HISTORY OF FRONTAL CONCEPTS IN METEOROLOGY: THE ACCEPTANCE OF THE NORWEGIAN THEORY

by

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ABSTRACT

The frontal concept, as developed by the Norwegian Meteorologists, is the foundation of modern synoptic meteorology. The Norwegian theory, when presented, was rapidly accepted by the world's meteorologists, even though its several precursors had been rejected or ignored. In order to understand why this had occurred, criteria are postulated which may be relevant to a theory's acceptance. All the theories are then evaluated relative to these criteria.

The results of these examinations show that (1) most of these theories were incompletely developed, (2) the critical criteria for the acceptance of a fully developed theory is its proper presentation, and (3) only the Norwegian theory met this critical criteria.

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INTRODUCTION

Shortly after World War I the Norwegian meteorologists proposed the now well-known frontal concept of the structure of the troposphere, in which storms (low pressure areas) develop along a surface of discontinuity between two air masses; one air mass being warm and moist and the other, cold and dry. The surface of discontinuity was envisioned to be essentially continuous around the globe, thereby separating polar and equatorial air. This concept was rapidly accepted by meteorologists throughout the world and has become the foundation of most present day synoptic meteorology. However, this concept, perhaps not so clearly presented, had been suggested by various meteorologists during the preceding hundred years without any success. This work determines, by analysis of the various theories,[1] the reasons for the startling success of the Norwegian meteorologists in contrast to the failure of previous attempts to do the same thing.

The central theme in the Norwegian theory and its precursors is the surface of discontinuity in the troposphere which is now commonly referred to as a front or

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[1]For the purpose of this dissertation, theory is defined as that which furnishes the most satisfactory account or rational explanation of a series or group of phenomena in a particular science (in this case, Meteorology).

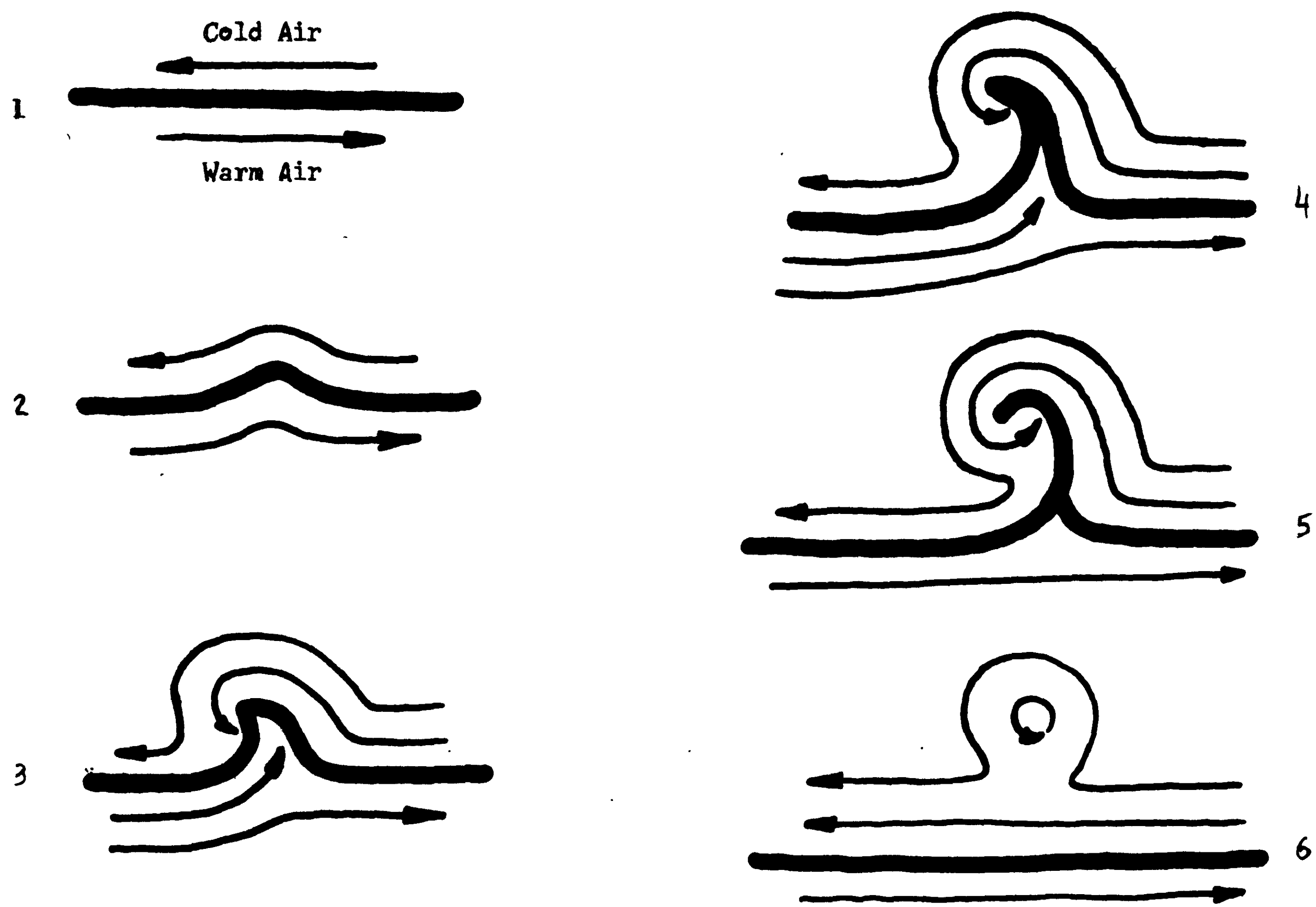

FIGURE 1

Life history of an atmospheric wave (storm) according to the Norwegian theory. Heavy lines are the fronts, and the arrows indicate airflow.

frontal zone. The Glossary of Meteorology provides an excellent definition of a front, which was as applicable fifty or a hundred years ago as it is today.

> In meteorology, generally, the interface or transition zone between two air masses of different density. Since the temperature distribution is the most important regulator of atmospheric density, a front almost invariably separates air masses of different temperature.
>
> Along with the basic density criterion and the common temperature criterion, many other features may distinguish a front, such as a pressure trough, a change in wind direction, a moisture discontinuity, and certain characteristic cloud and precipitation forms.[2]

Briefly, the Norwegian theory is as follows. There exist in the atmosphere sloping surfaces of discontinuity between warm moist equatorial air and cold dry polar air. A slight ripple on such a surface, drawing the necessary energy from the differences in the two air masses, will develop into an unstable wave which then, in time, will destroy itself. Figure 1 shows the various stages in the "life" of the wave as seen at the line where the front (discontinuity surface) touches the ground. An area of low pressure is developed at the peak of the wave; and the circulation around the low pressure area forces the warm moist air to rise over the cold dry air in front of the storm and the cold dry air to push under the warm moist air in the rear of the storm, usually producing precipitation in both areas. Figure 2 shows the three dimensional structure of a well-developed storm. The process of grad-

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[2]Ralph E. Huschke (ed.), Glossary of Meteorology (Boston: American Meteorological Society, 1959), p. 237.

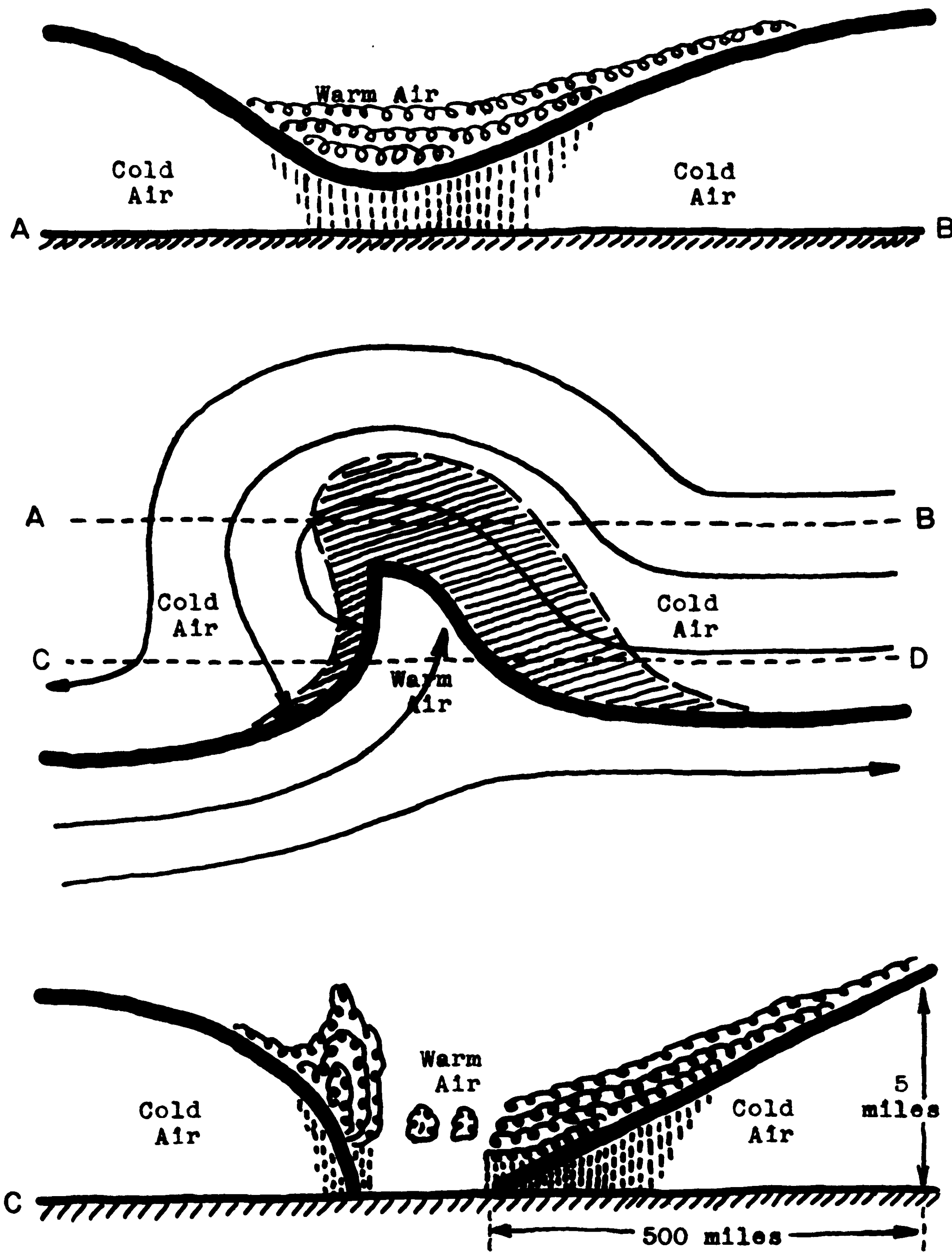

FIGURE 2

Detailed structure of a storm according to the Norwegian theory. Heavy lines are fronts; stippling and shading indicate precipitation; arrows represent airflow and curlicues indicate clouds.

ual destruction of the storm--occlusion--is illustrated in some detail (see figures 1 and 3) because it is the distinctively new feature in the Norwegian theory.

Since the Norwegian theory was readily accepted, and its precursors generally rejected or ignored, it is reasonable to assume that there were significant differences in either the theories or in the conditions surrounding the communication of these theories from their proponents to their intended audiences, or both. In order to explain the Norwegian theory's acceptance, several criteria, possibly relevant to the acceptance of a theory,[3] are postulated; and all the theories are carefully examined with reference to these criteria. The results of these examinations provide an explanation of why the Norwegian theory was accepted; and further, they suggest a general basis for the evaluation of any theory.

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[3]Note that the acceptance of a theory does not necessarily mean verification of the theory. In this particular case, for example, the Norwegian theory, during the last decade or so, has been proven defective in many respects. Today the subject of fronts and their role in atmospheric circulations is one of the most controversial subjects in the field of meteorology.

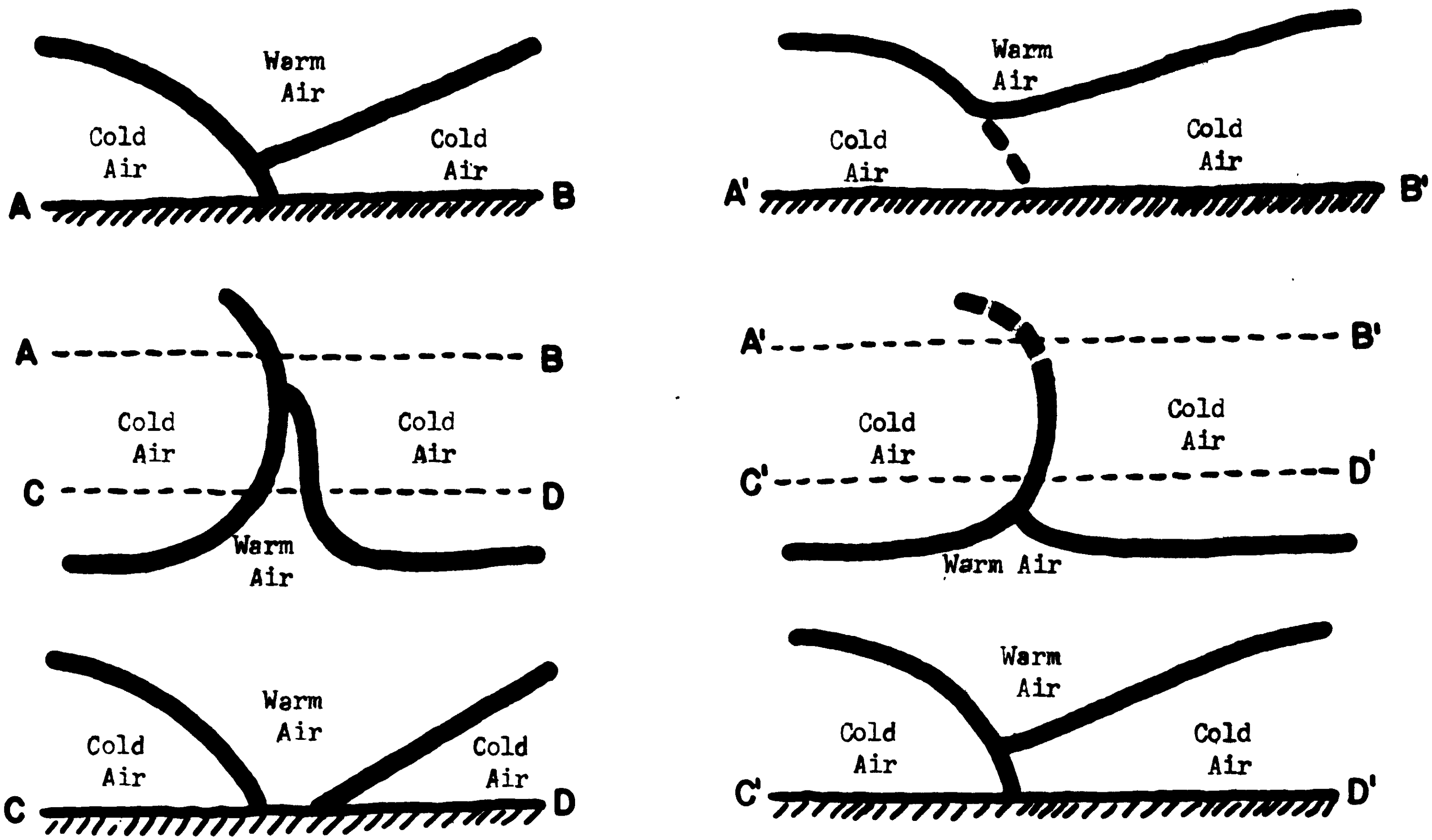

FIGURE 3

Details of the occlusion process, according to the Norwegian theory. Heavy lines are the fronts.

CRITERIA WHICH MAY BE RELEVANT TO THE ACCEPTANCE OF A THEORY

Five generalized criteria appear to include essentially all the specific criteria which could relate to the acceptance of a theory; and furthermore, the use of many specific criteria in examining these theories, aside from its complexity, would probably lead to results seemingly more accurate than the original data. Consequently, it is only the five generalized criteria that shall be enumerated and defined here.

The order in which the criteria are listed is important in that, in general, a theory which cannot pass one criterion will not usually be considered seriously on the following criterion. But it should be noted that since answers to each criterion will often be relative and quite susceptible to error the importance of order is not a rigid rule, but rather an over-all guide. Also peculiar situations can increase the importance of any one criterion, at times to the complete subordination of the other criteria.

The first criterion is that the theory is not just speculation. The theory should stand on some factual data which in turn may be related or supported by certain assumptions. Obviously, but maybe often forgotten, if the tools or instruments essential to the acquiring of the data have not been developed no theory can be forthcoming--just speculation.

The second criterion is that the theory is the most probable explanation of the observed data. This criterion consists of several parts: (1) that the data really fit the theory, (2) that the assumptions used are reasonable in the light of current knowledge, and (3) that all sections of the theory are equally sound, because, like most other things, a theory is only as strong as its weakest section.

The third criterion is that the theory is complete and unifying. It is not enough that the theory in itself is correct. It should also fit in with other theories in related areas and this fit should be shown. Further, to be accepted as a major theory, it should tie together many smaller theories which may come from both the pure and the applied branches of the field. In short, the theory should (1) tie together many loose ends, and (2) withstand critical examination in its own field AND all related fields.

The fourth criterion is that the theory is of current interest and application. The theory should, in general, answer a problem already posed or explain a phenomenon already observed. Otherwise it is likely to be ignored, whether of value or not. Then, at some later date when interest in this particular area has developed, it will reappear, possibly as original work by someone else.

The fifth criterion is that the theory is effectively communicated to its intended audience--the controlling members of the field; for it is these persons who, in the long run, will determine the acceptance or rejection of the theory. Consequently, it should be transmitted through the proper channels and in the proper terminology. Books, journals, lectures, and even demonstrations or instruction are all possible means of dissemination. Also it will probably be necessary to present it in drastically simplified terms to many persons, and then in its full complexity to relatively fewer persons. Further, it should be presented, directly or indirectly, over and over again, possibly with each presentation stressing a different application.

It should be recognized that these five criteria are, in some instances, closely related; and the determination of what belongs to which criterion will often be a subjective decision. Note particularly the relationship between the first, second, and third criteria; and also that between the fourth and fifth criteria. These relationships will be discussed in another light later.

Also note that in considering the order of the criteria the third and fourth could possibly be interchanged, or more exactly, neither has any dependency on the other.

EXAMINATION OF THE THEORIES

The details of the various theories to be considered are given in the appendix. Here the theories are only examined in relation to the previously defined criteria. In some cases this will not require more than a few words, whereas, in other cases considerable time must be spent to properly ascertain the relation between the theory and the criteria.

In the early 1820's Robert Hare, an American Professor of Chemistry, suggested that American east coast storms consisted of a warm southwesterly current over a cold northeasterly current.[1] His supporting assumptions and general explanation were, in light of today's knowledge, incorrect; and even then they were held in considerable doubt. He had no actual data to support his assertions and none could be obtained, consequently this was just speculation, and accepted as such.

About ten years later an Englishman, Luke Howard, as a result of his studies of clouds, concluded that warm air appeared aloft first and at the surface later.[2] This theory, likewise, had no actual supporting data and must be considered as speculation. However, the assumptions

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[1]See Appendix A for References and Details.

[2]See Appendix B for References and Details.

appeared reasonable and when Dove did his work a few years later, he acknowledged Howard's work as the first of its kind.[3]

Starting in the late 1830's Professor Heinrich Wilhelm Dove of Germany brought forth a similar theory in far greater detail and based on considerable factual data.[4] He made use of mountain observations to show that warm air did appear at the high levels first and at the surface later, and likewise that cold air appeared at the surface first and aloft later. He also deduced other interesting details, such as the difference in the slopes of the fronts, which were to reappear virtually unchanged in the Norwegian theory nearly a century later. Dove's theory certainly passed the first criterion--it was more than speculation. However, it had trouble with the second criterion in that Dove's primary interest was in showing that storms had a rotary motion; a point which was to be strongly contested for another half century until a vast accumulation of daily synoptic weather maps provided overwhelming evidence in support of this theory. It is probably on the third and fourth criteria, however, that Dove's theory really lost out. It was incomplete in that it was not strongly tied into the general concept of the atmospheric structure and circulation, mainly because there was no agreement and very few theories on this subject. Also, the primary cur-

[3]See Appendix C.

[4]See Appendix C for References and Details.

rent interest of the time was the cause and motions of storms, and these layers of warm and cold air did not appear to be very pertinent to the problem.

About 1860 Admiral Robert FitzRoy, English, in studying some of the first daily synoptic weather maps to be analyzed, reached some conclusions regarding tropical and polar air masses and the boundary (front) between them.[5] His two dimensional concept of the atmosphere was good and has since proven quite correct; but his three dimensional concepts and his other thoughts on meteorology were then highly controversial and have, in general, since been proven false. Consequently, his theory, though passing the first criterion, quickly came to grief on the second.

In 1875 William Blasius published his theory of storms, which was primarily conclusions based on his study of storms in the eastern United States during the 1850's.[6] These conclusions have proven to be, with only a very few exceptions, an exceedingly accurate description of the structure of the atmosphere. Not only were these conclusions a far better development of the previous works, but also the boundary between the polar and tropical air was considered a global phenomenon and justified as a mechanism of the general circulation. The work of Blasius clearly satisfied the first, third, and fourth criteria. However, his acceptance of Espy's theory of inblowing

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[5]See Appendix D for References and Details.

[6]See Appendix E for References and Details.

motion in storms rather than the rotary motion theory, which was rapidly becoming established with the advent of daily synoptic weather maps, gives a weak section to his arguments. Consequently, the second criterion was not fully satisfied. But where Blasius really failed was on the fifth criterion. He worked on meteorology alone and in his spare time, and his conclusions were not published until nearly twenty years after he had formulated them. Published in a book instead of in the scientific journals, by an unknown personage with no apparent recognition from the rest of the scientific world, these conclusions were doomed from the start, no matter how good they were.

Next to deserve mention are the theoretical works of two German scientists. Hermann von Helmholtz in 1888 showed that existent forces in the atmosphere should lead to the formation of surfaces of discontinuity.[7] Max Margules in 1904 showed that the energy generated due to the interaction of contrasting air masses separated by a surface of discontinuity is of the right order of magnitude for the storms observed; and then in 1906 he added that this surface would be sloping, even if stationary.[8] Both of these theories satisfied the first, second, and fourth criteria; but they completely failed on the third criterion. They are each isolated bits of information, vital to a complete theory, but in no way complete in themselves. It is

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[7]See Appendix F for References and Details.

[8]See Appendix G for References and Details.

hardly necessary to point out that they also failed on the fifth criterion in that they were so complex, as published, as to be scarcely comprehensible to many contemporary meteorologists.

The last of the Norwegian theory precursors is the work of the English meteorologists--Sir William Napier Shaw and collaborators--during the first dozen years or so of the twentieth century.[9] This work was extensive and accurate to an extent probably neve before achieved in the field of meteorology. The complete structure of storms was fairly accurately determined. The presence of warm and cold fronts, though not in these terms, and the associated weather phenomena and changes thereof were clearly indicated. Considered with respect to the criteria, the theory satisfied the first, second, and fourth very completely, but not the third and fifth. The theory was distinctly incomplete: it primarily was a generalization of observations and as such said little or nothing about causes. Also it clearly did not apply to all storms and no satisfactory explanation was advanced for this. Further, its proponents, it would appear, were not pushing it as a new theory, but rather were trying to fit some new observations into the more conventional over-all theories prevalent at the time.

The work of the Norwegian meteorologists provides an interesting contrast to that of the English a few years

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[9] See Appendix H for References and Details.

earlier.[10] It was similar in that they also determined the existence of fronts and the associated weather phenomena. However, it was markedly different in that they did not stop at this point, but went on to show that all storms were frontal phenomena even though they only showed frontal structure during a portion of their lives. They also postulated a plausible explanation of the existence of fronts and their role in the general circulation of the atmosphere.

As such the Norwegian theory not only satisfied the same criteria as the English theory (first, second, and fourth), but it also satisfied the third criterion; for it is clearly a complete theory. It ties together the work of the practical and the theoretical meteorologists quite acceptably; as it explains all types of storms observed, and it fits easily into the generally accepted concept of the general circulation; in fact it would appear to provide the solutions for some previously unsolved problems in this field.

Furthermore, the Norwegian theory clearly satisfied the fifth criterion, for it was presented to meteorologists throughout the world very forcefully. At the beginning Vilhelm Bjerknes traveled through many countries giving lectures to the appropriate scientific bodies.[11] Simultaneously Vilhelm Bjerknes and the three younger

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[10] See Appendix I for References and Details.

[11] Note references 4 and 6 in Appendix I.

meteorologists (J. Bjerknes, H. Solberg, T. Bergeron), notably Jacob Bjerknes, wrote lucid articles describing the theory and its practical applications, and these articles were printed in meteorological journals throughout the world.[12] Following this, meteorologists from varying countries were invited to Bergen, Norway for extended periods to participate in the daily application of the theory, and in its further development.[13] And finally, one or more of the Norwegian meteorologists would spend a year or so abroad, working with meteorologists in their own country in order to demonstrate the universal applicability of the theory.[14]

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[12]See references 1, 2, 3, 5, and 7 in Appendix I. In addition note that the article in reference 1 also appeared in the Monthly Weather Review, as well as abstracts of the articles in references 2 and 3.

[13]Meteorologists from the United States who went to Bergen included Miss Beck, 1920-21, and two Naval officers in the early 1930's. Several meteorologists from Canada also went in the early 1930's.

[14]Meteorologists in the United States from Bergen included Rossby, for many years starting in 1926, J. Bjerknes, 1933-34, and Solberg, 1939.

SUMMARY AND CONCLUSIONS

The Norwegian theory was the only theory of those examined to fully meet the criteria postulated as possibly relevant to a theory's acceptance: (1) it is not speculation, (2) it is the most probable explanation of the observed data, (3) it is complete and unifying, (4) it is of current interest and application, and (5) it is effectively communicated to its intended audience. Also the Norwegian theory was the only one to be accepted; the others were rejected or ignored for varying reasons.

The theories of Hare and Howard had no supporting data and consequently were only speculation. Dove's theory suffered from inadequate data and development, and, more importantly, from a field that was not ready for it, both in interest and technical development. FitzRoy's theory was doomed due to inconsistencies and errors. Blasius' theory lost partly due to an error, but primarily due to lack of communication. The theories of Helmholtz and Margules were incomplete and improperly communicated. Likewise, the English theory, though different, was incomplete and improperly communicated.

If the first, second, and third criteria are considered as a group defining the existence of a theory, correct and complete; then the fourth and fifth criteria must determine its acceptance or rejection. To a large extent the fourth criterion can be shown to be subordinate to the fifth. Proper presentation can often develop the necessary interest, and in turn the application. Consequently, the acceptance of a fully developed theory depends primarily on the adequateness with which it is presented.

Two theories, that of Blasius and that of the Norwegians, were fully developed; acceptance went to the Norwegian theory because they presented it far more effectively.

APPENDIX A

THEORY OF PROFESSOR ROBERT HARE

<u>References</u>

1. Hare, Robert. "On the Gales Experienced in the Atlantic States of North America," <u>The American Journal of Science and Arts</u>, V (1822), 352-256.

2. Mitchell, E. "On the Proximate Causes of Certain Winds and Storms," <u>The American Journal of Science and Arts</u>, XIX (1831), 248-292.

<u>Details</u>

This theory has been included, not because it has any real value, but rather because (1) it is one of the very first instances in which it is suggested that warm air may rise and flow over cold air producing rain, and (2) it is typical of the speculation that was to continue in this field for at least fifty years, some correct but most incorrect, built on very little data and a large quantity of imagination.

Hare deduced that due to several complex atmospheric processes plus the topography of North America it was possible, at times, to create a low level air current from the northeast over the eastern United States. This current would displace the warm, moist surface air in the

Gulf of Mexico; and the Gulf air would be constrained, by topography and various immovable air masses aloft, to rise and flow northeastward over the cold air below it. Both the forced ascent and the mixing of the warm and cold air in the boundary zone were the causes given for the copius precipitation which resulted.

Here was a chemist, and only interested in meteorology as a sideline. Later on he essentially recanted on this theory when he asserted that the primary cause of most atmospheric disturbances was electrical activity in the atmosphere.

In 1831 Professor Mitchell took the trouble to declare this theory incorrect. His reasons were, in part, that the air would rise only in the Gulf states region and consequently over the rest of the eastern United States the only process operative would be the mixing of warm and cold air. This would lead to heavy precipitation and strong winds in the Gulf states and only very light precipitation and winds elsewhere, which is not what actually occurs. He concluded, therefore, that some form of vortex motions must be involved in these storms instead. However, the rest of his reasons were such as to cast considerable doubt on the truth of his theories or criticisms.

APPENDIX B

THEORY OF LUKE HOWARD

References

1. Dove, H. W. The Law of Storms: Considered in Connection with the Ordinary Movements of the Atmosphere. 2d. Ed. Revised and Enlarged. Translated by Robert H. Scott. London: Longman, Green, Longman, Roberts, and Green, 1862.
2. Hawke, E. L. "Correspondence and Notes," The Quarterly Journal of the Royal Meteorological Society, LX (1934), 341-344.

Details

Luke Howard is known primarily for his cloud classification system which he formulated from his extensive studies of clouds. However, from these same studies he drew some conclusions relative to the movement of air in the atmosphere which he stated in his book, Climate of London, 2d. Ed. (1833). He noted the action of cold air in the atmosphere on warm air and vice versa--this is a fair description of cold and warm front passages. He further concluded that the warm air came in aloft first and described the situation as follows:

> A Southerly current, charged with vapour from a warmer region, may be passing Northward, at the

same time that a Northerly current may be returning towards the south, in the immediate neighbourhood of the former; and these two may raise each other, the colder running in laterally under the warmer current, and causing it to flow over laterally in its turn; while each pursues in the main its original course. In this case the country for a considerable space extending from about the line of their junction far into the Southerly current, may be the seat of extensive and continued rain.[1]

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[1]Reference 2.

APPENDIX C

THEORY OF PROFESSOR HEINRICH WILHELM DOVE

References

1. Dove, H. W. "On the Influence of the Rotation of the Earth on the Currents of its Atmosphere; Being Outlines of a General Theory of the Winds," The London and Edinburgh Philosophical Magazine and Journal of Science, XI (1837), 227-239, 353-363.
2. Dove, H. W. The Law of Storms: Considered in Connection with the Ordinary Movements of the Atmosphere. 2d. Ed. Revised and Enlarged. Translated by Robert H. Scott. London: Longman, Green, Longman, Roberts, and Green, 1862.

Details

Dove, a distinguished German scientist, after several years of careful observations of changes of the weather (wind, temperature, and pressure), including the use of mountain stations to assist in determining the three dimensional structure of the atmosphere, said:

> From these observations I conclude: that there are two opposite winds, which blow throughout the whole atmosphere.
>
> These winds I call air-currents, the one the northern, the other the southern. From the observations previously mentioned it follows that the phaenomena of the westside are a transition of the southern current into the northern; and in fact

> the driving out of the southern current by the northern first takes place in the lower regions of the atmosphere, and then in the higher. The phaenomena of the eastside, on the contrary, are a transition of the northern current into the southern; and the expulsion of the northern current by the southern takes place first in the higher regions of the atmosphere, and then also in the lower.[1]

Further, he made some very astute deductions concerning the slope of the boundary between the two air masses, as follows:

> The difference in density of the air in the two currents is very considerable in the lower strata, and decreases as the distance from the earth increases, so that the change will take place very rapidly at the surface of the earth, and will be accelerated by differences of temperature between the two currents. The barometrical indications are affected chiefly by the lower strata, and hence we obtain the following rule:- In oscillations of the barometer, the front of a wave is steeper than the back, or, more accurately, the warm and light air is displaced by that which is cold and heavy on the westside, more rapidly than the cold and heavy air by that which is warm and light on the eastside.[2]

Dove noted that Howard had suggested this structure several years previously, and he (Dove) includes several pertinent passages from Howard's work in his.

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[1]Reference 1, p. 361.

[2]Reference 2, p. 87.

APPENDIX D

THEORY OF REAR ADMIRAL ROBERT FITZROY

References

1. FitzRoy, R. *The Weather Book: A Manual of Practical Meteorology*. 2d. Ed. London: Longman, Green, Longman, Roberts, and Green, 1863.

2. Poulter, R. M. "Correspondence and Notes," *The Quarterly Journal of the Royal Meteorological Society*, LX (1934), 341-344.

Details

FitzRoy, in the early 1860's, after several years as chief of the English Meteorological Service and a few years of study of daily synoptic weather maps, proposed several theories concerning the structure of the atmosphere. Unfortunately many of his assumptions and deductions have since proven false, and even at that time they were not generally accepted. Consequently, the theories he proposed which were correct did not gain much acceptance either.

His better theories were those concerned with the general location and movement of tropical and polar air masses. He drew an excellent diagram of the location of polar and tropical air masses for a particular storm (see figure D-1), and commented on it as follows:

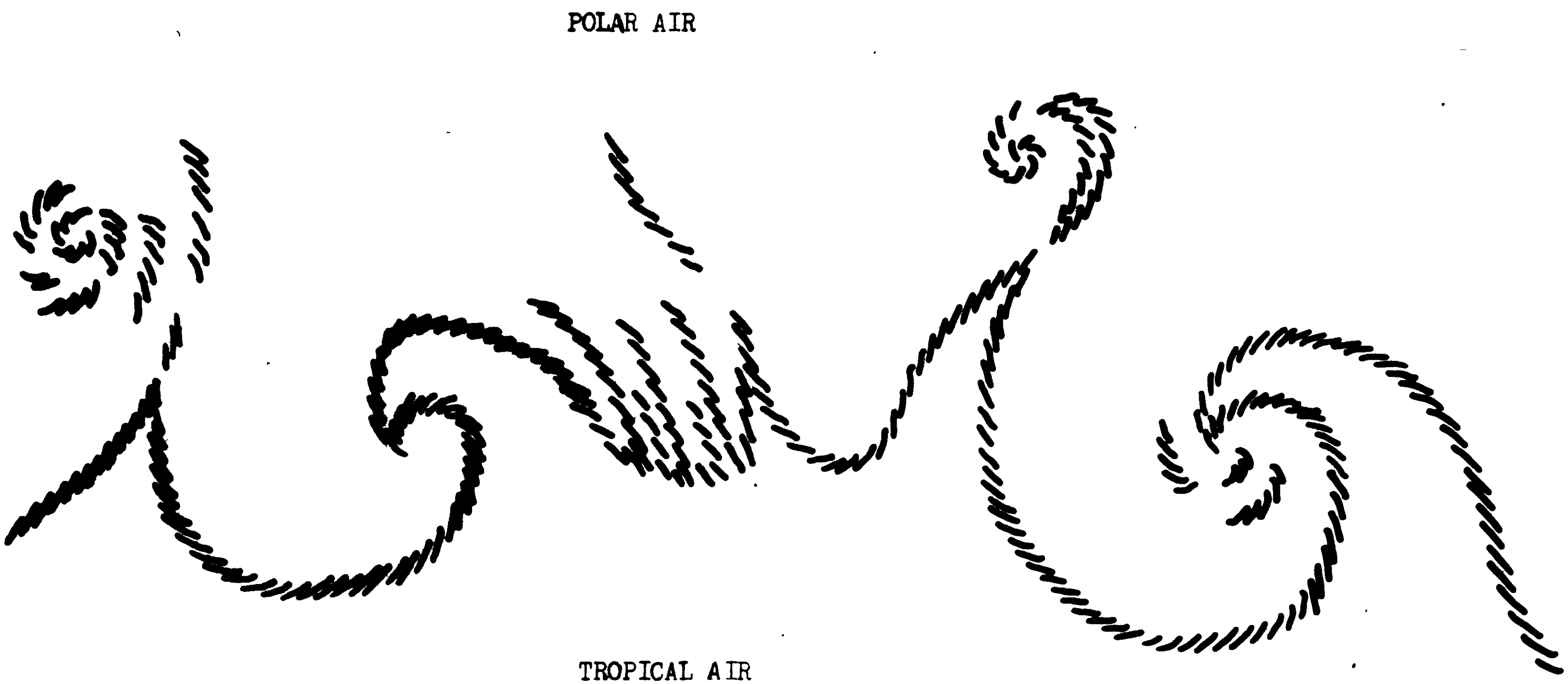

FIGURE D-1

Analysis of the Charter storm, after FitzRoy (reference 1). Markings indicate the northern limit of the tropical air, sometimes as isolated patches in the polar air.

> The polar air is insufficient in quantity to fill so great a breadth as opens to it, in moving towards the tropic. It divides, diverges, or splits into streams, interspersing with those advancing from more or less opposite directions as parallel currents. Hence in middle latitudes or temperate zones, the continuous alternation or succession of polar and tropical currents, which in their innumerable modes and degrees of opposition, or combination, occasion every variety of mixed wind, easterly or westerly, with more or less polarization.... The diagram shows tropical currents advancing with force ... to be yet more speedily driven back by polar, as in the instance of the Charter Storm.[1]

And more generally he said:

> But the varying states of equatorial and polar regions, consequent on the earth's rotation, on immense precipitation of vapour (rain).... These varying states must be accompanied or followed by alternations, or, as it were, pulsations of the atmospheric greater currents - those toward and from the equator or poles.[2]

And further, he commented as follows on the boundaries (fronts) between these air masses:

> ...If these currents meet with energy at very different temperatures and tensions, rapid changes are noticed as the wind shifts and circuitous eddies, storms or cyclones occur.[3]

However, when he came to depicting the three dimensional picture of these boundaries, he did not do so well. He concluded, from cloud studies, that all new (to the area) air masses, whether warm or cold, came in aloft first and at the surface last. No explanation was offered for the fantastic structures that would result from this

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[1]Reference 2.

[2]Reference 1, p. 91.

[3]Reference 1, p. 183.

hypothesis. Further, he asserted that high pressure was caused by the pressure of the tropical and polar currents against each other, and when the polar current eased up the pressure fell and the tropical current moved in.

APPENDIX E

THEORY OF WILLIAM BLASIUS

References

1. Blasius, William. Storms: Their Nature, Classification and Laws. Philadelphia: Porter and Coates, 1875.

2. Gold, E. "Fronts and Occlusions," The Quarterly Journal of the Royal Meteorological Society, LXI (1935), 107-157.

Details

Blasius, after studying several storms in the 1850's, had determined a method in which a more satisfactory study of storms could be made. However:

> He was unable to get the necessary funds to carry out investigation on the lines he had planned, and had to turn to commercial pursuits. He did not, however, lose his interest in meteorology, and published his book in 1875. The leading feature in it is the plane of meeting or the frontal surface between the polar current and the equatorial current. He recognized that the slope of the surface depended on the relative velocity of the two currents and their difference of temperature:...[1]

In his book he very clearly and explicitly described the overlapping of the warm and cold air:

> Horizontal currents of different temperatures moving in opposing directions overlap each other.

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[1]Reference 2, p. 108.

> The warmer, rising obliquely over the cooler current, moves to the cooler region, while the cooler current flows over the surface of the earth beneath the warmer current to the warmer region.... They (the two currents) overlap each other like two wedges ... and the plane of the region of meeting of the two currents is therefore inclined to the surface of the earth.[2]

And later he went on to describe further the movements of the currents and the resulting consequences at the boundary zone:

> It is evident that the currents ... must meet ... somewhere on the surface in the temperate zone.... The warm equatorial currents will then rise ... upward before the cool polar currents ... overlapping them obliquely, and will flow over them toward the poles,... while the polar currents press on the surface toward the tropics .... At these regions we must have belts of diminished pressure ... on account of the rising of the equatorial currents.[3]

He further commented that only with a sloping boundary, such as he had described, could sleet, freezing rain, etc. be explained. He also noted the extremely rapid changes in weather that often took place with the passage of a fast moving front. Further, he considered the boundary between the polar and tropical air as a global phenomenon and correctly deduced the effects on its position due to seasons, and land and water areas.

In respect to the storms themselves he said, in view of his studies:

> I became satisfied that storms in the temperate zone are the <u>effect</u> of the conflict of opposing aerial currents of different temperatures, and

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[2]Reference 1, p. 48.

[3]Reference 1, p. 66.

> not the <u>cause</u> of these currents and temperatures, as seems to be assumed by some cyclonists.[4]

However, it was here, in respect to storms, that the one error in his theories appeared. He concluded that the wind blew from high to low pressure, rather than approximately around highs and lows as the contemporary snyoptic weather maps (by the 1870's) were beginning to show.

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[4]Reference 1, p. 23.

APPENDIX F

THEORY OF PROFESSOR HERMANN L. F. VON HELMHOLTZ

References

1. Gold, E. "Fronts and Occlusions," The Quarterly Journal of the Royal Meteorological Society, LXI (1935), 107-157.
2. Helmholtz, H. von. "On Atmospheric Motions," in The Mechanics of the Earth's Atmosphere: A Collection of Translations by Cleveland Abbe ("Smithsonian Miscellaneous Collections," Vol. XXIV, No. 10 (Washington, 1893)), 78-93.

Details

Helmholtz, A German scientist distinguished in many fields, investigated the possibility of surfaces of discontinuity existing in the atmosphere and presented his findings and some conjectures thereon in a paper entitled "On Atmospheric Motions" (1888).[1] In concluding this paper he stated:

> The present memoir is intended only to show how, by means of continually effective forces, there arises in the atmosphere the formation of surfaces of discontinuity.[2]

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[1]Reference 2.

[2]Reference 2, p. 93.

However, in doing this he also suggested possible theories that could be deduced from his findings. Gold has summarized these nicely:

> Helmholtz, in his first paper on Atmospheric Motion (1888) examined the case of rings of air encircling the globe and separated by a surface of discontinuity: he formulated the condition for stability: and he said of the cold air at the poles that it endeavoured to flow outwards: that it formed a stratum which must remain at the surface: that it advanced irregularly: that there would arise at the surface of discontinuity vortex motion or whirls which constituted the principal moderating factor in the earth's circulation.[3]

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[3]Reference 1, p. 107.

APPENDIX G

THEORY OF MAX MARGULES

References

1. Gold, E. "Fronts and Occlusions," The Quarterly Journal of the Royal Meteorological Society, LXI (1935), 107-157.

2. Margules, Max. "On the Energy of Storms," in The Mechanics of the Earth's Atmosphere: A Collection of Translations by Cleveland Abbe ("Smithsonian Miscellaneous Collections," Vol. LI, No. 4 (Washington, 1910)), 533-595.

Details

Margules in 1904 published the results of his extensive work--the determining of the potential energy available when air masses of two different temperatures lay adjacent to one another. Most of this work was concerned with what he felt were smaller scale phenomena (squall lines and/or cold fronts). However, he had the following to say concerning complete storms:

> The phenomena of motion in great storm areas that we call cyclones are less intelligible than those of the squalls. But these also, at least in middle and higher latitudes, consist of warm and cold masses of air lying adjacent to each other horizontally; cold air often spreads out over the earth in the lower strata behind the passing storm. It is therefore not unlikely that

> these storms are fed by the potential energy of an initial stage similar to that which we have adopted in the preceding lines.... Our analysis gives us only a general idea as to the source of the energy of storms; a working model of the cyclone with symmetrical distribution of temperature has not yet been constructed.[1]

Two years later he computed the slope of the boundary between two air masses, and further, showed that this boundary would not be horizontal, even in the stable state.[2]

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[1]Reference 2, p. 541.

[2]Reference 1, p. 109.

APPENDIX H

THEORY OF THE ENGLISH METEOROLOGISTS (SIR WILLIAM NAPIER SHAW AND COLLABORATORS)

References

1. Lempfert, R. G. K. "The Development and Progress of the Line Squall of February 8, 1906," _The Quarterly Journal of the Royal Meteorological Society_, XXXII (1906), 259-280.

2. Lempfert, R. G. K. and Corless, Richard. "Line Squalls and Associated Phenomena," _The Quarterly Journal of the Royal Meteorological Society_, XXXVI (1910), 135-170.

3. Shaw, W. N. _Forecasting Weather_. London: Constable and Company, Ltd., 1913.

4. Shaw, W. N. and Lempfert, R. G. K. _The Life History of Surface Air Currents: A Study of the Surface Trajectories of Moving Air_. ("Meteorological Office Publication," No. 174) London: Darling and Son, Ltd., 1906.

Details

During the first dozen years or so of the Twentieth Century the English meteorologists, and in particular Shaw, made a concerted attempt to determine the structure of the atmosphere which went with various observed weather patterns or phenomena. They developed four principal points:

1. A squall line (cold front, usually) is a region of discontinuity of motion, therefore two different air masses are involved.[1]

2. In moving storms there are definite regions or lines of abrupt changes in wind direction, temperature, and weather.[2]

3. The boundary between two adjacent air masses, a situation which sometimes can be found in storms, will be inclined so that the cold air forms a wedge under the warm air; and the horizontal motion of the air masses will be such as to give rising motion in the warm air over the cold wedge and sinking motion in the cold air in the cold wedge.[3]

4. The forced rising motion of the warm humid air in certain regions is the cause of the precipitation patterns observed in moving storms.[4]

Lempfert and Corless[3] came to some specific conclusions regarding the motion of the air at the boundary between two air masses (see figure H-1), but made no attempt to determine the sources of the different air masses or the reason for their juxtaposition.

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[1]Reference 1.

[2]Reference 2, 3, and 4.

[3]Reference 2.

[4]Reference 3.

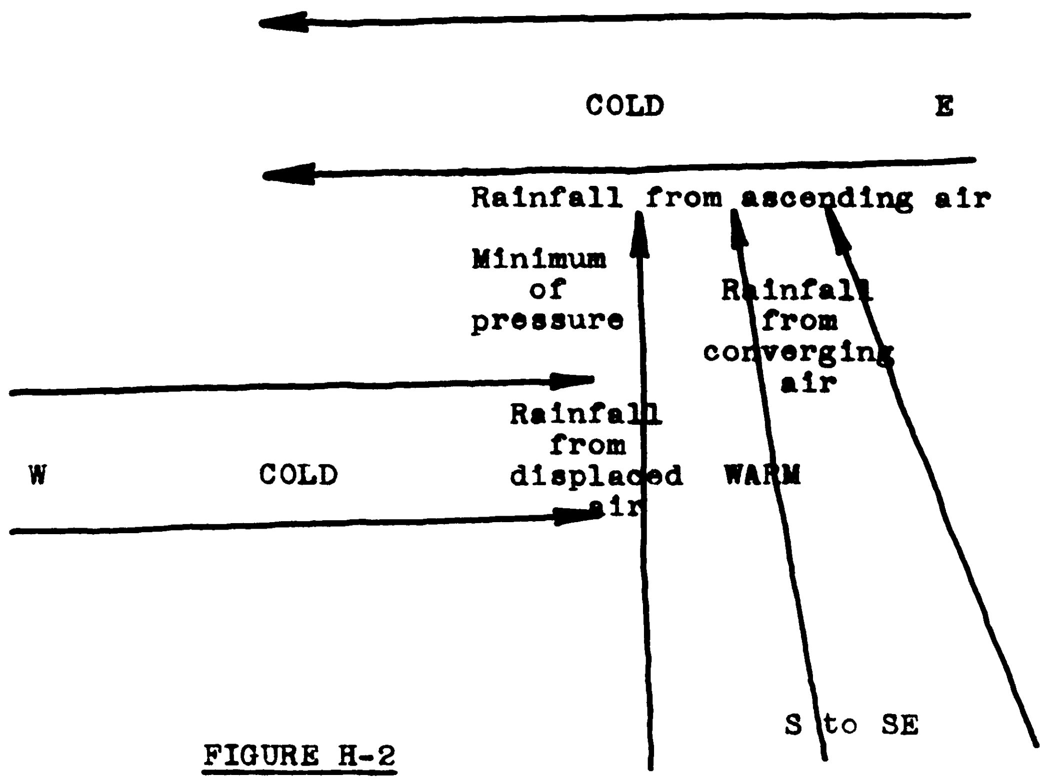

FIGURE H-2

Exaggerated storm model, after Shaw (reference 3). Arrows indicate air flow.

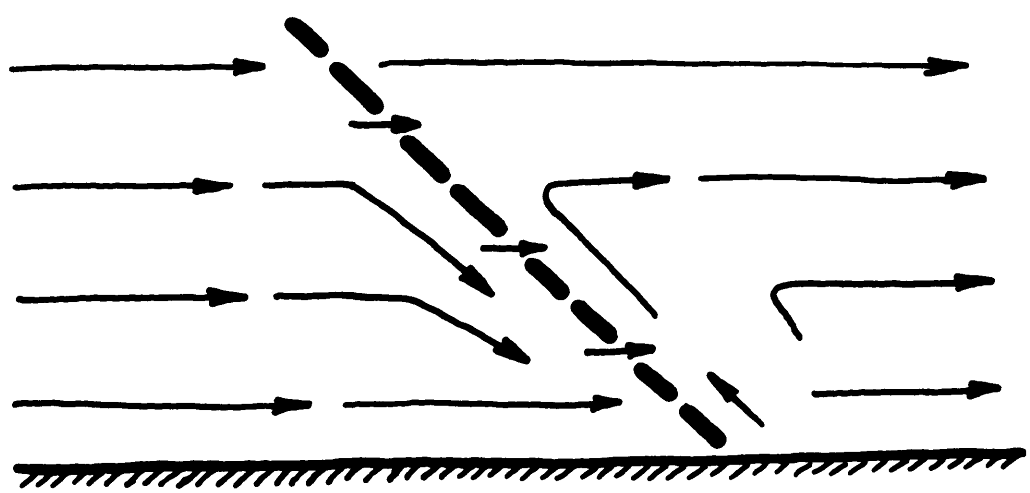

FIGURE H-1

Air motion at the boundary between two air masses, after Lempfert and Corless (reference 2).

Shaw[5] did go one step further and developed a storm model (see figure H-2) which he felt was exaggerated, but of more value than the previous circular models. He too, however, said little about the reason for the presence of the air masses or the cause of storms.

In fact, what the English meteorologists had done was to provide a more plausible immediate explanation of certain observed facts; but they had not, to any extent, fitted all this detail into any general concepts.

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[5]Reference 3.

APPENDIX I

THEORY OF THE NORWEGIAN METEOROLOGISTS (VILHELM BJERKNES, JACOB BJERKNES, H. SOLBERG, AND TOR BERGERON)

References

1. Bjerknes, J. "On the Structure of Moving Cyclones," Geofysiske Publikationer, I, 2 (1919).
2. Bjerknes, J. and Solberg, H. "Meteorological Conditions for the Formation of Rain," Geofysiske Publikationer, II, 3 (1921).
3. Bjerknes, J. and Solberg, H. "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation," Geofysiske Publikationer, III, I (1922).
4. Bjerknes, V. "Weather Forecasting," Monthly Weather Review, XLVII (1919), 90-95. (Address to Scandinavian Geophysicists at Gothenburg, Aug. 28, 1918.)
5. Bjerknes, V. "Possible Improvements in Weather Forecasting: With Special Reference to the United States," Monthly Weather Review, XLVII (1919), 99-100.
6. Bjerknes, V. "The Structure of the Atmosphere When Rain is Falling," The Quarterly Journal of the Royal Meteorological Society, XLVI (1920), 119-140. (Address to a meeting of the Royal Meteor-

ological Society, Nov. 7, 1919.)

7. Bjerknes, V. "The Meteorology of the Temperate Zone and the General Atmospheric Circulation," Nature, CV (1920), 522-524.

Details

The work, and the results published therefrom, of the Norwegian meteorologists, principally J. Bjerknes, occurred primarily during the period 1918-1921. The preceding work and teachings of V. Bjerknes were vital to this work, but do not concern us here. And the following work (post 1921) was principally refinement on the theory already postulated.

In 1920 V. Bjerknes, in an article in Nature,[1] presented a brief but excellent explanation of the work and its consequences up to that point. The following quotations from that article plus occasional comments on the work completed during the ensuing year very completely describe the Norwegian theory:

> In Norway, since the year 1918, an attempt has been made to base forecasts of weather on the application of a very close network of meteorological stations. The study of the corresponding very detailed synoptic charts has led to interesting results even for large-scale meteorologists....
>
> A very short summary of some of the main results will be given here. These will be seen to give, to some extent, both verifications and further developments of ideas, which, although advanced by leading theoretical meteorologists, have not yet exerted any noticeable influence upon the development of meteorology.

A footnote given at this point referred to the

[1]See Reference 7.

work done by Dove, Helmholtz, Brillouin, and Margules. Bjerknes then continues:

> Great changes in the weather in our latitudes have been found to depend upon the passage of a line of discontinuity which marks the frontier between masses of air of different origin. A line of this kind was first found to exist in every cyclone which is not perfectly stationary....

See figure 2, page 4 for the model of a cyclone as described by the Norwegian theory. Bjerknes next explains the mechanical details of this model:

> Along the front border warm air from the tongue ascends the barrier formed by the cold air, which, in return, passes round the tongue in order to penetrate below the warm air along the rear border. Two bands of rain are thus formed--a broad one in front of the tongue, where the warm air spontaneously surmounts the cold, and a narrow one, generally called the squall line, along the rear border, where the advancing cold air violently lifts the warm air of the tongue.
>
> It has been found by use of the detailed maps that the line of discontinuity exists even outside the cyclone, passing from one cyclone to the other; they follow each other along a common line of discontinuity, like pearls on a string....

Figure I-1 shows this concept of one following another along the same line, as well as illustrating the development process of the storms, a concept which was fully formulated during the ensuing year.[2] Bjerknes now continues in a more general vein:

> Though we have been able to draw the line only half around the pole, there can be no doubt that it surrounds the polar regions as a closed circuit.... There can then be no doubt concerning the origin of the line. Heavy, cold air flows out along the ground from the polar regions. It is separated from the overlying warmer air by a surface of discontinuity, the height of which above the ground decreases very slowly until it cuts the

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[2]See Reference 3.

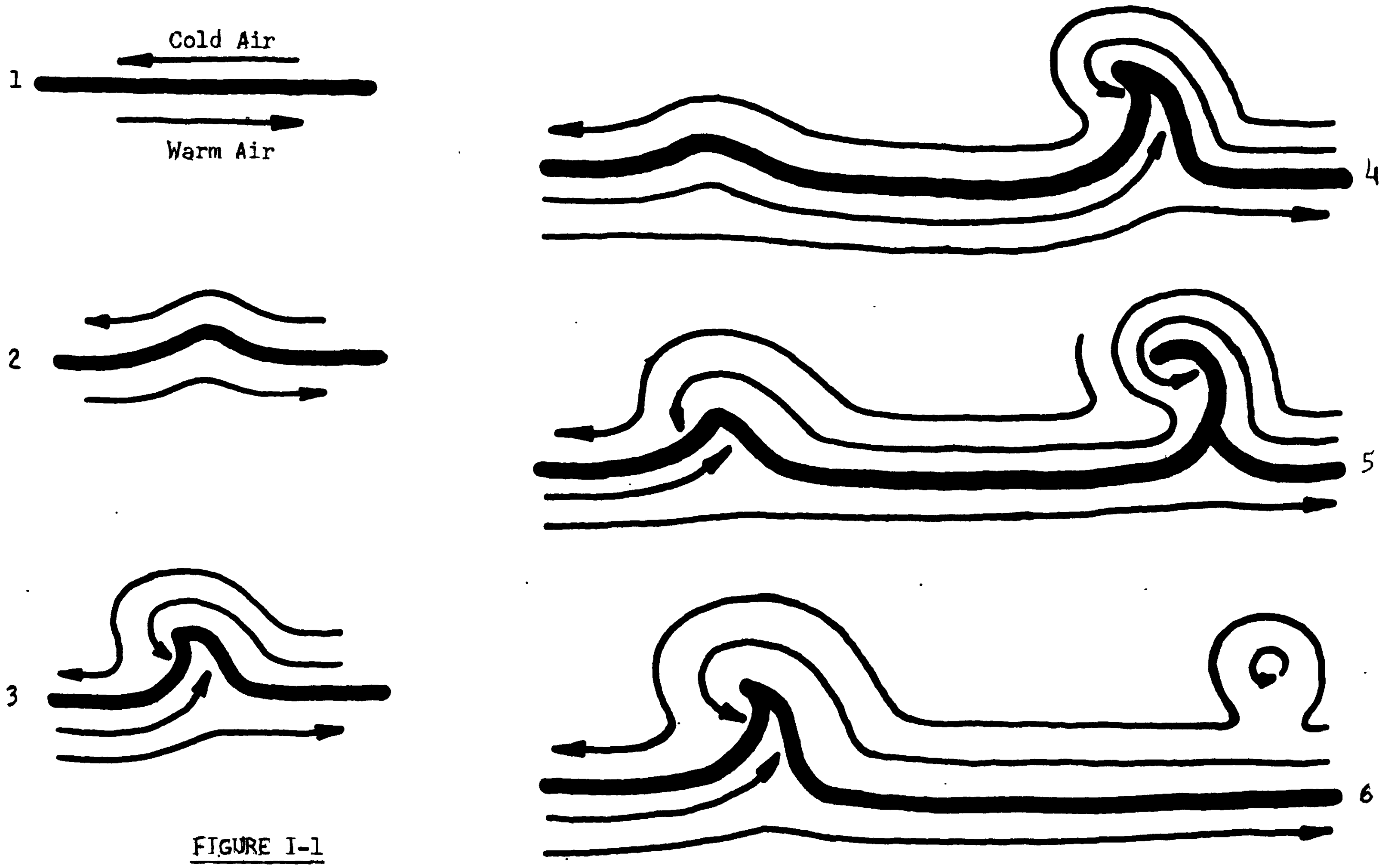

FIGURE I-1

Idealized model of storm development according to the Norwegian theory. Heavy lines are the fronts, and arrows indicate air flow.

> ground along our line of discontinuity. Thus this line shows how far the cold air has succeeded in penetrating; it is a kind of <u>polar front line</u>....

Bjerknes concludes by giving some details about the movements of the polar front, and in particular how it is necessary for it to be discontinuous in places. These breaks allow expulsion of large masses of polar air into the tropics--a mechanism which he asserts is essential to the over-all operation of the general circulation.

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References concerning any particular theory are given in the appropriate appendix (see the Table of Contents). The following are only the general references.

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