Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation

by

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In previous papers[1] we have described the ideal type of moving cyclones represented by Fig. 1. Its principal features may here be briefly recapitulated.

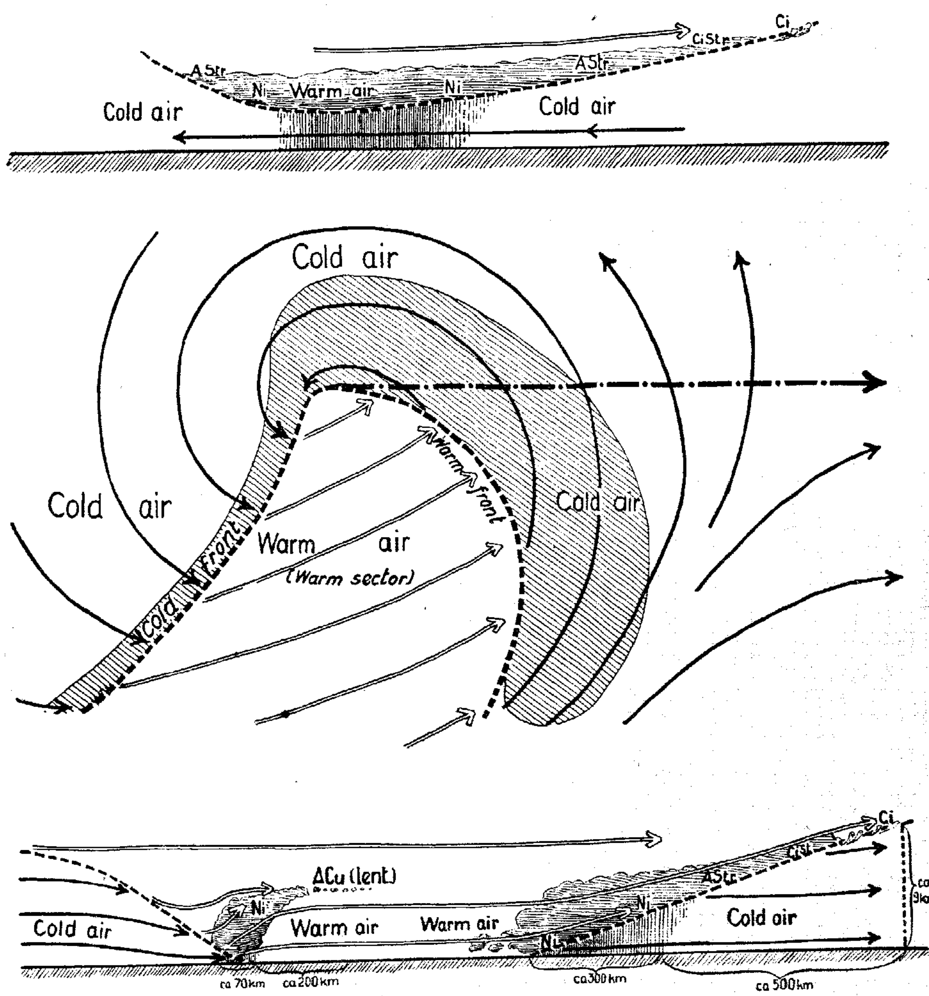

Fig. 1.
Idealized cyclone.

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[1] *J. Bjerknes,* »On the Structure of Moving Cyclones«, Geofysiske Publikationer, Vol. I, Nr. 2.
J. Bjerknes and *H. Solberg,* »Meteorological Conditions for the Formation of Rain«, Geofysiske Publikationer, Vol. II, No. 3.

The cyclone consists of two essentially different air-masses, the one of cold and the other of varm origin. They are separated by a fairly distinct boundary surface which runs through the centre of the cyclone. This boundary surface is imagined to continue, more or less distinctly, through the greater part of the troposphere, being everywhere inclined towards the cold side at a small angle with the horizon (order of magnitude 1° or even $^1/_{10}$°). In the case of eastward-moving depressions on the northern hemisphere, the warm air is conveyed by a south-westerly or westerly current on the southern side of the depression. At the front of this current, the warm air ascends the wedge of colder air and gives rise to the formation of precipitation (warm front rain). The warm current is simultaneously attacked in its flank by cold air-masses from the rear of the depression. Thereby part of the warm air is lifted and precipitation is formed (cold front rain).

The Life Cycle of Cyclones.

Later investigations have shown that the cyclone type described above is only a special case of a more general one, changing regularly during the life of the cyclone. Fig. 2 represents schematically the different types of structure successively adopted by an individual cyclone. The »ideal cyclone« described corresponds to the types 2 c or d. In earlier stages the same cyclone has had the structures a and b, and in the future it will successively pass through the structures e, f, g, and h.

The initial phase of cyclone formation (Fig. 2 a) is given by two oppositely directed currents of different temperatures, separated by a nearly straight boundary, e. g. a cold easterly current adjacent to a warm westerly current.[1] At the place where the new cyclone is to be formed the originally straight boundary bulges out towards the cold side, and the centre of the cyclone will be found at the top of the projecting tongue of warm air (Fig 2b). The warm tongue is identical with the warm sector of the cyclone, and the ascendig air from this warm tongue forms the »warm front rain« and the »cold front rain«. The newly-formed cyclone follows the current of the warm tongue eastwards, propagating like a wave on the boundary surface between warm and cold air.

During the eastward motion, the amplitude (in a horizontal N—S direction) of the warm wave increases (Fig. 2 c). The cold air curves round the northern end of the warm tongue and arrives as a northwesterly current behind the centre. This type corresponds to the previously described »ideal cyclone«. Simultaneously with the further increase of amplitude (Fig. 2d), the warm tongue narrows laterally, especially in the southern outskirts of the cyclone. Finally (Fig. 2 e) the cold air from the rear of the cyclone reaches the cold air from its front, and thereby cuts off the warm sector. In this phase, when the cyclone has cut off its own warm air supply, it is said to be »secluded«. The remaining part of the warm sector near the centre also disappears fairly soon, so that the cyclone on the ground only consists of cold air (Fig. 2 f). For this type we have chosen the name »occluded cyclones«. At the place where the warm sector disappeared, a boundary line still exists for some time between the cold air from the rear and the front of the cyclone respectively. Finally, also this boundary vanishes (Fig. 2 g), and the cyclone becomes a nearly symmetrical vortex of cold air. The large zones of continuous

[1] The situation would not become essentially different if a constant field of translation was added. We may therefore have analogous phenomena at the boundary between a slight westerly current of cold air and a strong westerly current of warm air to the south of it.

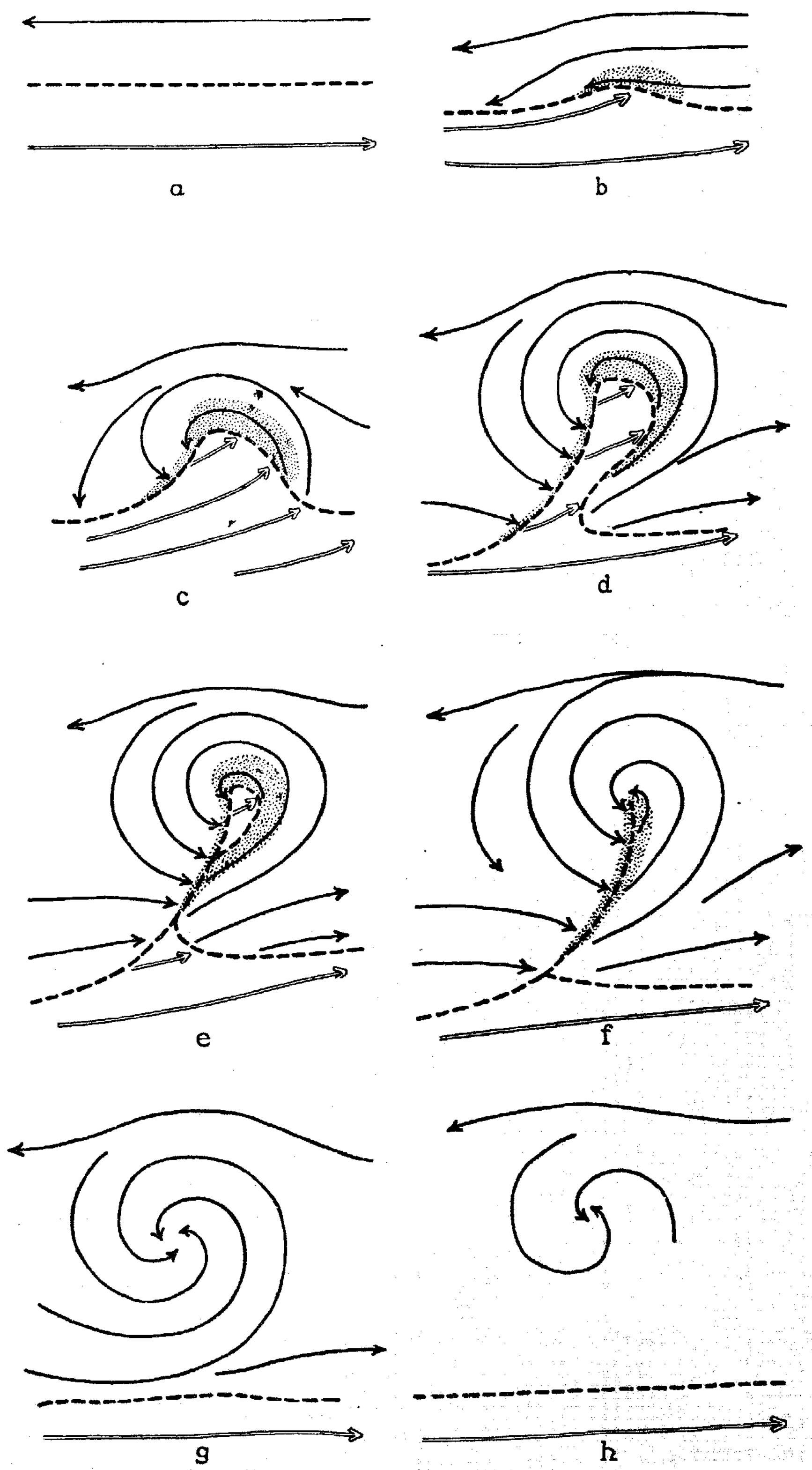

Fig. 2. The »Life cycle« of cyclones.

rain have then disappeared, and the precipitation falls only as showers. These conditions then persist until the cyclone dies (Fig. 2 h).

The development of a cyclone thus described may also be illustrated by the vertical sections of Fig. 3. The sections are imagined to cut across the cyclone south of the centre, and are seen by an observer when facing northwards. The dotted lines indicate the intersections with the thermal boundary surface of the cyclone, the other system of curves gives the general trend of isothermal lines in the vertical section. The isotherms running horizontally through the warm sector region follow the boundary surface downwards, and leave it at a lower layer when entering into the cold air. Through the cold air the trend of isotherms is again approximately horizontal. The cold air is assumed to

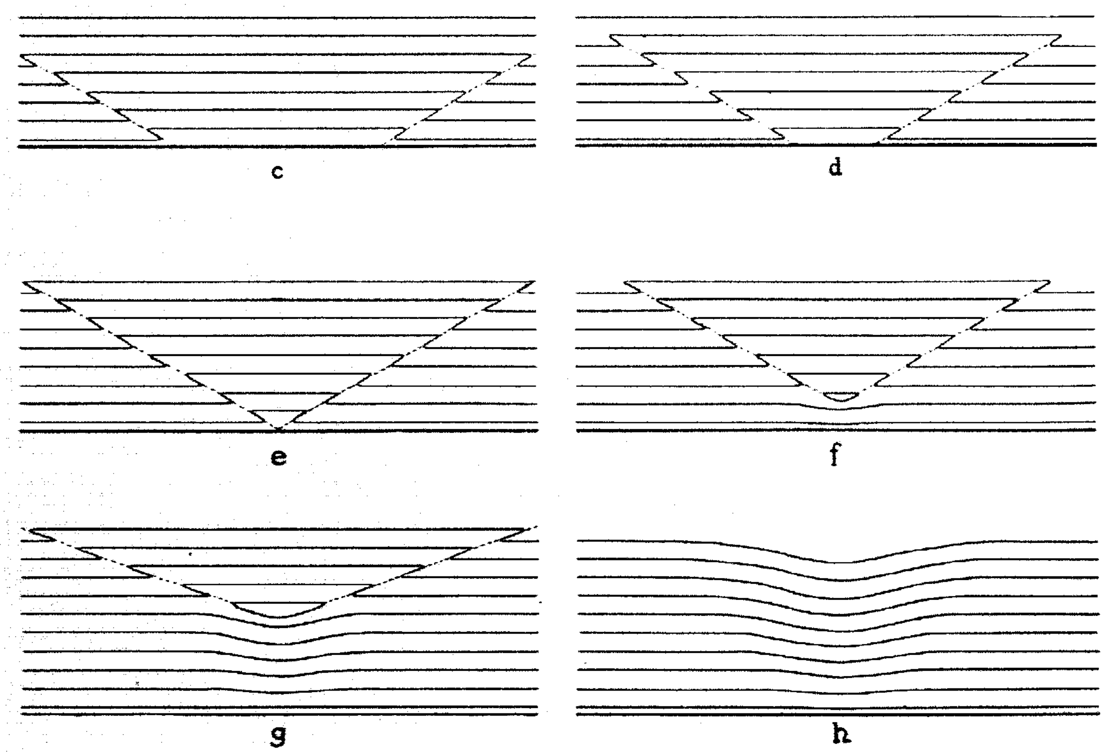

Fig. 3. Vertical sections through cyclones in different stages of development.
——— isothermal lines.
····· lines of discontinuity.

be of exactly the same thermal structure on both sides of the warm sector, so that no boundary surface results when both branches meet during the occlusion of the cyclone.

During the first phase of cyclone development, from its birth to the moment of occlusion, the warm air ascends, being lifted by the two wedges of cold air, which gradually approach each other. This process transforms part of the potential energy stored in the initial system into kinetic energy. We therefore obtain the practical rule: *All cyclones which are not yet occluded, have increasing kinetic energy.* This appears distinctly on the maps as an increase of wind forces, and usually as a deepening of the depression. The above rule seems to be verified practically without exception. When a cyclone is found to be of the structure 2 a, b, c, or d, it may thus with great security be forecasted that it will deepen.

After the two wedges of cold air have met on the ground, the still existing »upper warm sector« will be lifted further by the cold air on both sides, untill the warm sector air has been cooled adiabatically to the temperature of its surroundings on the same level. As long as this stage is not yet reached, kinetic energy will be gained through the process. Afterwards, when the cyclone has become a homogeneous air vortex, it has no store of potential energy which can be directly transformed into kinetic energy, and the existing motion can only be maintained by the inertia of the moving air-masses.

From the moment of occlusion (Fig. 3 e) parts of the cold air must also begin to ascend. This ascending motion is, however, not directly favoured by gravity forces. The adiabatic cooling will soon make the ascending column of cold air colder than its surroundings on the same level (Fig. 3 f, g, and h), so that the gravity forces will even counteract the ascending motion in the cyclone. The kinetic energy of the cyclone from that moment is used to pump the cold air upwards against gravity forces, a process by which the system loses kinetic energy.

Thus in the interval of time just after the occlusion (Figs. 2 f and g), we have still in higher layers a process which produces kinetic energy, and in lower layers another process which consumes kinetic energy. The first of these processes will, however, stop as soon as the »upper warm sector« has reached the layers of its own potential temperature, and the effect of the latter process will finally alone determine the transformation of energy in the cyclone.

The work of friction on the moving air-masses also favours the latter process, so that the factors which destroy kinetic energy will preponderate soon after the occlusion of the cyclone.

We may formulate this experience in the following practical rule: *After the occlusion the cyclone soon begins to fill up.*

We have carried through our considerations under the supposition that the warm and cold air are separated by sharply defined boundaries or real surfaces of discontinuity. This ideal condition is never perfectly fulfilled, especially owing to the effect of adiabatic cooling in the ascending warm air adjacent to the boundary surface. This air will ascend more rapidly than the rest of the warm air, and will acquire a temperature between that of the two original air-masses, thus forming a transitional layer which diminishes the »discontinuity« of temperature. For the mechanism of the cyclone, however, it makes no great difference if instead of a real surface of discontinuity we have a less accentuated boundary surface. *The essential condition for the formation of a cyclone is the co-existence of cold and warm air adjacent to each other.* The tendency of the cold air to spread along the ground, lifting the warm air, will then, with the modification caused by the rotation of the earth, create a cyclone and render energy to its growth. In later stages of development, the cyclone becomes a *homogeneous vortex of cold air, which soon consumes the kinetic energy which it has previously received.*

A very large percentage of European cyclones are occluded ones, being dying remainders of previously strong Atlantic depressions. The predominance of occluded cyclones in Europe has led to the statistical result that cyclones usually have a cold core. A special investigation of the relatively infrequent young deepening cyclones will certainly afford evidence of their assymmetric thermal structure.

In these considerations we have made the further supposition that no thermal boundary surface forms between the two wedges of cold air meeting each other at the occlusion of the cyclone. Usually, there will be some difference in temperatures between the two, so that a boundary also remains after the occlusion. We may then have either of the two cases illustrated in Fig. 4. In the first case, Fig. 4 a, the cold air from the rear of the depression is colder than the cold air in front. The occlusion then assumes the character of a cold front with a rather narrow rain zone. It is, however, preceded by the high clouds Ci. and Ci.-Str. from the upper warm front surface, and differs thereby from ordinary cold fronts. This type of occlusions is in Europe experienced especially in the warm time of the year, when the cold air coming directly from the ocean, is likely to be colder than the cold air which has rested some time over the continent. The other type of occlusions (Fig. 4 b) occurs in Europe in winter, when the cold but maritime air from the rear of the cyclone, is not cold enough to undermine the still

Fig. 4. The two kinds of occlusions seen in vertical section.

colder continental air in front of the cyclone. This sort of occlusion has the character of a warm front. They bring, however, rather small amounts of precipitation according to the small content of moisture in both cold air-masses.

On a perfectly uniform globe the first type of occlusion will be the most probable one. The cold air from the rear of a cyclone has been over the polar regions more recently than the cold air in front, which has been brought southwards already in the rear of the preceding cyclone. The occlusion of the type Fig. 4 a will therefore as a whole be a more common phenomenon than the type Fig. 4 b.

Both types of occlusion with a remaining boundary surface have a greater store of potential energy than that represented by Fig. 3. The ascending motion will be confined to the lightest of the two cold air-masses and will be supported by forces of gravity. Occluded cyclones with remaining great contrasts of temperature will therefore have a greater vitality than those which at once become homogeneous air vortices.

We have purposely not yet mentioned all the complications connected with the

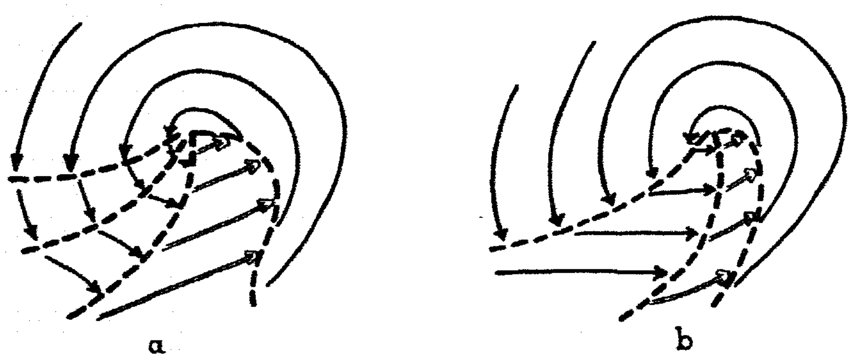

Fig. 5. Cyclones with »secondary cold fronts».

question of the energy of cyclones. They are of such various characters that we could scarcely treat them from general points of view. We shall only mention the rather common case when the cold air contains in itself a series of secondary cold fronts (Fig. 5), which step by step bring veering of wind and fall of temperature. If the secondary cold fronts are slight formations (Fig. 5 a) accompanied by only small contrasts of temperature and wind, they may be considered as internal phenomena in the cold air — just as the instability showers — which have no important effect on the total energy of the cyclone.

It may happen, however, that one of the secondary cold fronts has a temperature and wind contrast much greater than that of the foremost boundary of the cold air (Fig. 5 b). All air contained between the warm front and the strong »secondary cold front« may then act as a single large »warm sector«. This artificial enlargement of the warm sector means a greater store of potential energy and enables the cyclone to increase its kinetic energy. The appearance of a strong secondary cold front, therefore, indicates a reinforcement of the cyclone. Even occluded and apparently dying cyclones (especially of the type Fig. 4 b) may be reinforced by strong secondary cold fronts.

The propagation of a cyclone has a close relation to its structure and energy.[1] The centre of a young cyclone may be defined as the crest of the projecting warm tongue, and its propagation will thus depend upon the wind in that part of the warm tongue. *The cyclonic centre then moves in the direction of the warm sector current, i, e.: approximately parallel to the isobars of the warm sector.* The velocity of propagation of the cyclone increases simultaneously with the increase of wind in the warm sector. The cyclone accordingly moves with accelerating velocity during the first part of its life. The maximum velocity seems to be reached at about the same time as the maximum strength.

When approaching the structure of the homogeneous air vortex, the velocity of propagation decreases rapidly, and the dying cyclone finally becomes almost stationary, provided that it is not conveyed as a »secondary cyclone« in a larger system of currents.

As dying cyclones usually move slower than younger ones, they are frequently seen to be handicapped and absorbed by the latter. The front side of a cyclone, therefore, often contains the dissolving remains of absorbed cyclones. In their last stage of absorption they are only seen as banks of Alto Cumulus and Alto Stratus below the Cirro-Stratus of the warm front surface.

The quite newly-formed cyclones, which have not yet had an oppurtunity of absorbing dying cyclones, generally show a uniform inclined stratum of Cirro-Stratus and Alto-Stratus without any separate banks of cloud underneath.

Polar Front.

New cyclones usually form on thermal boundary surfaces which run through an already existing »mother cyclone«. The formation may take place either according to the scheme of Fig. 6 or that of Fig. 8.

At the moment when the warm sector of an old cyclone is cut off (Fig. 6), two branches of the cyclonal boundary join south of the place, where both sides of the warm sector have closed together. At this place of junction a new cyclone is fairly frequently formed. This cyclone has at once the structure of a well-shaped young depression: a large »warm sector« projecting into colder surroundings.

This type of cyclone formation occurs especially often at the southern ends of mountain ranges (for instance in the Gulf of Genoa, or in the Skagerak). The mountains have the effect on cyclones passing to the north of them of stopping the warm front till the cold front arrives and completes the cutting off of the warm sector (Fig. 7). The southern sections of warm front and cold front, which then join at the southern end of the mountains, border the warm sector of the new cyclone.

[1] As to the laws of propagation of cyclones see also: *V. Bjerknes:* On the Dynamics of the Circular Vortex, Geof. Publ. Vol. II. No. 4, page 75.

The most common type of formation of a new cyclone is shown in Fig. 8. At the extreme end of the cold front surface, the cold air turns westwards, and flows parallel to the boundary surface, which thus becomes stationary. We have then realized the situation from which we started on Fig. 2, and the new cyclone begins to form like a slight wave on the cold front surface of the mother cyclone.

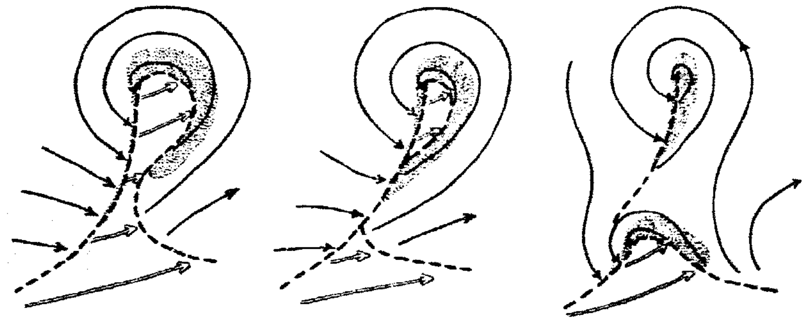

Fig. 6. Formation of a secondary cyclone simultaneously with the seclusion of the »mother cyclone«.

The creation of a new cyclone generally appears to take place according to either of the schemes of Fig. 6 or Fig. 8. In both cases there is an obvious »genetic« connection between already existing cyclones and the cyclone under formation.

The newly-formed cyclones may again create conditions for the development of further new ones, so that a long series of cyclones may be formed like waves on one single boundary surface (Fig. 9). The boundary surface, connecting such a series of cyclones in the temperate zone, will separate the cold air of polar origin from the warm air supplied to the cyclones from the subtropic Highs. The boundary surface thus marks the temporary southern limit of the polar air-masses, a property which has suggested the

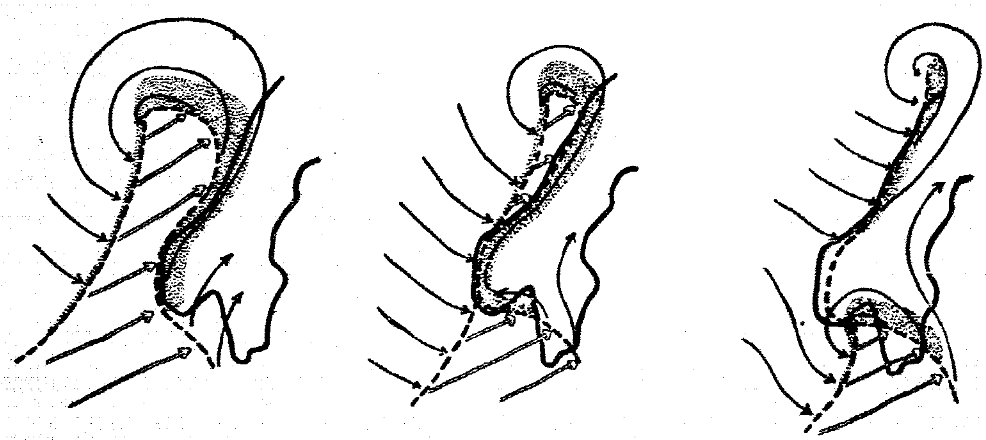

Fig. 7. Formation of a »Skagerak cyclone.«

name »Polar Front Surface«, and correspondingly for its line of intersection with the ground: the »Polar Front«.

The polar front is generally a wavy line, in continual motion through all latitudes of the temperate zone, bordering large tongues of polar and tropical air. The tongues of tropical air form the warm sectors of the young travelling cyclones and the intermediate tongues of polar air constitute the moving wedges of high pressure between successive

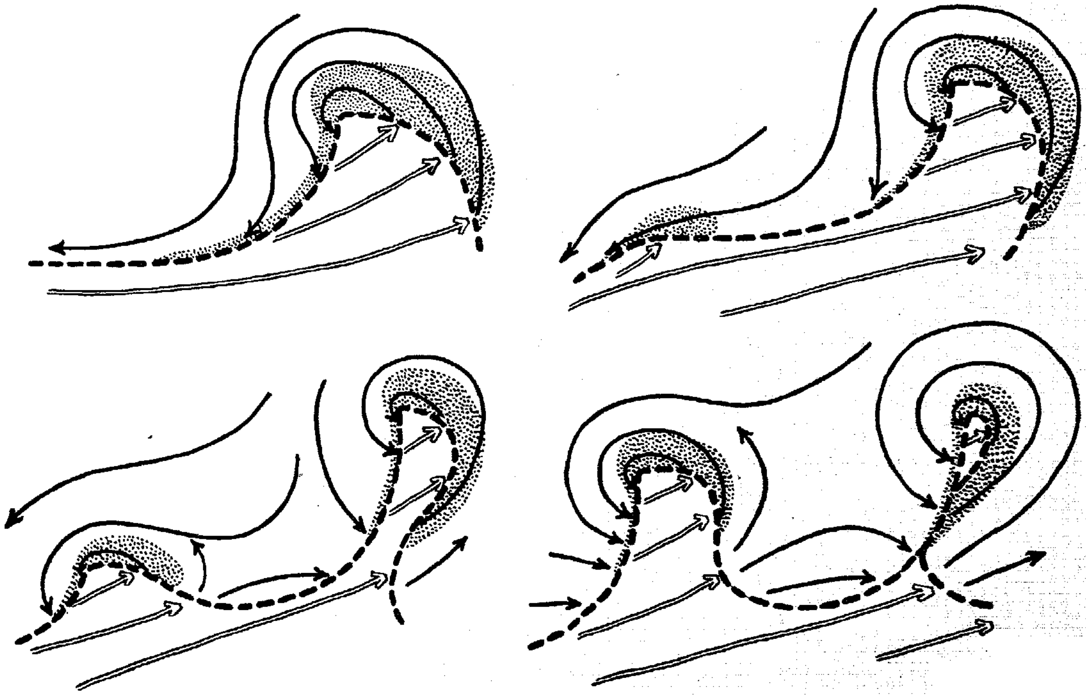

Fig. 8. Formation of a secondary cyclone as a wave on the cold front of the »mother cyclone.«

cyclones. The occluded and dying cyclones which have lost their warm sectors will all lie north of the polar front, which only passes through the southern outskirts of the depression.

In addition to the polar front itself several other thermal boundaries exist, especially within the polar air (secondary cold fronts of the cyclones). The tropical air is usually more uniform and does not often contain distinct internal boundary surfaces (secondary warm fronts).

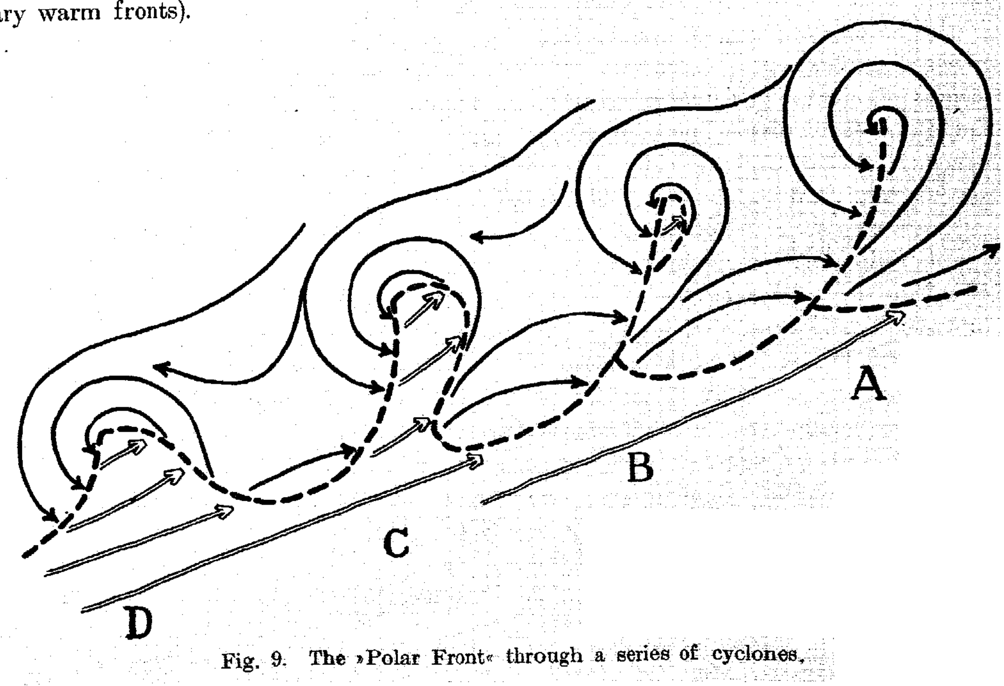

Fig. 9. The »Polar Front« through a series of cyclones.

The temperature contrasts between stations north and south of the polar front are not everywhere equally conspicuous. As a rule, the polar front is a distinct thermal boundary at places where it simultaneously forms a distinct line of discontinuity in the fields of winds. For instance, near the centres of young cyclones, where the two opposite currents bring together air-masses with perfectly different life histories, the polar front is often a true discontinuity line in respect of temperature. On the other hand, where both air-masses for some time have flowed nearly in the same direction, the temperatures will, as an effect of the identical outer influences, tend to become equal on both sides. This will, for instance, take place at the extreme southern ends of the tongues of »polar« air, in which the winds are nearly the same as in the surrounding »tropical« air. The heating from the ground will there increase the temperatures of the polar air, so that the boundary against the adjacent tropical air becomes indistinct or even vanishes.

In order to find the polar front in such cases, indirect methods must be applied, some of which may be briefly mentioned here.

The trajectoires of the air may, for instance, be used in order to find an indistinct boundary line which has been distinct on previous maps. When exact measurements of air motion are not available to a sufficient extent, the gradient wind may be used as the representative upper wind, which determines the displacement of air-masses and their mutual boundary surfaces. It should thereby be borne in mind, that a cold front must move at least as fast as the horizontal flow of cold air behind it, provided that the cold air does not ascend. On the other hand, a warm front will usually move somewhat slower than the horizontal flow of warm air behind, as the latter ascends the wedge of cold air in front of it.

The absolute humidity of the air may be used in order to identify air-masses and boundaries between different air-masses, in cases when insolation or radiation have effaced the thermal discontinuity.

At sea and at free maritime stations, the difference between air and sea temperature is a good criterion as to the origin of the air, and thereby indirectly determines the boundaries between different air-masses. Tropical air conveyed from warmer parts of the earth will be as warm as, or warmer than, the surface of the sea, whereas polar air will be colder than the surface even after a rather long passage over warmer regions (for instance, in the extreme southern ends of the tongues of polar air). Tropical air-masses arriving in more northern latitudes often bring fog or mist, formed by the cooling of lower layers at their contact with the ground or sea surface. The cooling from below moreover gives the tropical air of temperate latitudes a great thermal stability, which also appears in the predominance of stratified clouds in this kind of air. On the other hand, polar air-masses arriving in lower latitudes are constantly warmed from below. The resulting convective currents give rise to the formation of Cumulus and Cumulo-Nimbus clouds and corresponding instability showers.

The temperature in the free atmosphere, which is a more conservative element than the temperature on the ground, usually affords the best indications of the origin of air-masses. Temperatures from kite and aeroplanes ascents, as well as from mountain observatories, are therefore very useful for the analysis of the polar front.

When applying all these indirect methodes of analysis, it is usually possible also to trace the more indefinite parts of the polar front.

The Cyclone Families.

In a series of cyclones formed on one and the same polar front, each cyclone usually follows a track lying south of that of the preceding cyclone. After a certain number of such cyclones, the polar front reaches the region of the subtropic Highs, from whence a steady transport of air takes place through the trade-winds towards the equator. In some conspicuous cases, the arrival of the polar air may be observed as a sudden but slight decrease of the temperature of the trade-wind, but usually the polar air soon amalgamates with the adjacent tropical air. The polar air, thus entering the trades, leaves the cyclone circulation of the temperate zone for a considerable length of time and will be transformed into real tropical air during its stay in equatorial regions.

At places where the polar air finds opportunity for entering the trade wind, the polar front will thus be interrupted (Fig. 10).

When the polar air from the rear of one cyclone enters into the trade winds, the next cyclone will usually appear on a more northern track, and follow a new polar front, which is not directly connected with the previous one.

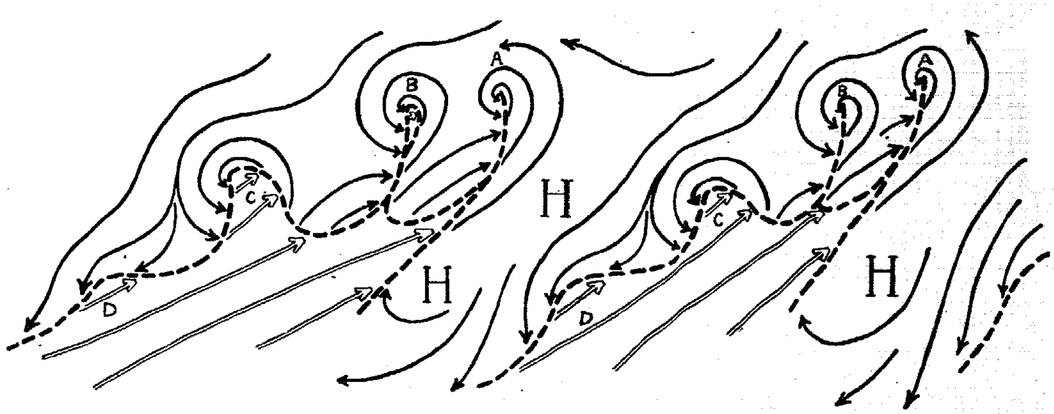

Fig. 10. Cyclone families.

On this new polar front, the same phenomena will be reproduced as on the old polar front. The cyclones will follow step by step more southern tracks, until the polar air again reaches the tropics, and the same cycle of events is repeated.

The resulting periodicity of the position of cyclone tracks enables us quite formally to divide the cyclones into groups, which we call *cyclone families.* Each family begins with the first cyclone travelling along a track north of that of the preceding cyclone, and ends with the cyclone travelling so far south that it brings the polar air down into the trade wind system. All cyclones of one family are thus formed on one and the same polar front. Moreover, each new family is formed on another polar front, not connected either with the polar front of the foregoing or of the following cyclone families.

When such a cyclone family passes, usually 4 particular cyclones are observed from a fixed place, centrally situated within the cyclone belt. This number may, however, vary considerably from case to case. In the Norwegian forecasting service, the cyclone families are enumerated with numbers beginning with the first family entering Europe on or after the first of January. The enumeration starts anew at the beginning of each year. The single cyclones in addition to the family number are denoted by a letter *A*, *B*, *C*, etc., showing their place within the family.

The single members of a cyclone family are usually of different ages. In Europe, the first and second cyclones (*A* and *B* cyclones) are mostly of the dying type already when arriving from the Atlantic. The later members (*C* and *D* cyclones) are, however, mostly of younger age, and show increasing intensity during their passage through Europe. We may from this draw the conclusion that *A* and *B* cyclones are formed relatively far west of Europe, and have travelled for several days before they reach us, whereas *C* and *D* cyclones are formed nearer to the European network of stations. Likewise we may expect that the *A* cyclone will die already within the region of the map while the *B* cyclone will reach farther, and *C* and *D* cyclones still farther eastwards before they die.

When the *A* cyclone dies, the *B* cyclone will be the foremost member of the family; when the *B* cyclone dies, the *C* cyclone will become the foremost member, and so on. The names *A*, *B*, *C*, and *D* are thus dependent on the place where the enumeration of cyclones is made. An *A* cyclone in Europa may, for instance, have been a *D* cyclone in America. Owing to its north-easterly motion, it may come from low latitudes in America, but still appear as an Arctic cyclone on the European maps. All the preceding cyclones of the family have then died somewhere on the way across the Atlantic Ocean, and new cyclones have formed behind.

Although the single cyclone usually lives only about a week, the cyclone family may theoretically live indefinitely, as it is constantly rejuvenated by the creation of new cyclones behind the dying ones.

The Polar Front Theory of General Atmospheric Circulation.

The source of energy for the general circulation of the atmosphere lies in the contrast of temperature between the polar and the equatorial regions. The system of motion which is comprised under the name »General Circulation«, tends to smoothe this contrast by bringing polar air to tropical regions, and vice versa. The simplest form of this system, a tradewind along the ground from polar to equatorial regions and a returning antitrade in the height, is on higher latitudes impossible on account of the effect of the earth's rotation. The »trade« would after some travel southwards obtain a strong westward component, which would theoretically increase to 460 m/sec., if the travel to the equator should be carried through. Likewise, the »antitrade« would reach enormous eastwards components on its travel from equator to the pole. The system of trade and antitrade may therefore only be established on low latitudes, where the effect of the earth's rotation is still moderate. In the temperate zone a more complex system of motion is established (Fig. 11). The »tradewind« from the pole divides into different branches — polar currents — between which channels

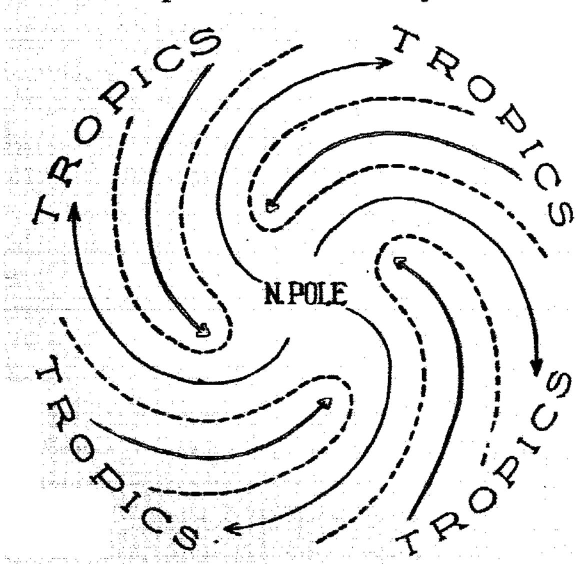

Fig. 11. Schematic picture of the general atmospheric circulation in extratropical regions. Divided »polar trade« and intermediate »tropical currents«.

remain open to corresponding branches of the »antitrade« — tropical currents. Thus the »antitrade« of the temperate zone appears not only as an upper polewards current but also as »tropical currents« on the ground.

The particular polar currents will, when starting as northerly currents, tend to deviate into NE or even ENE currents; likewise the tropical currents deviate from

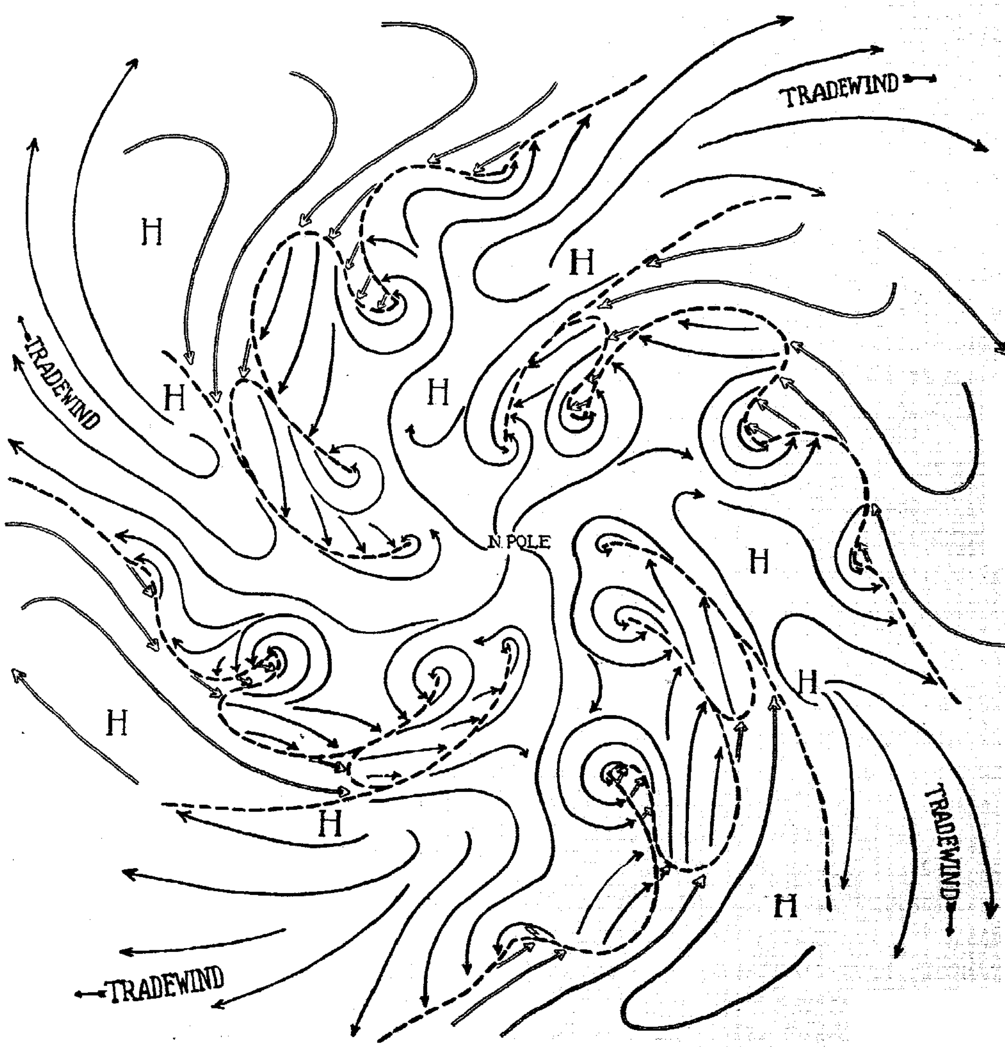

Fig. 12. General extratropical circulation of the atmosphere.

southerly to SW or WSW currents. We thus have a system of alternate polar and tropical currents beside each other, winding up spirally round the axis of the earth.

These currents will hinder each other from obtaining the great west-east or east-west components, which were to be expected as an effect of the earth's rotation.

At the limit between a polar current and a tropical current to the east of it, the two currents are deflected from each other, so that an air deficit results above the region of their mutual limit. The low pressure system, formed in that way, corresponds to a cyclone family (see Fig. 12). *The cyclone family is thus a boundary phenomenon between the left flank of a polar current and the adjacent tropical current.* The single cyclones of the family transform the boundary between the two currents — the polar front — into a complicated wavy curve, which constantly changes its form. Moreover, the polar current will contain within itself all the eddies of dying cyclones, so that each polar air particle of necessity performs complicated motions before it reaches the tropics.

The formation of cyclones as boundary phenomena between a polar and a tropical current is one of the natural brakes against the enormous east-west and west-east components, which should otherwise result in both currents. As soon as an easterly polar current and a westerly tropical current become too strong, a cyclone forms between them and makes the currents encroach upon each other, diminishring their differences of velocity. A polar air particle, travelling from pole to tropics, successively comes under the influence of the different cyclones of the family. Each cyclone deviates the motionof the particle from easterly to northerly or even westerly, so that it again may advance some distance towards the tropics without obtaining too great a westward velocity component.

A second brake against the great west-east and east-west components acts where a polar current borders a tropical current to the west of it. The two currents, owing to the earth's rotation, will there press together, so that they hinder each other from obtaining the velocities to be expected as an effect of the earth's rotation alone. The result of this pressing together appear in an accumulation of air-masses above the region of the mutual limit of the two currents, or in the field of pressure as the formation of a High. This process represents the general formation of moving anticyclones: *A moving anticyclone forms as a boundary phenomenon between the right flank of a polar current and the tropical current to the west of it.*

The moving anticyclone is thus formed between two successive cyclone families and follows their motion from west to east round the pole. Consequently the anticyclone moves with the same speed as the cyclone families, but more slowly than the particular cyclones which during their lives move from the rear to the front of their family.

The moving anticyclones have, according to their way of formation, a cold eastern side which is constantly renewed by a supply of polar air from the rear of the last cyclone, and a warmer western side, more or less distinctly separated from the cold side. The descending motion in the anticyclone will mainly go on in its heaviest part, i. e. in the polar air. The resulting adiabatic heating gradually transforms the polar air into warmer air, which under certain circumstances may enter the »tropical« current along the western side of the anticyclone.

For obvious reasons the lower layers of the anticyclone are hindered from obtaining as strong descending motion as the upper layers, and will therefore also be heated to a correspondingly lesser amount. This often leads to the formation of quasi-horinzontal temperature inversions, which are charachteristic of the anticyclones.

The adiabatic heating thus described takes place in every cold air-mass which has an opportunity of descending, thus also in the tongues of cold air between two cyclones. According to recent Lindenberger investigations, this descending motion in the cold tongue often produces a distinct inversion of temperature (*Abgleitfläche*), which is analogous to the anticyclonic inversions. In a rapid succession of cyclones, however, the process has not sufficient time to heat the entire cold mass to such an extent that it may act as tropical air.

When a moving anticyclone for some reason becomes a stationary one, it can no longer obtain an air supply in low layers from its surroundings, while such a motion would lead from lower to higher pressure. The stationary anticyclone therefore only obtains its air supply from above, and will soon assume a thermal structure determined by the adiabatic heating acting on the descending air current. The moving anticyclone, becoming a stationary one, will accordingly change its structure, and after some time become a homogeneously warm and slowly descending air column. The descending motion in such a stationary anticyclone proceeds against the forces of gravity as relatively warm and light air descends. The energy for its maintenance must therefore be derived from the energy of the bordering system of currents, belonging to adjacent low pressure systems.

Very often the stationary anticyclones are confined to relatively cold regions of the earth, for instance the cold continents in winter. In these cold anticyclones the descending motion, at least in lower layers, is directly favoured by forces of gravity, and the anticyclone has already in itself some energy for the maintenance of its system of motion. Usually, these anticyclones exist only in low layers of the atmosphere, but they may nevertheless, when they are centered over large cold continents, have a great persistance and form effective obstacles to moving cyclones.

Periods of Meteorological Elements due to Cyclone Families and Moving Anticyclones

If we disregard the obstacles formed by the large continents, the cyclone families and intermediate moving anticyclones may be imagined to travel continually round the pole. This rotating system (Figs. 11 and 12) will produce a periodicity of meteorological elements all over the temperate zone. Places far north will, for instance, only receive precipitation from the first passing members, and places far south only from the last passing members of the cyclone family. Places situated centrally in the cyclone belt, so that they receive precipitation from all the cyclones passing, will have a short spell of fair weather during the passage of the moving anticyclone, which separates successive cyclone families. Other meteorological elements such as pressure, temperature and wind, will of course exhibit corresponding periodicity.

If the cyclone families perform perfect circuits round the pole, the length of the periods should be equal in all parts of the cyclone belt. They may, however, be of different length on the two hemispheres, as the cyclone families north and south of the tropics form two independent systems.

The length of the period in question is equal to the time which elapses between the passages of the *A* cyclone of one family and the *A* cyclone of the next one. During the year 1921 66 cyclone families passed across Europe, which gives a mean duration of each passage of 5.5 days. As the families were not always quite well defined, (especially when they passed too far north for our maps), we may estimate the number of families quoted for 1921 to have a possible error of about 10 %.

We recognize in this period of cyclone families a wellknown and distinct short period of climatology, found by different investigators.[1] The most thorough investigation on this problem has been rendered by Defant[2], who has examined the short periods of precipitation in different parts of both hemispheres. He finds for the year 1909 a period of about 5.7 days on the northern and about 7.2 days on the southern hemisphere. The cyclone family period of 1921, 5.5 days, agrees so well with the precipitation period from

[1] *H. C. Russel*: »Moving Anticyclones in the »Southern Hemisphere«, in »Three Essays on Australian Weather« by *R. Abercromby*, Sydney 1896.

William J. S. Lockyer: »Southern Hemisphere Surface Air Circulation«. Publication of the Solar Physics Committee, London 1910.

In America the 5.5 days period is known under the name *Clayton's Period*. Cf. *W. J. Milham*, Meteorology 1912, p. 410.

[2] *A. Defant*: »Die Veränderungen der allgemeinen Zirkulation der Atmosphäre in den gemässigten Breiten der Erde.« Wiener Sitzungsberichte 1912, Vol. 121, p. 379.

1909 (northern hemisphere) of 5.7 days, that we may consider them as identical within the possible limit of errors. It thus seems very probable, that the precipitation periods found by Defant have been produced by the passage of cyclone families and moving anticyclones.

Defant concludes that the 5.7 days period is produced by a circumpolar system of waves, each with a wave-length of 90° longitude, proceeding from west to east. This view also agrees well with the east-west extent of the cyclone families found on circumpolar maps, and we may accordingly conclude that the system of circumpolar waves usually consists of 4 cyclone families and 4 intermediate moving anticyclones.

The explanation of the circumpolar waves is implicitly the same as that of the cyclone families and moving anticyclones given in the previous chapter. According to this view, the circumpolar waves are, in a way, waves in the general circulation, produced by the effect of the earth's rotation.[1] Their source of energy is the same as that of the general circulation, i. e. the contrast of temperature between poles and tropics.

The stationary pressure systems in temperate latitudes are great obstacles to the formation and motion of circumpolar waves. By strongly developed Siberian anticyclone, for instance, one cyclone family after the other may be crushed at its western border, thus being unable to advance across the continent. Likewise in spring and early summer, a monsoon-like polar current may be established across Europe to the Central Asian Low, and interrupt the west-east passage of cyclone families and anticyclones. The circumpolar waves are always superposed upon these stationary pressure systems, and therefore appear with less regularity, than they would have on a perfectly uniform rotating globe.

[1] This view does not completely agree with that of *Defant*, who ascribes the circumpolar waves to the different heating effects of oceans and continents on the atmosphere of the temperate zones.