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THE EARTH'S ATMOSPHERE AS A CIRCULAR VORTEX.

By Anne Louise Beck.

[Berkeley, California.]

Miss Anne Louise Beck, of Berkeley, Calif., received one of the Fellowships awarded by the American-Scandinavian Foundation of New York. This Fellowship carried the privilege of a year's study of weather forecasting at the Bergen Geophysical Institute of Bergen, Norway, under Profs. V. Bjerknes and B. Helland-Hansen.

On her return to this country, Miss Beck has kindly authorized the publication of the following account of her studies at Bergen.—Editor.

SYNOPSIS.

The general circulation of the atmosphere considered as a circular vortex, as postulated by Professor Bjerknes is briefly discussed; it is pointed out that surfaces of discontinuity must arise along the margins of air streams moving equatorward and poleward, respectively, and that under certain conditions these surfaces of discontinuity are unstable, a wave motion sets in with the cold air pressing southward in the rear of warmer air moving northward; thus a series of wave motions in the atmosphere originate and are propagated eastward.

The criteria are given for fixing the position of that surface of discontinuity to which the name "polar front" has been applied, and the effect of differing conditions which arise in nature in connection with the changes of position of the polar front is discussed in some detail. The occurrence of cyclones in groups or families of two to six, with four being the most probable number according to the statistics of the Norwegian weather maps, is discussed and several families are considered in detail.

The forecasting of the weather of Norway by the Bjerknes theory, as carried on at Bergen, is described for representative weather types and finally an attempt is made to apply the Bjerknes theory to the synoptic weather maps of the U. S. Weather Bureau for January, 1921. The observational material printed on these maps lacks much of the data available in the Norwegian Meteorological Office, nevertheless surfaces of discontinuity can be traced and more exact and detailed forecasting seems to be possible when more detailed observational data are available.

When we consider the motion of the atmosphere, in reference to coordinates which do not participate in the rotation of the earth, we may assume for the sake of simplicity that the earth is at rest and heated by a sun in the form of a ring in the earth's equatorial plane, then we have the well-known scheme of circulation only in the meridian planes. Insolation at the Equator, radiation toward space at the poles causes the isobaric surfaces to slope from the Equator toward the poles in the upper atmosphere. According to Professor Bjerknes's theory of circulation,[1] polar air flows at the surface of the earth toward the Equator, and equatorial air in the heights toward the poles.

The insolation at the Equator then, overcompensating radiation at the same place, causes the air to ascend, whereas radiation causes cooling and, consequently, descent of the air at the poles. This circulation develops until it becomes constant. Polar and equatorial air are thus seen to be separated by a discontinuity.

This picture is modified by the rotation of the earth and a "planetary vortex"—as Professor Bjerknes has named it—is formed. The southerly upper-air current is deflected eastward by the rotation and gives in lower latitudes the antitrades, the northerly current by the same force is deflected into the easterly trades. They are separated by a surface of discontinuity, "the sliding surface of the trades," which according to the formula of Margules (and in its extended form by Bjerknes), slants upward from the Equator. Part of the upper current is sufficiently cooled to be forced to descend in the region of the tropical highs. That the cooling actually takes place is proved by the fact that the temperature at the latitude of the tropical highs is lower than at the Equator in a higher level. A surface circulation from the tropical highs toward the Equator forms part of the cycle in each hemisphere inclosed between the tropical highs and the Equator. The rest of the upper current below the stratosphere continues to flow northeastward and eastward as the upper part of the main westerly current of the Temperate Zones. Part of the latter also emanates from the tropical highs.

At the poles, especially over the high plateau lands of Greenland and the Antarctic Continent the polar cooling is especially efficient, finally transforming the original equatorial air into the outflowing current of polar air. The easterly surface winds at the poles, together with the theoretically necessary winds of westerly component in the outflowing upper current and the difference in temperature, develops a second surface of discontinuity, "the polar sliding surface" which according to the Margules-Bjerknes formula slants upward toward the higher latitudes forming the "polar calotte" of Helmholtz.[2] The difference in temperature at a given level between an air column over the central part of the polar calotte and another at its border, according to the Bjerknes's circulation theorem gives rise to a closed circulation, descent in the central part of the polar calotte, outflow at the ground, forced rise at the polar sliding surface, and inflow in the heights. Thus there are for each hemisphere three circulations "running like cogged wheels."

A surface of discontinuity sloping north-south with easterly cold winds below it on the northern side of its intersection with the earth's surface and warm westerly winds above and to the south is unstable. A wave motion sets in with the cold air pressing southward as a "spreading cold tongue" and warm air running northward ascending the surface of discontinuity as a "warm sector." As in wave motion in any fluid with appreciable friction of viscosity, these waves have a marked life cycle with characteristic stages of development.

[1] V. Bjerknes: On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmospheric Vortex and Wave Motions, Christiania, 1921, *Geofysiske Publikationer*, Vol. II, No. 4.

[2] All the air inclosed by the sliding surface and the surface of the earth at the poles.

The life cycle begins with a mere waver in the line of discontinuity, becoming more and more marked as the cold air forces southward, finally curving into spiral-formed "breakers." [3]

In the course of this process the warm air is at last embedded in the cold and cut off from its supply. It will continue poleward in the upper air, while cold air spreads down toward the Equator. Thus this wave motion in the sliding surface is a necessary link in the general circulation. The stronger effect of the deviating force of the earth's rotation at higher latitudes, as well as the greater contrast in temperature between the air masses of different origin to either side and the fact that the polar sliding surface cuts the earth's surface, ought to give the wave motion in question a more conspicuous character at higher latitudes than nearer the Equator. The investigations of the Geophysical Institute at Bergen have confirmed these general conclusions.

The intersection between the polar sliding surface and the surface of the earth has the character of a line of discontinuity in the fields of temperature, as well as in pressure and wind. The investigations of J. Bjerknes, H. Solberg, and T. Bergeron proved the existence of such a line, for which the appropriate name of "polar front" was adopted.

The germs [4] of the theory are contained in Dove's theory of the struggle between equatorial and polar currents. In a theoretical paper Helmholtz has developed the idea that there is always a tendency toward the formation of a surface of discontinuity between the cold polar air tending toward the Equator and the warm equatorial air tending toward the pole, while the cyclone consists in a kind of "rolling up" of this surface. Similar views have been taken up in theoretical papers by Brillouin and by Margules. Sir Napier Shaw has arrived at the same result from the empirical side.[5]

The polar front is a line of demarcation between two air masses, one of Arctic origin, the other flowing from the horse latitudes. As a rule this line can be followed through all the centers of the cyclones of the circumpolar zone of LOWS. Between the centers it makes a long swing toward the south. The movement in the front is usually experienced as a cold front (squall line) southward; the movement northward as a warm front (steering line).

The following facts may be regarded as indicating the position of the polar front: First, discontinuities of temperature found on the synoptic chart; second, temperature variations at stations passed by the polar front; third, trough lines in the field of pressure and corresponding discontinuities of air motion; fourth, tendencies in the pressure record; fifth, rain areas along the polar front; sixth, precipitation at stations passed by the polar front; seventh, amount of and form of clouds; eighth, fog and haze; ninth, discontinuities and variations in absolute humidity.

There are special phenomena to note under these headings, as follows:

(1) The difference in temperature along the polar front in autumn and in winter usually is rather marked, about three or four degrees Centigrade between adjacent stations on the two sides of the front. In spring and in summer, the discontinuity of temperature at the surface of the earth may have disappeared, the temperature differences in summer, upon the whole, being much smaller than in other seasons because insolation, cloudiness, precipitation, distribution of land and water, etc., exert a stronger influence upon the temperature of the air masses at the surface.

(2) In the vicinity of the low, the polar front is almost always accompanied by pressure formations in the form of a trough. Often the troughs are well marked; sometimes, however, they can only be seen when a close network of stations is used. Sometimes convergences of the wind are the only signs of these troughs. At the slowly moving parts of the polar front between the cyclones the troughs for the most part are missing, and the wind may be the same on either side of the front.

(3) The trace of the barograph is one of the best criteria in fixing the position of the polar front. In front of the steering line pressure drops rapidly; at the passage of the line the fall suddenly ceases and the curve becomes nearly horizontal. When the pressure falls also in the warm sector this often indicates the LOW is deepening; when the pressure rises in the warm sector the low is often filling up.

In front of the squall line [6] there is often a slight drop in the pressure, then at the passage of the line the pressure suddenly rises.

The falling pressure in front of the squall line may be altogether lacking. Barometric tendencies in synoptic representation are very useful in fixing the line of demarcation.

The typical warm-front passage shows a barogram with a fairly sharp downward deflection. It is often accompanied by a strong gust of suddenly veering wind, the precipitation diminishes rapidly, passing to fog and drizzle or even to cloudy humid weather, while visibility sinks to a low degree owing to the dust-laden tropical air. The typical cold-front passage is indicated by an upward deflection of the barogram.

(4) and (5) Rain areas form at the boundary of the warm tongue where the warm air ascends above the cold. At the center of the low, two rain belts start, one along and in front of the steering surface, the other accompanying the squall line, generally to the rear of it. The first is usually 200 to 400 kilometers broad, the other seldom more than 100 kilometers, often only 10. With a close network of stations these rain belts are very good indications of the polar front positions. On using the observations of precipitation it should always be borne in mind that orographical conditions play an important part in the formation of rain.

Precipitation is almost always found at stations where the polar front has passed. Only in the outermost part of the cold tongue, the front may pass without causing precipitation. This may also be due to protection by topography.

The cold front is followed by a belt of precipitation in the form of showers often with thunder and hail or soft hail—if the temperature contrasts are strong enough. This stripe of precipitation is always narrower than the rain area before the warm front.

(6) In front of the first rain belt, there is a broad zone, about 300 kilometers, of cloudy weather. The cloud forms in this zone are cirro-stratus and alto-stratus, sometimes the tufted cirrus are the first signs of approaching rain, approximately simultaneous with the beginning of the fall in the barogram. In the warm sector the usual succession of cloud forms is strato-cumulus, stratus, fracto-stratus, but often it is clear. By and by, marking the approach of the cold front,

[3] Fig. 28, p. 80, V. Bjerknes: On the Dynamics of the Circular Vortex, etc.
[4] V. Bjerknes: On the Structure of the Atmosphere when Rain is Falling. *Quarterly Journal of the Royal Meteorological Society*, April, 1920, p. 128.
[5] Fig. 10, p. 129, loc. cit.

[6] Since squalls are frequently absent in connection with this so-called line in the United States, the expression "wind shift" line is to be preferred.—EDITOR.

lenticular alto-cumulus may occur, later changing to alto-stratus and nimbus. In most cases, the weather is overcast a hundred kilometers ahead of the rain front. The rear of the squall line is marked by cumulo-nimbus, cumulus, and fracto-cumulus.

The foremost discontinuity (in the direction of the propagation of the cyclone) the so-called warm front or steering line marks the course of the warm air traveling up the slope of the polar sliding surface. When this warm moist current of tropical origin[7] ascends, it is cooled adiabatically and cloud formation takes place. The "optraek,"[8] before an advancing cyclone generally consists in a series of cloud forms beginning with cirrus or cirri in tufts merging into cirronebula with the common optical phenomena followed by cirrostratus, altostratus, and lastly the nimbus (pallio nimbus) of the rain belt just preceding the warm front.

As will be seen these cloud forms follow each other from higher to lower levels, and as the sequence is a continuous one already proves that they are the effect of dynamical cooling caused by travel along a slanting surface. It is further proved by aerological observations * * * from the close net of stations in Flanders during the war that this surface really exists in wind, temperature and humidity.

(7) Directly behind the steering-line, especially when the wind velocities are small, fog is often to be found, due to the presence of warm air above the cold surface. Also along the slowly moving part of the polar front (at the southern end of the tongue of polar air) fog occurs. Haze is to be found almost exclusively on the southern side, especially marked, immediately preceding the squall-line.

(8) The polar air is dry and the equatorial air quite humid. Good visibility is a normal characteristic of polar air, though it sometimes happens that the polar air is also polluted—that is, when it has traveled a long way over northern France and England before it reaches the western coast of Norway.

Finally, the following method in fixing the position of the polar front may be used. The front having been surely marked on one map, its future position may be calculated from the gradient wind at the rear, considering both direction and velocity. This is not quite true for steering lines, the air at the rear of them in general moving more rapidly than the line itself. In the case of squall-lines this rule works very well, however, because the air behind the line can not possibly move faster than the line itself. This method is to be used especially when the front has arrived in districts where only few observations are available.

The first investigations concerned discontinuities in moving cyclones of the Temperate Zone, as they are experienced in northwestern Europe, and especially Scandinavia, which is a convenient place for the study of this phenomena.

It is no mere chance, in fact, that the existence of the polar front was first proven for the western coast of Norway, that coast being perpetually swept over by waves in that front.

It should be added that cyclones generally come from the west, but they may come from any point of the compass and actually have been shown to so move in the three years' forecasting, according to the Bjerknes principles which have been practiced in Scandinavia. This is due to the varying position of the polar cap during different periods[9] and under different conditions.

The first cyclone model, described by J. Bjerknes in his paper on "The structure of moving cyclones,"[10] refers to a wave in the polar front in the medium stage of its development or life cycle. It soon proved impossible, however, to apply this first cyclone model in all the actual cases of forecasting. Further analysis led to the tracing of unbroken polar fronts from cyclone to cyclone and showed the existence of waves in all stages of development.

In the life cycle of a cyclone the principal stages of development may be represented by Figure 31, page 88, V. Bjerknes: On the dynamics of the circular vortex, etc. The birth is indicated first by a slight curving in the front between two air currents of 180° difference in direction. The pressure is falling, the winds weak and only indicate a tendency toward circulation around a hardly appreciable center. The young cyclone has the form of a water wave with a broad base in the second stage, though its pressure field is still very flat. The propagation of the cyclone in these two early stages is generally rather slow. The third stage is the model referred to above from the paper by J. Bjerknes. The rate of progress at this stage is rather great and velocities of 150 kilometers (93 miles) an hour have been experienced in Norway for cyclones from the Atlantic Ocean.

The point of intersection of the two fronts lies well to the center of the cyclone. The area of warm tropical air between the two fronts is the so-called warm sector. It is characterized by little precipitation, unless it be in the form of fog or drizzle when the warm air is very moist and flows over colder water. If the warm sector comes over a part of the earth's surface where the air has been heated considerably and is already warmer than the air of the warm sector, precipitation may occur in the form of slight occasional showers due to the resulting instability. As regards the weather experienced by different places, according to their situation relative to the moving cyclone, reference is again made to the paper by J. Bjerknes, "On the structure of moving cyclones."

The decline of the cyclone is marked by the tendency of the cold front to gain on the preceding warm one on the equatorial side of the center. As the cold front overtakes the warm the cyclone becomes a "seclusia" (Bergeron)[11] and the warm sector is now cut off from its supply of warm tropical air. A continuation of this motion carries the cold polar air in the rear of the wave up the discontinuity surface of the warm front. This process, with the attendant destruction of the warm-air supply causes the warm-front precipitation area of the cyclone to diminish, while the discontinuities of pressure and wind may still exist at the surface of the earth for some length of time. This is the case which Bergeron calls the "upper front."

In the final stage the warm front is overtaken by the cold throughout, and the cyclone has become an "occlusia" (Bergeron), its warm sector existing only in the upper air as an isolated mass inclosed by polar air. This warm sector becomes more degenerate until the cyclone is thermically dead, its discontinuities no longer apparent

[7] The expression "of tropical origin" must not be taken too literally. It must frequently happen that the warm air in front of a cyclone only a day or so previously came from high latitudes on the front of an anticyclone.—EDITOR.

[8] We have no word among our meteorological terms which exactly translates the Norwegian word "optrack," the complete succession of cloud changes before a storm. * * * Professor Bjerknes, as chairman of the committee for the investigation of the higher atmosphere of the League of Nations has in his keeping records from aeroplane, kite, and balloon ascents covering nearly the whole period of the war, French and English observations as well as copies of material captured from Germany.

[9] There is a striking relation between the position of the polar front marking the boundary of the polar calotte and the southward extension of the ice fields which in the winter of 1920-21, for example, were far south in the Labrador Straits while the Iceland-Spitsbergen Gap was practically free.

[10] MO. WEATHER REV., February, 1919, 47: 95-99.

[11] Statements arising from discussions in the laboratory.

either at the ground or in the upper air, yet such a dying cyclone has often a powerful wind field apparent at the surface. Doctor Calwagen, at the Bergen Institute, has suggested this may be explained as follows:

The newborn cyclone, with its broad warm sector, represents a great amount of potential energy due to the temperature contrasts between polar and equatorial air, but it has relatively little kinetic energy. During the life cycle this potential energy is transformed into kinetic and the kinetic energy is transformed into heat by friction, external as well as internal, and we have the often very strong wind field in the apparently dead cyclone. It should be observed in forecasting, therefore, that an old cyclone, due to its kinetic energy, acts as a "dynamic shelter" against new cyclones with less strongly developed wind fields.

These forms of cyclones above described follow each other constantly. Moreover, it has been recently found that they follow each other in series or "families." During the early months of 1921 an attempt to count and classify these waves was made at the Bergen Institute.

A number of earlier investigations had been made [12] which are reviewed by Hann.[13] These investigations are, for the most part, more of a statistical nature dealing with amplitude and time intervals of pressure variations. They are not in the nature of thermical or dynamical discussion, therefore are not closely akin to our subject. A suggestion along the same lines was made by Exner[14] in which he spoke of the probable periodicity of cold outbreaks in northern America, in the area about Iceland, Greenland, and Norway, and in an area including Spitzbergen, northern Norway, and Nova Zembla. He speaks of cold outbreaks followed by rainy periods without discussing the matter fully.

At an informal discussion at the Bergen Institute when the fact was noted that very strong cold outbreaks were followed by new cyclones in higher latitudes than the last of the preceding series, the question arose as to the possibility of a cold wave closing a series and after the cold outbreak the arrival of a new. The first wave of the series was jestingly called "Protesilaos." The discussion led further and it was suggested that there seemed to be a preferred number of waves in a series; Mr. H. Solberg considered the number to be four according to his observations.

The above discussion led to the earnest attempt to count and classify these waves. The series of 14 families of January, February, and March, 1921, seem to indicate the number is really four where the waves come from the westerly or southwesterly direction. There was one example of a southwesterly series from March 7 to March 12 confined to three waves. From March 12 to March 20 a south-southwesterly type occurred with as many as six in the series.

The westerly type is a common winter type, which evidently originates west of Iceland in the Atlantic or, rather, one should say, first appear on the synoptic charts of Norway in that portion. They are probably generated by cold air currents over Greenland which come down against the warm air over the Gulf Stream and are characterized by broad warm sectors emphasizing the fact that these cyclones are born within a relatively short distance from Scandinavia. This type is prevalent when the tropical highs over the Atlantic have a great east-westerly expanse and lie rather far to the north.

The southwesterly type is characterized by more occluded warm sectors when the first of the series appears on the chart, thus indicating a birth farther off than in the westerly type.

The first of the series passes often to the west of Iceland through Denmark Sound or over the western part of Iceland. Though nearly occluded, these first waves are often marked by long tails which sweep over the western part of Scandinavia giving rain and strong winds in favorable points, as against a prominent headland where a distortion of the cold front causes the so-called "corner effects."

The waves following generally have better developed warm sectors, as the cold air in front of the first one is swept away. The fourth is often the strongest and draws after it the strongest outbreak of cold air. This gives either anticyclonic conditions confined to the North Atlantic or a wedge of high pressure extending southward to the tropical highs.

The last cyclone thus being a deep one, generally has several cold fronts or squall lines marking the steps of advance of the cold outbreak. One of these secondary squall lines may give rise to one or more secondary waves. The generation of these secondaries generally takes place over southern England or France—though if the area of general circulation is perceptibly moved, for instance, far to the north, these secondaries, too, develop farther north. An example of this is found in Series 14, D wave (April 4 and 5, 1921).[15]

At their first appearance these secondaries may seem very innocent and diffuse, often difficult to detect in the charts, but may develop into deep depressions. These are the real rain bringers in central Europe and in some cases also in Sweden (13 D 1a).[15]

The third wave in series 11, 11C [15] has a remarkable secondary. The third squall line of this depression, 11C, marked a heavy outbreak of cold air over Ireland (March 10, 7 p. m. chart [15]). On that chart the primary had moved as far north as Lafoten. The transport of relatively warm air by winds at the rear, together with the low temperatures as the squall line swept over Ireland built up a very large quasi-warm sector, accentuated as it traveled northward by the contrasts of air relatively warm and air lying over the Arctic Ocean (Spitzbergen −31° C., Bjorn-oen −5° C. in the polar air, in the warm sector the temperatures average +7° C. to the north, +10° or 11° C. in the south). That secondary consequently grew to a very strong cyclone, deepening from 749 mm. in the center to 732 mm. by the time it had passed Spitzbergen. Its warm sector had diminished but it remained strong enough to reach much farther north, probably even to the North Pole. During the passage the temperature at Spitzbergen increased to −5°. This was at the center of the cyclone. With the passage of the warm sector at Bjorn-oen, the temperature rose to +3°. This cyclone was a good example of those which have been experienced passing Franz Joseph's Land by different observers.

During the formation of these secondaries the cold front in which they form becomes stationary in that part or moves slowly as a whole, corresponding to the behavior of the polar front of the mother "calotte" in the formation of new cyclones. This is of vital importance in forecasting. Northwesterly outbreaks, which are usually accom-

[12] W. J. S. Lockyer: Southern Hemisphere Surface Air Circulation, London 1910—Publications of the Solar Physics Committee.
Arctowski: Resultata du Voyage S. Y. Belgica, 1897-1899.
Minardus: Deutsche Südpolarexpedition, 1901-1903, Band III, Meteorologie 1, 1, S. 33.
Bodman: Schwedische Südpolarexpedition, 1901-1903, Band III, 4 S. 17.
[13] Lehrbuch der Meteorologie, Book II, Kapital IV, p. 200.
[14] Exner, Dynamische Meteorologie, 1916.

[15] Synoptic charts, Bergen Weather Bureau.

panied by strong squally winds, absolutely require storm warnings, but it often happens that these outbreaks fail, due in the cases especially reviewed to just the above-described and partly unexpected formation of a secondary in the awaited cold front.

On the 8 a. m. chart for February 9 (Synoptic charts, Bergen Weather Bureau) a squall-line was lying east of Iceland, with a rising tendency in the pressure in some places of as much as +7 mm. in three hours. A storm warning was issued for the coast from Bergen northward. The expected gale did not come, but on the 2 p. m. chart of the next day a secondary was revealed forming southwest of Lofoten. This secondary gave a southwesterly prefrontal gale for quite another part of the coast.

Secondaries occur in both the southwesterly and westerly types. The series may or may not be marked by them. Perhaps we think they are lacking only because they have not been detected on the chart. The question is certainly open to much discussion and study.

The type termed southerly, or more properly south-southwesterly, is more of a spring or summer phenomenon in contrast to the winter westerlies. The series is marked by long occluded waves, seldom by waves having a well-developed warm sector. They extend from a stationary center to the south of Iceland south over England and France. These waves are probably generated farther south than those of the series mentioned earlier in this discussion. The general trend of the isobars is north-south and the extended valley of relatively low pressure south of Iceland is an effective shelter against the protrusion of cold polar air under warm tropical, until somewhere rather far south of Cape Farewell.

The tropical high in this case generally is pushed eastward until its center lies near Spain and the Mediterranean. The high is accentuated. This is partly due, in all probability, to the descent of the outflow of air in the upper strata from the cyclones to the west of the high. The length of the path of the cold air from this source to its turning point and back toward the British Isles naturally exhausts much of its original potential energy. The temperature difference between polar and tropical air is less marked under these circumstances, and on this account the cyclone is poorly developed in the beginning, and consequently after its journey northward is still feebly developed, which is seen by the dimensions of its warm sector, the boundaries of which then, especially in the more central parts of the cyclone, between Iceland and the British Isles, are clapped together.

Secondaries also occur in the southwesterly type, although of a somewhat different nature than in the westerly type. Apparently every primary wave has secondaries which appear first over England and France as quasi-warm sectors attached to the occluded primary. The origin of these secondaries is in reality not so far different from the origin of the secondaries in the types mentioned above.

The occlusion has the character of a so-called cold front, advancing from the south-southwest although the instability of the cold air over the warm surface is less marked. When the cold front advances against air that is warm enough in comparison with the polar air, a warm or quasi-warm sector is formed in that part of the cold front. This generally is the case over south England and western France. This is also characteristic of the secondaries of the first-mentioned types. Showers follow the passage of the occluded wave, indicating the unstable nature of the air.

Secondary cyclones often originate in a well-developed cold front. This may occur after the third wave, but more especially the fourth of a series, because these sweep so far south that they come up against air warm enough to feed a warm sector. These secondaries may often have a very innocent aspect upon their first appearance on the synoptic chart, but develop into cyclones with gradient and wind field exceeding that of the primary cyclones. This is the case especially in summer, when the general circulation is less accentuated, with the regeneration of old "secluded" cyclones or cold fronts which have been nearly obliterated but may be revived by a renewal of the warm air supply from a warm continent. It may also happen that new fronts are developed in the cold polar air of a recent outbreak, when the air has been sufficiently warmed in parts to give enough contrast in temperatures. Thus, also, new fronts may develop along the coast of a continent in the winter time due to the contrasts in temperature between the cold air masses of an anticyclone cooled by radiation and the relatively warm air over the adjoining sea or ocean. For instance, such a "maritime" front gave the snowstorm of 500 millimeters of precipitation at Bergen in November, 1919. Secondary fronts in summer frequently develop over Denmark and northern Germany, and, moving very slowly following the upper drift, give great amounts of rain in Denmark and southern Sweden. This type of discontinuity is often very intricate and extremely hard to trace on the map, often lacking a marked resemblance to the life forms described above. The pressure field often takes the form of a barometric valley or trough. The slow propagation of these "amoeba" cyclones and the strong convergence of winds make them one of the strongest rain producers in southern Sweden. The same is the case when an originally real polar front is retarded in its movement or becomes stationary.

It may be pointed out that the average duration of each wave in a family according to the statistics of the first 140 days at the beginning of 1921, is 6.5 days for Scandinavia in good accordance with the period of Defant for average precipitation periods found for the Northern Hemisphere. The existence of a periodicity is also known for the Southern Hemisphere. Quite probably further details could be determined from a study of the phenomena of the "southerly burster" of Australia and the "pampero" of Argentina, both typical cold-front phenomena.

The step to tropical cyclone is natural. Professor Bjerknes[16] has advanced the theory that they have their origin in the "sliding surface" of the Trades.[17] According to H. U. Sverdrup[18] the general variations in the features of this surface account for the various phenomena in certain parts of the tropics and their frequent appearance in other parts.

NORWEGIAN WEATHER SERVICE: FORECASTING BY BJERKNES THEORY.

The Norwegian Weather Service is directed from three forecast centers, Christiania, Tromso, and Bergen. Bergen ranks second to Christiania in population, and has really a more important forecast division—that along the western coast, divided into 30 districts, north to a certain point where Tromso district begins, fishing being the prin-

[16] V. Bjerknes, On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmospheric Vortex and Wave Motions. Christiania, 1921, *Geofysiske Publikationer*, Vol. II, No. 4, p. 83.

[17] This is referred to in the summary, MONTHLY WEATHER REVIEW, March, 1921, of an article by C. E. P. Brooks and H. W. Braby as the "mobile center of action" under the clash of Trades in the Pacific.

[18] H. U. Sverdrup, Der Nordatlantische Passat, *Veröffentlichungen des Geophysikalischen Instituts der Universität Leipzig*, II, Ser., 1917.