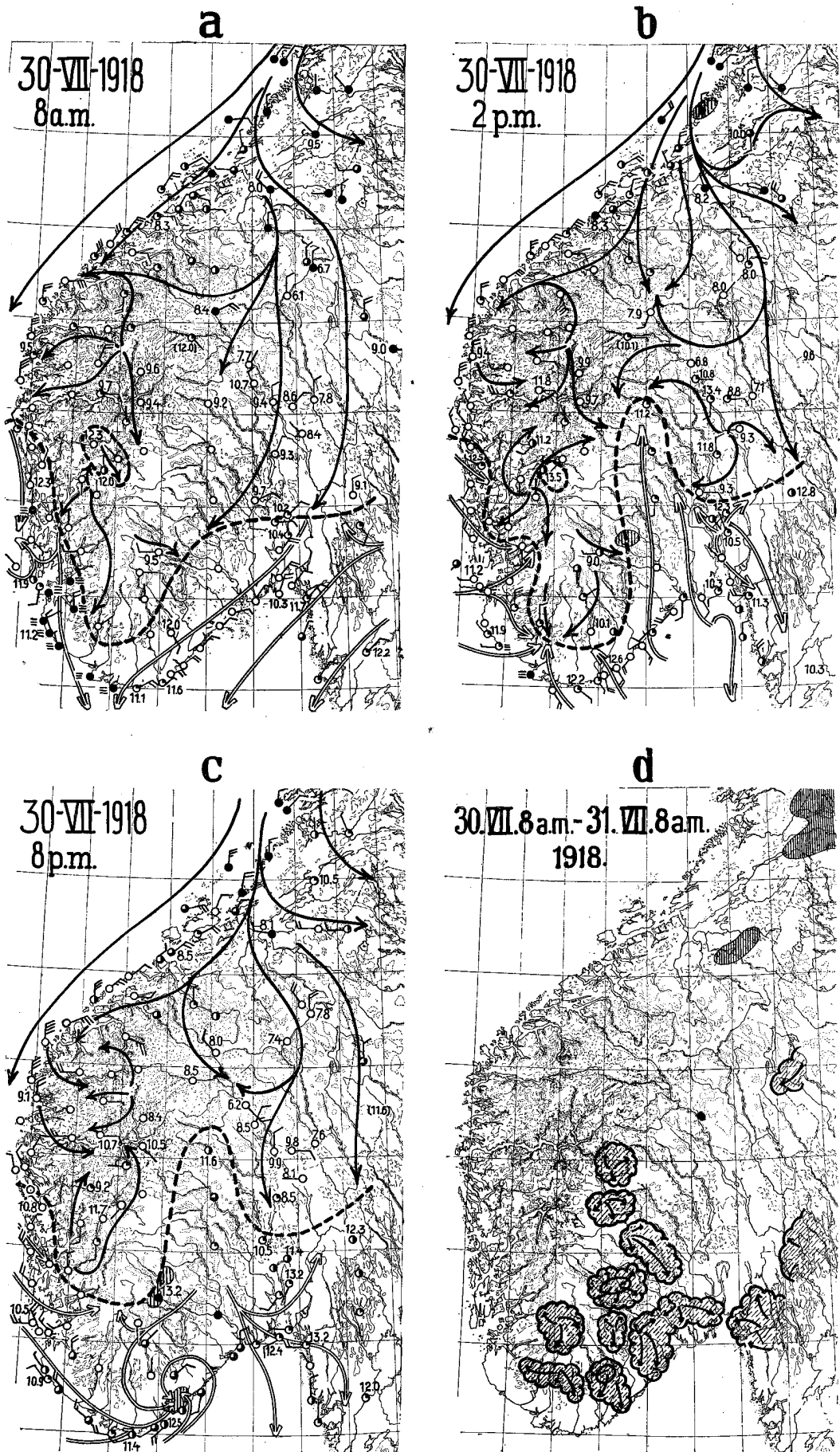


Fig. 29.

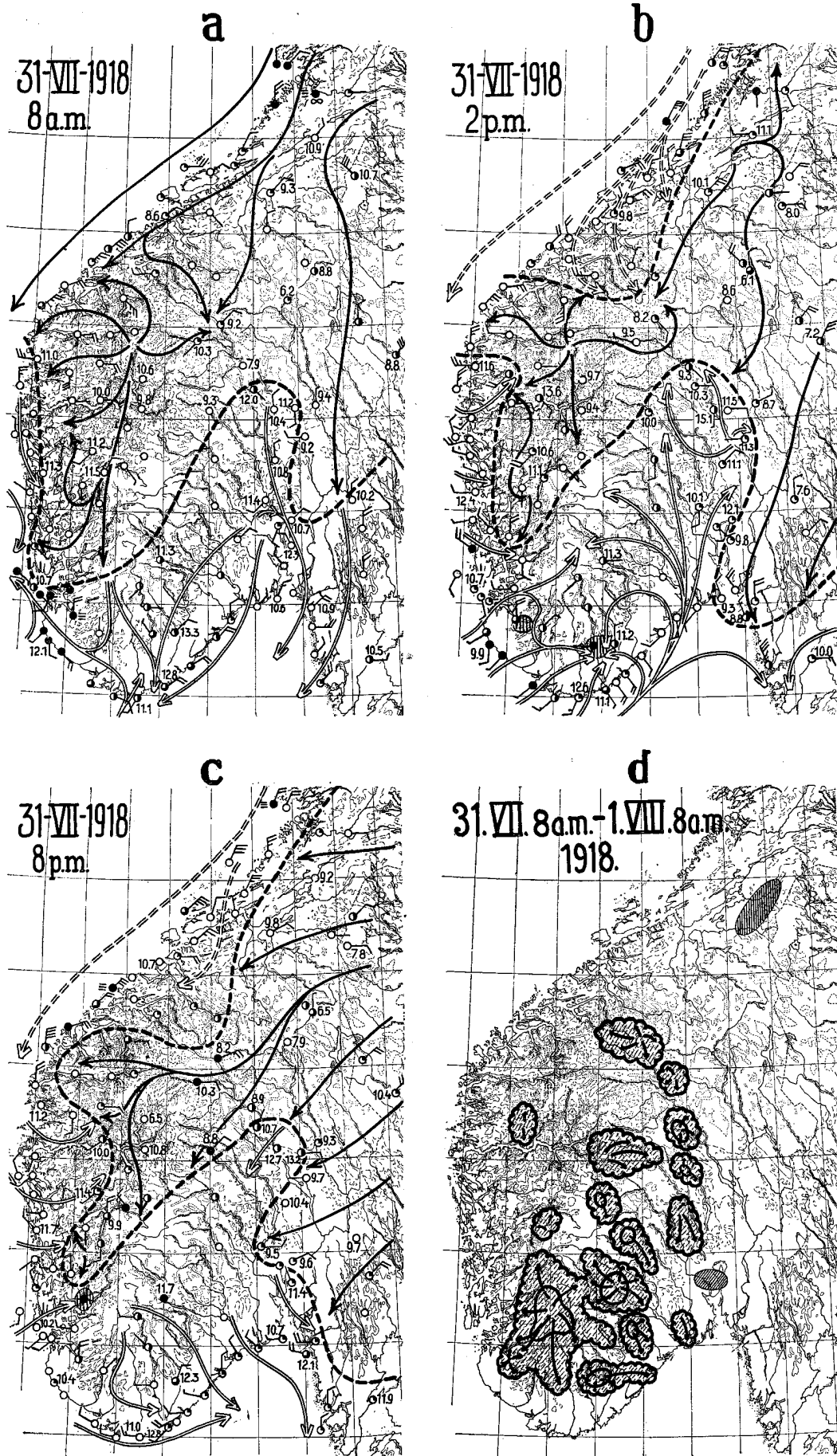


Fig. 30.

the valley stations are reached by the rain first in the night, some of them are not reached at all.

The convection in the dry air has no condensation effect this day, too.

The night between July 30 and 31, the land breeze again for a shorter time transports air towards the sea, but during the forenoon of the 31st (Fig. 30) the moist air has again occupied the lost ground. This day, the projecting tongue of sea air reaches even the region of Gudbrandsdalen.

The strong North-East current along the northwestern coast had the foregoing days prevented the formation of sea breeze, but on this day the interchange of air between land and sea begins there too. The absolute humidity on Kristiansund increases thereby considerably. Unfortunately, there were in 1918 no stations farther inland in that region to control the reach of the sea breeze, but we may, judging from the wind force of the sea breeze, assume that the moist air reached up towards the Dovre mountains. As the sea breeze on the northwestern coast is supplied from a rather cold sea, the content of moisture must be somewhat smaller than in the sea breeze from the Skagerak. In order to point out the difference, the lines of flow in this sea breeze are drawn as dotted lines.

All the shower centres from the foregoing day are again in action (Fig. 30 d), especially strong in the upper Sætersdalen and over the Gausta mountains. In addition, also some new shower centres appear, thus along Gudbrandsdalen and over the Dovre mountains, the last one, however, only giving slight rain. These new formations certainly correspond to the invasion of moist air up Gudbrandsdalen and Romsdalen from the south and north respectively.

Also the first shower centre in western Norway appears this day on the mountains just north of the Sognefjord. The sea breeze from the western coast has thus first after three days brought enough moisture for the formation of showers. Probably, the fact that the sea breeze must enter the country along the fjords is unfavourable for the formation of showers, as the sea breeze is not effectively heated when entering the country and keeps too cold to be able to ascend.

On the maps for the noon and the evening of the 31st, we may see in which districts the sea air has the greatest difficulty of invasion. Apparently, the two big glaciers Jostedalbræen and Folgefonnen have shared in stopping the invasion of moist air. A slowly descending current of cooled air brings a constant supply of dry air from the glaciers to their surroundings. There is no doubt that just this effect of the glaciers makes it possible for the projecting tongue of dry air to keep so long rather near the supply of moist air along the western coast. The mentioned glaciers always form a sort of small anticyclones above themselves in clear calm summer weather.

Similar effects have the greater lakes, especially those containing great amount of cold water from the melting snow and ice of the higher mountains. That is, for instance, the case with the greatest Norwegian lake, Mjøsen, having its water supply from Jotu. Although the area of the sea is not more than 360 sq. km., its cooling influence on the air above it usually suffices to form an anticyclone on hot summer days. This anticyclone also protects the area against local showers.

Over the little shaded isolated area in the Kristianiafjord district (Fig. 30 d), rain has fallen during the night. It can thus not be usual convective rain due to insolation heating, nor can it be showers formed during the day having travelled to the place. Probably, this rain is due to the vertical motions at the boundary between the dry and moist air masses. It is not impossible that the different daily periods of temperature in dry and moist air influence the equilibrium of their mutual boundary surface. If it be so, the moist air would be colder than the dry air in the day-time and warmer than it in the night. Accordingly, the moist air would have a tendency to form a wedge

undermining the dry air in the day-time, and, vice versa, the dry air would penetrate under the moist air in the night. Only this last process, cold and dry undermining warm and moist air can produce rain. Oscillating fronts of this sort between dry and moist air will thus especially give night rain, just as that formed over the Kristianiafjord district on Fig. 30 d. Rain of the same sort still persists the next morning over Tyrifjorden and two days later it also occurs in the district of Mjösen.

On August 1 (Fig. 31), the sea air enters still farther into the country, so, for instance, between the two big glaciers Folgefonna and Jostedalbræen. This invasion renders the formation of showers possible also over the mountains of the Voss district. In spite of the favourable position near the coast, this district does not get any showers before the 4th day after establishment of the monsoon type. Probably, the two mentioned glaciers have prevented the free development of the sea breeze and hindered the necessary supply of moisture.

The inflow of sea air from the northwestern coast has led to the formation of a new shower centre to the north of Jotunheimen and to a reinforcement of the old centre on the Dovre mountains.

In addition, all shower centres from the foregoing days are in action, bound to exactly the same dominating mountains. The formed showers have this day a still greater vitality than the days before, and travel longer distances before they dissolve. The rain-free space between the shower centres then becomes narrower or even disappears entirely. Thus, the whole range of shower centres between Hallingdal and Jæderen in the course of the day bring rain over a large continuous area.

On August 2 (Fig. 32), the moist air has occupied the whole country to the west of a line running approximately south-north from the Kristianiafjord to the northwestern coast at Kristiansund. The outflow from the glaciers seems still to indicate the presence of descending air, but even this air is not so dry as it was the foregoing days. Only around Jostedalbræen, the formation of showers is prevented by the «anticyclonic» influence of the glacier.

Otherwise, showers travel over nearly the entire region occupied by the moist air, producing in the course of the day a great complex area of precipitation. In the multitude of showers having travelled within this area there is still some sort of law-bound order. The regions which have had showers before 2 o'clock p. m. are certainly now greater, but lie still on the same mountains where the first shower centres of the period appeared some days earlier. Likewise, the showers travel also this day down the sloping ground towards the valleys or the coast where they dissolve in the evening.

Along the limit between dry and moist air running across the country, the rain continues even in the night and persists still the next morning. The effects of this boundary line begins thus to resemble those of the great atmospheric cold fronts and warm fronts. Its effects are, however, still especially confined to the night time.

In the course of the described period, the Norwegian monsoon system has not been seriously disturbed by stronger general winds, especially as the southern part of the country has been lying in the lee of the Northerly current. On August 3 (Fig. 33), the arrival of a depression over the British Isles developed a rather strong Easterly current in the Skagerak and the southernmost part of Norway. This Easterly current, belonging to the outer part of a cyclone, is always divergent and accordingly dry. The absolute humidity drops in the southernmost part of the country from about 12 mm. to below 9 mm. (See also the diagrams on Fig. 27 for the stations Mykland and Oksö).

The effects of this dry air supply appear immediately on the map of precipitation (Fig. 33 d). The whole series of shower centres along the southern coast become inactive, and a coast stripe of 60—100 km. becomes perfectly rainfree for the whole day. First

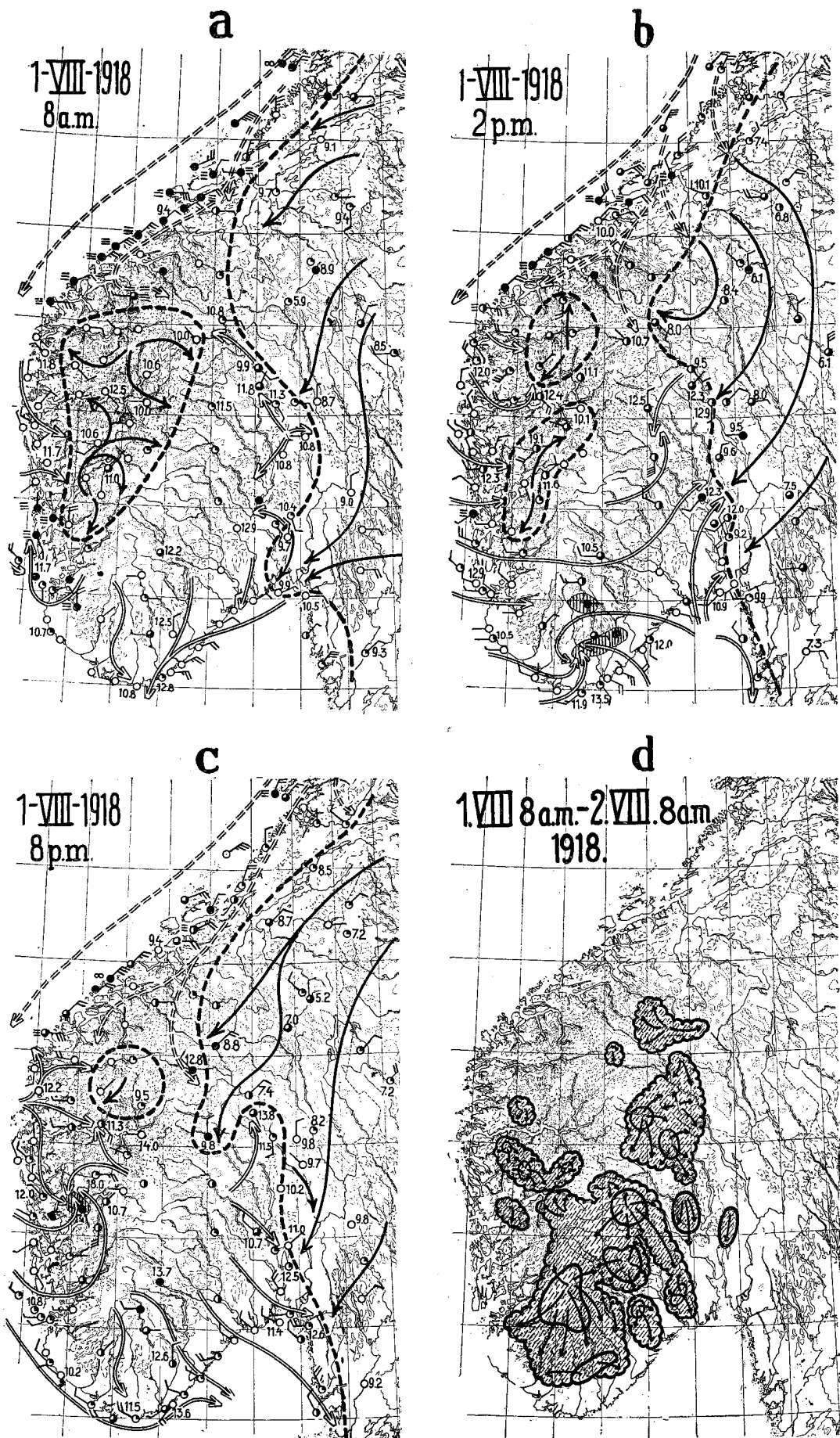


Fig. 31.

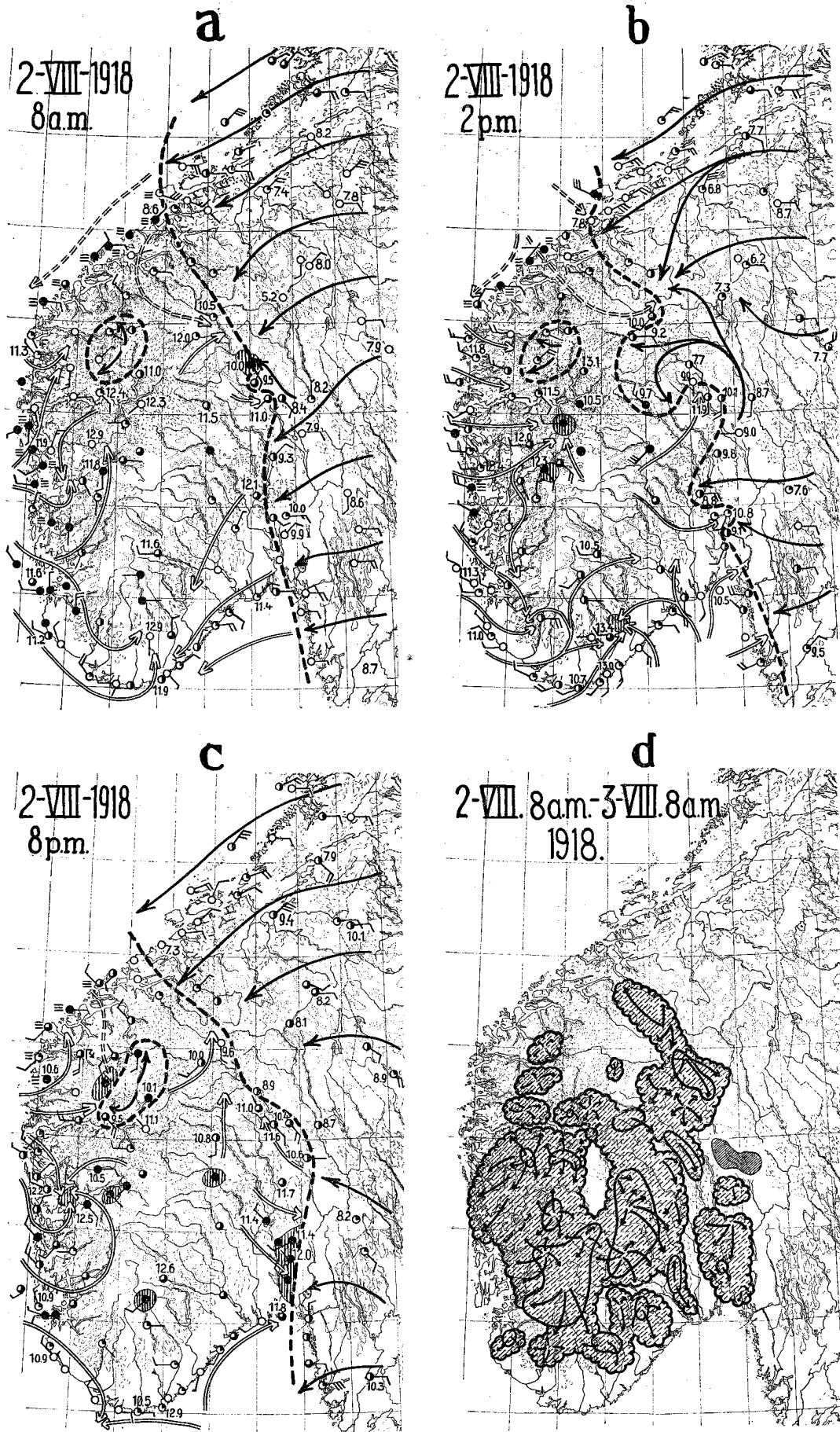


Fig. 32.

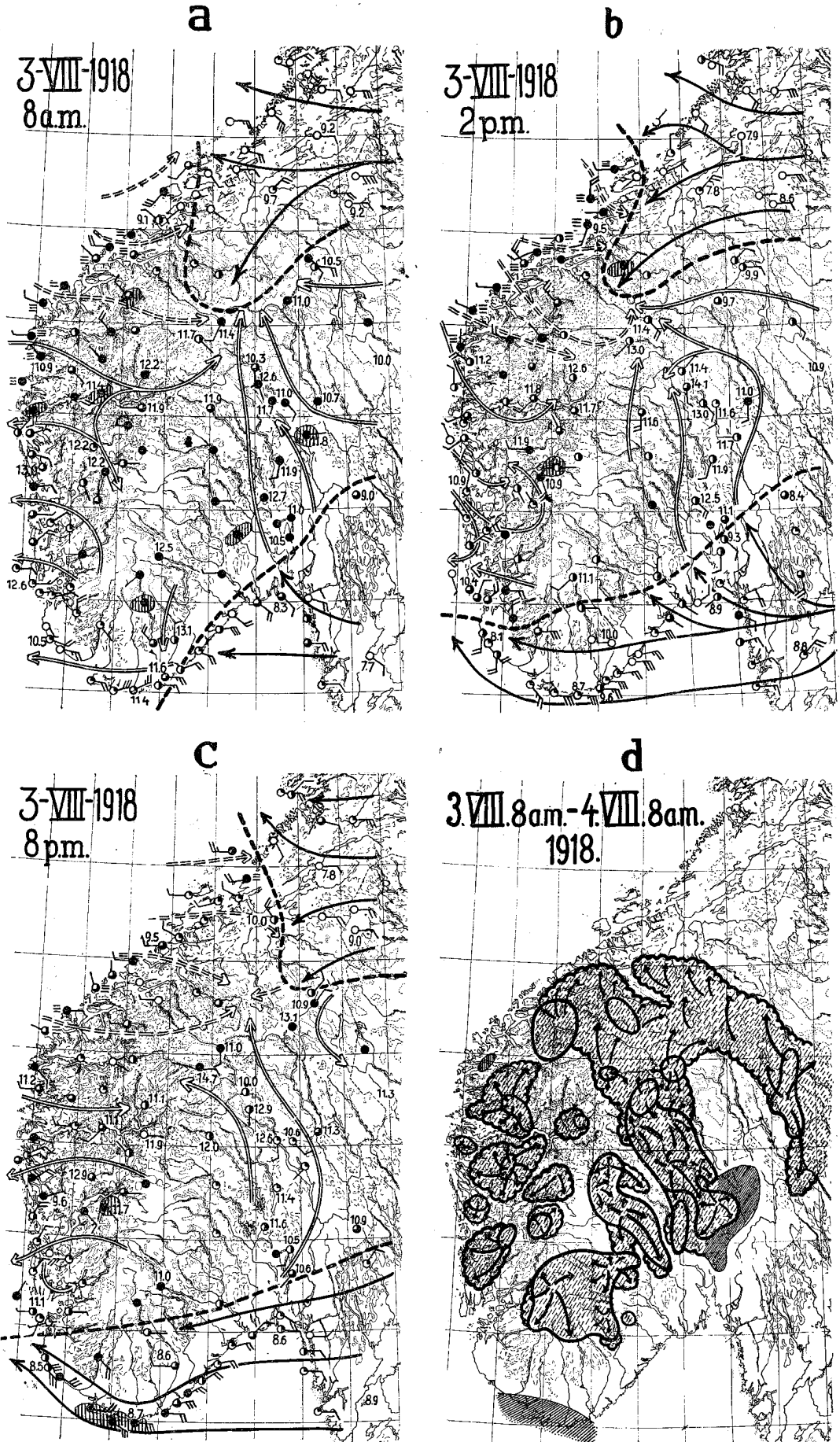


Fig. 33.

in the evening and the night, the foremost front of the cyclonic rain reaches the utmost, southwestern corner of Norway (shaded area).

Farther up in the mountains, where the moist air still remains, the shower activity continues as strongly as it did the preceding days. In western Norway, the showers again drift out to the sea following the Easterly drift in the height.

To the NE of the district of Mjösen there has been no supply of moist air from the Skagerak during the whole series of days. This day, however, the Easterly current brings moist air from the Bothnian Sea across Sweden to the easternmost part of Norway. Humidities have already increased considerably on the three eastern stations Rörös, Tönset and Rena in the morning, and in the course of the day showers also developed over this part of the country.

Six days have elapsed till the moist air and the local showers have perfectly invaded the central parts of the country. The noticeable slowness of this process is due to the slight wind velocity of the monsoon system and the counteracting land breeze in the night.

The characteristic slow development from dry to showery type can often be observed from a fixed point. The convective cumulus clouds attain bigger dimensions from day to day, till finally the cumulo-nimbus stage is reached and showers develop, the intensity of which still increase the following days.

Another series from July 23 to 27, 1919, will show the opposite development from a showery type to a dry one.

Development from Showery to Dry Summer Weather.

The maps, Figs. 34—38, represent a series of rather similar weather situations over Europe from the morning of the 23rd to the morning of the 27th of July, 1919. On the 23rd, the first day of the series, showers have occurred over the greater part of southern Norway. On the 27th, only a single local shower occurred in the whole region.

Such striking contrasts of weather at nearly the same distribution of pressure are frequently experienced, and bring much trouble for forecasters. In this case, the air supply

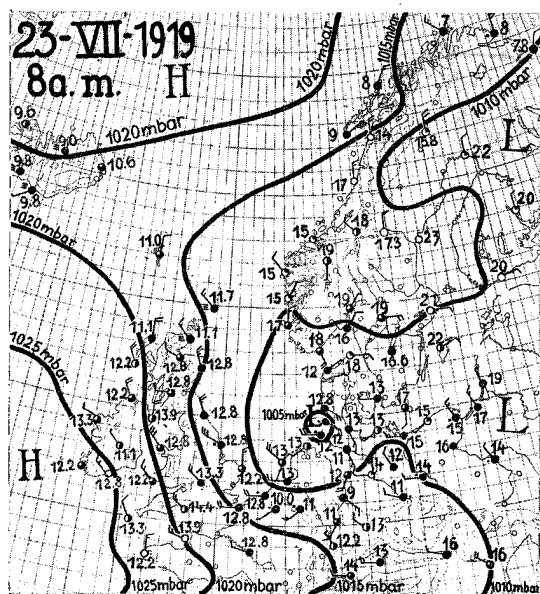


Fig. 34.

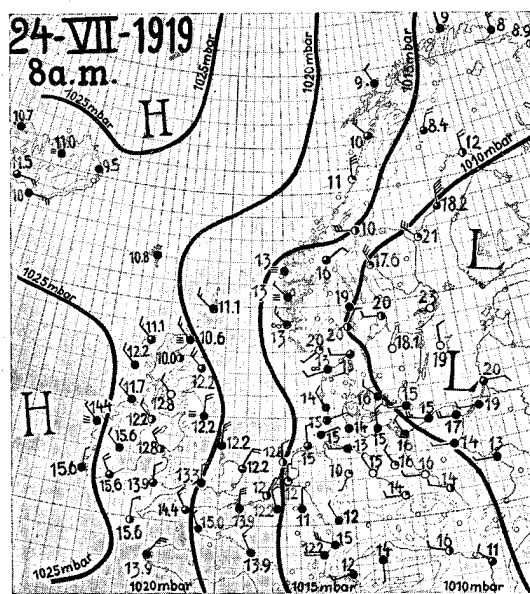


Fig. 35.

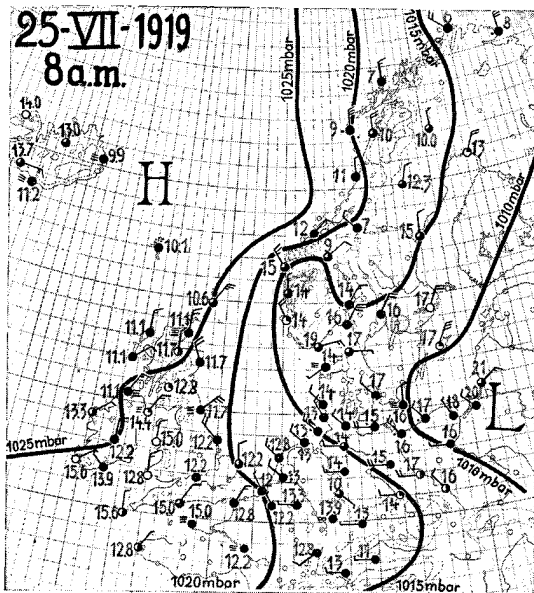


Fig. 36.

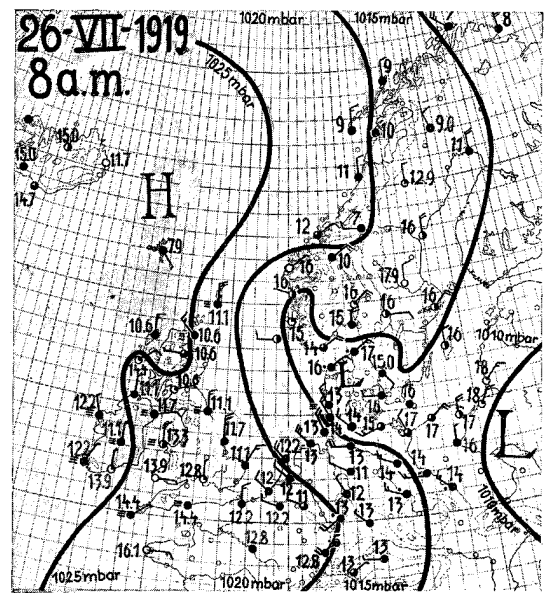


Fig. 37.

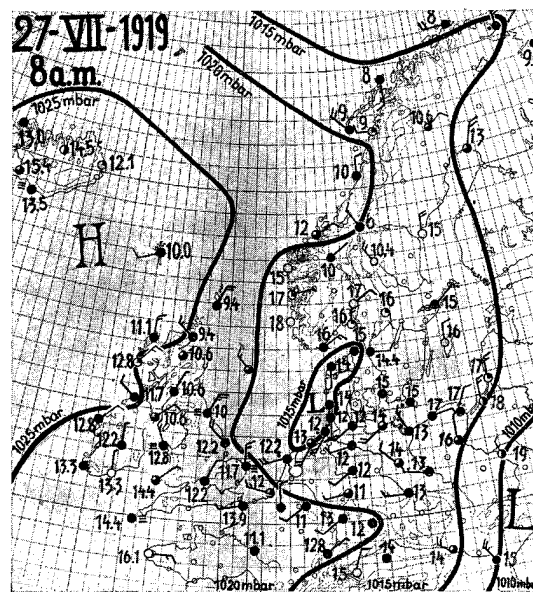


Fig. 38.

and the corresponding change of humidity and stability account for the development from showery to dry type.

In the days preceding July 23, a stationary cyclone lay in the North Sea, causing Southerly winds over Norway. The Southerly current originated from polar regions and had become moist and unstable over the warmer regions which it passed when curving round the stationary depression. Conditions for the formation of local showers were thus favourable as soon as the dull cyclonic weather had cleared, and the insolation began to produce convective currents.

The map (Fig. 39) illustrates the result of the first day of sunny weather. Over a greater part of southern Norway, local rain developed, forming greater continuous areas in the southeastern part and scattered showers over the rest of the country.

Provided, that the same air stays over the country, the effects of the convective currents are likely to be the same the following days. In this case, however, a change of air supply occurred.

This can already be seen from the diagrams on Fig. 40, illustrating the variations of absolute humidities on different Norwegian stations during the period in question. All stations begin with high absolute humidities followed then by an abrupt transition to very low values. As the fall of humidities sets in earliest on the northernmost stations, we must conclude that the new air has arrived from a Northerly direction. Using all available observations of humidity from the rest of Scandinavia, we have been able to draw isochrones for the arrival of the new dry air. This system of isochrones is outlined on the map Fig. 41.

The development of weather during the invasion of dry air in southern Norway (Figs 42—45) is discussed below.

On the morning of July 24 (Fig. 42 a), the dry and rather cold North-Easterly current had entered from the northern frame of the map. The absolute humidities, which are plotted reduced to sea level, show distinctly how far the new air supply has reached. The dotted line is drawn where the greatest contrasts of humidity are found, thus between the adjacent stations Engerdalen 7,1 mm. and Rena 11,9 mm. Tönset 5,7 mm. and Dombaas 13,0, Sundalen 8,5 and Aandalsnes 10,4, etc. It represents thus the foremost front of the new dry air.

In order to indicate the different origin of the two air masses, the lines of flow in the southern humid air are again drawn with double lines, and in the northern dry air with broad black lines.

At noon of July 24 (Fig. 42 b), the invasion of the dry air has reached down to the Mjösen district, at the same time it advances also along the western coast down to Bergen, sweeping away an extensive fog layer belonging to the humid mass. Note, for instance, the contrasts of humidities between Flisen 7,7 and Aabogen 12,7, Stai 7,9 and Lillehammer 13,4, Runde 8,1 and Florö 10,9, etc. In the evening of the same day (Fig. 42 c), the dry air has continued its way southwards and has just reached Kristiania, and approaches Stavanger on the western coast. A very marked discontinuity in absolute humidity can be seen between Kristiania 8,0 and Aas 15,3, further, for instance, Gausdal 7,9 and Granheim 13,8, Florö 7,5 and Bergen 13,1.

The mountainous parts of the country have not yet been reached by the dry air, obviously as this air during its propagation forms a flat wedge above which the mountain-block still protrudes. The dotted line may be considered as the line of intersection between the upper boundary surface of the wedge and the mountain slopes. This view

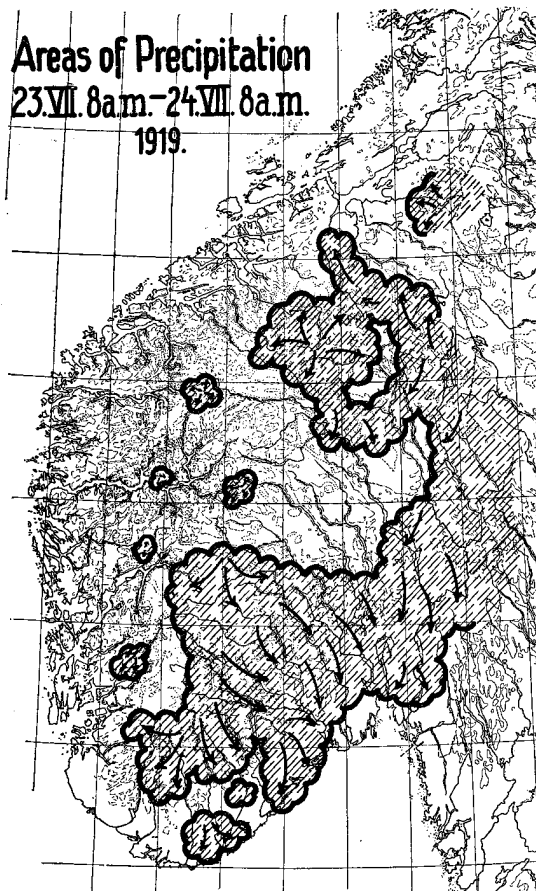


Fig. 39.

would correspond to an inclination of about $1/300^*$) for the boundary surface, a value, however, which has no great accuracy, as for instance friction will influence the propagation of both air masses in the mountainous regions, and produce irregularities in the course of their reciprocal limit.

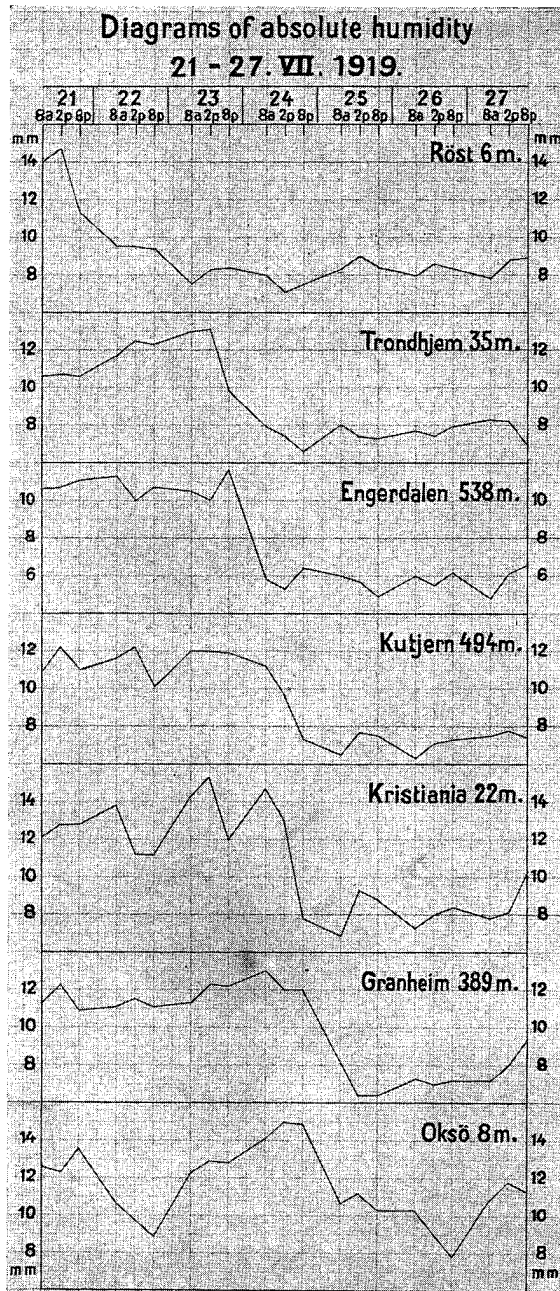


Fig. 40.

plotted on the map, also give a good illustration of the development of weather. Take as an example the situation at noon to the 24th (Fig. 42 b). On the whole map, 15 stations report cumulo-nimbus; 14 of these are lying to the south of the front of the invading polar air.

The distribution of dry and humid air has obviously determined the distribution of local showers. The district, which has had rain during the period July 24 8 a. m. till July 25 8 a. m. (Fig. 42 d), coincides rather exactly with the region still covered with moist air. Within a territory, which is almost limited by the southern coast and the front of the polar air at 7 o'clock p. m., local showers have developed generally. On all the greater heights, showers appear in the forenoon, and during the afternoon they have also spread to the lower districts where they continue for the most part until the evening.

In the polar air, the heating from the ground will likewise cause convective currents. These will, however, be stopped by the stability at the boundary surface to the warm air, and not penetrate into the upper moist layer. Underneath, moisture and vertical displacement will not be sufficient to produce clouds and rain as long as the level of condensation is not reached within the cold wedge.

Over the territory, which the polar air has taken into possession, accordingly no rain falls, with the exception of the orographical rain further north on the northern slope of the Dovre mountains. The local showers can easily be distinguished from the orographical rain as they develop during the warm time of the day and dissolve in the evening, whereas orographical rain occurs at all times of the day or even predominantly in the night. Further, the amounts of precipitation are generally greater from the local showers than from the slight orographical drizzle.

The observed cloud forms, which are

* The inclination of the surface is smaller than those observed on boundary surfaces of cyclones (about $1/100$).

and only one behind it (Kutjern). This last one is, however, lying so near the front, that the observer probably has had cumulo-nimbus above the moist mass of air still within range of view. The numerous cumulus in the moist air also indicate the general convection over it. In the polar air, almost no clouds of convective origin occur, although its noon temperatures are almost quite as high as those in the moist air beyond the front. With the exception of two reports of cumulus formation in Söndmöre and Romsdalen, only higher clouds such as cirrus, cirro-stratus, and alto-cumulus lie above the polar air. All these certainly belong to the warm mass which still remains in the higher layers.

On the next morning, July 25, Fig 44 a, the polar air has forced its way further on in the form of a narrow tongue along the southern coast to Oksö, while the current to the west of the mountains has reached Egersund. The moist air, persisting in the mountain-districts right up to Jotunheimen, becomes more and more surrounded by the polar air. In the evening (Fig. 43 c), the moist air is completely surrounded, as the eastern and western branch of the polar current meet outside the Naze.

The advance of the polar air in Denmark led to the formation of a cyclone, which gave rain all over the southern coast of Norway on July 25 and 26. The chart of rainfall (Fig. 43 d), therefore does not give quite a clear picture of the distribution of local showers in the southern part of the country. Farther north, as far as the rain from the cyclone did not reach, no precipitation is recorded, except in Trøndelagen, where the orographical rain still continues.

— The next morning (Fig. 44 a), the cyclone in Denmark is dying away, so that we again can follow the development of local showers in Norway.

The moist air has remained to the lee of the mountains, over a district from Bergen to Lister, and makes there conditions favourable for the formation of showers (Fig. 44 d). These showers keep precisely within the territory, which is indicated by the extension of the moist air in the morning. At Jæderen, the showers are driven right out to the coast as they follow the North-Easterly drift in the height. Besides, there is a small shower area in the lower Telemarken, probably corresponding to small rests of moist air, which have been left behind. The rain on the coast stations is the last remainder of the cyclonic rain, which covered the whole southern part of the country the day before.

The forenoon of the following day, July 27, (Fig. 45 a) small portion of moist air was still left at Jæderen, but only sufficient for the formation of small showers, which gave 0,2 mm. rainfall at only a single rainfall station. Apart from that, there was no measurable rainfall in Norway to the south of the Dovre mountains.

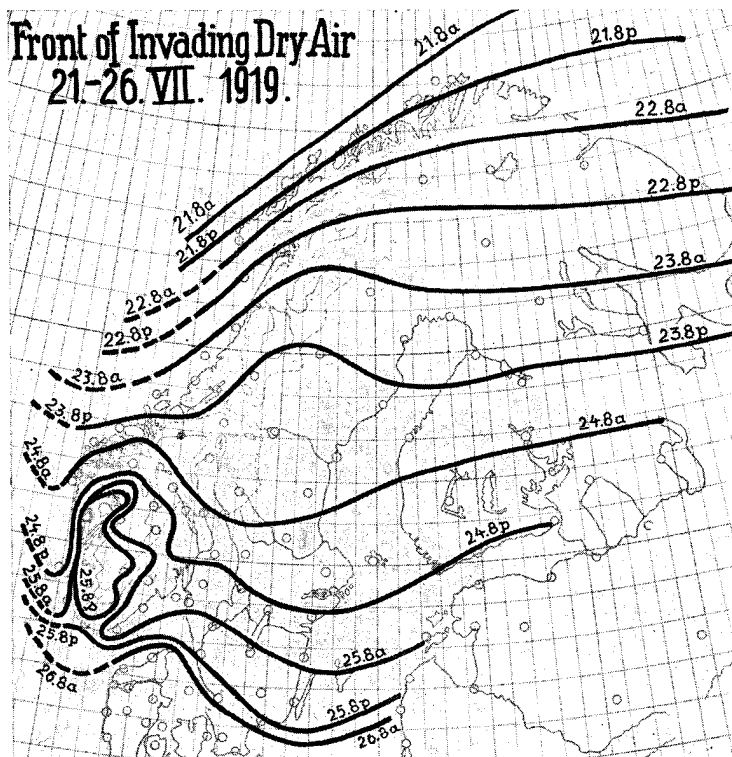


Fig. 41.

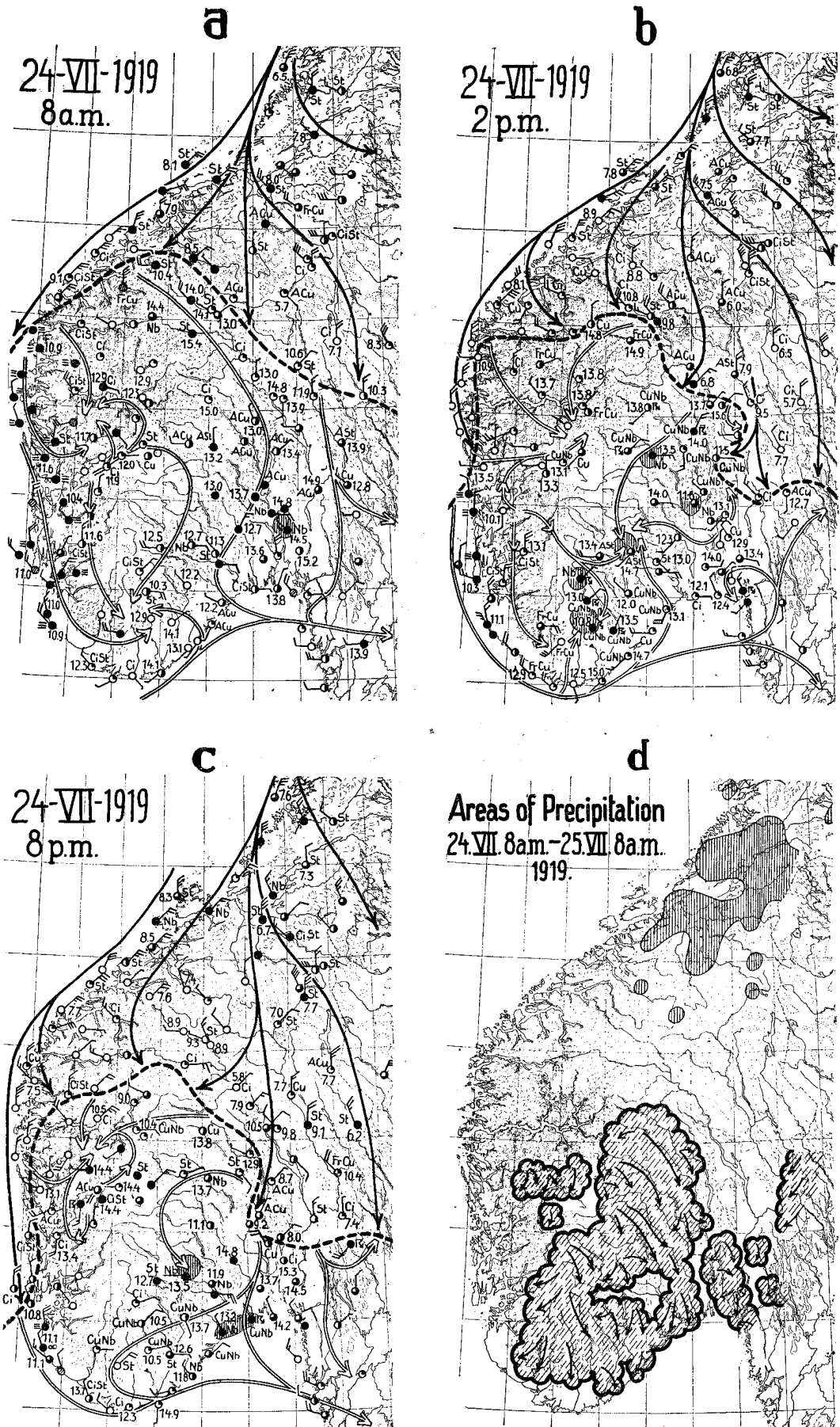


Fig. 42.

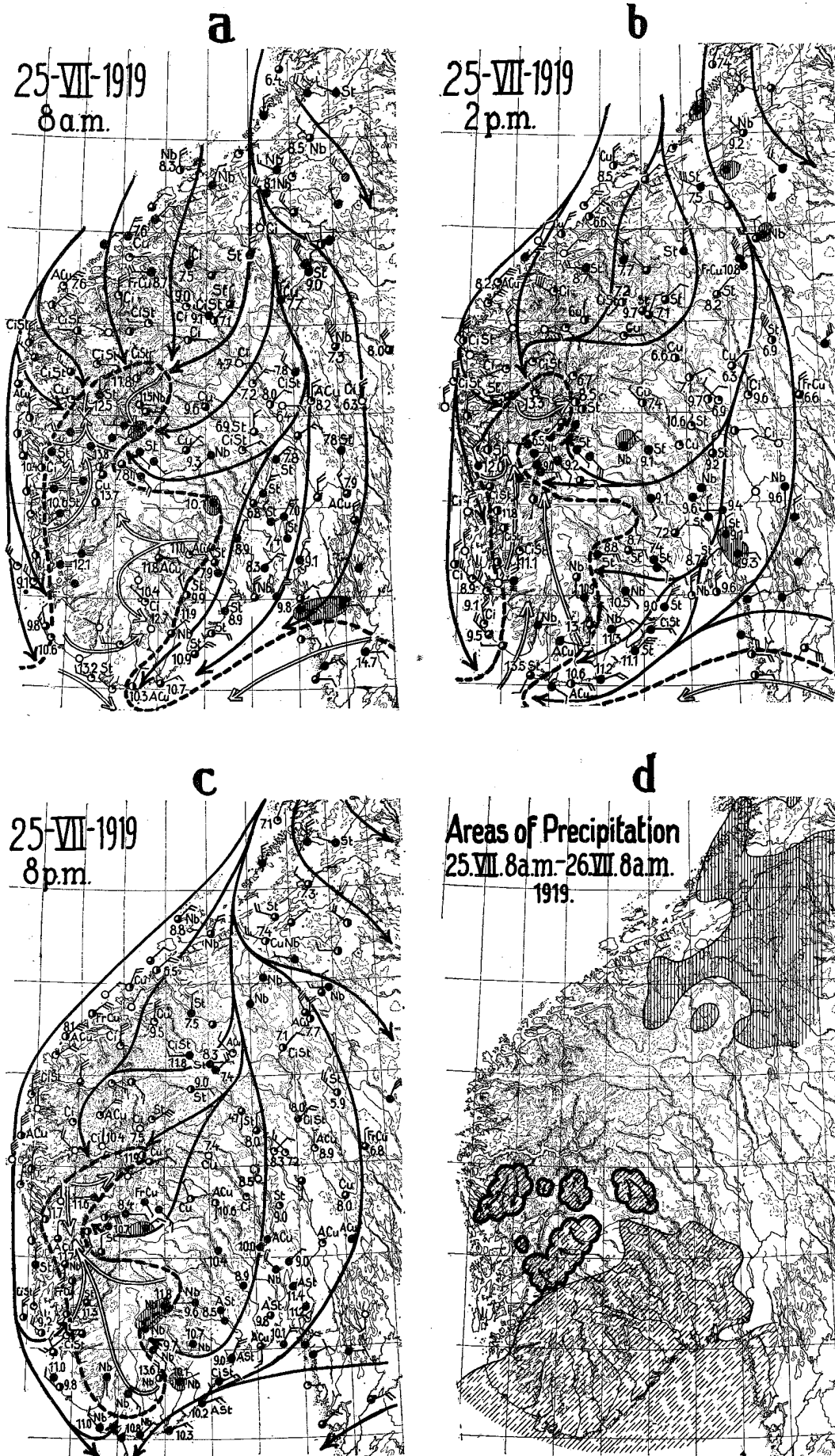


Fig. 43.

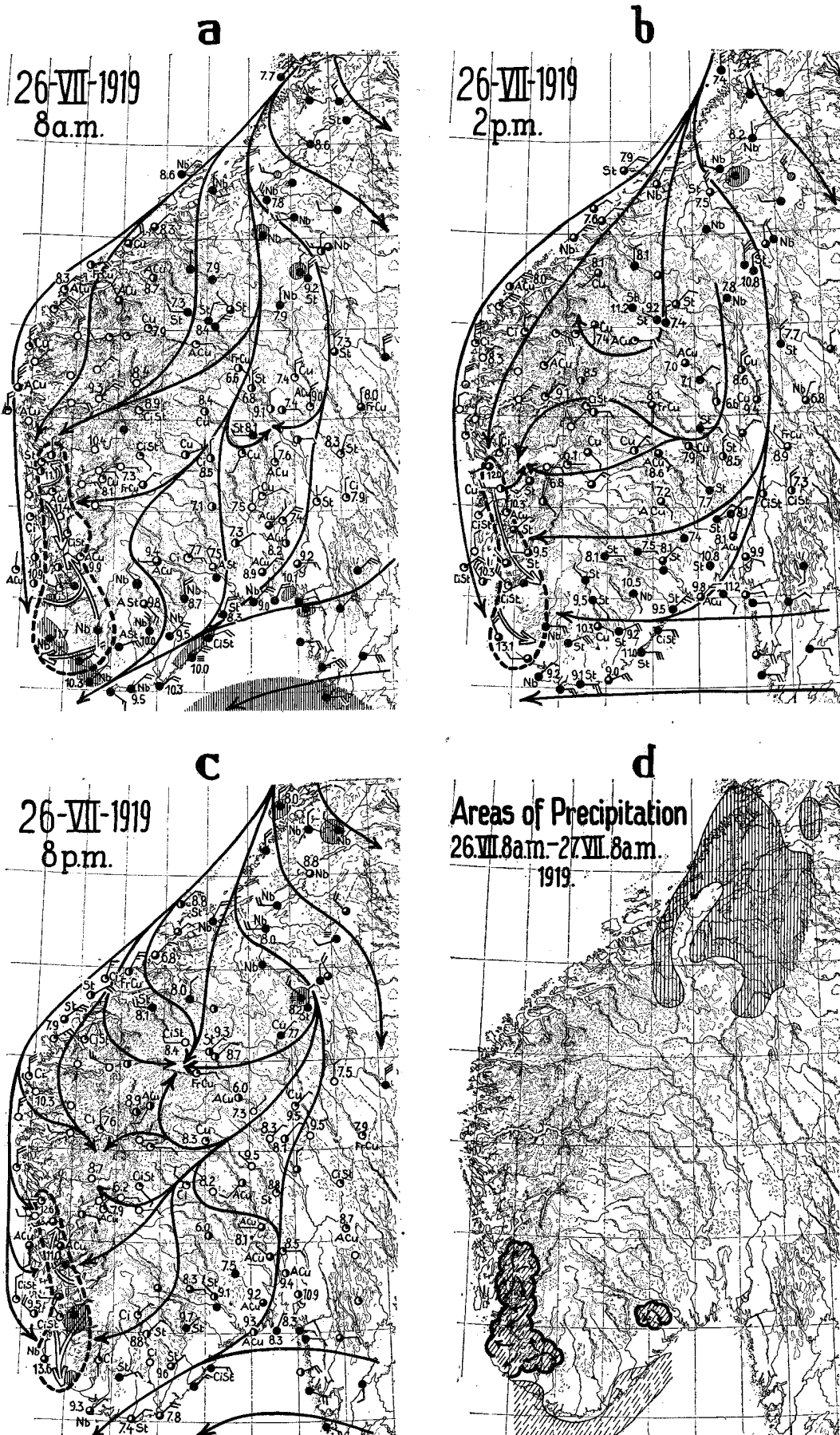


Fig. 44.

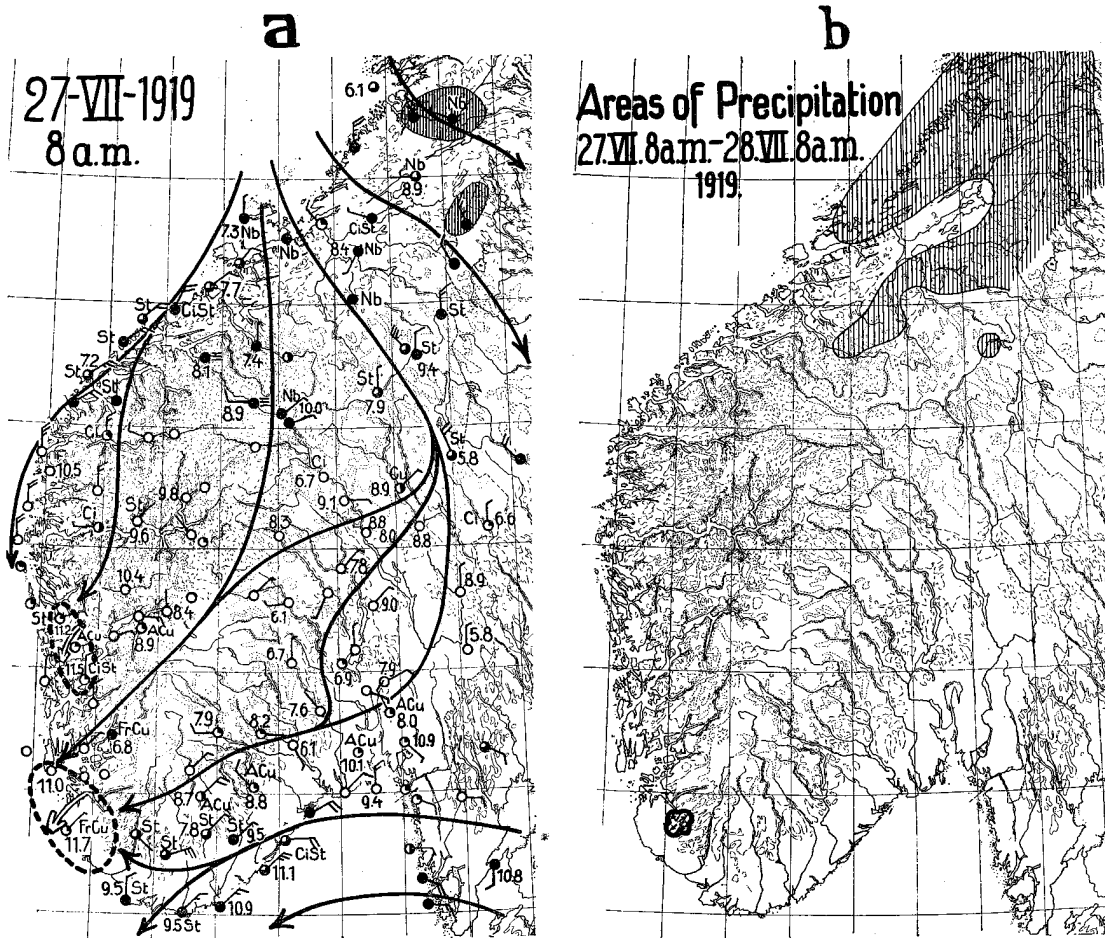


Fig. 45.

Therewith the development from showery to dry summer weather was fulfilled.

The two series of maps, July 28 to August 3, 1918, and July 23 to 27, 1919, represent typical cases of the opposite developments which may take place in the continental summer rain, when no greater atmospheric disturbances influence the weather situation: either a gradual increase of shower activity from day to day combined with a slow spreading over previously dry areas invaded by moist air, or a sudden stop of shower activity at the arrival of dry air.

They both lead to the conclusion that *the properties of the air in respect to stability and content of moisture are more important factors for the occurrence or non-occurrence of local showers than the general distribution of pressure.*

The numerous meteorological factors acting upon the process of shower formation of course may give the phenomena a great complexity. The tendency of development is not always so determined, and does not go on so long undisturbed in the same sense as in the described series. The nature of the single local showers must, however, also in such situations be the same as in the simple cases, and the complexity of the situation can only be a result of complicated conflicts between the different factors determining their formation. A perfect survey of these factors in all layers of the atmosphere will certainly bring considerable improvement in the understanding of the problem of local showers.

Conclusion.

The classification of rain given in this paper may be comprehended in the following scheme:*)

1. *Cyclonic rain.*

- a. *Warm front rain* formed in warm air pushing upwards a retreating wedge of cold air.
- b. *Cold front rain* formed in warm air displaced by an advancing wedge of cold air.

2. *Instability showers.*

- a. Instability produced by heating from warm sea surfaces.
- b. Instability produced by insolation over land (local showers).

3. »*Fog-rain*« (Drizzle).

Slight rain formed in low layers by cooling of air in contact with relatively cold sea or land surfaces.

4. *Orographical rain*

formed in air currents ascending mountains.

This scheme has resulted from the daily forecasting by which the forecasters are obliged to give a plausible explanation for all rain occurring, in order to have a working hypothesis on a scientific base for later forecasts. The scheme accordingly contains all sorts of rain occurring in the practice of *Norwegian* forecasters, i. e., in the meteorology of northwestern Europe. The results won by investigations of the weather in that region may probably be generalized for all other parts of the temperated and polar zones.

Geophysical Institute, Bergen, May, 1921.

*) As to its essential features, this scheme has existed since the year 1918, after the first summer of the new Norwegian Weather Service, but its application to every new weather situation has by and by required many modifications in detail, leading gradually to the form here given. For his valuable participation in this work we are very much indebted to Mr. *T. Bergeron* who stayed at Bergen during the year 1919, and afterwards has continued his researches at the Meteorological Office in Stockholm. His results which we have partly mentioned in anticipation, will soon be developed more completely in a paper which he is preparing.

Local names used in the paper.

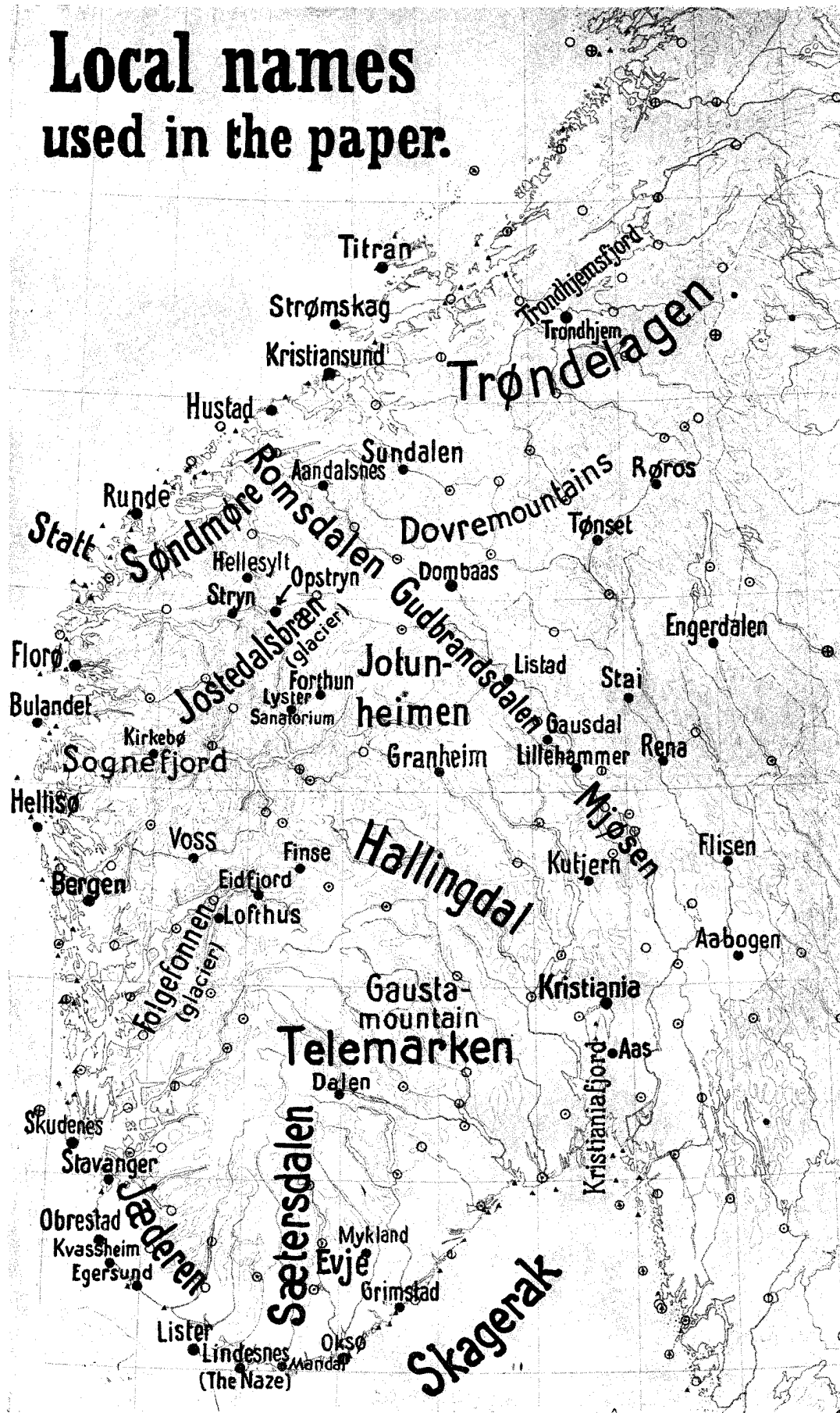


Plate I.