meshes of the old net of observations. With our close net of stations we can, to a certain extent, follow and forecast them, and the closer becomes the network the farther we can advance. But at last the limit of what is obtainable is reached. We can not make it close enough to predict every local rain shower. There is, however, one way open by which the system can be completed, and this way I hope will be tried by next summer.

A similar view of the sky, only still more extensive than from the coast, can be obtained from favorably situated mountains. Everyone who has traveled in the mountains knows that we can see wandering rain showers at a great distance. The question is then to find practical methods by which their tracks can be determined, just as the course of distant banks of storm clouds are found from the coast stations. Now, if we study the view from the top of a mountain by the use of good charts, we can identify a great number of points on the ground, such as summits, ridges of mountains, rivers, lakes, towns, villages, and churches, etc. The chart can be especially prepared for the purpose by marking all the characteristic lines and points we are able to see and hatching the regions, which can not be seen. Then when the showers of rain advance the observer will be able to draw on the chart the part of the front line of the shower which is turned to him. By drawing this line from hour to hour he will see how the shower develops and propagates, which districts are being threatened, and when the rain will reach them. The observer will then not only be able to give valuable information to the central offices but he can also send forecasts direct to the threatened districts. From a comparatively small number of mountain stations, which cooperate and supplement each other, it must, in this way, be possible to organize a system of forecasting local showers for the greater part of the country.

Addendum, October, 1918.—For the same eight districts as above, the percentage of verifications for the months of August and September have been the following: August, 85.1, 77.7, 83.3, 79.5, 85.1, 92.4, 90.7, 96.3; September 94.0, 94.0, 92.0, 96.0, 90.0, 94.0, 88.0, 88.0.

The average percentage of verification has thus been for the three summer months: July 83.7, August 86.3, September 92. The decided progress at the end is due above all to the experience from August 14 and 15, as from this date the forecasts have, in dubious cases, been based with increased confidence upon the steering line.

ON THE STRUCTURE OF MOVING CYCLONES.

By J. BJERKNES.

[Dated: Bergen, October, 1918.]

When the equations of hydrodynamics are to be applied directly to concrete atmospheric motions, two conditions should be fulfilled: The distances between the stations giving the observations should be small enough to be considered as differentials of space, and the time intervals between the successive periods of observation should be small enough to be considered as differentials of time. Neither of these conditions is fulfilled by the observations available from daily weather maps and printed in yearbooks. Distances amounting to hundreds of kilometers and time intervals of six hours are too great.

In order to get at least the first of these conditions fulfilled, to some degree at least, I have collected detailed data from the archives of the meteorological institutes in Norway, Sweden, and Denmark, including observations from third-class stations. In addition I have examined the comparatively very detailed daily maps used for weather forecasting in western Norway during the summer of 1918, and combined them with the simultaneous study of the sky.

In this way I have been led to some general results concerning the structure of cyclones, which I shall outline in this paper, and shall consider in detail later.

THE STEERING LINE AND THE SQUALL LINE.

The lines of flow in a cyclone have approximately the character of logarithmic spirals. By increasing the number of observations, however, several deviations from the regular spiral shape appear. Among a multitude of details, certain characteristic traits seem to recur more or less markedly in all cyclones yet examined.

Every cyclone that is not stationary has two lines of convergence, which are greater and more conspicuous than any others, and are distinguished by characteristic thermal properties, as shown in figure 1.

The first of these lines comes in to the center from the front of the cyclone, lying in its entire extent on the right side of its path. The tangent to the line at its terminus in the cyclonic center seems to be identical with the path of the latter. As the line is thus giving the momentary direction of propagation of the cyclone, it may, with propriety, be called the *steering line*.

The other line of convergence comes in from the right rear of the cyclone, and is identical with the well-known *squall line*, which accompanies cyclones.

The steering line and the squall line are intimately related to the distribution of temperature, as they border

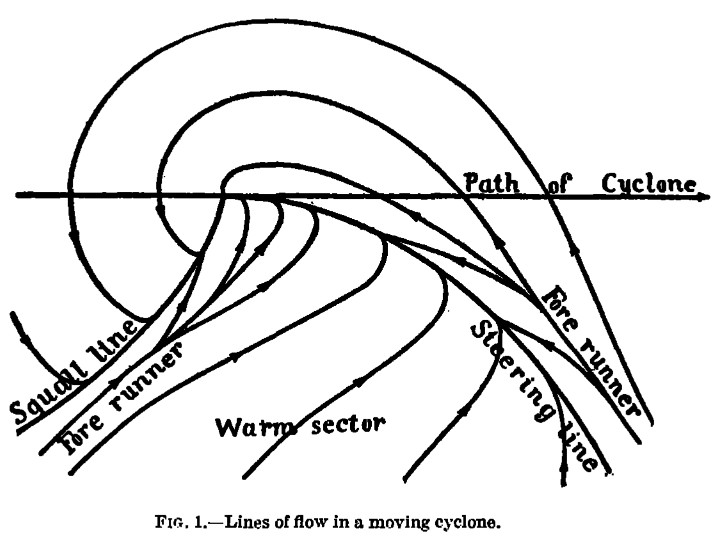

FIG. 1.—Lines of flow in a moving cyclone.

the warm area of the cyclone, or, as we may call it, its "warm sector."

Both the steering line and the squall line move according to the law of propagation for lines of convergence,[1] viz, in the northern hemisphere toward the right, relatively to the direction of the wind along the

[1] J. Bjerknes: "Über die Fortbewegung der Konvergenz- und Divergenzlinien." Meteorologische Zeitschrift 1917, 10/11.

line. The passage of the steering line, having warm air to the left, will therefore cause an increase of temperature, and the passage of the squall line, having cold air to the left, will accordingly give a decrease of temperature. These thermal effects correspond to the well-known increase of temperature in front of cyclones and the decrease behind them. The discontinuous character of the change of temperature is peculiarly striking during the passage of the squall line, but the change due to the passage of the steering line is also easily perceptible.

THE STEERING SURFACE.

The air masses flowing in from both sides toward the steering line will not mix. Up to great heights there will exist a distinct boundary surface, which separates them. This boundary surface, cutting the earth's surface along the steering line, may for convenience be called the steering surface. This surface leans toward the cold side, the cold air thus forming a flat wedge under the warm. Figure 2*b* shows the horizontal field of flow in the near vicinity of a steering surface, and figure 2*a* gives a representation of the motion in vertical projection.

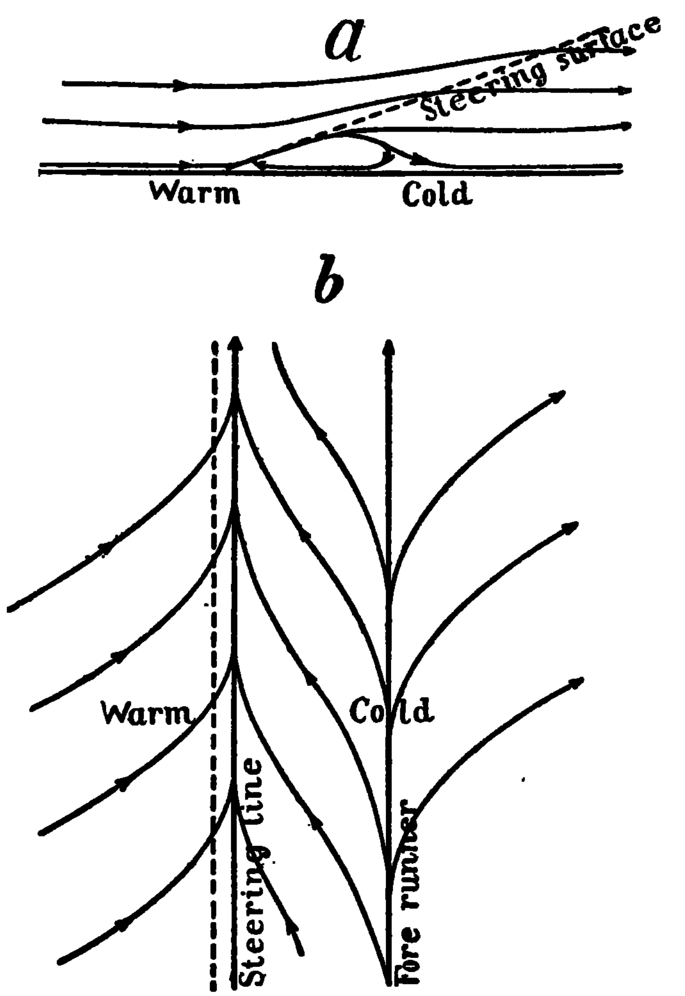

FIG. 2.—Moving steering line.

The warm air flowing in from the left ascends the steering surface, sweeping with it the nearest layer of underlying cold air. This cold air, however, can follow only to a certain height. It soon drops down again, and on the place where it reaches the ground a line of divergence will appear in the field of horizontal flow (fig. 2*b*).

Every moving steering line is thus preceded by a line of divergence, which is very often seen on the detailed maps at a distance of about 50 kilometers. The air between this forerunner and the steering line itself has a rolling motion. The air to the right of this rolling mass moves off horizontally, having a velocity component in

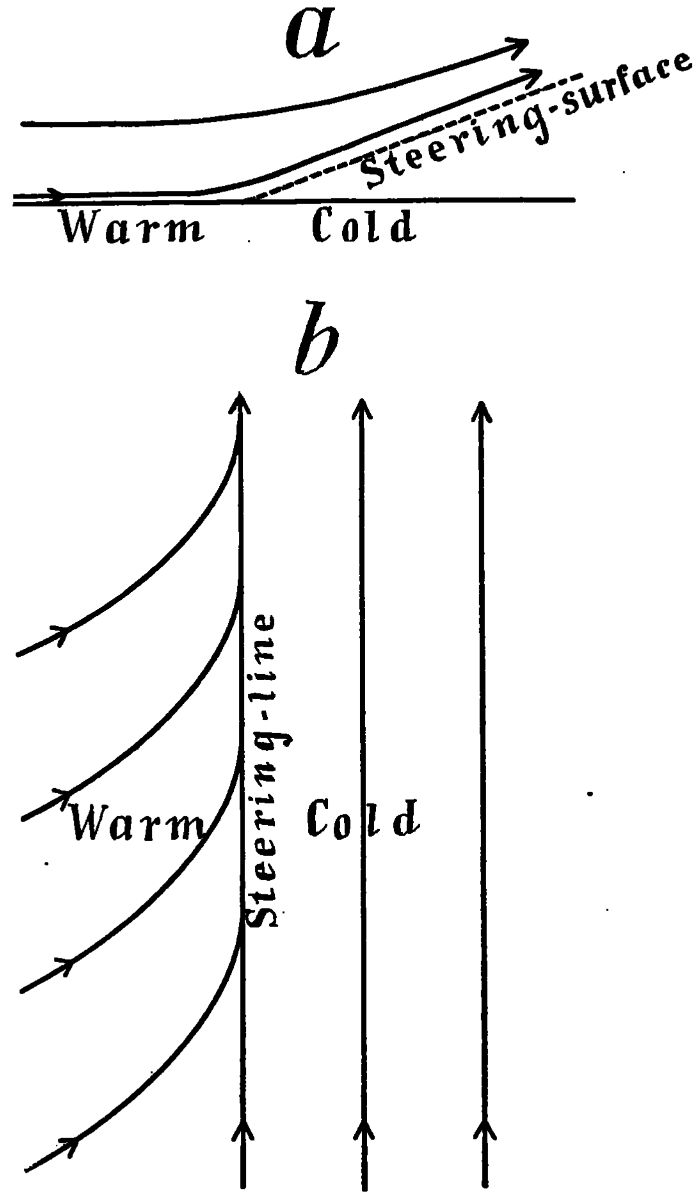

FIG. 3.—Stationary steering line.

a direction normal to the steering line, corresponding to the velocity of propagation of the system.

It should be noticed that the line of divergence preceding the steering line as a forerunner has a forced propagation in a direction opposite to that generally found for such lines. The term due to the rotation of the earth, under ordinary circumstances predominating, is apparently overcompensated by frictional terms generally neglected.

It will be useful also to refer to figure 3, representing the motion found at stationary steering lines, having no forerunner. Should this steering line be propagated toward the right, the entire cold mass must ascend to give place for the warm. The existence of the forerunning line of divergence seems thus to be a necessary condition for the propagation of the steering line.

THE SQUALL LINE.

The air masses flowing from both sides toward the squall line will remain separated by a boundary surface that for convenience may be called the squall surface. This surface does not, like the steering surface, simply resemble an inclined plane. As shown by W. Schmidt's investigations[2] it is fronted by a "head," at the back of which it has, as far as we know, an almost horizontal course, interrupted only by some small waves. Data concerning its continuation to greater heights are not yet at hand.

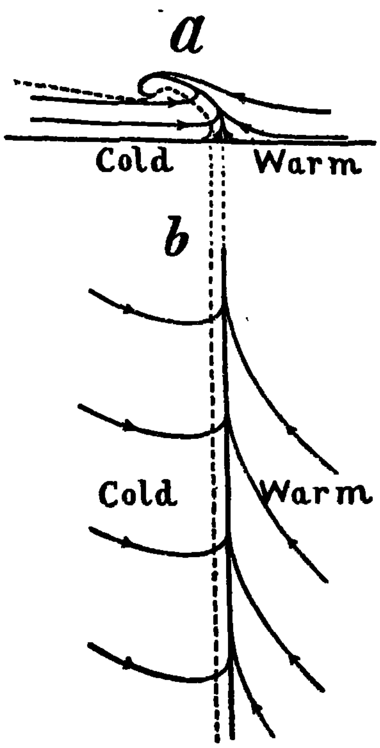

FIG. 4.—Squall line.

Figure 4*b* shows the horizontal field of flow in the immediate vicinity of the squall surface, and figure 4*a* gives a vertical projection of the same motion. The squall surface itself is represented by the broken line on both figures. The cold air flowing in from the left displaces the warm air in front of it. The warm air is forced to ascend rapidly the abrupt front of the head, and afterwards to perform only occasional ascensions and descensions.

At the center of the cyclone, the steering and the squall surfaces join into one. The entire surface, cutting the ground along the steering and squall lines, forms a wide flat valley, conveying the warm air current upward over the underlying cold air.

THE DISTRIBUTION OF VERTICAL MOTION, AND OF CLOUDINESS AND PRECIPITATION.

When the field of horizontal motion is known through the wind observations from meteorological stations, the vertical motion in lower strata may be constructed by the aid of the equation of continuity. Such constructions have made apparent characteristic distributions of vertical motion. The following practical, although not exact rule, has in this way been obtained for cyclones: The areas of small deflection of the wind from the gradient are generally areas of fast upward movement; and vice versa. The areas of great deflection are generally areas of slow upward or even of downward movement.

The smallest deflections are found on the right front of cyclones, viz: in the warm sector. Accordingly the ascending motion starts at the ground in the warm sector, and has its greatest values along the two lines of convergence bordering it. Outside the warm sector, only slow upward movements are found, and on the rear of the cyclone even descending movements occur.

In fig. 5, the distribution of cloudiness and precipitation over the cyclone area is outlined. As all ascending motion of importance originates from the ground in the warm sector, cloudiness and precipitation pre-eminently are involved there. The warm air spreads, however, over greater areas in the higher strata than at the ground, the surface of separation leaning from the warm sector outwards over the adjacent cold areas. Therefore the effect of ascending warm air may also be observed from the surrounding districts, which are cold at the earth's surface.

A surface of discontinuity at which there is a sudden change of temperature and of wind velocity may, according to a formula of Margules,[3] have an inclination of equilibrium, depending upon the difference of temperature and the difference of velocity. In the case which we are considering, the surface of discontinuity is moving,

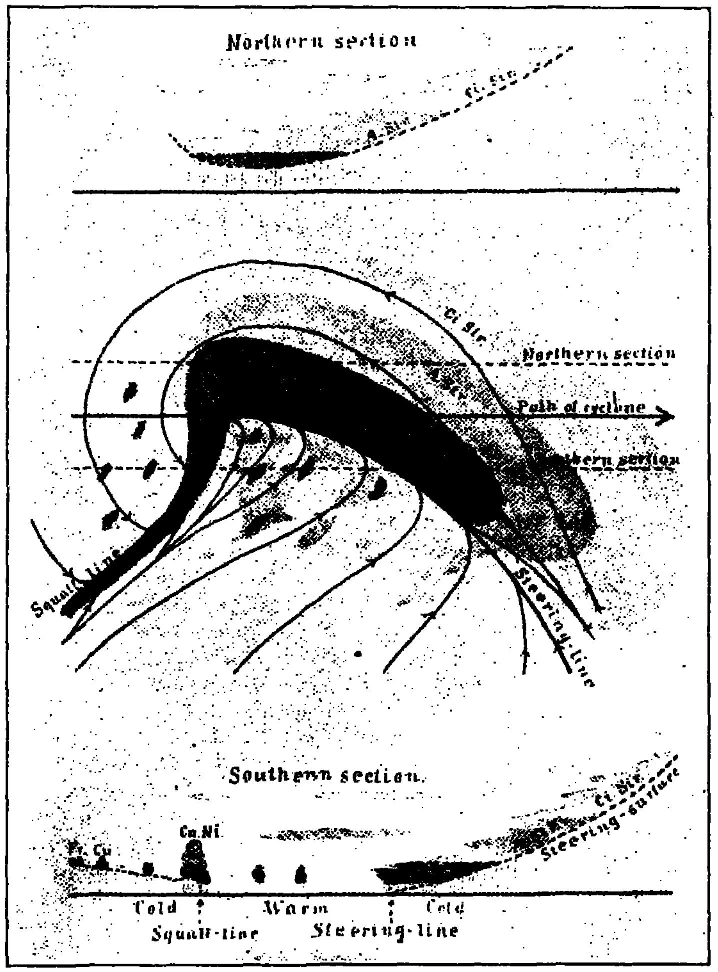

FIG. 5.—Distribution of cloudiness and precipitation.

and thus the condition of equilibrium is not fulfilled. But in case of slowly moving systems we are entitled to consider the deviations from the equilibrium as small and reckon approximately with the equilibrium values.

The formula of Margules, when applied directly to steering surfaces found on detailed maps, has led to values of its angle of inclination amounting to a fraction of a degree. To get an idea of how far precipitation and cloud areas, caused by the ascension of warm air, will extend

[2] W. Schmidt: Wien. Sitzungsberichte I. 119, IIa, 1910, p. 1101. Meteorologische Zeitschrift 1911, p. 357.

[3] Margules: "Energie der Sturme" Jahrbuch der K. K. Zentr. Anst. fur Meterologie 1903 Anhang. English in the Mechanics of the earth's atmosphere, a collection of translations by Cleveland Abbe. Smithsonian Miscellaneous Collections, Vol. 51.

112533—19——3

beyond the steering line, we may calculate with an average inclination of 1:100. Lower nimbi, at the height of 500 meters, will then extend 50 kilometers beyond the steering line, and the intense rain will fall to this distance. Higher nimbi, up to 2,000 meters, may bring weaker rain 200 kilometers in front of the steering line, and single raindrops may occur at a still greater distance. Outside the district of rain clouds, the higher clouds, alto-stratus and cirro-stratus, will extend. If we suppose the same inclination up to the highest strata, the Ci.St. would appear 800 kilometers ahead of the steering line.

Cloudiness and precipitation in front of the cyclone, extending not only over the warm, but also over great cold areas, may thus be sufficiently explained by the ascension and spreading out of warm air along the great surface of separation. If the steering line in the before mentioned numerical example had a length of 500 kilometers, the ascension along the corresponding steering surface would afford simultaneous rainfall over an area of 100,000 square kilometers, and cloudiness over 4 to 5 times this area, in addition to that of the warm sector.

The rainfall over the cold area behind the squall line comes from the warm air lifted by the advancing cold wedge. On account of the "head" at the front of this wedge the ascending velocity will be rather great, but its effects will not be perceived far behind the line. The ascending motion along the squall surface apparently does not reach higher strata, as no higher clouds occur.

In fig. 5 two sections through the cyclone are outlined, both parallel to the path. They give, from right to left, the succession of meteorological phenomena at a fixed place on the right and the left sides of the path, respectively, during the passing of the cyclone.

An observer to the right of the path will perceive the passage of both lines of convergence, namely, the steering line and the squall line. While the steering line is approaching, the steering surface will gradually sink down to the earth's surface. Since the steering surface coincides with the under cloud limit from the height of Ci.St. to that of the lowest Ni., the cover of clouds will gradually sink. Thus the observer will first see the highest clouds belonging to the steering surface, viz: the Ci.St., forming a light veil over the firmament. This veil transforms, gradually thickening into a uniform cover of A.St. As the cover of cloud becomes lower and more compact, the A.St. transforms into a stratum of Ni. The first raindrops now fall, but it is still some time before the rain grows to its greatest intensity. Simultaneously, the lower limit of the nimbus goes down to the level of condensation in the warm air. From that moment the lower cloud limit will retain a constant height, and the rainfall will have a continuous character. Soon after, a slow turn of wind and a small increase of temperature will indicate the passage of the steering line and the entrance into the warm sector.

In the warm sector no striking changes will occur until the squall line is approaching. Then the wind suddenly turns to the right, simultaneously increasing to violent force; the temperature falls rapidly; the nimbus transforms into Cu.Ni., and the rain pours down in heavy squalls. *The heavy rainfall does not last long.* Soon after the passage of the squall line, a clear blue sky appears, all higher clouds having already disappeared. The clearing of the sky is only interrupted by smaller showers.

An observer to the left of the path will be passed by neither the steering line nor by the squall line. He will, however, observe the phenomena due to the ascending motion up through the valley formed by the joined steering and squall surfaces. Thus he will see the veil of Ci.St. gradually thickening down to A.St. and Ni. The nimbus, however, will not go as low down as in the warm sector, and the rainfall will not increase to the same intensity. The clearing of the sky takes place later without any striking changes of wind, temperature, or form of cloud.

The cold air in cyclones performs a part like that of a high continent against which a warm wind is blowing. Above the level of condensation of the ascending air the "continent" will be covered by "fog." This "fog," which may be observed from below through the transparent continent of cold air, is according to the height, called Ni., A.St. or Ci.St.

ON THE MECHANICS OF CYCLONES.

The preceding results concerning the structure of cyclones may, in so far as the motions in the lower strata are concerned, be represented schematically by figure 6.

The cyclone consists in the lower strata essentially of two opposite currents, a cold one represented by the heavy black lines and a warm one represented by the light double lines. As a combined effect of the barometric depression and the deflecting force of the earth's rotation both currents are turned about the cyclonic center. As the combined effect of this turning motion and their different specific weights, the cold current is screwed underneath the warm one, and the warm current screwed up above the cold one. This combined motion propagates along the steering surface, not unlike a wave motion, the kinetic energy being furnished by the potential energy of the system of warm and cold *air, lying beside each other on either side of the steering* surface. The cyclonic motion effects the transformation into a state with reduced potential energy, involving a reduced angle of inclination, or even a complete disturbance of the surface of discontinuity.

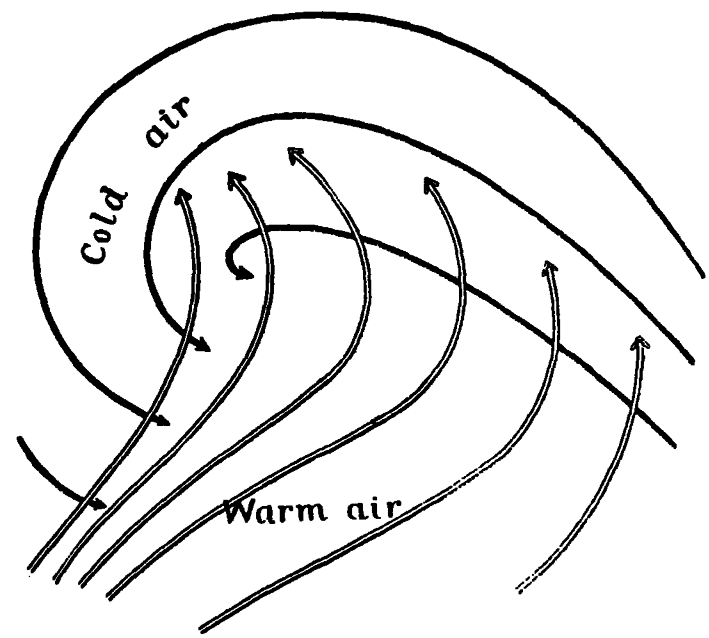

FIG. 6.—Cyclonic motion in lower-air strata.

This view leads to a natural explanation of well-known facts. Cyclones are most frequent, and developed to greatest intensity, in the zones and during the seasons of great horizontal temperature gradients, the surface of discontinuity pre-eminently evolving under such conditions. Further, a series of cyclones often follows approximately the same path, the surface of discontinuity having been only partly destroyed by the first cyclone, so that it may, after a short period of restoration, serve as a steering surface for the next one.

In the case of a stationary steering surface the path of the center would follow the fixed steering line. But as the steering surface is generally already in motion, we can only assert that the momentary direction of propagation of the center is given by the tangent of the steering line at this center.

Taking the general case of a cyclone propagating to the east, the cold current will cover the ground on the northern and western sides of the center, while the warm current will be able to keep to the ground only in the warm sector, southeast of the center. From there it will flow over the cold current, joining the general western drift in the higher strata.

The general effect of the motion described is that cold air is conveyed to regions previously covered with warm, and there spread along the ground; and that in compensation, warm air is conveyed to previously cold air regions, and there distributed in the higher strata. Generally speaking, therefore, the cyclones may be said to be links in the interchange of air between the polar regions and the equatorial zone. This interchange, which is effected continuously in the zone of the trade winds, takes the irregular and intermittent character of cyclonic motions in the latitudes outside the high-pressure belts limiting the trade winds.

The results to which we have arrived may to a great extent be considered as a verification of views developed theoretically by Margules:[4] "The phenomena of motion in great storm areas that we call cyclones are less intelligible than those of the squalls. But these also, at least in middle and higher latitudes, consist of warm and cold masses of air lying adjacent to each other horizontally; cold air often spreads out over the earth in the lower strata behind the passing storm. It is therefore not unlikely that these storms are fed by the potential energy of an initial stage . . . . Otherwise these results verify certain traits in different older theories of cyclones, while they disprove other traits.

We are reminded both of Dove's old theory of the conflict between polar and equatorial currents as well as of the modern "counter current" theory of Milham.[5]* Ferrel's convectional theory is confirmed in its essential part, in as much as the ascending air in the cyclones is warm. This warm air, however, does not form a central core, but comes from the side, covering a warm sector. The general argument against the theory of Ferrel, that statistical investigations have proved a circular area around the center of the cyclone to be cold rather than warm, does not disprove the principal point, that the ascending air is warm, but only the accidental assumption of the symmetrical structure of the cyclone. The confusion concerning this point led to the paradoxical assumtion that the mounting air in the cyclone is cold and heavy. As under conditions theoretically specified by Sandström,[6] a symmetrical cyclone can really act as a kind of centrifugal pump, lifting the cold air of its central core, this assumption contains no intrinsic contradiction, but can now simply be dropped. While thus an unnecessary element of v. Hann's "driven eddy" theory has to be left out, the general view of this theory, that the cyclones are merely partial phases of the general atmospheric circulation, has been fully confirmed.

[4] Ibid.

[5] Meteorology, Milham, New York, 1912, p. 311.

* Milham attributes this to Frank H. Bigelow. See "The mechanism of countercurrents of different temperatures in cyclones and anticyclones." Mo. Wea. Rev., 1903, 31: 72-84.

[6] J. W. Sandström, Ueber die Beziehung zwischen temperatur und Luftbewegung. Met. Zeits., 1902, 19: 161-171.

POSSIBLE IMPROVEMENTS IN WEATHER FORECASTING.

With special reference to the United States.

By V. BJERKNES.

Probably the most important step that can at present be taken for the improvement of the weather forecasting will be the introduction in the daily weather service of good charts representing the lines of wind flow.

The drawing of these charts presents no special difficulties. When a meteorologist has gained sufficient acquaintance with them, he will draw them as easily and as quickly as somewhat complicated isobaric or isothermal charts. My Gothenborg address [1] and J. Bjerknes's paper [2] give useful hints concerning the use of these charts, and their connection with the weather. But accumulated personal experience will also be of great importance.

These charts will, however, have their full prognostic value only when the observations permit them to be drawn in such detail that the two fundamental lines of convergence of the cyclone, steering line, and squal lline, can be accurately identified.

For this purpose it is necessary that the observations of the wind be made and telegraphed as accurately as possible. In this respect there is occasion for an important improvement in the system of observations in the United States. At present only eight directions of wind are reported. Making the observations of the wind directions as accurately as the conditions of each station will permit and telegraphing in detail the results thus obtained will be an important step in making it possible to draw the true lines of flow.

On the other hand, it will be highly desirable to get a closer network of stations. How far it will be necessary or desirable to go in this respect can only be shown by experience.

Besides about 300 telegraphic stations, the United States has a great number of climatological stations, about 3,000 if my memory is correct.* If all the sewere made telegraphic we should get about the same number of stations in proportion to area as are used in western Norway. As desirable as an expansion on this scale would be, considered as an experiment, it would probably meet with difficulties from the point of view of the telegraphic service; and quite likely it will not be necessary. The close network of stations in western Norway is necessary, partly on account of the complicated topography and partly on account of the exceptional difficulties during the war, when practically no weather telegrams from abroad are received. With the simpler topographical conditions in the United States, and the comprehensive view obtained from the great area of observations,

[1] Weather forecasting. This REVIEW, pp. 90-95.

[2] On the structure of moving cyclones. This REVIEW, pp. 95-99.

* About 4,500.—Ed.