ON THE STRUCTURE OF MOVING CYCLONES

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

In order to obtain at least the first of these conditions fulfilled at any rate, I have collected detailed data from the archives af the meteorological institutes in Norway, Sweden and Denmark, including also observations from third class stations. In addition, I have examined the comparatively detailed daily maps used for weather-forecasts in Western Norway during the summer 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 moving cyclones, which I shall outline in this paper, trusting to return to the subject in detail later on.

THE STEERING-LINE AND THE SQUALL-LINE.

The lines of flow in a cyclone have approximately the character of logarithmic spirals. By increasing number of observations, however, several aberrations from the regular spiralic shape appear. Among a multitude of details, certain characteristic traits seem to return more or less markedly for all cyclones yet examined (Fig. 1).

Every moving cyclone has two lines of convergence, which are greater and more conspicuous than the others, and distinguished by characteristic thermal properties.

The first of these lines comes in to the centre 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 centre seems to be identical with that of the path. As the line thus gives the momentaneous direction of propagation of the cyclone, it may, for practical purposes, be called the *steering line.*

The other line of convergence comes in from the right rear of the cyclone, and is identical with the wellknown *squall line*, which is known to accompany moving cyclones. Both lines of convergence are often seen to be preceded by a line of divergence.

The steering line and the squall line are intimately related to the distribution of temperature, as they boarder the warm area of the cyclone, or, as we may call it, its »Warm Sector«.

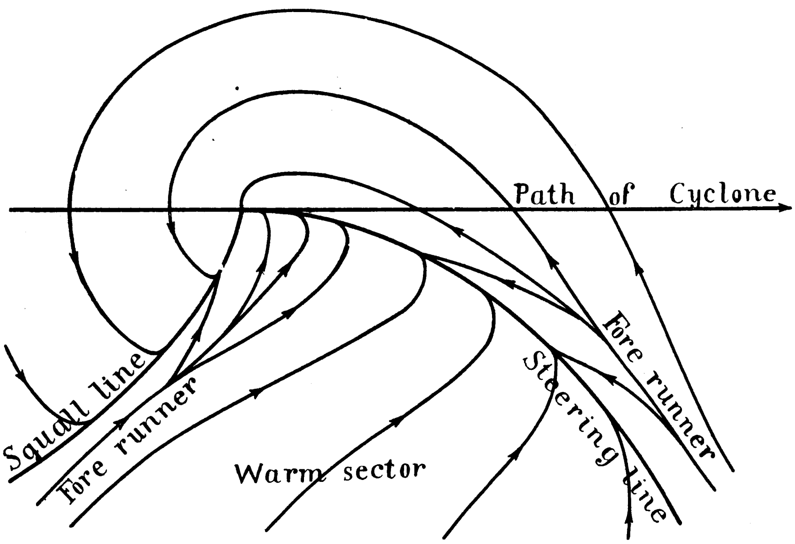

Fig. 1. Lines of flow in moving cyclones.

Both the steering line and the squall line move according to the law of propagation for lines of convergence, viz: in the northern hemisphere towards the right, relatively to the direction of the wind along the 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 wellknown increase of temperature in front of cyclones, and 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 steering line is also easily perceptible.

THE STEERING-SURFACE.

The air-masses flowing in from both sides towards the steering line, will not be mixed. 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*. It leans towards the cold side, the cold air thus forming a flat wedge under the warm. Fig. 2 b shows the horizontal field of flow in the nearest vicinity of a steering surface, and Fig. 2 a gives a representation of the motion in vertical projection. The steering line itself is represented by the dotted line in both figures.

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 only follow to a certain height. It soon descends again, and at the place where it reaches the ground, the line of divergence, which has already been mentioned, appears in the field of horizontal flow. (Fig. 2 b.)

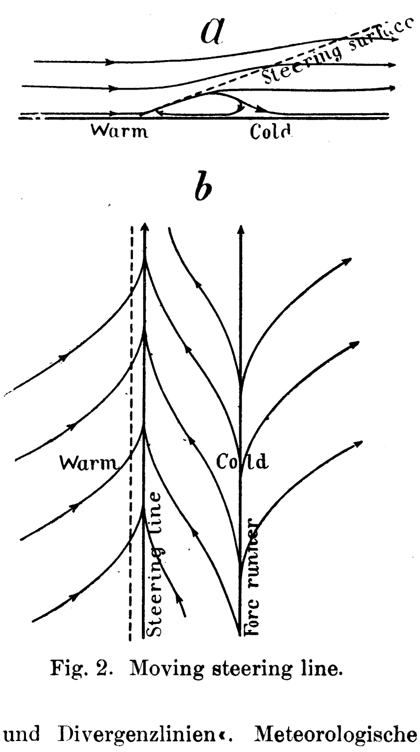

Fig. 2. Moving steering line.

*) J. Bjerknes: »Über die Fortbewegung der Konvergenz und Divergenzlinien«. Meteorologische Zeitschrift 1917, 10—11.

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 fifty kilometers in front. The air between this fore-runner and the steering line itself, performs a rolling motion. The air to the right of this rolling mass moves off horizontally, having in the direction normal to the steering line a velocity-component corresponding to the velocity of propagation of the system.

It should be noticed that the line of divergence preceding the steering line as a fore-runner, 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 pre-dominating, is apparently overcompensated by terms, due to friction against higher air currents, generally neglected.

It will be useful also to refer to Fig. 3, representing the motion found at stationary steering lines, having no fore-runner. If this steering line should propagate towards the right, the entire cold mass must successively ascend to give place for the warm. The existence of the forerunning line of divergence thus seems to be a necessary condition for the propagation of the steering line.

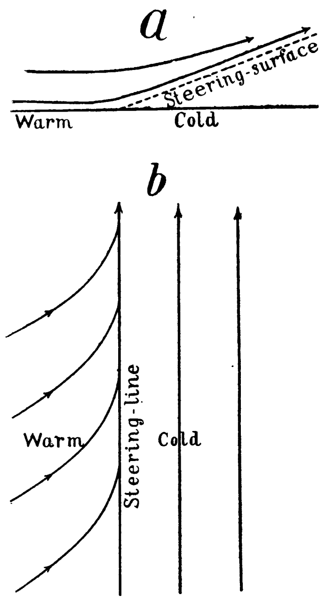

Fig. 3.
Stationary steering line.

THE SQUALL SURFACE.

The air-masses flowing from both sides towards the squall line will remain separated by a boundary surface that for convenience may be called the *squall surface*. This surface does not, as the steering surface, simply resemble an inclined plane. Just as in W. Schmidt's well known experiment**), it is fronted by a »head«, which seems, however, in some cases to have another character than in the experiment. The question is connected with that of the existence of a line of divergence preceding the squall line as a fore-runner, and involving a rolling motion at the front. But the distance between the two lines is much smaller than in the case of the steering line, and this makes it difficult to get a clear view of the system. The back of the head 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 to hand.

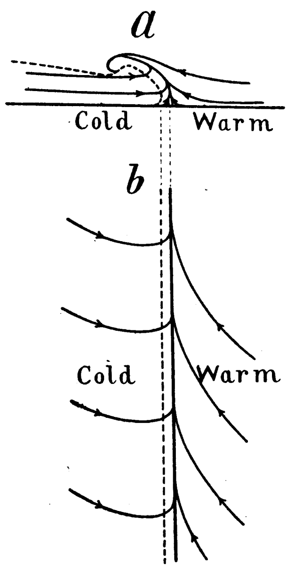

Fig. 4. Squall line.

Fig. 4 b shows the horizontal field of flow in the nearest vicinity af the squall surface, and Fig. 4 a gives a vertical section of the same motion, under the supposition that the »head« has the same character as in W. Schmidt's experiment. The sqall surface itself is represented by the dotted 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 rapidly to ascend the abrupt front of the head, in order afterwards to perform only occasional ascensions and descensions.

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

*) J. Bjerknes: L. c.

**) *W. Schmidt*: Wien Sitzungsberichte I. 119, II a, 1910 p. 1101. Meteorologische Zeitschrift 1911, p. 357.

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

When the field of horizontal motion is known from the wind observations from meteorological stations, the vertical motion in lower strata may be constructed by aid of

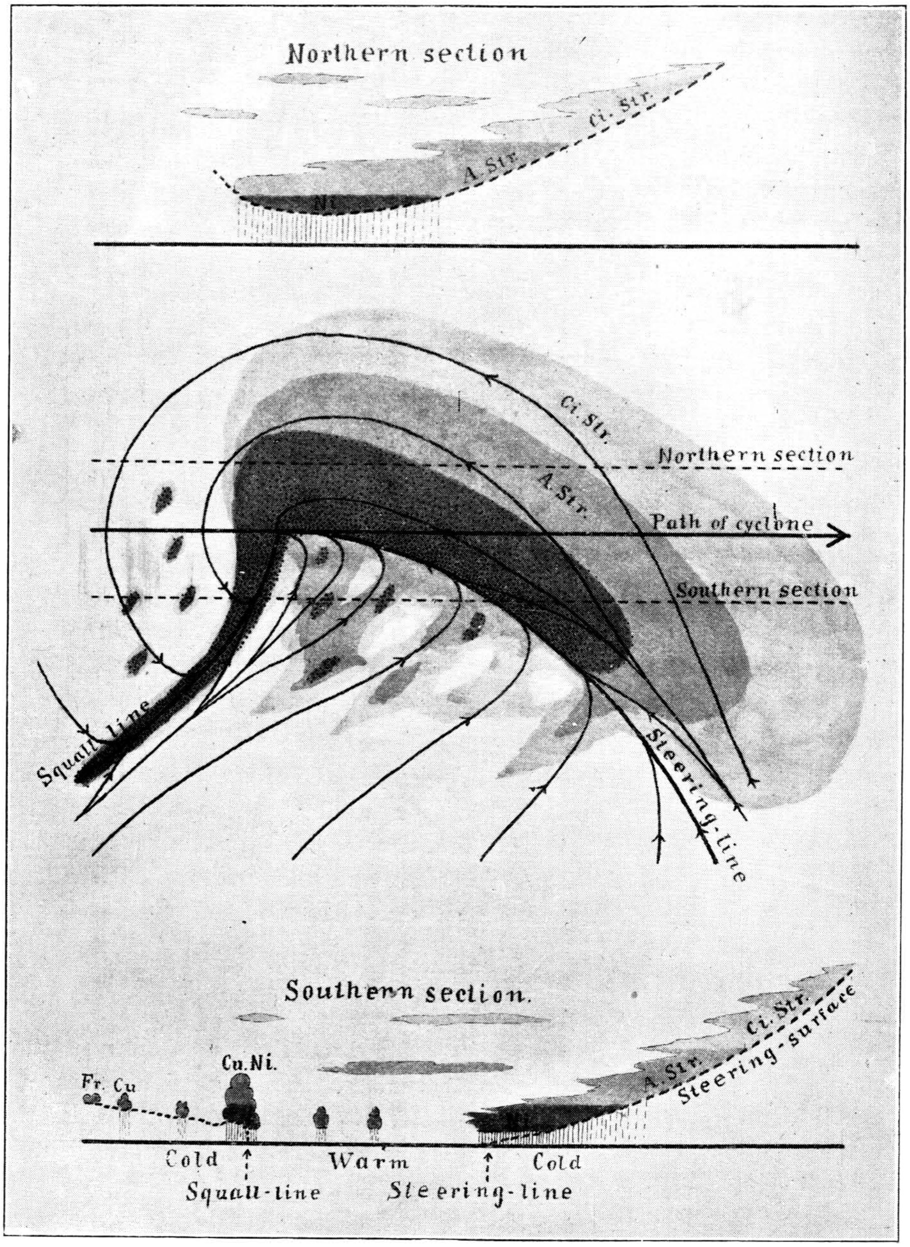

Fig. 5. Clondiness and Precipitation in moving cyclones.

the equation of continuity. Such constructions have made characteristic distributions of vertical motion appear.

In the cyclonic area ascending and descending velocities occur alternately. Greater transport of air upwards takes place only along the two lines of convergence, steering line and squall line, where the warm and cold air-masses meet each other. Otherwise the warm and cold masses of air in its entirety have no ascending motion of importance, in the cold even descending motion preponderates.

Fig. 5 gives the distribution of clouds and precipitation generally found in moving cyclones. The area of rainfall extends as a broad zone on the cold side of the steering line, and as a narrow one along the squall line. The area of clouds extends as a zone further in front of the steering line. In addition, rain and clouds occur irregularly dispersed in the warm sector and also over the cold area behind the squall line.

The distribution of vertical motion, and that of rain and clouds show thus striking correspondance to each other.

The broad zones of rain and clouds in front of the steering line are apparently caused by ascension of warm air upwards the slowly inclined steering surface. The clouds, developed in this way, will according to their heights arrange in zones parallel to the steering line. As the steering surface runs quite continuously from the ground to the highest strata, there will moreover exist no distinct limits between adjacent zones, the character of clouds changing continuously from that of Nimbus through that of Alto Stratus to that of Cirro Stratus.

A rough calculation will show that the effects of the ascending air, originating from the ground at the steering line, really will reach far enough to explain the great breadth of the zones.

The steering surface at which there is a discontinuous change of temperature and of wind velocity, may according to a formula of Margules *), have an inclination of equilibrium depending upon the differences of temperature and velocity between both sides of it. In the case which we are considering, the surface of discontinuity is a moving one, 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 small, and reckon approximately with the equilibrium values.

The formula of Margules, when applied directly to steering surfaces found on detailed maps, have led to values of its angle of inclination amounting to a fraction of a degree. For practical purposes we may thus calculate with an average inclination of 1 : 100.

Let us, for instance, assume the lower limit of Ni. at 500 meters. The steering surface will reach this height 50 kilometers in front of the steering line. From there the lower cloudlimit will rise gradually. 200 kilometers ahead of the steering line the Ni. will be found at the height of 2000 meters, and at a still greater distance there will only exist higher clouds, A. Str. and Ci. Str. If we still suppose the same inclination, A. Str. would reach 500 and Ci. Str. 800 kilometers in front of the steering line.

The rain falling from the Ni. will consequently extend as a zone about 200 kilometers broad, on the cold side of the steering line. The intensity of the rainfall will decrease gradually from the zone of lower Ni. to that of higher Ni., from the highest ones there will only fall single raindrops. If the steering line had a length of 1000 kilometers, the zone of rain would cover an area of about 200 000 square kilometers.

These calculations corresponding to average conditions make it probable that the large areas of precipitation and clouds, observed in front of cyclones, really are caused by ascension of warm air upwards the slowly inclined steering surface.

The zone of rain along the squall line is apparently caused by ascension of warm air at the front of the cold wave. The form of the squall surface makes it intelligible why the squall line is only accompanied by a narrow stripe of rain. Ascension will only take place at the front of the »head«, and its effects consequently will not reach far. In return, the rapid ascension will give the rainfall a great intensity.

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*) Margules: »Energie der Stürme«. Jahrbuch der K K Zentr anst. für Meteorologie 1903 Anhang. English: »The Mechanics of the Earth's Atmosphere«, a collection of translations by Cleveland Abbe. Smithsonian Miscellaneous Collection. Vol. 51.

The disconnected areas of rain over the rest of the cyclone, correspond to small lines of convergence, in most cases of the squall line typus. Extending only over some few square kilometers, these squalls are, however, often impervious to exact investigations on the base of our present synoptical weather maps.

Recapitulating the essential process of development of clouds in cyclones, the cold air may be said to play a part like that of a very high »continent« against which a warm and humid wind is blowing. The warm air, being forced to ascend, will above its level of condensation cover the »continent« with »fog«. This »fog«, which may be observed from below through the transparent »continent« of cold air, is according to the height called Nimbus, Alto-Stratus, or Cirro-Stratus.

Other formations of clouds, especially those of the Cumulus typus have more local characters, and are not specific cyclone clouds as they also occur in other situations of weather.

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 on a fixed place, on the two sides of the path during the passing of the cyclone.

An observer to the right of the path will perceive the passage of both lines of convergence, the steering line and the spuall line. While the steering line approaches, the steering surface will gradually sink down to the earth's surface. Thus the observer will first see the highest clouds belonging to it, viz: the Ci.Str. forming a light veil over the firmament. This veil transforms, gradually thickening, into a uniform cover of A. Str. As the cover of cloud is getting lower and more compact, the A. Str. transforms into a stratum of Nimbus. The first raindrops now fall, but it still takes some time before the rain has grown to its greatest intensity. Simultaneously, the lower limit of the Nimbus gradually goes down to the level of condensation in the warm air. Soon after a change of wind and a small increase of temperature will indicate the passage of the steering line and the entrance into the warm sector.

From that moment the continuous rainfall stops and is succeeded by the changing weather which is characteristic for the warm sector. During intervals between showers, higher clouds are still to be seen, but they do not perfectly hide the blue sky any longer, as they often give place to partial clearings.

After some time the passage of the squall line will be perceived. By that time the wind suddenly turns to the right, simultaneously increasing to violence, the temperature falls rapidly, the clouds transform 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 neither by the steering line nor 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 surface in the »continent« of cold air. Thus he will see the veil of Ci. Str. gradually thickening down to A. Str. and Ni. The Ni., however, will not go as low down as in the warm sector, and the rainfall does not grow to the same intensity. The clearing of the sky takes place by and by without any striking changes of wind, temperature, or form of cloud.

ON THE MECHANICS OF MOVING CYCLONES.

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

The moving 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 bright double lines. As a combined effect of the barometric depression and of the deflecting force of the earth's rotation, both currents get a turn round the cyclonic centre. As the combined effect of this turning motion and the 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 rendered by the potential energy of the system of light and heavy air lying adjacent to each other horizontally. 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.

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 preeminently evolving under such conditions. Further a series of cyclones often follow 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 even for the next one.

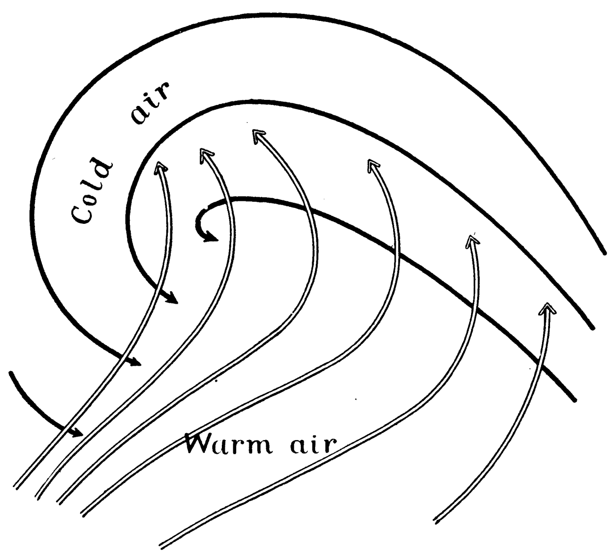

Fig. 6. Cyclonic motion in lower strata.

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

Taking the general case of a cyclone propagating to the east, the cold current will cover the ground on the northern and western side of the centre, while the warm current will only be able to maintain the ground in the warm sector, south-east of the centre. From thence it will flow over the cold current, in the higher strata joining the general western drift.

The general effect of the motion described is that cold air is conveyed to regions previously covered with warm air, and there spreads along the ground, and that in compensation warm air is conveyed to previously cold air regions, and spreads there in the higher strata. Generally speaking, cyclones may therefore 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 *highs* limiting the trade wind belt.

The results to which we have arrived may in great extent be considered as a verification of views developed theoretically by Margules*): »The phenomena of motion in *great storm areas that we call cyclones are less intelligible than those of the boe-en* (squalls). But these also, at least in medium and higher latitudes, consist of warm and

*) Margules. L. c.

cold masses of air lying adjacent to each other horizontally, cold air often spreading 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 various older theories of cyclones, while they disprove other traits in them. 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*). Ferrel's convectional theory is confirmed in its essential part in as much as the ascending air in the cyclone is warm, only that this warm air does not form a central core, but comes from the side, at the ground covering a warm sector. The general argument against the theory of Ferrel, that statistical investigations have proved a circular area round the centre 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 assumption that the mounting air in cyclones is cold and heavy. As under conditions theoretically specified by Sandstrøm,**) 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.

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*) Cfr the summary given by Humpreys, »Weather Forecasting in the United States«, pp. 51—53. Washington 1916.

**) J. W. Sandstrøm: Über die Beziehung zwischen Temperatur und Luftbewegung in der Atmosphäre unter stationären Verhältnissen. Met. Zeitschrift, April 1902, p. 161.