DISCUSSION.

GREENLAND'S GLACIAL ANTICYCLONE: A REVIEW

Introduction.—Students of polar meteorology and glaciology will find several valuable contributions in the second and final volume of reports on the scientific work of five University of Michigan Greenland Expeditions (1926-1933).[1] These expeditions were initiated and the first four were directed by Wm. H. Hobbs, now Professor Emeritus of Geology at the University of Michigan. The fifth expedition, supported in part by Pan American Airways, was directed by Prof. R. L. Belknap, also of the University of Michigan, and a member of the first three expeditions.

As explained by Professor Hobbs in the first volume of reports (University of Michigan Studies, Scientific Series, Vol. V, 1931), "the prime object [of the expeditions was] the study of the meteorological conditions over and about the inland-ice dome which so nearly covers the continent [of Greenland]." Professor Hobbs' interest in this "prime object" arises from his having originated and developed the theory of the glacial anticyclone, a theory that was presented to explain the nourishment of great continental glaciers and the effect of such glaciers on widespread meteorological phenomena throughout large parts of the world.

All five of the expeditions occupied stations in western Greenland, the first three (1926 and 1927-1929) being located in the Holstensborg District (lat. 67° N.) and the last two (1930-1931 and 1932-1933) in the Upernivik District (lat. 72° to 74° N.). As a part of the fourth expedition an additional station was established at Ivigtut in southern Greenland, but data from there are not included in the reports. Other stations were temporarily established on the inland ice (notably a station occupied by Belknap for seven weeks during the summer of 1933) and at coastal points near the main bases.

All expeditions carried out routine ground observations and, by means of pilot balloons, upper-air observations of wind direction and velocity. During the summer of 1926 sounding balloons were also used.

The primary meteorological and aërological data of the first three expeditions were discussed and presented in tabular form in the first volume. The second volume, now under review, contains meteorological and aërological studies from the last two expeditions,

[1] Reports of Greenland Expeditions, Pt. II, Univ. of Mich. Studies, Scientific Series, Vol. VI, Ann Arbor, 1941. (Univ. of Mich. Press. Price $5.00.)

reports on physiographic, glaciologic, and botanical work done by members of the first four expeditions, and a miscellany of interesting information on rates of evaporation of snow and water, and temperatures of arctic soils and waters.

This last information is presented in Chapter I under the title of "Meteorological Studies." It is written by Prof. J. E. Church, Meteorologist, Nevada Agricultural Experiment Station, who served as one of the meteorologists with the expeditions from 1926 to 1928. The first half of the chapter, called "Climate and Evaporation in Alpine and Arctic Zones," offers a study of the factors influencing snow and water evaporation in the Holstensborg District of Greenland and in the Sierra Nevada near Lake Tahoe. As the author points out, the two regions are in many respects comparable, for both have low winter temperatures, the one because of high altitude and the other because of high latitude. The influences of temperature, pressure, wind, relative humidity, vegetation, and topography on evaporation in the two regions are discussed. An interesting result of these studies is a demonstration that net evaporation on snow surfaces, both in Greenland and in the Sierra Nevada, is almost always in excess of condensation. In view of Belknap's conclusion (see below) that condensation of 'rime' from shallow near-surface clouds of ice spicules is an important source of nourishment on the interior parts of the ice sheet, it would be interesting to know if Church's conclusions may apply to the central parts of an ice sheet as well as to the land area marginal to the sheet. If so it may well be that Belknap's conclusion is not valid.

The second part of Church's chapter contains a collection of scattered and largely inconclusive data on water and soil temperatures taken along the Greenland coast and over the broad ice-free hinterland of the Holstensborg District. In connection with possible future studies these data will no doubt be of great value, so it is well that they are now available in published form.

The primary meteorological and aërological studies are contained in Chapters II and III, written respectively by W. S. Carlson, now Associate Professor of Education at the University of Minnesota, and R. L. Belknap. Carlson discusses data gathered by the fourth expedition, which occupied a station in latitude 73° N. (Upernivik District) from September 1, 1930 to April 27, 1931. Belknap discusses data of the last expedition, which spent a full year (1932-1933) in the same district but at a locality 90 miles farther north.

The value of studies made by these expeditions is enhanced by the fact that other scientists were making meteorological observations in other parts of Greenland during the same years, and fortunately their data were made available to the authors.

Many readers will be interested to know the extent to which Professor Hobbs' theory of the glacial anticyclone has been substantiated or modified by these extensive studies. It is therefore unfortunate that neither of the authors has given a critical statement summarizing the present status of the theory. It is only by careful reading of both Carlson's and Belknap's reports that the reader can get a concept of how the theory is to be regarded; and then he will not get an entirely clear concept, for on some points the authors are not in agreement, and on other points one or both of them are in disagreement with other students of polar meteorology. This is perhaps inevitable, since many more data must be collected and many more studies must be made before any final word can be given covering all points of the theory. Yet it would be helpful to the general reader were there a clear summary of points on which meteorologists agree and a statement of existing controversial problems.

Dominance of the Glacial Anticyclone.—Like Professor Hobbs (report on the first three expeditions), both Carlson and Belknap find that the glacial anticyclone dominates weather conditions over the Greenland ice sheet and over adjacent regions within a few tens of miles from the ice sheet borders. Summaries of pilot balloon observations show that the prevailing winds in low altitudes are down-slope winds blowing off the ice. On the west coast of Greenland these winds are from the southeastern quarter, being deflected by the earth's rotation. Above elevation of 1500 to 4000 meters compensating inflowing winds from the southwest blow toward the center of the anticyclone. According to Hobbs' theory these inflowing winds descend over the center of the ice sheet to feed the low altitude outflow. Such circulation is primarily controlled by the slope and low temperature of the ice sheet, the cold surface of which induces the radial down-slope winds at low altitudes.

Nourishment of the Ice Sheet.—The theory tells us that the principal nourishment by which the ice sheet is maintained is due to precipitation from air in the downdraft at the center of the anticyclone. Such precipitation is then spread radially over the ice sheet by the outward blowing surface winds. In opposition to this theory of nourishment others have maintained that cyclonic disturbances moving onto and along the outer parts of an ice sheet are primarily responsible for nourishing snowfalls, and that any precipitation in the center of the anticyclone is of relatively minor importance. This concept does not necessarily dispute the theory of the glacial anticyclone, but it does imply that the anticyclone is not at all times strong enough to prevent lows from moving considerable distances onto the ice sheet.

Observations of the Wegener Expedition (1930-1931), which maintained meteorological stations on both the west and east coasts and at the center of Greenland, seemed to show that cyclonic disturbances do cause precipitation over a broad marginal part of the ice sheet. However, Georgi of that expedition points out that in general the great ice sheet and the anticyclone that tops it act as a barrier to the migration of cyclonic disturbances. As he put it, Greenland is a "switch" for cyclones, causing them to be deflected along the ice sheet borders. Both Carlson and Belknap, after analyzing cyclonic storms that occurred along the Greenland coast, find agreement with this idea. Carlson, having no meteorological data from the ice sheet, draws no further conclusions as to the effect of cyclones in nourishing the ice sheet. Belknap, however, spent seven weeks in the summer of 1933 at Camp Watkins, his ice sheet station located 170 miles from the border in latitude 74° 40′. From observations there and at his main base station he concluded that cyclonic disturbances "did not appear to be effective beyond the marginal 25 miles of the inland ice." This distance being largely within the area where ablation is dominant, any precipitation from cyclonic winds would hardly be effective in nourishing the ice sheet. Following Professor Hobbs, Belknap apparently considers that precipitation from the center of the anticyclone is the chief source of nourishment. He does not discuss the question *per se*, but on page 181 he notes that at Camp Watkins and elsewhere inland from the marginal zone of the ice sheet, shallow 'fogs' or clouds of ice spicules were observed. He then says: "Sometimes they are undoubtedly important sources of nourishment for the glacier since, when present, they are continually being precipitated. With a slight increase in wind velocity two to three centimeters of 'rime' can be deposited during the night." Remembering Professor Church's observation that evaporation generally exceeds condensation on snow surfaces, the reader will wonder if this 'rime' is to be considered as snowfall or as surface condensation. If it is the latter and if Church's observations hold for the central regions of an ice sheet as well as for the Sierra Nevada and coastal parts of Greenland, one may wonder how important such nourishment actually is. Obviously the question can not be settled without extensive evaporation studies on the ice sheet. At present the important thing is to recognize that the question exists.

In fairness to Professor Hobbs' theory, it must be kept in mind that forms of precipitation other than Belknap's 'rime' may occur within the central part of the anticyclone, and they may be of sufficient volume to more than offset any possible evaporation. However, Belknap does not mention other forms of precipitation.

The remaining question with regard to nourishment is one of whether cyclonic disturbances do or do not penetrate considerable distances across the margins of the ice sheet, for if they do it is likely that they bring greater volumes of precipitation than could be derived from descending air in the center of the anticyclone. Unfortunately Belknap gives no clue to his reasons for believing that cyclonic disturbances "did not appear to be effective beyond the marginal 25 miles of the inland ice." All the data that he discusses were collected at Camp Watkins, 170 miles inland, and at his main base, three miles from the ice sheet margin on the coast. No mention is made of conditions between the two stations. He notes that depressions of air pressure occurred at Camp Watkins from time to time, but does not consider them to be of cyclonic origin because "there was not sufficient shift in the wind direction to account for the passage of a cyclone." Nevertheless he notes strong winds from the southwest. Every wind of more than 20 miles per hour came from that direction; and 20 per cent. of all winds came from the south-southwest. These are not prevailing winds. The prevailing winds (from the southeast and south-southeast) definitely indicate a dominance of anticyclonic circulation over the ice sheet. However, judging from Hobbs' topographic map of Greenland, reproduced by Carlson, page 90, the exceptional, non-prevailing winds from the southwest quarter are centripital rather than centrifugal and therefore could not be down-slope anticyclonic winds deflected by the earth's rotation. Belknap does not mention whether or not these winds were accompanied by precipitation, but it is the recollection of the reviewer, who as Belknap's navigator made two dog-sled trips to Camp Watkins, that several strong blizzards blew out of the southwest leaving considerable quantities of snow. It seems possible that these were cyclonic winds bringing important amounts of nourishment to the ice sheet. The reviewer has not made any such careful analyses of data as have been made by Belknap, so his impressions are not to be taken too seriously. Yet, despite the fact that "there was not sufficient shift in wind direction to account for the passage of a cyclone" at Camp Watkins, some other explanation than centrifugal down-slope winds may possibly be found to account for the exceptional non-prevailing winds and blizzards from the southwest. Should these winds prove to be of cyclonic origin, it may well be that the largest amounts of nourishing precipitation brought to the ice sheet surface are not a result of anticyclonic circulation.

Greenland "foehns."—Another important phenomenon connected with the glacial anticyclone is the warm, dry "foehn" wind that occurs characteristically along the Greenland coast. Professor Hobbs, in his publications on the anticyclonic theory, states that these winds are a result of cyclic or periodic pulses in circulation over the ice sheet. He believed that the down-slope winds, initiated by gravitative flow of the cold surface air, became accelerated to storm velocities in their descent to the ice sheet margins. During this descent the air was thought to be adiabatically heated to the extent that it became warm and dry. Following the advent of such winds, a period of relative atmospheric stability was said to occur, this being brought to an end by repetition of surface cooling and inception of a new down-slope avalanche of air with its accompanying "foehn." It was implied that the whole of the ice sheet was affected simultaneously by these periodic reoccurrences of the "foehn."

Carlson and Belknap agree in disputing this feature of the glacial anticyclonic theory. Without discussing the question, Carlson simply states in his *Specific Conclusion,* page 106, that "there did not appear to be any periodic pulsations of strophs."[2] On page 107, however, he offers an amazing explanation of the "foehns." He points out that they are related to cyclonic disturbances migrating northward along the coast. In his words, ". . . the down-slope winds [off the ice sheet] supplied the warm element of the cyclone. This was especially true during complete or total foehns. The explanation is that air was drawn all the way across Greenland." He then gives the well known explanation of foehn winds as resulting from movements of air across a high topographic elevation. To the reviewer, the amazing thing is that cyclonic disturbances which find an effective barrier in the ice sheet, should nevertheless be able to "draw" air from all the way across the barrier!

Belknap's discussion of the Greenland "foehn" is more critical. He points out, in keeping with the theory of the glacial anticyclone, that there are down-slope winds resulting from gravitative flow of cold air on the surface of the ice sheet. This sort of wind may sometimes reach storm velocities, but (p. 196) "Even though such wind would be adiabatically heated in its descent, if it started with a very low temperature its temperature ought not to differ greatly from that of the surrounding air when it reaches the bottom of the atmosphere along the margin [of the ice sheet]. This means that, since it starts down as a very cold air mass, there should not be a great change of temperature at the base when such a wind develops." Belknap emphasizes that winds of this sort are properly called gravity or katabatic winds, and that foehns are of a very different nature. Yet he finds that many of the storm winds were accompanied by the characteristic high temperatures and low humidity of a foehn. Such winds could not be gravity winds and he therefore suggests that they may be a sort of foehn. He then says (p. 197): "The objection which might be raised to classifying them as foehn arises from the fact that the typical foehn is supposed to cross over a mountain range or other high elevation and, as we have shown, there is no evidence in northern Greenland at least that the down-slope winds on the west coast originated on the east coast [a contra-

[2] Stroph is Professor Hobbs' term for the violent winds that are generated by the accelerated down-slope sliding of cold air. The "foehn" is said to be an end stage of the stroph and is felt only near the ice sheet margins.

diction of Carlson's suggestion]. An alternative explanation is presented . . ." It is as follows:

"The variation in cloud forms during the early part of the storm is exactly the same as that associated with the approach of a warm front. This, together with the fact that the storm is usually associated with the passage of a low, means that a warmer air mass of the Polar Atlantic type—and in the greatly elongated narrow lows it may even be Tropical Atlantic—is crowding in along the coast. As it approaches Greenland the warm front rides up over the air of the anticyclone covering the inland ice. The surface of contact of these two must, as is typical of most warm fronts, be at a very low angle with the horizontal. Such a condition would mean, of course, a temperature inversion which has frequently been noticed and which is mentioned by Albright. . . . Taylor . . . mentions the fact that, with such a temperature inversion over a stagnating anticyclone, there normally would be a subsidence of the layer above the cold air. If at this time the cold air moves out and down into the low, the warm upper air will also be brought down with increasing velocity. Since it starts down as relatively warm air, by the time it reaches sea level along the margin of the icecap it would, with the adiabatic heating on the descent, bring about a very rapid rise in temperature. This is the condition that is frequently observed."

It seems to the reviewer that in presenting this explanation of the Greenland "foehn" and in drawing a distinction between the gravity and "foehn" winds, Belknap has done much to clarify the Greenland atmosphere.

Greenland as the wind-pole of a hemisphere.—In various discussions of the theory, Professor Hobbs has emphasized that the Greenland anticyclone acts as the wind pole of the Northern Hemisphere. As he puts it, Greenland is the "north pole of the winds" where high-level circulation from other parts of the hemisphere is drawn through the glacial anticyclone to start its return southward at lower altitudes. In the Southern Hemisphere, where the great Antarctic ice sheet occupies a symmetrical position over the polar regions, a good case is made for such a wind pole, and its existence is accepted by many meteorologists and climatologists.

For the Northern Hemisphere Professor Hobbs has conceived of the Greenland anticyclone as exerting an equally important though somewhat weaker influence on hemispheric circulation. Carlson, in his *General Conclusions* (p. 105) offers a more moderate point of view. In his words: "That the huge topographic feature, the icecap of Greenland, exercises a dominant control in the weather of *at least a part* of the Northern Hemisphere becomes indisputable in the light of the quantitative data gathered during recent years. The size of Greenland, an ice plateau extending from the ice of the Arctic Ocean 1,600 miles southward into the realm of the relatively warm Atlantic Ocean, is enough to make it an important factor in the general circulation of the atmosphere in northern latitudes." The words "at least a part," italicised by the reviewer, express the more moderate concept, for it seems logical that other more or less permanent areas of high pressure must also be of importance as wind poles of hemispheric circulation. The Canadian and Siberian highs of winter and the Aleutian high of summer must exert strong influences in their respective parts of the world. The Greenland high, existing as it does through winter and summer, may be more permanently effective, but it can hardly be expected to exist as the one and only unique "north pole of the winds."

Summary—Professor Hobbs' theory of the glacial anticyclone is largely substantiated though some modification seems to be called for, and some questions remain unsettled. The existence of the anticyclone is certain, and it seems to dominate atmospheric circulation over at least a part of the Northern Hemisphere. The high topography of the ice sheet, together with the anticyclone, form an effective barrier against migrating cyclonic disturbances. The original concept of periodic strophs and gravity generated "foehns" seems to be rejected, and the question of whether the ice sheet is primarily nourished by precipitation from descending air at the center of the anticyclone or from cyclonic winds blowing considerable distances onto the ice sheet remains unsettled.

In closing the reviewer extends his congratulations to Professor Hobbs. His theory of the glacial anticyclone was first published in 1910, at a time when few meteorological studies had been made along the borders of either the Greenland or Antarctic ice sheets, and when the only observations from the interior regions of the ice sheets were those made by hard-pressed sled parties whose primary objectives were not of a meteorological nature. From such sources Professor Hobbs made meteorological history and, despite more than a decade of opposition from several eminent meteorologists and climatologists, he now finds his theory largely substantiated by the research of recent years.

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