SOME METEOROLOGICAL ASPECTS OF THE GREENLAND ICE CAP

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ABSTRACT

The published results of previous investigations reveal that meteorologists and glaciologists are not in agreement as to the role of the Ice Cap as a cold source in the general circulation, the importance of the Ice Cap as a barrier to air movements in the lower levels, and the principal sources of nourishment for the Ice Cap itself. These questionable issues regarding the Ice Cap arose from conflicting opinions as to the mechanism of the "Glacial Anticyclone," and from a lack of conclusive observational data.

Modern knowledge concerning Greenland from the standpoint of synoptic meteorology has been enriched by an abundance of surface and upper-air data. This new survey of Ice Cap problems, based upon a study of synoptic weather charts and the author's experiences on the Ice Cap, leads to the following conclusions: The important outbreaks of Ice Cap air require a favorable stage in the general circulation and are not due to "strokes" of the Glacial Anticyclone; the transit of fronts and storms across the Ice Cap is governed by the general atmospheric circulation, fall and early winter being normally more favorable than summer, but crossings are possible at any time of the year; the principal nourishment for the Ice Cap is derived from normal cyclonic and orographic precipitation processes, and only little is obtained from sublimation deposits.

1. Introduction. Since there are conflicting opinions about the significance of the Greenland Ice Cap with respect to the general atmospheric circulation, a new survey of the problem has been made in an attempt to correlate the data available from both recent and past investigations. This discussion is mainly devoted to specific weather patterns which lend support to certain theories and illustrate various recurrent situations affecting surface and air operations over the Ice Cap throughout the year. No attempt is made to analyze the many local effects imposed upon observations from the Greenland meteorological stations, but such information may be obtained from references cited below.

Because most of Greenland is covered by the only remaining large ice sheet in the Northern Hemisphere, it occupies a unique position of meteorological influence. The crest of the Ice Cap rises from 8,000 to 10,000 feet above the sea through more than 1,200 miles in a north-south direction. In spite of considerable past investigation, questions still arise as to the role of the Ice Cap as a cold source in the general circulation and as to its importance as a barrier to the air movements in the lower levels. Furthermore, glaciologists are not in agreement as to the principal sources of nourishment for the Ice Cap itself. It may be impossible to formulate precise answers to these questions until a number of Ice Cap observation stations have been in operation for several years, but enough data are available to assist in formulating logical conclusions based upon a study of synoptic weather charts.

2. General considerations. A basic assumption of dynamic meterology is that the atmospheric circulation is driven by energy derived from the temperature difference between warm- and cold-source regions of the earth. Heat transfer takes place by means of large-scale interactions between polar and tropical air masses. In confirmation of the above hypothesis, the areas of outstanding storminess are found near zones having great temperature contrasts. The lowest annual mean temperature in the Northern Hemisphere has been observed on the Greenland Ice Cap at an elevation near 10,000 feet above sea level, but colder conditions occur in northeastern Siberia during winter months. Consequently the "Aleutian Low" is more active than the "Icelandic Low" in winter. Yet the more permanent nature of the Greenland cold source is verified by continued North Atlantic storminess through the warmer months when North Pacific cyclonic activity is relatively weak. It is entirely reasonable to call Greenland the "cold pole" of the Northern Hemisphere, but some qualifying remarks on the role of the Ice Cap as a cold source will appear later.

Any study of the general atmospheric circulation must consider the complex factors introduced by the irregular distribution of land and water surfaces, and the topography of the terrain has to be taken into account. Greenland is separated from Baffin Island in the west and from Iceland in the east by two or three hundred miles of sea. Except for the highlands of Tibet, the Ice Cap plateau is the largest of its height in the Northern Hemisphere. The relatively warm waters surrounding southern Greenland are favored highways for cyclonic storms, but the ice wall of Greenland is a formidable barrier, which can only be surmounted by

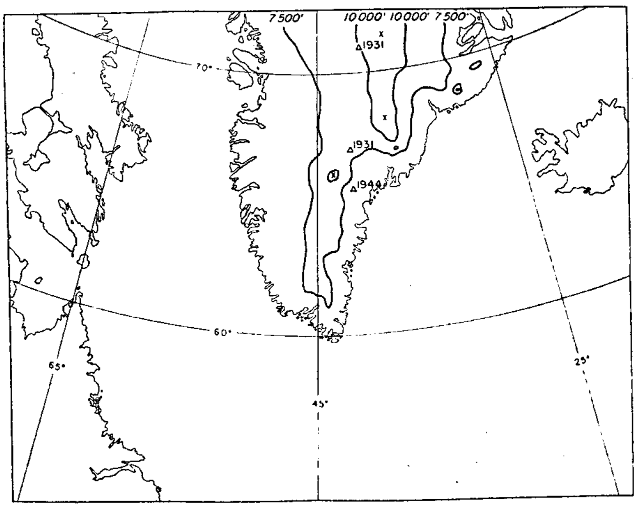

FIG. 1. Provisional contours and Ice Cap stations. Major domes above 10,000 feet marked by crosses.

well developed disturbances whose circulation extends to great heights. Moderately intense or weak storms, approaching Greenland from a southwesterly direction, normally pass northward along either Davis or Denmark Straits avoiding the Ice Cap. Several ways by which the Davis Strait depressions appear to cross the ice barrier, or cause the formation or new disturbances east of Greenland, will be disclosed in another section of this report.

There can be little doubt that most of the precipitation falling on coastal sections of Greenland is due to the normal processes associated with cyclonic storms. A high percentage of the annual total comes as snowfall, this percentage being consistently greater at the more northerly localities from which records are available. Similarly, the usual decrease from south to north in total precipitation and in mean temperature has been observed. However, the extent to which the normal cyclonic and orographic precipitation factors contribute to the nourishment of the Ice Cap is not completely known. Recent data indicate that the accumulation due to sublimation deposits such as rime, hoarfrost and ice spicules is only a small percentage of the total precipitation on the Ice Cap.

3. Questionable hypotheses. An early and long-continued series of investigations on the meteorology of Greenland and its Ice Cap was conducted by geologists and glaciologists associated with the University of Michigan. Results of this research were published in volumes IV, V, and VI, University of Michigan Studies, Scientific Series. It is of some interest to note that the theories concerning the "Glacial Anticyclone," which were first publicized by the director of these investigations in 1910 and reiterated in the first volume of the series (Vol. IV, 1926), were derived from scanty information and have been rigidly maintained despite a gradual increase in adverse observational data. Glaciologists and meteorologists engaged in independent Ice Cap investigations have concluded that, while much valuable data were collected by the Michigan expeditions, the notorious "Glacial Anticyclone" has been overemphasized.

The existence of a semipermanent wedge of high pressure over the Ice Cap is well established; likewise, there is no doubt as to the location of the Northern Hemisphere's "cold pole." It is the mechanism of Greenland's Glacial Anticyclone (2) that is questionable, although its name finds justification in the system of outblowing winds activated by the gravity flow of cold air down from the Ice Cap. Periodic and tempestuous "pulses" of the Glacial Anticyclone are assumed to occur when the air becomes sufficiently cooled by outgoing radiation to start downslope movement and subsequently acquire "the steadily accelerating velocity characteristic of bodies sliding on inclined planes." The outblowing hurricane must be replenished by air drawn down from aloft, which is adiabatically warmed in its descent and eventually raises the surface temperature to the point where gravity flow ceases. In this final phase of the cycle, nourishment is supposedly supplied to the Ice Cap by condensation and sublimation processes when the descending air is cooled near the ice surface. With the next "stroke" of this hypothetical refrigerating engine, a new increment of drift is swept out to the marginal zone of the Ice Cap. Each cyclic blast of cold air presumably activates an Atlantic storm or reenergizes an old disturbance.

This interesting concept of the Glacial Anticyclone gives it a dominant role in the general circulation. It "switches" cyclonic disturbances away from Greenland (1) but provides and distributes nourishment for the Ice Cap while also acting as the major cold source in the Northern Hemisphere (3). Some meteorologists unfamiliar with Greenland's topography and the local peculiarities of the various observing stations have been guilty of assuming that storms cross the Ice Cap as readily as they traverse the open sea. The abundance of surface and upper-air data more recently available has largely eliminated such errors. A well considered summary of modern knowledge concerning Greenland from the standpoint of synoptic meteorology has appeared in *Report No. 108* reproduced by the U. S. Army Air Forces, Weather Division. The present discussion further clarifies the questionable issues pertaining to the Glacial Anticyclone.

4. The Ice Cap as a cold source. General statements have already been made regarding the role played by Ice Cap air in connection with North Atlantic storminess off Greenland's eastern coasts. Reference is now made to Figure 1, which presents generalized contours of the Ice Cap. It should be noted that the eastern slopes are steepest and that the area east of the crestline is relatively small. Due to the domed shape of the Ice Cap, no great thickness of radiationally cooled air can accumulate upon it. Normal gravity flow, represented by winds of force 3 to 5 Beaufort, drains away the excess cold air and rarely allows the inversion layer to become more than a few thousand feet thick. Furthermore, the cold air of the icy plateau undergoes adiabatic warming in its descent to sea level. A temperature increase of 40 to 50 degrees Fahrenheit is not uncommon in winter, resulting in a large loss of potential energy before the air mass becomes involved in the atmospheric circulation over the North Atlantic. By way of comparison, large masses of continental polar air move southeastward from Canada to the Atlantic coast with very little modification in winter when the underlying surface is mostly snow covered. It will be shown that the most important outbreaks of Ice Cap air require a favorable stage in the general circulation and are not due to "strokes" of the Glacial Anticyclone. Evidence of this requirement may be seen in one form or another in all of the synoptic charts presented in this discussion.

The first illustration is taken from a period in 1931 when two expedition stations were in operation on the Ice Cap. (See Fig. 1 for approximate locations and elevations.) Although the southern station was only slightly east of the crestline, it reported an equal frequency of gales from both upslope and downslope directions (5). Records from the northern station further confirm the fact that cyclonic influence extends to the interior zone of the icy plateau (6). The chart for January 15 (Fig. 2) shows upslope winds at both points on the Ice Cap. Lowest pressures aloft are probably northwest of the center indicated by the sea-level isobars.

Some remarks should be made at this point on the question of indicating a low over the Ice Cap. Pressure reductions from high stations on the ice can not be

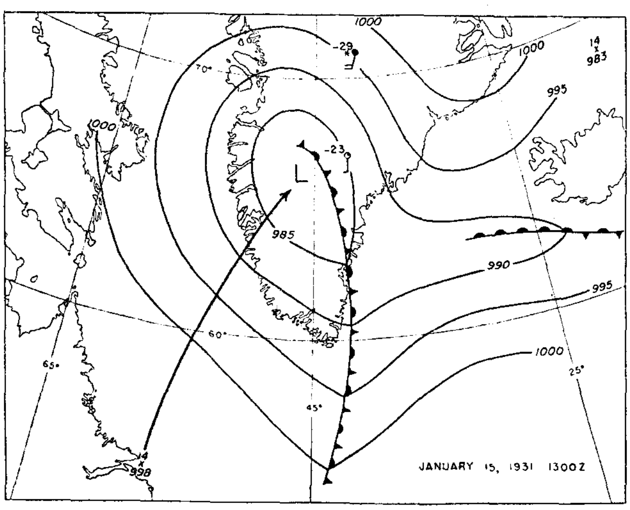

FIGURE 2.

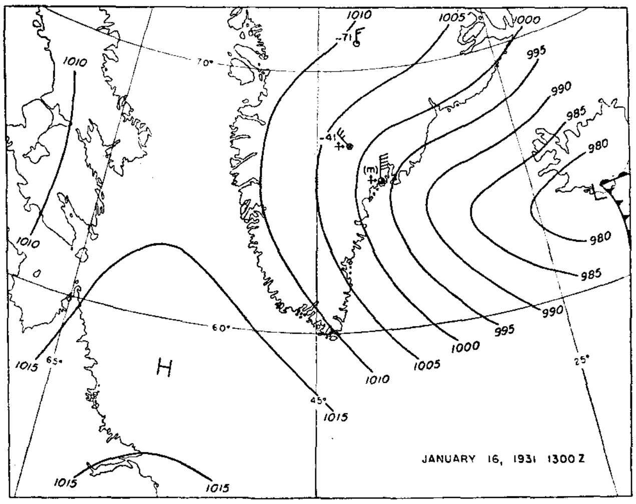

FIGURE 3.

entirely accurate and may never result in values lower than those observed at coastal or fjord locations. Yet the modern network of upper-air soundings has revealed low pressure systems aloft over the inland ice on numerous occasions. In situations resembling this example, it might be better to indicate the lowest sea-level pressure as staying near the western fjord-heads until pressure falls on the east coast result in lower values there. But the case of Januarty 15 came at a time when pressures over the Ice Cap apparently had been low for several days, and, since a frontal and upper pressure system clearly crossed the inland ice, the original analysis has been reproduced. A policy of omitting practically all station data was chosen with the idea of placing primary emphasis on the isobaric patterns and frontal systems.

Returning to Figure 2, it appears that the formation of a new center will soon occur in the warm-front trough southwest of Iceland. Ice Cap air is beginning to flow off southern Greenland, making the occluded front a cold front for the new disturbance. Figure 3 shows the situation 24 hours later when the anticipated development has resulted in a deep cyclonic system centered near southern Iceland. Its influence extends to the western slopes of the Ice Cap, where a north wind is observed at the northern station instead of the normal southeasterly katabatic flow. The southern Ice Cap and base stations indicate that a major outbreak of cold air is being drawn into the Atlantic behind the Icelandic storm. Any connection between the foregoing weather sequence and a "stroke" of the Glacial Anticyclone is rather difficult to visualize.

Another process resulting in a strong flow of Ice Cap air will now be illustrated. This sequence was observed in July and exhibits an interesting departure from the normal condition of high pressure banked against the east Greenland coast with most frequent

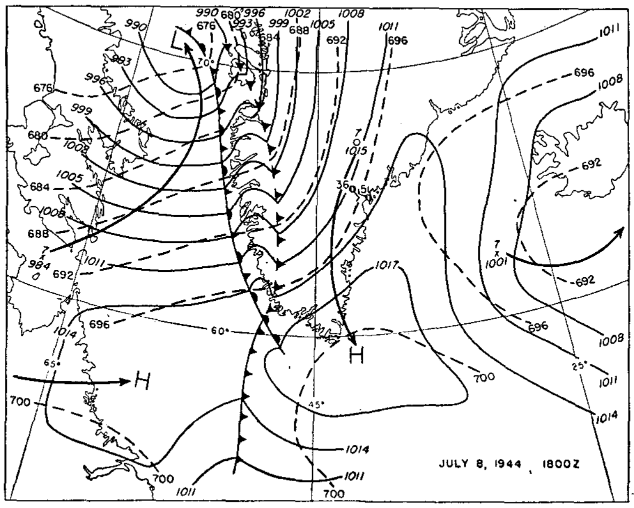

FIGURE 4.

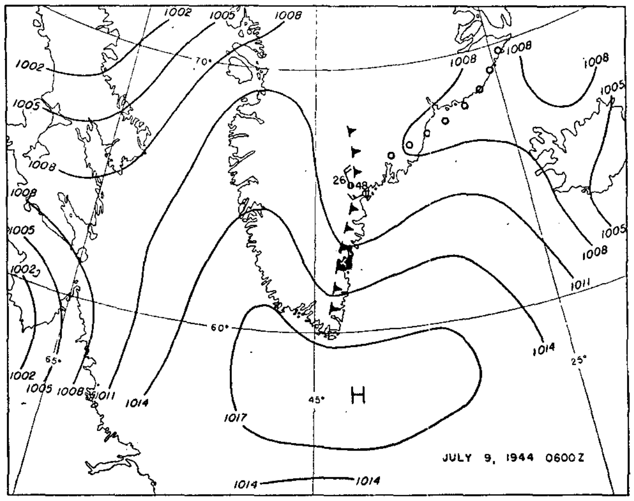

FIGURE 5.

North Atlantic storminess occurring near or southeast of Iceland. In addition to a wealth of surface and upper-air data, observations were available from Atterbury Dome and the Ice Cap. Atterbury Dome had the best exposure of all East Greenland stations, and the Ice Cap weather building at 5,650 feet was more than half the height of the nearest 10,600-foot dome on the inland ice. The weather situation at the start of this series is shown in Figure 4. Dashed isobars, depicting the pressure pattern at 10,000 feet, were based on 1600Z observations. An abnormally deep cyclonic system over Davis Strait is initiating a strong westerly flow across the Ice Cap, which favors steady eastward movement of the upper cold front. Upslope winds are observed on the Ice Cap, but katabatic winds continue at Atterbury Dome. Twelve hours later (Fig. 5), the progress of the upper cold front across Greenland is confirmed by its passage at the Ice Cap station. Southwesterly winds are rare at Atterbury, but here they indicate the approaching frontal trough. Pressures have risen rapidly in the west, but large falls on the eastern coast together with the development of a frontogenetic trough suggest that a new disturbance is about to form. Figure 6 shows the synoptic situation after a lapse of 12 hours, when the pressure gradient around the vigorous young storm caused strong downslope winds at the Ice Cap station and Atterbury Dome. This was the most pronounced cold flow during the summer period of station observations on the Ice Cap, and it should be noted that the strongest winds came not with the cold front but after the coastal low-pressure center had formed and continued to deepen. A favorable downslope pressure gradient, both at sea level and aloft, was required before winds of gale force were observed.

Several other synoptic situations associated with large-scale outbreaks of Ice Cap air are illustrated in Figures 7 and 8. In the first case, the extreme wind velocity recorded during a regular observation at Atterbury Dome was reached in the 24 hours following the chart shown. Pressure continued to rise in Davis Strait but remained low behind the storm as it moved across Iceland. The resultant isobaric pattern was similar to that of Figure 3, and a superhurricane of 106 miles per hour with the thermometer reading 3°F was experienced at Atterbury. Figure 8 shows a slightly different situation in March. Pressures are generally higher but, being abnormally high over Baffin Island, the now familiar pattern of favorable gradients combining with the gravity effect is again responsible for the cold northerly gales at Atterbury. It may be of interest to note that, because of its excellent exposure on top of a rocky dome at 1,190 feet above the sea, this station's extreme minimum temperature (−7°F) was recorded in a northerly gale. Slight warming normally accompanied abating gales, but lower temperatures undoubtedly were attained during subsequent radiational cooling in local sheltered areas near sea level.

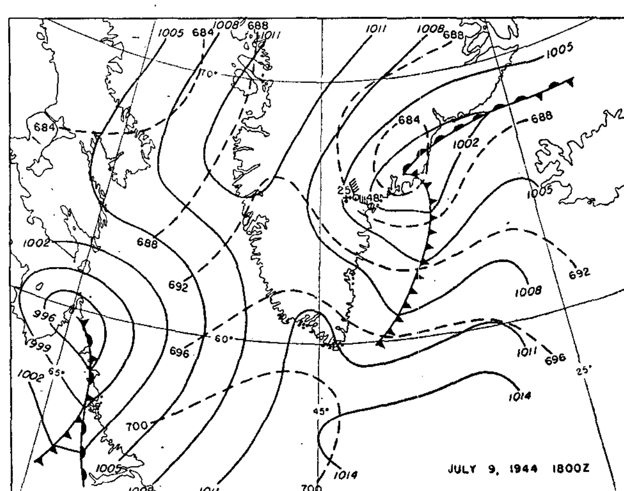

FIGURE 6.

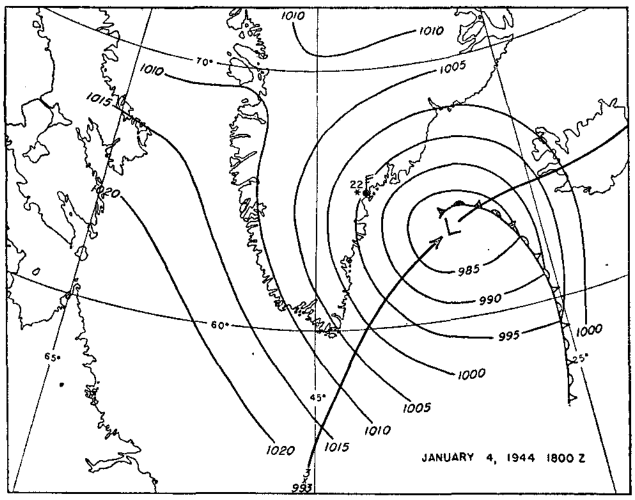

FIGURE 7.

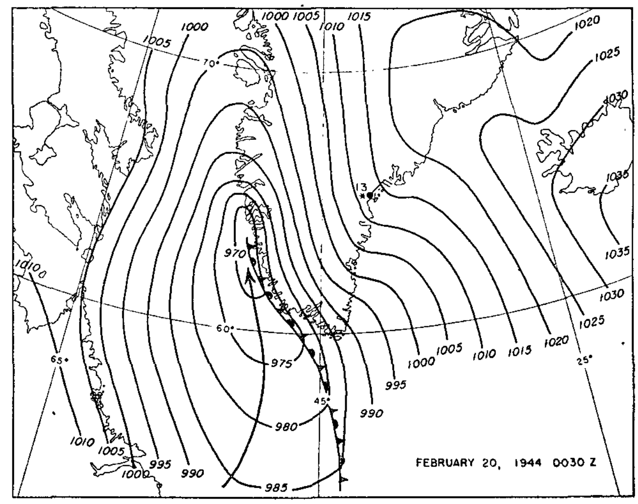

FIGURE 9.

The foregoing examples have demonstrated that important injections of Ice Cap air into the general atmospheric circulation occur in the rear quadrants of cyclonic storms. Under the most favorable conditions these outbreaks may pass the Azores or even reach southeastern Europe. Since nothing resembling anticyclonic control of the Ice Cap gales has been found, attention is now directed to the strength of outblowing winds on two occasions when anticyclonic conditions were extremely well developed over the Ice Cap. Maximum winter and summer pressures were observed at Atterbury Dome in these two periods. Figures 9, 10 and 11 illustrate the weather processes leading up to the huge anticyclone of February 25. A meridional type of flow had been developing in the North Atlantic, where abnormally high pressure between England and Iceland was blocking the usual west-east circulation. Long range forecasters are familiar with the fact that such blocking normally moves slowly westward and broadly dominates the atmospheric circulation. This is an outstanding example of retrograde movement, and a high percentage of the most stable anticyclonic conditions over Greenland are initiated in a similar fashion. Consideration of the present case (Fig. 9) shows that eastward movement was impossible for the storm of February 20. It moved rapidly northward, retrograding across Baffin Bay and leaving a small center behind in southwest Greenland. This system also filled and followed the primary disturbance on February 22–23 (Fig. 10). Meanwhile, pressures were rising south of Greenland at the surface and upper levels due to warm advection aloft in the circulation around a deep cyclone to the southwest. The resultant northward moving high (Fig. 10) caused a gradient shift from southerly to westerly over southern Greenland and strengthened the normal frontogenetic zone or Ice Cap front along the east coast. These factors combined to develop a small wave disturbance, which moved rapidly northeastward. A brief northwesterly hurricane was recorded at Atterbury Dome as this wave deepened, but gale winds blew for less than 6 hours. Nothing more than a normal katabatic flow was observed on February 24–25 (Fig. 11), while the Atlantic high continued its northerly movement and reached a maximum anticyclonic development with pressures exceeding 1,050 millibars over the Ice Cap.

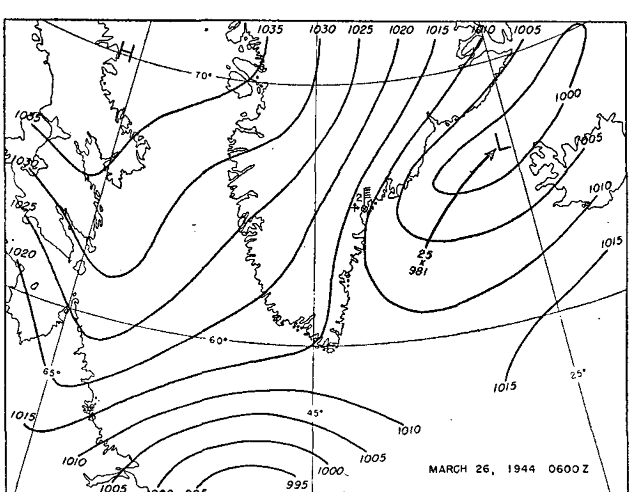

FIGURE 8.

A summer sequence resulting in the highest pressure of the season at Atterbury Dome (July 22) is shown in Figure 12. This is a chart of 5-day mean isobars at sea level and 10,000 feet for the period July 20–24. It will be noted that the development of anticyclonic conditions over the Ice Cap was initiated by pressure rises moving northwesterly from Iceland. The mean temperatures, sky conditions and resultant winds at the Ice Cap and Atterbury stations for this period are plotted. Due to strong solar heating the katabatic winds are light in summer, and here in an example of

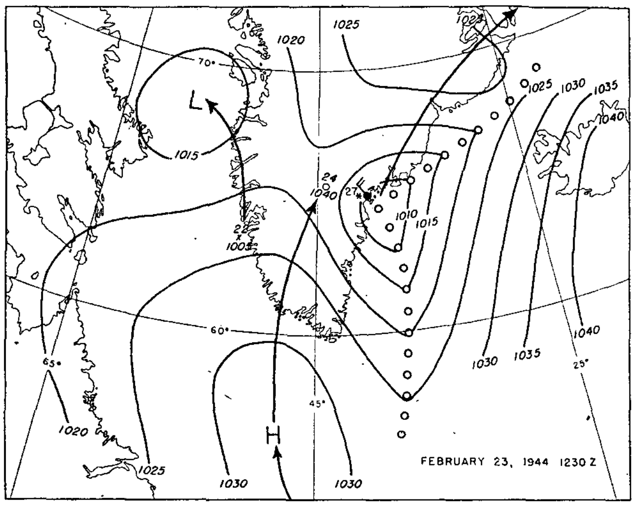

FIGURE 10.

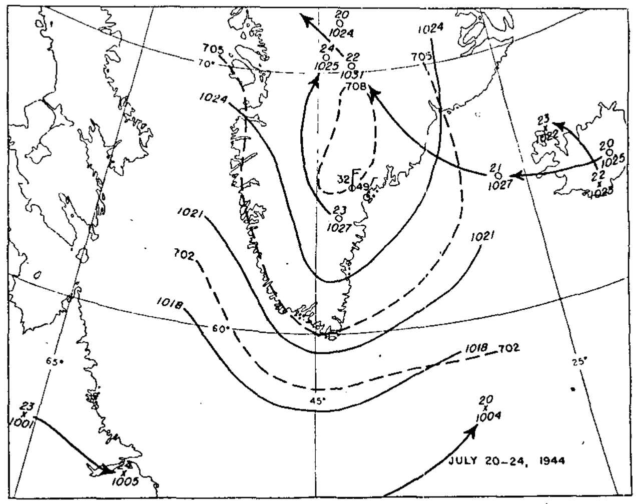

FIGURE 12.

strong anticyclonic control there is no sign of any important cold flow from the Ice Cap.

5. The Ice Cap as a barrier to cyclonic storms. It has been mentioned that meteorologists have erred to the extent of indicating the passage of storms across the Ice Cap as if it were an open sea (4). The modern network of surface and upper-air observations has done much to eliminate such errors, yet it also has furnished evidence that storms occasionally surmount the ice barrier. Insofar as the circulation near sea level is concerned, there is difficulty in visualizing the passage of a cyclonic disturbance across the Ice Cap. This is a familiar difficulty in synoptic analysis over the elevated terrain of the western United States and Canada where pressure reductions are uncertain quantities. Upper-air charts provide the only satisfactory solutions in many questionable cases and are invaluable in an analysis of Greenland weather.

Before exhibiting a transit of the Ice Cap by an upper-level cyclonic system, reference is again made

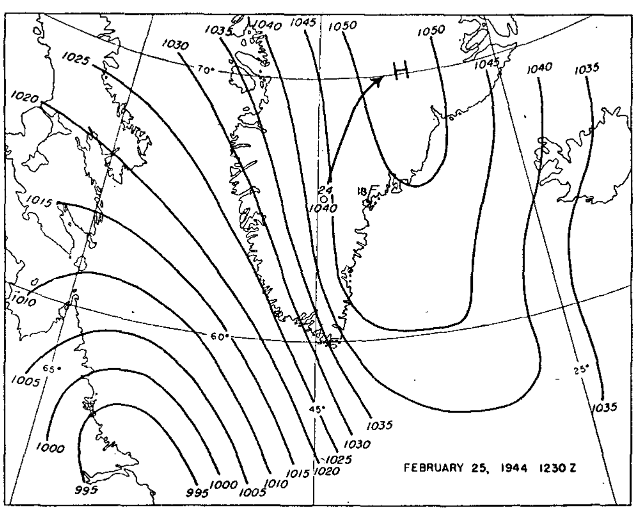

FIGURE 11.

to Figures 4 and 5. The passage of a front aloft across the inland ice was clearly marked. This front was in contact with the elevated surface and could have been indicated as a surface front on the Ice Cap. Since frontal passages of this type are not uncommon when they are driven by strong westerlies aloft, it is believed that clarity of analysis is favored by indicating them to be upper fronts in their transit of the Ice Cap. A mistake is often made in situations somewhat similar to the development shown in Figures 4, 5, and 6 by indicating the passage of a David Strait storm directly across southern Greenland. What really happens is that the upper front operates as above to activate a new disturbance on the east coast, while the old low stagnates and fills near the western fjord-heads. At other times a secondary may form near Cape Farewell, after the pattern of Bjerknes' classic Skagerrak low, and move rapidly up the east coast giving the impression that the primary storm has crossed the Ice Cap. The above types of misleading situations undoubtedly caused trouble in earlier years when synoptic charts were drawn at 12- or even 24-hour intervals, but they have been easily detected in recent years when a complete surface analysis was available four times daily.

The sequence to be considered now does not possess any deceptive characteristics in the sea-level development, since the presence of a secondary disturbance was detected at an early stage (Fig. 13). But it is a situation where a transit over the Ice Cap by an upper-level cyclonic system might not be readily inferred from an inspection of surface charts alone. Although the charts presented are for 24-hour intervals, the intervening 12-hourly 10,000-foot charts clearly substantiate this analysis. Temperatures plotted for the 10,000-foot level are in degrees centigrade, and movement of the closed low aloft is indicated by short arrows (Figs. 14 and 15). Atterbury Dome did not

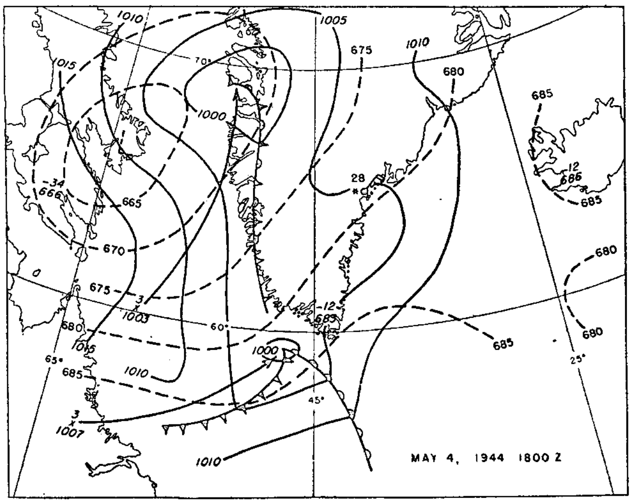

FIGURE 13.

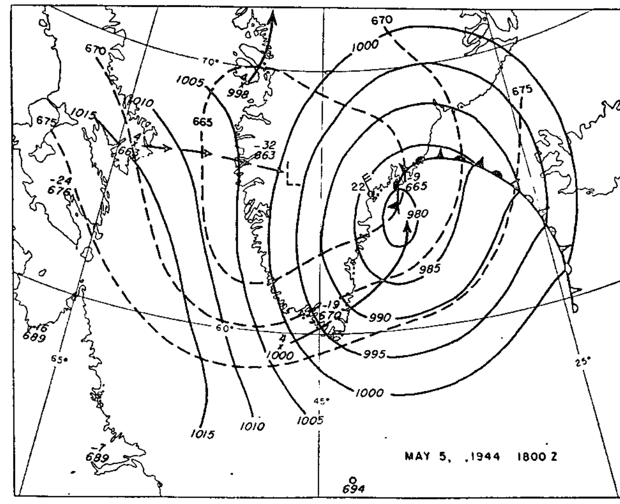

FIGURE 14.

observe a strong flow of Ice Cap air until several hours after the time of the observations plotted in Figure 15, which again emphasizes the necessity for favorable isobaric gradients at the surface and aloft before gales can blow from the Ice Cap.

Some investigators have suggested that cyclonic systems may cross the Ice Cap more readily in the warmer season when insolation should weaken anticyclonic conditions dependent on radiational cooling. A check on the record of wind shifts coincident with pressure troughs at the northern Ice Cap station (Eismitte) during 1930–31 does not verify the above remark. Normal pressure charts likewise indicate that few storms or fronts reach the eastern coasts of Greenland in summer. The same is true of charts, based on 30 to 40 years' data, showing the frequency distribution of lows over the north Atlantic area. It is believed that the major factor in Greenland's action as a "switch" for cyclones is the topographic barrier presented by the Ice Cap. This barrier is a constant factor throughout the year. Any added layer of radiationally cooled air is easily dissipated by strong winds. Therefore it appears that the transit of fronts and storms across the Ice Cap should be governed by the general atmospheric circulation. Conditions characterized by weak polar easterlies and strong zonal flow at high latitudes are undoubtedly favorable for frontal assaults on the icy barrier. In terms of seasons, fall and early winter are normally more favorable than summer but crossings are possible at any time of the year.

Several remarks should be made on the latitude of most frequent transits. With reference to Figure 1, the Ice Cap crestline is seen to rise for several hundred miles north of 62.5°N, but there is a major saddle at about 67°N. This saddle appears to be an important gap in the barrier, providing a channel for westerly winds approximately 2,000 feet below the major domes. The orientation of the crestline changes sharply in this locality and the Ice Cap is relatively narrow to the south. It is probable that the turbulent flow induced by such a topographic irregularity will tend to dissipate all but the most intense upper fronts at this point. That condition is implied in the analysis of Figure 5, and, considering the likelihood of cyclogenesis in similar situations over the area between Atterbury Dome and Angmagssalik, it seems that few fronts will be found making a complete west-east transit of the Ice Cap north of 67°N. Figures 14 and 15 suggest that the above hypothesis may also be applicable to the movement of upper-level cyclonic systems. Little is known regarding the flow patterns over northern Greenland but, since the crestline descends gradually north of 72°N, it is possible that some upper-level systems make a northern crossing. According to the observations at Eismitte in 1930–31, this appeared to occur at times with a tendency for systems to split near 70°N, so that separate centers crossed

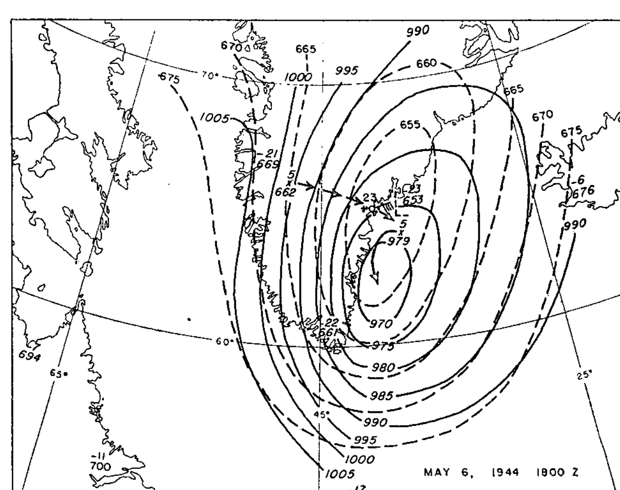

FIGURE 15.

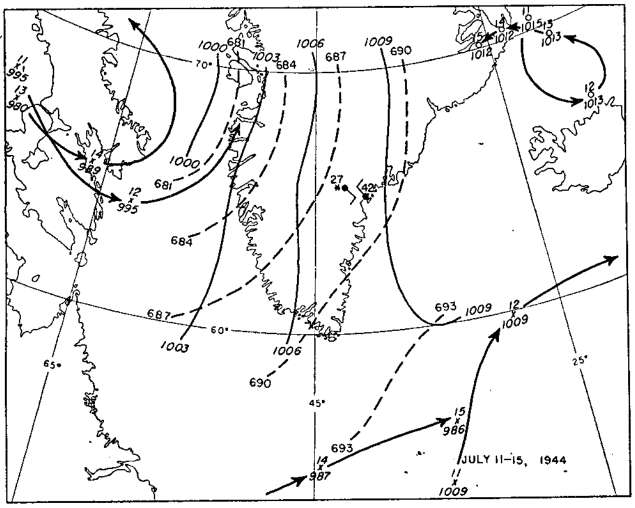

FIGURE 16.

north and south of the larger area about 10,000 feet (Fig. 1) on the Ice Cap.

6. Sources of nourishment for the Ice Cap. The extent to which the inland ice receives nourishment by means of normal cyclonic or upslope precipitation processes will not be known until records of precipitation are available for many interior localities. However, estimates may be made regarding the relative amounts received during periods dominated by cyclonic or anticyclonic conditions. Theories which postulate a high percentage of anticyclonic precipitation are mainly based on evidence intended to show that cyclonic influences do not extend to the interior zone of the Ice Cap. This type of reasoning is not supported by the observed pressure changes and upslope winds which appear in the published records of the 1930–31 Ice Cap stations. Warm-front cloud types and precipitation, as well as orographic snowfall, have been frequently observed on the Ice Cap. Anticyclonic conditions may be more persistent in northern Greenland, but one day of orographic precipitation should result in a greater accumulation than that produced by many days of radiational cooling.

A number of situations in which Ice Cap weather was influenced by predominantly cyclonic controls have already been discussed in preceding sections of this report. It is believed that most of the precipitation over the marginal zone of the Ice Cap is cyclonic in character. A considerable amount of snowfall drifts away, and an unknown proportion is replaced by drift from the interior. Precipitation on the higher slopes of the Ice Cap appears to be mostly of an orographic type. The heaviest snowfalls should occur on the western slopes during long periods of southwesterly flow aloft and correspondingly on the eastern slopes when southeasterlies prevail. These conditions are often observed when the general circulation is of a meridional type similar to that shown in Figure 9 and indicated as becoming reestablished in Figure 11. It also should be mentioned that maximum winter temperatures on the Greenland coasts come with sustained southerly winds of the type just illustrated.

An interesting example of a persistent meridional flow over the Ice Cap is shown in Figure 16. This type of synoptic situation is frequently observed in summer and resembles the normal isobaric pattern for July. Figure 16 is another 5-day mean chart. It is seen that snow fell almost continuously during this period of upslope winds at the Ice Cap station. The observers noted that the position of the sun was often visible through prevailing low clouds. This precipitation was undoubtedly orographic, and some of it drifted upslope. Winds at Atterbury Dome continued from the katabatic direction—probably due to a slight downflow from the lower ice slopes below the onshore gradient level.

Observers on the southern dome and at the Ice Cap station recorded orographic snowfall and upslope drift on the two days following the situation illustrated in Figure 12. Pressures fell on July 25–26 over southwest Greenland and remained relatively high along the east coast. There were no strong downslope winds following either of the snowfalls mentioned above. Consequently it appears that much of the orographic precipitation on the upper slopes may become settled by upslope and cross-slope drifting before it can be blown toward the marginal zone.

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