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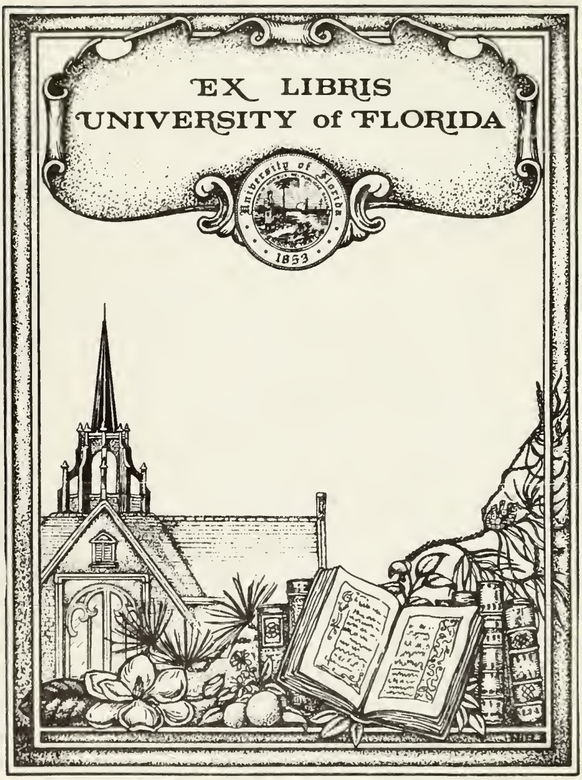
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Bowman Memorial Lectures

Glacier Variations and Climatic Fluctuations

BY

H. W:SON AHLMANN

SERIES THREE

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BOWMAN MEMORIAL LECTURES

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Foreword

THE THIRD in the series of the Isaiah Bowman Memorial Fund lectures was delivered by His Excellency Hans W:son Ahlmann on August 13, 1952, as the principal address at the meeting of the Seventeenth International Geographical Congress in Washington, D. C. The original text of "Glacier Variations and Climatic Fluctuations" has been augmented for publication by additional data and references to serve as a summary of the author's latest thinking on the subject. It brings together the findings of the human and physical geographer, the geomorphologist, the climatologist and even the historian. Dr. Ahlmann has been Professor of Geography at the University of Stockholm, and from 1948 to 1951 served as President of the Commission on Snow and Ice of the International Association of Hydrology (I. U. G. G.).

Dr. Ahlmann, now serving his country as Sweden's Ambassador to Norway, has for two decades been the leader in the work of relating changes in glaciers to climatic fluctuations. His concept of the need for collaboration between sciences—the team approach—and the necessity for initiating detailed observations to achieve a better understanding of glacier regimen has changed the whole scope of glaciology. He has pioneered in developing methods for making precise measurements of accumulation and wastage from which to determine a glacier's economy or hydrologic balance. These techniques not only provide means of learning more about glaciers themselves, but also make possible a much more accurate and satisfactory interpretation of their response to meteorological factors and other external influences.

Dr. Ahlmann's studies began in Norway in 1918, were extended to Spitsbergen in 1931, to Iceland in 1936, and to northeast Greenland in 1939. The Norwegian-British-Swedish Antarctic Expedition, 1949–1952, was largely a product of his planning and organization. In the summer of 1952, following the meeting in Washington, he made a brief visit to Southeastern Alaska under the auspices of the American Geographical Society, supported by funds generously provided by the Office of Naval Research. His objective was to observe the principal glaciological features of that area and to evaluate the studies being made there by this Society and others, in order to further the development of a well-integrated international program of glaciological-climatological research.

We may appropriately recall the Foreword he wrote in the first issue of the *Journal of Glaciology*, January, 1947 (p. 3): "As a science glaciology is young, even though snow, ice and glaciers have been noticed for centuries . . . but they have been remarkably late in becoming the subject of systematic investigation. And this in spite of the fact that snow and ice are of great practical importance in northern countries. . . . We are as yet only on the threshold of the world of ice in the Antarctic that conceals the answer to questions of the greatest importance to the understanding of physical-geographical conditions both at the present time and during the Ice Age. The glaciers at all latitudes round the earth are of no less interest. As yet we know very little about the meteorological reasons for their existence and variations in size, about their structure, movement and other features. . . . The tasks confronting us are immense and various . . ." In this volume, as in his many other writings, Dr. Ahlmann clearly points the way to the future development of glaciology in both its practical and theoretical aspects, especially as it may contribute to the study of climatic change.

W. O. Field, Jr.

Glacier Variations and Climatic Fluctuations

I regard it as a very great honor to have been asked to give this lecture in memory of Isaiah Bowman, a man whose attainments as a scientist I have long appreciated through his writings and whom I had the pleasure to know personally, not only as a man of great distinction and a citizen of the United States, but as a citizen of the world.

As the subject of my lecture I have selected a chapter in climatology. This science is of importance not only to glaciologists; it affects the whole social and economic life of mankind. Isaiah Bowman was much interested in climate and its changes. In studies of the pioneering process, for instance, he gave full recognition to climate as a critical element. He often cited the early Norse settlement of Greenland as an experiment on the "verge of the possible," where even a slight climatic change brought disaster.[1] And he stressed the need of quantitative study. He himself "carried out measurements on physical indications of climatic change—on tree rings and on strandlines in Great Basin lakes—and later he prompted the National Academy of Sciences to undertake cyclic-change studies in weather and climate."[2] Glaciers and glaciation were a subject of special attention in his field work in the Peruvian Andes.

Of recent years, glaciers have been the object of intense scientific research. That research, moreover, is differentiated by today's cooperation between various scientific disciplines whereby many new aspects of a more profound geophysical nature have been opened up. To take one example, it is only within the last 20 years that any close attention has been given to the glacier ice itself.[3] The earlier unconcern has run through the whole course of polar exploration; it applies particularly to Antarctica, with 99 per cent of its area ice covered.

Today we have a better appreciation of the necessity for more intimate knowledge of present-day glaciers if we are ever to understand Pleistocene glaciation. Richard Foster Flint's "Glacial Geology and the Pleistocene Epoch," published in 1947, is one of the first comprehensive works to use glaciology as a basis for study of this period. His approach became feasible only as a result of the recent rapid advance in glacier study.

Our extraordinary technical progress has made it possible to achieve results in practically all branches of science that no one would have dreamed of only a few decades ago. Such, for instance, in the field of polar research, is the determination by the seismic reflection method of the depths of the inland ice plateaus of Greenland and Antarctica. In Greenland this has been carried out by the French Polar Missions of Paul-Emile Victor,[4] and in the Antarctic by the Norwegian-British-Swedish Expedition to Queen Maud Land, 1949–1952.[5]

SOME PRELIMINARY GLACIOLOGICAL RESULTS FROM QUEEN MAUD LAND

Figure 1, reproduced with the permission of Gordon Robin of the Queen Maud Land expedition, gives the result of his seismic depth measurements from 71° S. to 74°

30′ S. It reveals a wild alpine topography covered with ice to a depth of up to 2500 meters—an immense mass. On the basis of the French results in Greenland, André Cailleux[6] is quite right in saying that previous estimates of the world's existing glacier ice are too small. He calculates that the total volume of land ice must be between 26 and 36 million cubic kilometers. Melting of this volume of ice would raise the sea level by some 65 to 90 meters. Even after making allowance for isostatic adjustments, the rise would be from 43 to 60 meters. Now, as a result of the work in the Antarctic, we can say that the higher figure, 60 meters, is probably a minimum value.

I should like to mention here some other results of general interest from the Queen Maud Land expedition. V. Schytt's measurements at Maudheim show that temperatures in the inland ice and in the shelf ice below the level to which the seasonal fluctuations penetrate (below about 20 meters) correspond to the local mean air temperatures. Thus we have a method of determining this very important climatological element in a given place on the ice, even though we can only stay there for a day or two. Near the southern end of the profile in Figure 1, at 2700 meters above sea level, the average temperature for the year has been calculated in this manner to be about –40° C. Temperatures below –50° C. must be common in the winter months.

The possibility of traveling over the Antarctic and the Greenland icecaps with mechanical snow vehicles may soon bring us to the day when we shall know the average air temperature over the inner parts of these regions. Aside from the value of such information to regional geography, we can reasonably expect that the results obtained may

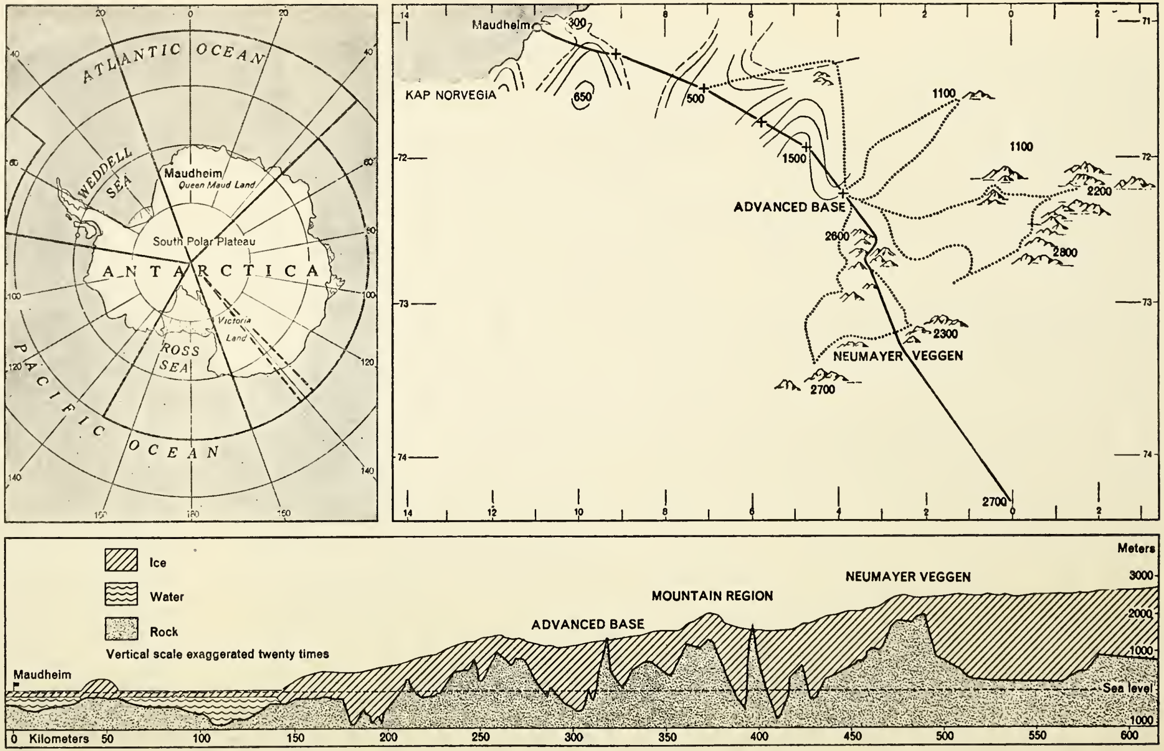


FIG. 1—A) The Antarctic showing Queen Maud Land (Dronning Maud Land) and Maudheim, headquarters of the Norwegian-British-Swedish Antarctic Expedition, 1949–52; B) The line of the seismic soundings; C) Profile of the ice surface and of the bedrock surface as determined by the soundings. The vertical scale is exaggerated 20 times. (After G. de Q. Robin).

serve as a basis for increased knowledge of the climate on and around the masses of Pleistocene inland ice—in other words, of the climate during the Ice Age. Present-day knowledge about the great ice sheets of the past is extremely limited. I am still convinced that at least most parts of the Pleistocene ice sheets were of polar and not of temperate type, that is to say their temperatures were below the freezing point to a depth of at least a couple of hundred meters, with the upper score or more consisting of frozen snow, firn, not ice.[7] Schytt's geophysical and crystallographic analysis of a 100-meter-long core at Maudheim has shown that there was no real glacier ice at lesser depths than 60 meters.

FACTORS INFLUENCING GLACIER VARIATIONS

Glaciers, being conditioned by climatological factors, register by their variations fluctuations and changes of climate. Even the present climates of the world are not stable as was once believed by meteorologists, among them the great Hann. They are, and always have been, subject to fluctuations and changes over both long and short periods. The scope of this field of research is so vast that I must limit myself to the Scandinavian countries and Iceland, with some comparisons from North America.

The relations between glaciers and climate are highly complicated and still far from clear. Until we have solved the problems of the existence and the variation in size of glaciers, their structure, movement, and other features, we cannot fully utilize them as the climatological registers they really are. Robert Sharp[8] correctly says that accumulation is the life blood of a glacier and that "its state of health

TABLE I—CONVECTION, CONDENSATION, AND RADIATION FACTORS IN THE ABLATION PROCESS

Percentage Values

Glacier and Year	Position and Elevation		Convec.	Condens.	Rad.	Surface
Isachsen's Plateau (1934)	79°09′N. 12°56′E.	805 m.	40	27	33	snow
The Fourteenth of July Glacier (1934)	79°08′N. 12°E.	175 m.	65 incl. condens.	—	35	ice
Fröya Glacier (1939)	74°24′N. 20°50′W.	453 m.	83	9	8	snow
Kårsa Glacier (1942–48)	68°20′N. 18°20′E.	1000 m.	29	16	55	ice
Kårsa Glacier (1942–48)	″ ″	1000 m.	44	24	32	snow
Hoffellsjökull (1936)	64°30′N. 15°30′W.	1000 m.	92 incl. condens.	—	8	ice
Vernagtferner* (1950)	46°50′N. 10°45′E.	3000 m.	15	3.5	81	ice

* Detailed observations of an 11-day ablation period in the latter part of August. H. Hoinkes and N. Untersteiner: Wärmeumsatz und Ablation auf Alpengletschern, 1. Vernagtferner, August 1950, *Geografiska Annaler,* Vol. 34, 1952, pp. 99–158.

Glacier state

can best be defined in terms of the relation between accumulation and wastage." Ablation, or wasting (melting and evaporation), is the crux of the matter. It seems as if ablation is at least as important as accumulation in this apparently simple relation. But it is only recently that attention has been turned to the question of which meteorological factors determine ablation in different regions.

The basic work in this subject was carried out in 1934 by H. U. Sverdrup on Isachsen's Plateau, a vast snow-covered transection glacier in Spitsbergen.[9] It was continued on the Kårsa Glacier, a small cirque or valley glacier in Swedish Lapland, by C. C. Wallén in 1942–1948.[10] From Wallén's recent review of the most conclusive results,[11] the following can be summarized. The relative importance of the climatic elements determining the "health of the glacier" varies from one region to another. As a rule we have to take into account: (1) the amount of the annual precipitation in solid form; (2) the temperature during that period of the year when it is above the melting point; (3) the length of that period; (4) the amount of incoming and outgoing radiation, both being influenced by the degree of cloudiness; (5) the wind velocity; (6) the humidity.

The relative importance of the different factors gradually changes from the beginning of the ablation season to its end. The influence of radiation diminishes from early July onwards. Its effect also depends on the nature of the surface, whether snow or ice, for ice has a smaller albedo than snow.

In spite of differences in latitude and local conditions, the most important factors in the ablation process are shown to be convection (heat received from the air) and radiation. Condensation plays a much smaller part, evaporation a still lesser. It seems that the importance of radiation increases with decreasing latitude. Table I is reproduced from Wallén's report.

The more maritime and humid the climate the more important in the process is convection. Vatnajökull in Iceland is a good example of a glacier where ablation takes place under these conditions and where convection plays a much more important part than radiation.[12] On the other hand, in Peary Land in northernmost Greenland, where the climate is extremely continental and arid, evaporation from the icecap is the most important factor in the ablation process.[13]

Our present knowledge of glacier variations is mainly based on observations of their size and especially of their marginal variation. But the variations are primarily a consequence of the thickening and thinning of glaciers, in other words, of changes in volume.

These latter changes are far more difficult and troublesome to determine than the oscillations of the termini. Here an important question is: When does a glacier front react and, by advancing or retreating, affect its "health"? A small glacier will naturally react sooner than a large one. The rate of reaction is dependent also on the topography. If the gradient is steep or the depth great the glacier will move rapidly and the changes will be transmitted to the terminus more quickly than if the slope is gentle or the thickness small. Advances and retreats will therefore usually begin and end at different times, even in the same region. There is also a difference between glaciers terminating on land and in water, especially if the glacier tongue is afloat. The importance of calving is to be considered and the fact that the rate of movement of the glacier increases towards the ice cliff.[14]

In the polar regions we must distinguish between the main inland ice masses on the one hand and on the other their outlet glaciers and local glaciers of different types.

Because of the very great area of the inland ice in the Antarctic and in Greenland it is difficult to obtain measurements that are either representative or accurate enough to lead to any certain conclusion about the ice regime; that is to say, whether the total volume is increasing or decreasing. The Antarctic inland ice is largely surrounded by floating shelf ice, the extension of which is dependent on other factors than those of climate and glacial regime alone. In relation to the whole Antarctic inland ice and the main body of the Greenland inland ice, we must also bear in mind that the reaction to changes of climate is very slow. The Antarctic "cold center" especially offers strong resistance to external forces. In both these parts of the world the summer temperature is so low that a rise of a few degrees may not bring the temperature above the melting point, and thus affect the ablation. Variations in the positions of the termini of outlet glaciers from inland-ice masses are related to the supply of ice as it was determined by climatic conditions of a long time before.

In a short preliminary review of the scientific work of the Norwegian-British-Swedish Expedition, E. F. Roots[15] points out that "the lag between climatic change and change in form of the glacier may be longer than the period of climatic change itself" and that the Antarctic icecap is one great accumulation area. He adds: "A further possibility is that the thickness of the Antarctic ice-cap is not dependent on climatic conditions at all, provided there is sufficient snow accumulation to develop an equilibrium cross-section determined by the physical properties of ice and the resistance offered by the rock floor."

In recent years we have gained knowledge of some special types of high-polar glaciers. The icecaps in Peary Land, where evaporation is predominant among the causes of ablation, are characterized by Fristrup as masses of dead ice, which have possibly grown up under conditions of much greater annual accumulation and surplus in the regime than is the case under present conditions. The outlet glaciers of the inland ice are of a different type; they move fast and transport large quantities of ice. Glacier caps very similar to those found in the interior of Peary Land occur on Baffin, Bylot, and Devon Islands, and the southern part of Ellesmere Island. They have been described by Baird,[16] and are classified by him as the "Baffin Type." Their nourishment is not by accumulation of firn but by superimposed ice from the immediate refreezing of summer melt water. Baird has the same impression as Fristrup, namely that these glacier caps are relics from a climatic epoch of the past, one that was neither so cold nor so arid as the present.

The following statement by F. E. Matthes[17] on the laws of ice flow is further of great importance: "Ice confined in a reservoir remains inert under steadily increasing pressure until a certain point is reached when flow sets in slowly at first, but increasing rapidly in velocity, even though the pressure remains constant or is diminished. The flow then continues with gradually diminishing velocity until the reservoir is well depleted, when the ice-mass returns to its inert state. The annual overflow from a glacier cirque does not correspond to the annual accretions; but the snow keeps on accumulating for several years as a rule, until sufficient pressure is reached to inaugurate a strong and rapidly accelerated forward movement. A conspicuous advance of the glacier front results, which does not stop until the cirque is drained to a lower level."

In a lecture to the Norwegian Polar Club, Oslo, early in 1952, O. Liestöl expressed the same opinion. Glaciers have a tendency to establish time variations of their own that are more or less independent of climatic factors. Over a long period of time a surplus may be built up in the accumulation area, while the lower part of the glacier concurrently wastes away until the frictional limit is exceeded, and the ice slides forward. Such a condition, he says, is most evident in polar and subpolar glaciers and, it may also be added, is especially applicable to glaciers whose accumulation areas are situated on plateaus high above the valleys constituting their main ablation areas. Such are the Spitsbergen glaciers, which, moreover, mostly terminate in floating tongues in fiords.

For the great majority of glaciers there is obviously a greater or lesser time lag between the beginning of a climatic fluctuation and the ensuing marginal variations. Hence it is very unlikely that variations in length of a glacier are strictly comparable with short climatic fluctuations, as, for example, an 11-year sun-spot period. The reactions of different glaciers to climatic fluctuations extending over considerable periods—several decades or centuries—may, on the other hand, reach their climax at about the same time, provided that the physical structures and morphology of the glaciers are not too different.

GLACIER REGIME IN SWEDISH LAPLAND, 1941–1952

For diagnosis of the "health of a glacier" Wallén from 1941 to 1948 carried out systematic studies on the small

Kårsa Glacier (2 sq. km.; see Pl. IA). Since 1946 similar but more detailed investigations have been carried out by Schytt and Woxnerud on the Stor Glacier (3.3 sq. km.; see Pl. IB) on the highest mountain range of Sweden, Kebnek-

TABLE II—REGIME OF THE KÅRSA AND STOR GLACIERS

Kårsa Glacier (68° 20′N., 18° 20′E.; alt. 820–1440 m.)

Budget Years	Accumulation	Ablation	Def. (—) or Sur. (+)	Def. or Sur. per km.²	Alt. of Firn Line	Retreat of Front
	Million cubic meters of water				*Meters*	*Meters*
(1941–42	2.3	3.8	−1.5	−0.8	1350)	6.5
1942–43	3.7	4.0	−0.3	−0.15	1150	
1943–44	3.9	3.9	0.0	0.0	1100	3.0
1945–46	3.5	4.3	−0.8	−0.4	1250	10.0
1947–48	3.6	3.2	+0.4	+0.2	1050	6.0
1948–49	—	—	—	—	—	4.0
1949–50	—	—	—	—	—	5.0
1950–51	—	—	—	—	—	
Total	17.0	19.2	−2.2	−1.35		34.5
Mean 1942–43 to 1947–48	3.7	3.9	−0.2	−0.1	1150	

Stor Glacier (67°50′N., 18°30′E.; alt. 1080–1700 m.)

Budget Years	Accumulation	Ablation	Def. (—) or Sur. (+)	Def. or Sur. per km.²	Alt. of Firn Line	Retreat of Front
1945–46	3.5	5.5	−2.0	−0.6	1480	15
1946–47	3.2	9.6	−6.4	−1.9	1600	20
1947–48	4.5	4.5	0.0	0.0	1450	22
1948–49	6.9	4.1	+2.8	+0.8	1410	14
1949–50	4.4	8.4	−4.0	−1.2	1550	19
1950–51	2.5	4.5	−2.0	−0.6	1500	15
1951–52	ca. 2.7	ca. 3.2	ca. −0.5	−0.15	1460	15
1952–53	4–5	—	—	—	—	—
Total	27.7	39.8	−12.1	−3.6		120
Mean	4.0	5.7	−1.7	−0.5	1493	17

ajse.[18] The glacier regime, or material balance, is determined for each "budget" year. A budget year begins in the autumn, when the accumulation first exceeds ablation at the firn limit; it thus extends from the first snow fall of winter through the ablation season of the following summer.[19] By regime is meant the total accumulation volume through one accumulation season minus the net ablation during the following melting season, expressed in terms of water.

Preliminary results from the Lapland projects are shown in Table II. The values for the Stor Glacier are based on about 10,000 measurements.

Total accumulation and ablation have varied considerably from one year to another. On the Kårsa Glacier the balance between them was negative three years, positive one year (1947–48), and balanced in one (1943–44). The sum total for the five budget years shows a net deficit of 2.2 million cubic meters of water, or 0.1 million a square kilometer a year. The corresponding figures for the Stor Glacier were five years with negative regime, one with positive and one with balanced; the total deficit for these seven years was 12.1 million cubic meters or 0.5 a square kilometer a year.

The retreat of the termini of both glaciers was continuous and proportional to the regime. The regime of the Stor Glacier, it may be added, is representative of the 16 small glaciers lying in the same massif. The highest peak of the Kebnekajse Range is covered by a small glacier that accurate measurement[20] has shown to vary in height with the regime of the Stor Glacier. In 1950 this highest point in Sweden was 2117 meters above sea level.

It is important to note that the significance of the air temperature to the glacier regime is determined in particular by its variations around freezing point. It makes no appreciable difference to the majority of temperate glaciers if the winter is more or less cold, whereas the amount of melting during the ablation season is of the utmost consequence. High spring and autumn temperatures prolong the ablation period, high summer temperatures intensify it.

The negative regime, the thinning, and the retreat of the Stor Glacier during the seven years in which it has hitherto been observed, is a continuation of its behavior during the preceding decades. Since 1908 it has been characterized by recession; concurrently there has been a rise in the spring, summer, and especially autumn temperatures in Lapland.

THE RECENT GLACIER RECESSION

Most glaciers in both northern and southern hemispheres are known to have been receding more or less rapidly for several decades. This, "the recent glacier recession," is exemplified by the curves (Fig. 2) showing the variations of glacier termini in some of the best known areas: Scandinavia,[21] Iceland,[22] the Alps,[23] and parts of North America.[24] Large glaciers have become smaller (Pl. II), small ones have disappeared completely or have become dead ice.

I will mention some few examples from the Arctic. Most of the outlet glaciers of the Greenland inland ice have been in recession for several decades.[25] Fröya Glacier (74° 24' N., 20° 50' W.) on Clavering Island in northeast Greenland, a local glacier with well-defined boundaries, was in-

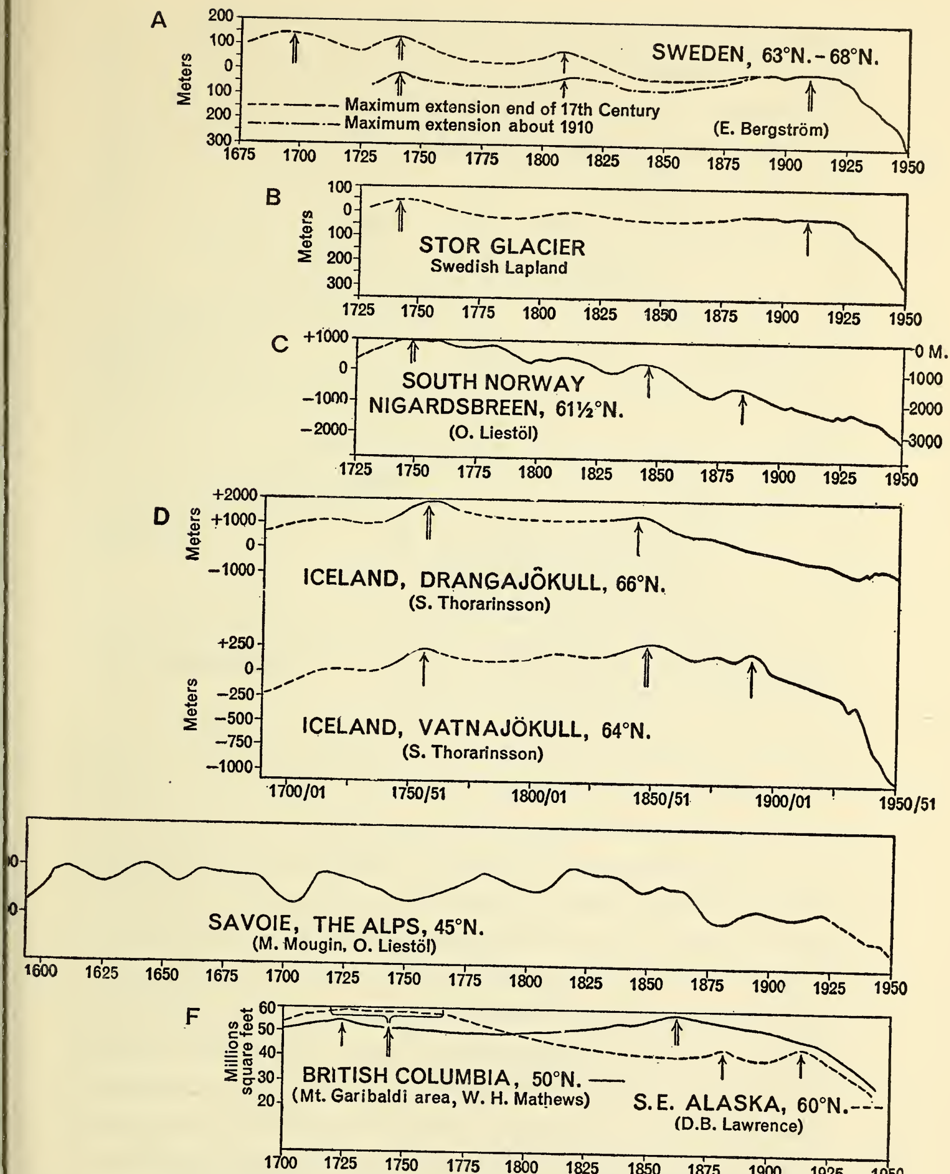


FIG. 2—Curves showing the variations of glacier termini. For details on construction of the curves see footnotes 21, 22, 23, and 24.

vestigated in 1939–1940, the position of the snout was measured again in 1947 and in 1952.[26] It has continuously receded in a manner which may be said to be representative of the recent glacier behavior in that part of the Arctic.

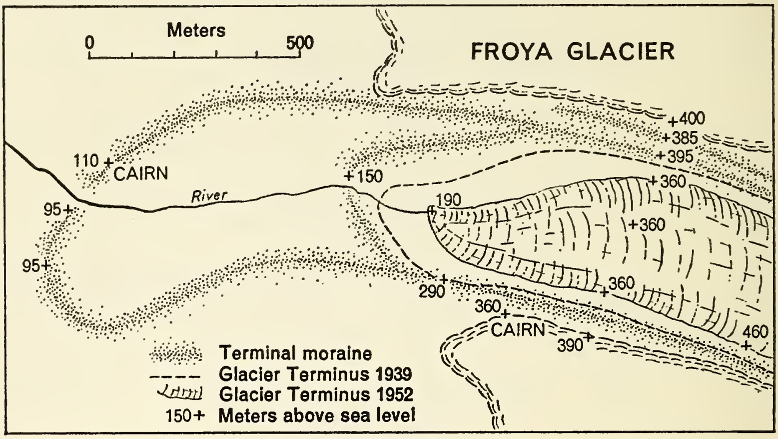


FIG. 3—The snout of Fröya Glacier, Northeast Greenland (74° 24′N.), in 1952. with terminal moraines indicating its maximum extension, probably in about 1750. The dashed line is the terminus in 1939.

On the basis of sketch maps and photographs taken in these years Swithinbank concludes that the snout had receded 75 meters between 1939 and 1947 and a further 50 meters up to 1952 (Fig. 3); this retreat, however, represented a decrease of only about 2 per cent in the total area of the glacier. There was a corresponding thinning of the ice even at altitudes well above that of the snout; for instance, at 450 meters above sea level the glacier surface in 1952 was about 15 meters lower than in 1939. The active bulging tongue that formed the snout when the older photographs were taken had completely disappeared by 1952, leaving only a smooth, partly moraine-covered front of a type more characteristic of a dead ice mass.

The Chr. Erichsen Glacier, a special high-polar type in Peary Land investigated by the Danish Expedition, 1947–1950, and described by Fristrup, had a negative regime and was receding. A great part of the tableland around the glacier gives the impression of having been only recently laid bare. The Barnes Ice Cap on Baffin Island[27] showed a small deficit for the budget year 1949–1950, that year not being greatly different from the normal during the previous decade. Photographs taken in 1934 and in 1950 show only a barely perceptible thinning in its lower section.

It has already been mentioned that in Spitsbergen conditions are in many respects peculiar. A summary prepared for me by Liestöl, points out that glacier snouts that have receded over a hundred years or so, suddenly begin a rapid advance, sometimes reaching as far as the outermost recent terminal moraines. Every glacier has its own period of variation, which is, however, dependent on the more pronounced climatic fluctuations and changes. Measurement of the position of the glacier terminus alone cannot give satisfactory knowledge of the relation between its variations and the climate. It is necessary to investigate the whole glacier. The Finsterwalder Glacier in Van Keulen Fiord, Bell Sound, West Spitsbergen, has recently been the subject of comprehensive studies of the kind needed. In the district south of Bell Sound the total volume of ice in the glaciers was more or less unchanged from 1920 to 1936. The Finsterwalder Glacier itself decreased in volume between 1936 and 1950 and showed a strong negative budget in 1950–1952, mainly because of exceptionally scanty accumulation.

Thorarinsson's map (Fig. 4) of two glaciers in southern Iceland, Breidamerkurjökull and Hrútarjökull, supplements the curve showing the oscillations of Icelandic glaciers (Fig. 2D). The present position of the termini should be about the same as it was in the last part of the

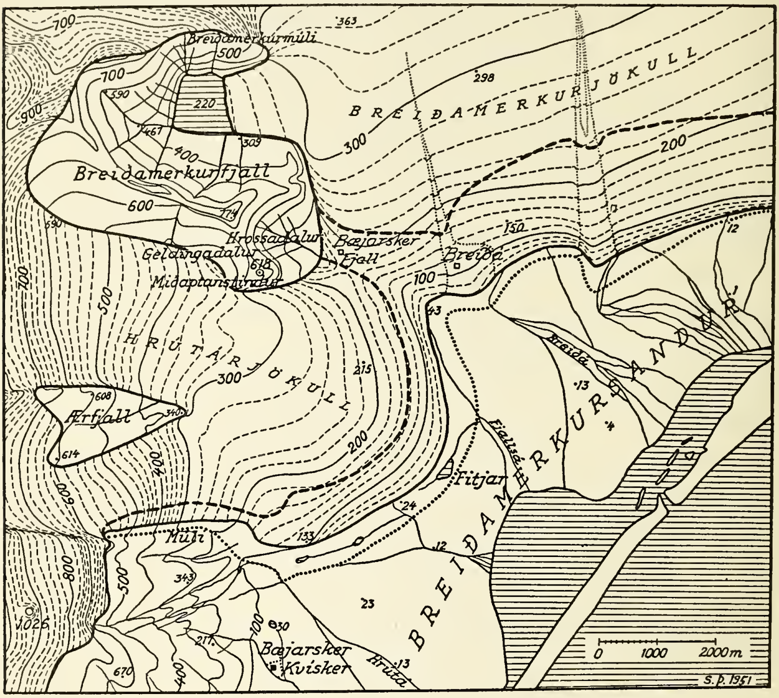


FIG. 4—The termini of Breidarmerkurjökull and Hrútarjökull in southern Iceland. The glacier front in 1904 (continuous line) is according to the Danish General Staff; position in about 1850–1890 (dotted line) is based upon the terminal moraines; position in 1950 (dashed line) is according to a survey by the Durham University Iceland Expedition.

17th century; they are much more advanced than in the time of the Sagas (A.D. 870–1264).[28]

Before turning to North America the recent general recession of European glaciers may be noted in summary. A list of measured glaciers for 1947–50[29] shows the following per cent in retreat in 1947–1948: French, 100; Swiss, 77;

Italian, 98; Austrian, 89; Swedish and Norwegian, 97; Icelandic, 88. In total, of 262 measured glaciers 88 per cent were in retreat, only 6.5 per cent advancing. For 1949–1950 the figures are: French, 93; Swiss, 99; Italian, 96; Austrian, 100; Swedish and Norwegian, 91; Icelandic, 67. In total, of 318 measured glaciers, 96 per cent were in retreat, 3.5 per cent advancing, 0.5 stationary.

Our knowledge of the oscillations of the North American glaciers[30] rests partly on old descriptions and photographs and on tree-ring studies and partly on systematic measurements. Conditions in different regions sometimes differ greatly because of morphological and other causes, as I have already mentioned. Moreover a large number of glaciers in Alaska end in fiords and are thus in the same class as the Spitsbergen glaciers with their anomalous variations.

Reference should be made here to two important systematic investigations—the Arctic Institute of North America's project "Snow Cornice," located on the Seward-Malaspina Glacier System on both sides of the international boundary line in the St. Elias Mountains, and the Juneau Ice Field Research Project of the American Geographical Society, supported by the Office of Naval Research. Both have as a common object to help in putting American glaciology on a dynamic and qualitative base.

On the general situation D. B. Lawrence has this to say:[31] "The glaciers emanating from the southern part of the Juneau Ice Field . . . seem to have advanced in unison to a maximum some time in the early or middle eighteenth century, which surely had not been exceeded since before the 1300's, and from which recessions of 1.3 to 5 miles beginning by 1765 at the latest subsequently occurred. The same chronology has been reported from Glacier Bay, Alaska, from Garibaldi Park, British Columbia, from Mt. Hood, Oregon, and even from Norway and Iceland."

In Alaska the behavior of the glaciers has been more heterogeneous than in most other parts of the world.[32] As Matthes earlier pointed out "in a region of such marked topographical diversity as Alaska, it is to be expected that some glacier basins will respond more quickly than others, and on a different scale, to a given change in climatic conditions." Concerning the immense recession in Glacier Bay—over 60 miles since the 18th century, of which 16 have been since 1892—I am of the opinion that the most noteworthy fact is the advance of the glaciers in the eighteenth century rather than the recession which followed. The climate in the lower parts of Glacier Bay district, where the ice has thinned out and from which it has retreated, is not suited to the survival of great ice masses. Even during a climate more favorable to glaciers than that of the present time, ice transported to the lower parts of the region must melt away more or less rapidly. The problem to be solved is the reason for the catastrophic advance of the glaciers which covered these areas with such a thick sheet of ice. The recession in Glacier Bay cannot be taken as evidence of the importance of the present climatic fluctuation. On the other hand, the glacier advance in the eighteenth century points towards the probability of there having been a climate favorable for glaciers during the preceding centuries. The present advance of Taku, while all other outlet glaciers of the Juneau Ice Field are receding, has attracted attention. Perhaps Matthes' claim of "an upward shift of the zone of maximum snowfall" has actually taken place in some sections of Alaska.[33]

A summary, prepared for me by William O. Field, Jr. in the spring of 1952, gives glacier variations in recent years in that part of North America lying south of Alaska. It makes clear that the rate of recession of several glaciers has decreased appreciably, or has even changed to an advance paralleled by a thickening of the ice. The turning point in some cases occurred about 1945.[34] The renewed activity of these glaciers has been intensified rather than diminished during the last two seasons (1951 and 1952) in spite of their exceptional melting. The behavior of Nisqually Glacier and the other glaciers of the same type is dependent on the relation between snow and ice sources in their upper parts and the melting of their lower parts.[35]

Even if the times of maximum glacier extension in different parts of the world have differed slightly, there is a striking resemblance in the general trend of variations in Europe and North America. Comparing the results of budget studies in Lapland and Alaska we find a close parallel in glacier behavior and temperature development. The 1948–1949 budget year, which had a strongly positive regime, was clearly marked in both. The size and composition of the accumulation area on the Seward Glacier also gives evidence of a close parallel in other years.

And though the data from other parts of the world is less complete, there are nevertheless signs that the marginal variations of glaciers have been more or less concurrent in recent centuries all over the world.[36] The ice fields on the large extinct volcanoes of Central Africa have diminished greatly.[37] Old terminal moraines in front of the present glaciers show that they have been much larger in relatively recent times. From the post-glacial maximum extension their retreat appears to have been interrupted by periods of stagnation and advance. The recession of some was greater after 1930 than it was in the period 1900–1930. At present, however, the Ruwenzori glaciers seem to be in a rather stable condition; accumulation normally exceeds ablation, keeping them well nourished.

More or less definite glacier retreats have been reported from Asia Minor,[38] South America (especially Chile[39]), and also from New Zealand.[40] From the Antarctic we have Schytt's observations from Queen Maud Land in 1950–1951. They indicate that at present a state of equilibrium exists between nourishment and outflow of the inland ice, and that the ice cover has not thinned during the last decades.

THE PRESENT CLIMATIC FLUCTUATION

As to the present climatic fluctuation, I should like first to refer to some comprehensive studies, in particular to Leo Lysgaard's "Recent Climatic Fluctuations" and H. C. Willett's "Temperature Trends of the Past Century."[41] The numerical values on Figure 5 are in tenths of a degree Fahrenheit for the last 20 years, winter temperature change centered to 1930. It is of particular interest to note that the temperature rise has been most pronounced in the northern hemisphere, where it increased with the latitude, the rise reaching its maximum values in Spitsbergen (Fig. 6) and in Greenland. No counterpart is indicated in the higher latitudes of the southern hemisphere. We must remember, however, how scattered and temporary the observations have been and still are in the Antarctic. Speaking generally, the difference between the sum-

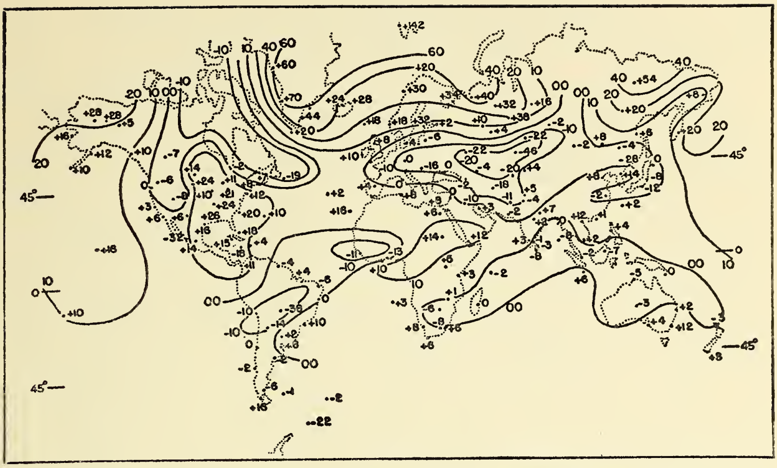


FIG. 5—Twenty-year changes of the mean winter temperatures centered on 1930. The numeric values in tenths of a °F. (After H. C. Willett, see footnote 41).

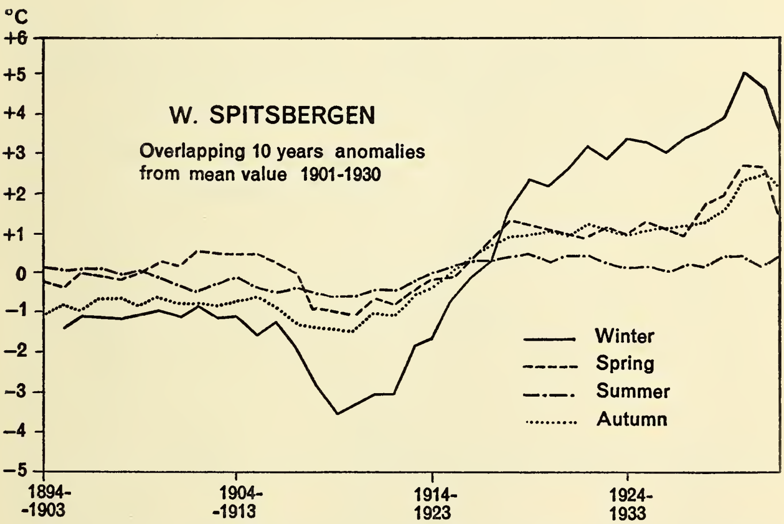


FIG. 6—Seasonal mean temperatures in West Spitsbergen (78° N.). Overlapping 10-year anomalies from the mean value 1901–30.

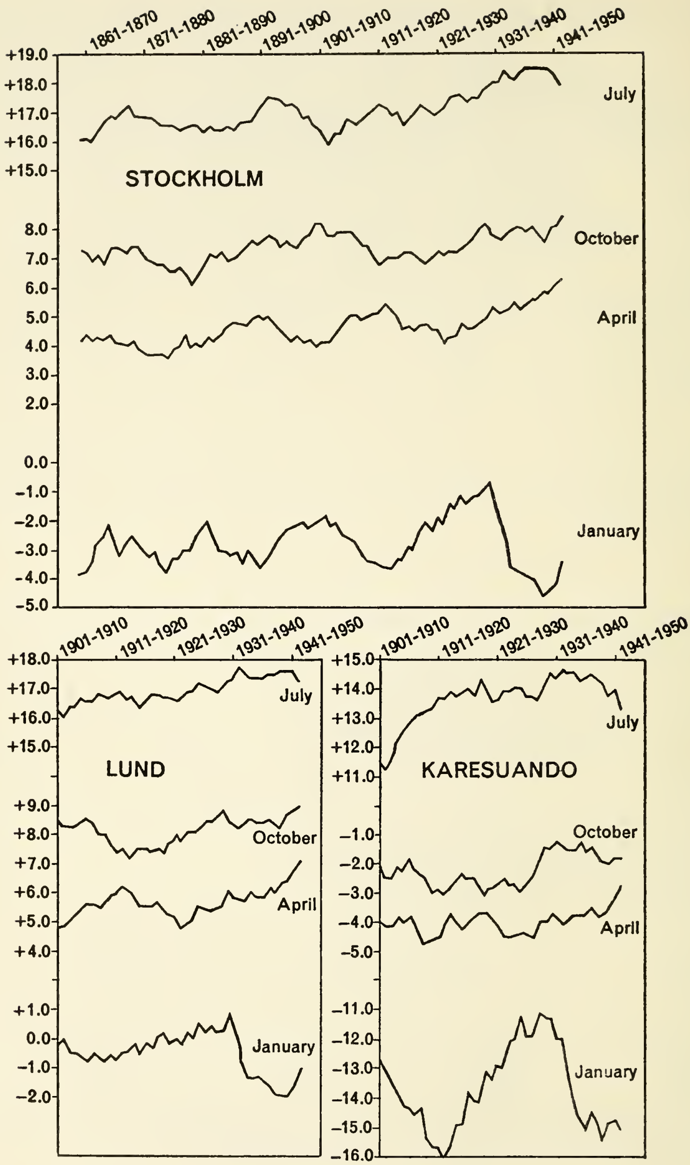


FIG. 7—Seasonal temperatures at Swedish stations plotted in 10-year overlapping means: Stockholm (59° 20′N.); Lund (55° 40′N.); Karesuando (68° 20′N.).

mer and winter temperatures became smaller up to the 1930's, or in other words, up to that time the climate had shown a definite tendency to become more maritime.

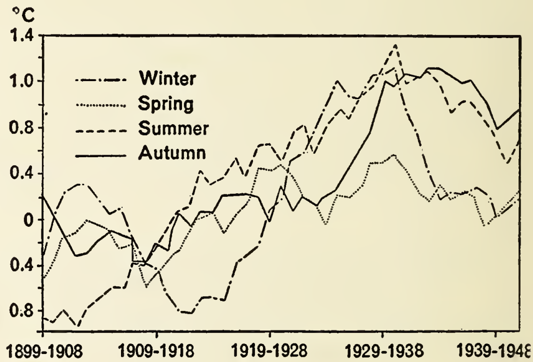
This is fully confirmed by the curves published by the late A. Labrijn[42] showing the difference between the mean temperature of July and that of the preceding January, in 14 places throughout Europe, for the period from 1750 until 1945. The same trend was clearly marked in Leningrad, Stockholm, Edinburgh, and Lancashire (England). Since the 1930's however, it has been reversed. It is worth noting that Paris, Prague, Vienna, and Budapest do not show a parallel tendency before the 1930's but since that time the reversed trend (i.e. towards a more continental climate) has been prominent. Moreover, most other places, and even subpolar regions, provide evidence that *the present climatic improvement culminated during the 1930's or 1940's.*

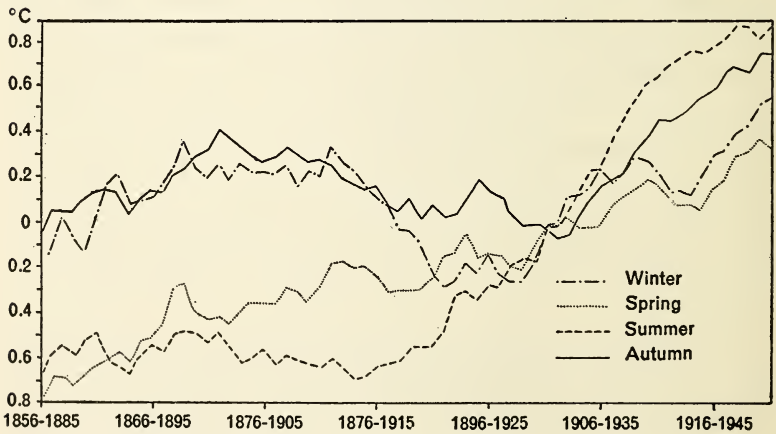
Curves giving ten-year overlapping mean temperatures from several stations in Sweden (Fig. 7) show that the increase in winter temperatures ceased with the 1930's and was succeeded by an equally clear decrease. At some stations the January temperatures in the latest decade are lower than they have been at any time since the turn of the century. In Stockholm they have not been lower since 1860. Of course the remarkably cold winters of 1940, 1941, and 1942 play an important part in this decrease; yet even if overlapping means are calculated on the assumption that those winters had normal temperatures, a definite decrease is revealed.

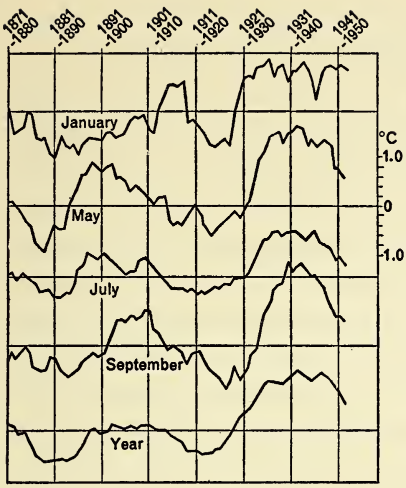
However, spring and even more autumn temperatures are still rising. In some parts of Sweden summer temperatures also are rising, in other parts the maximum has already been reached. It is particularly evident that the rise of summer temperatures in the glacier regions of northwestern Scandinavia has culminated. At Karesuando and at Tromsö (Fig. 8), for instance, July temperatures show continuous decrease since 1930–1939. In southern Sweden, in Lund and Stockholm for example, the maximum was reached only a few years ago or has not yet been reached. The annual mean temperature is still showing a rising trend.

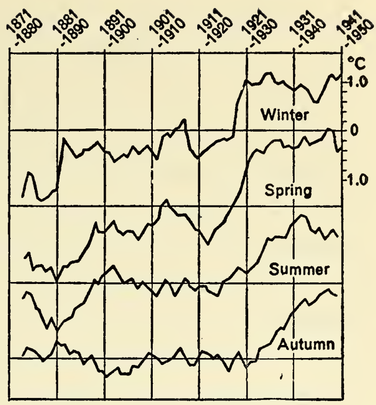
FIG. 8—Seasonal temperature anomalies from the 1901–30 mean value at Tromsö, Norway (66° 40′ N.).

On the right 10-year overlapping anomalies; below, 30-year overlapping anomalies. Notice the great difference between the two groups of curves.









FIGS. 9 and 10—Overlapping 10-year temperature anomalies in Iceland from the mean value 1901–30. Figure 9 (left) is for Reykjavik. (64° 10′ N.); Figure 10 (right) is for Grimsey (66° 30′ N.).

At Reykjavik in Iceland (Fig. 9) the climatic improvement culminated in the 1940's and was succeeded by a deterioration, particularly in spring and autumn temperatures. But winter and average annual temperatures are still much higher than they were in the years preceding 1925–1930. The high temperatures recorded since 1890–1900 in all seasons at Grimsey on the north coast (Fig. 10) are still being maintained.

In the United States the decade 1941–1950 seems to have been characterized by lower temperature and increased precipitation in comparison with the decade 1931–1940.[43]

From many points of view—both scientific and practical—it is thus of great importance that we should follow, carefully and systematically, the climatic developments of the near future. This applies especially to the polar and subpolar regions.

CAUSES OF THE RECENT GLACIER RECESSION AND THE PRESENT CLIMATIC FLUCTUATION

REMOVAL

The coincidence in time of the recent glacier recession and the present climatic fluctuation suggests a causal connection between them. I have come to the conclusion that increased ablation, consequent upon the increase in temperature, has played the fundamental role in the recession of glaciers around the northernmost Atlantic. I also find it probable that the rise in spring and autumn temperatures, i. e. the lengthening of the ablation season, has been of particular importance. As I have said before,[44] "The great shrinkage and recession of the glaciers is to a preponderating extent due to an increased transfer of heat through the atmosphere by a strengthening of the winds carrying heat from southern parts to the Arctic." The discussion about the meteorological causes of the present climatic fluctuation that is still going on has for the most part supported this general thesis.

Twenty-five years ago Wagner explained the current climatic fluctuation by increased general atmospheric circulation with an increased exchange of heat and other atmospheric elements between northerly and southerly latitudes.[45] More recently B. E. Eriksson[46] found the most important feature of this fluctuation over the northernmost Atlantic to be a change in the pressure gradient causing an increased flow of warm air into northern latitudes. Willett[47] introduced the terms "high-index" and "low-index" to characterize two quite different types of circulation in the middle latitudes. With the "high-index" circulation cyclones move in winter in a strong zonal flow on fairly northern tracks from the Atlantic towards northwestern Europe giving mild southwesterly to westerly winds. The "low-index" circulation is characterized by a meridional flow pattern with the winter cyclonic tracks shifted southward giving cold easterly and northeasterly winds over most of Europe. However, Petterssen[48] has shown that "a warming up of northern latitudes in winter during the 1930's has been connected with a development towards another type of 'low-index' circulation pattern where the zonal components are also weak and the north-south components dominate." Instead of an increased zonal flow over northwestern Europe there has been a more meridional type of flow pattern giving rise to an increase in the northward transport of air from southern and eastern Central Europe towards Scandinavia; and simultaneously an increased northward transport of air from the eastern Atlantic towards Iceland and the Norwegian Sea.

Partly in contradistinction to my own opinion is Wallén's belief[49] that the most important cause of the retreat of the Kårsa Glacier during the last decades—and probably of other glaciers in Scandinavia—has been the rise of the summer temperature,[50] with prolongation of the ablation season of secondary importance. Wallén says:[51] "The essential cause for the regression and shrinkage in recent decades has been the increase for the heat supply from the air conveyed by convectional, conductional and condensational processes . . . there has also been a definite rise in the moisture content of the air . . . and it is likely that the average wind-velocity has increased." In an article in preparation Wallén shows that the increase of southerly winds towards northern Scandinavia and the Arctic during the last 40 years is true not only for winter, as Petterssen pointed out, but also for summer. Referring to Petterssen's interpretation he concludes: "The increased general circulation in recent decades has given rise to an increased exchange of air between north and south over the Atlantic-European sector of the hemisphere. Both in winter and summer there has been an increased frequency of winds with a southerly component with a corresponding increase in temperature, humidity and cloudiness but giving no appreciable increase in winter precipitation."

The "blocking-action" over western Europe[52] which has occurred quite often during recent decades and which has given rise to warm southerly and southwesterly winds over Scandinavia may well have contributed to glacier retreat.

The opinion seems to be gaining ground among meteorologists that both brief fluctuations and long-range changes of climate, including the Pleistocene glaciations, are of the same general character and are ultimately dependent upon solar variations. In an article on the general circulation of the atmosphere Petterssen[53] points out "that the radiative processes, in tending to establish radiative equilibrium, create dynamic instability which gives rise to meridional circulations that contribute to the exchange of heat and atmospheric properties." He emphasizes the importance of mountain ranges, inland water bodies, etc. in the formation of local circulation systems. A large-scale statistical analysis of the behavior patterns of cyclones and anticyclones in the northern hemisphere during the period 1899–1939 shows agreement between his theoretical results and existing conditions, thereby giving scientific support to the old ideas of the importance of mountain chains and orographically active epochs to the climate in past ages.[54]

Petterssen's circulation models for the lower part of the troposphere in the northern hemisphere reveal an even greater similarity in the dynamic-meteorological and climatological character between Alaska and western Scandinavia than has been presumed earlier. D. E. Martin, in an unpublished communication, confirms this by showing that positive and negative anomalies of the 700 millibar surface over Scandinavia are more directly related to similar anomalies in the Alaskan-Aleutian region than they are to anomalies elsewhere.

Willett in his study of temperature trends has gone a step further. He maintains that changes in the ultraviolet part of the solar spectrum are not only causing the present climatic fluctuation but have also caused the great and small climatic changes of the past. Time will show whether his theory survives better than its predecessors. His idea has the advantage over most others in that the ultraviolet solar radiation varies more than the total radiation of energy. According to Willett, the present amelioration of the climate has now come to an end, and the temperature will fall for the next 10 or 15 years, reaching a minimum between 1960 and 1965.

Whatever the future may bring, we are justified in saying that of the endless series of climatic fluctuations that have occurred from the beginning of the earth and that will continue in the future, the present one is the first that we can measure, investigate, and possibly explain.

CHANGES IN ARCTIC DRIFT ICE AND IN ANIMAL AND PLANT LIFE

The thickness of the ice forming annually in the North Polar Sea has diminished from an average of 365 centimeters at the time of Nansen's *Fram* expedition of 1893–

96 to 218 centimeters during the drift of the Russian icebreaker *Sedov* in 1937–40. The extent of drift ice in Arctic waters has also diminished considerably in the last decades. According to information received in the U.S.S.R. in 1945, the area of drift ice in the Russian sector of the Arctic was reduced by no less than 1,000,000 square kilometers between 1924 and 1944. The shipping season in West Spitsbergen has lengthened from three months at the beginning of this century to about seven months at the beginning of the 1940's. The Northern Sea Route, the North-East Passage, could never have been put into regular usage if the ice conditions in recent years had been as difficult as they were during the first decades of this century.

The same influences that have affected the drift ice have affected the animal life of the North Polar Sea. Various kinds of fish, especially cod, have migrated northwards. Now for the first time cod is available to many Greenland Eskimos who previously had to rely on seal for food.[55] In a speech five years ago the Danish Prime Minister said: "In the last generation changes that have had a decisive influence on all social life have occurred in Greenland. A new era has begun. These changes are primarily due to two circumstances. Firstly, the Greenland climate has changed, and with it Greenland's natural and economic prospects."[56]

On the other hand, herring catches off the north coast of Iceland have greatly diminished in the last seven years, possibly because of changes in the sea currents connected with the present climatic fluctuation. Herring has become an open sea fishery; its 1952 season was extended to November instead of ending as usual in August.

It is such phenomena that caused the International Council for the Exploration of the Sea to adopt the following resolution at its meeting in Denmark in 1948: "Having considered a number of lectures on climatic fluctuations, the Council recommends that these important and far-reaching problems ought to be more closely investigated, and that these investigations might be adequately supported by the Governments in the different countries."[57]

Many land animals in northern Europe and Asia are now ranging farther north than before. The migration seems to have begun slowly at the end of the eighteenth century, but has been greatly accelerated since 1910. Birds in particular have reacted quickly and markedly to the present climatic fluctuation. According to a report I have recently received from C. Edelstam of Stockholm, careful observation shows that about 25 per cent of all North-European bird species have taken part in this movement. The causes are two-fold: throughout the northern regions winters have been milder and springs warmer. At the same time lakes and bird-feeding grounds in large parts of Africa and southwest Asia have dried up. As a result, southern species dependent on shallow eutrophic waters are strongly represented in the migration.

Effects of the present climate fluctuation are seen to advantage in Finland, a country of marginal location. On the initiative of I. Hustich, the Geographical Society of Finland has just published a symposium on the phenomena,[58] studied from a biological and biogeographical point of view and embracing effects on forestry, agriculture, fishing, and hunting.

In the first place, it has been observed that the freezing period in the Baltic decreased during the 120 years before the 1930's, after which a return to a longer freezing period began. This later climatic deterioration culminated in the beginning of the 1940's. Since then there has been a rise in winter temperature, resulting in a longer navigation period.[59]

Floristically there has been a distinct shift towards earlier flowering and earlier ripening of berries and other seeds, and towards later defoliation. Ranges of plants and trees have expanded northwards, with attendant disturbance of species equilibrium in the plant communities.

Effects on the coniferous forests are of particular interest. Between 1910 and 1920 the average annual ring index increased in all parts of Finland, especially in northern districts. Analyses of annual rings, which date back over 200 years, show scarcely any other period as favorable as the 1920's. The significance of the change in climate, particularly of the higher temperatures, is even more clearly indicated by the northern timber line. About 40 years ago the outlook for the northernmost pine forests was rather poor, as there had been no seed years there since 1850. Now, almost all age classes are represented in the seedling stands (Pl. III A).

Hustich himself shows the importance of the climatic factor in the increase in the yield of rye, the commonest cereal, in the period 1921–1939.

Birds have reacted in the same general manner noted for northern Europe as a whole. In Finland many species of mainly northern distribution have become scarcer at their southern limits, and the accidental species found in 1880–1941 have mainly been newcomers from the south.

Contributions from other countries have been limited to specialized studies and scattered observations. I think, however, that in Sweden and Norway the effects may on the whole be said to be similar to those in Finland. A critical analysis of the very extensive Swedish material on annual rings in pine and spruce, though not yet complete, justifies the statement that the present climatic fluctuation with its consequent prolongation of the growing season has probably helped towards the gradually increasing yield of the Swedish forest, as B. Eklund of the State Institute of Forestry Research has described in correspondence with me.

Changes in the vegetation, as in Finland, are more marked in the far north, for instance, in the Abisko National Park (68° 20' N.), undoubtedly because there the temperature has on the average risen more than in southern Sweden. Peat hummocks containing ice, the so-called *palses,* a typical subpolar phenomenon, have been destroyed by melting of the ice.[60] The timber line for mountain birch has risen about 20 meters during the last decades and the surrounding vegetation has extended and become much richer (Pl. IV), especially during the 1940's; partly, it seems, because of the earlier disappearance of the snow cover and the quicker drying of the soil. Sparse pine stands that formerly averaged only one new generation a century have added several new generations since the 1920's. During the 1930's in particular, regeneration was unusually rapid.[60]

An investigation into the water economy of eight catchment areas in various parts of Sweden from 1920 to 1947 shows that evaporation has increased markedly since about 1930.[61]

In most parts of Norway, as in Sweden, the timber line has risen during the last decades. Among the several causes are the reduction or discontinuance of lumbering in the uppermost parts of the birch and coniferous belts and the reduction of grazing and reindeer keeping. All students of the problem agree, however, that an improving climate has played an important part in accentuating the consequences of such cultural conditions, most especially in northern Norway.[62]

In a recent communication, R. Sögnen, of the Norwegian Watercourse and Electricity Board, points to an unfortunate effect that might follow continuance of the present trend. Continued and rapid recession of glaciers might prove fatal to some of the Norwegian power generating stations, for it would reduce the quantity of water which the ice has stored for centuries and upon which the stations partly depend for their supply.

The present climatic fluctuation has been even more marked in Iceland than in the other Nordic countries and its influence on local plant and animal life is perhaps more apparent than in any other region. A few of the current and still continuing changes may be noted: The peat and ice hummocks, *rústs,* (same type as the *palses* of Lapland), which characterize the marshes, *flás,* in the interior of Iceland (Pl. III B), are gradually disappearing under the milder climate. The whole landscape, in fact, is changing.[63] There has been a rise in the lower *flá* limit; it corresponds with the northward recession of the southern limit of the Siberian permafrost zone. In this connection, attention may also be drawn to the so-called "oriented lakes"[64] of northernmost North America created by melting of the permafrost.

Because of Iceland's geographical position, elements of both southern and arctic faunas live there under peripheral conditions and react quickly to climatic changes. Seven new southern species of birds have begun breeding in Iceland within the last 50–60 years, there has been a considerable increase in the wintering of partly non-migratory species, and there has been a very noticeable increase in winter visitors and vagrants from the south. No less than 37 new species or subspecies of birds have been added to the Icelandic list since 1938, and at the same time some of the few arctic and high-arctic species have disappeared.[65]

THE PRESENT CHANGE IN THE SEQUENCE OF CHANGES

How then do the present climatic fluctuation and the recent glacier recession compare with conditions in earlier centuries and millenia? How do they fit into the progression since the melting of the Pleistocene glaciers?

The two curves of Figure 11 are plotted to illustrate our present conception of the sequence in Sweden[66] and Norway[67] from about 8000 B.C. to 1950 A.D. The glacier-variation scale is relative and the time scale logarithmic, in order to show clearly the recent centuries and decades of time, which are, of course, the best known. The third, dashed curve, gives the position of the firn or climatic snow line on Vatnajökull, Iceland, according to Eythórsson.[68]

In the lake district of south Sweden, and within the present coastal region of Norway, the waning inland ice re-expanded in about 8000 B.C. It subsequently retreated under the improving climatic conditions. The economic regime of the Ice Age, which year after year provided a surplus of snow, had long since been abandoned. The rest of its immense capital of ice was consumed by a milder regime, more favorable to mankind. The Climatic Optimum occurred between about 7000 B. C. and about 1000 B. C. In that epoch the firn line of Vatnajökull is estimated to have been at about 1400 meters above sea level. Studies

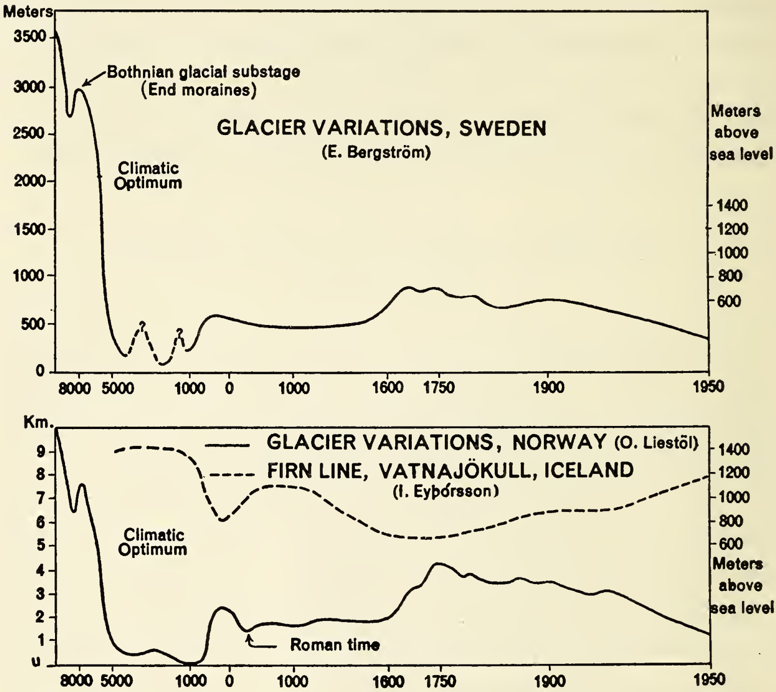


Fig. 11—The recession of the last Pleistocene inland ice from Sweden and Norway and the variations of the local Scandinavian glaciers during the last 12,000 years. For sources see footnotes 66 and 67.

of peat bogs in Sweden have shown that there were probably changes, in atmospheric humidity at least, in about 2300 and 1200 B.C. The subsequent deterioration of the climate culminated in about 500 B.C. and the firn line of Vatnajökull dropped to 500–600 meters. That climate still exists even if it has improved somewhat during certain times. There is no evidence in either Sweden or Norway of any glacier variations or climatic changes during the following 2000 years, except in the favorable Roman period (A.D. 0–400). We know, however, as has been mentioned before that from the first colonization of Iceland in A.D. 870 until about A.D. 1200 the glaciers were much smaller than they are now. The Vatnajökull firn line is calculated as having been at about 1100 meters at that time. From the latter part of the 17th century right up until the latter part of the 19th and the beginning of the 20th century, glaciers both in Iceland and on the continent of Europe were more extensive than at any time since the melting of the last remnants of the Pleistocene inland ice in the Scandinavian mountains. The Vatnajökull firn line dropped to its minimum. The recent glacier recession, which began earlier in some districts and later in others, has in the last few decades reduced the glaciers so much that they are now probably as small or even smaller than they were in Roman time. The Vatnajökull firn line has risen successively to its present altitude of about 1100 meters above sea level.

Thorarinsson's studies of the past and present cultivation of cereals in Iceland have shown that in recent years climate there has been at least as favorable, and probably even slightly milder than it was in the centuries immediately after A.D. 900, and it is warmer now than at any time since 1200.[69] According to Thorarinsson, the amplitude of the climatic fluctuation in Iceland has in all probability been greater since the 1880's than at any time since about 600 B.C.

It has already been pointed out (p. 18) that the present position of the termini of some glaciers in southern Iceland ought to be about the same as in the last part of the seventeenth century. They are however much more advanced than in the time of the Sagas (A.D. 870–1264). The position of the farms Fjall and Breidá (Fig. 4) is not known exactly but must have been close to that shown. They were probably built around A.D. 900, and cannot at that time have been in a dangerous position to a glacier front or to drainage of ice-dammed lakes. Yet Fjall was abandoned in 1695 and buried by the glacier in 1708. Breidá was a large farm until the fourteenth century, but in 1698 it also was abandoned and in 1702 the glacier front had almost reached it. Thorarinsson points out that the decline of Breidá is not only a result of the deterioration of the climate but also largely of the eruption of the volcano Öræfijökull in about 1360. It seems, he says, that this climatic deterioration had already begun in the thirteenth century, accelerated in the fourteenth, and culminated during the seventeenth to nineteenth centuries.

These conclusions from Iceland agree with some conclusions from Greenland. It is hardly possible that the climate of southwest Greenland could have been so severe when the Norse colony there was an independent society with about 300 farmsteads, 3000 people, and a surprisingly large number of cattle and sheep, as it was some decades later.[70] In 1921 excavations of the cemetery at Herjolfsnes yielded well-preserved clothing from about the year 1400.[71] Interment must have been in loose earth but preservation was possible because the ground was frozen soon after the interment.[72]

Concerning the Alps, Kinzl[73] has come to the conclusion that the glacier advance of the last 300 years is the greatest that has occurred since the Pleistocene Ice Age. "Those

300 years therefore," says Matthes,[74] "comprise a separate epoch of glacier expansion, a lesser ice age, that was preceded by a warm period of considerable duration." It is worth while reflecting that our modern machine culture was born and has grown up under climatic conditions even more unfavorable, certainly, than those which extended since Celtic time, i.e., since the Persian wars and Classical Greek time.

In large areas of North America, as has been mentioned before, a strong glacier advance attained its maximum in the first half of the 18th century. It also was the maximum state of advance since the twelfth century.

Matthes has characterized the period of the last 4000 years as "the little ice age." I am more inclined to say: *Regeneration of the glaciers began in about 500 B.C.; after some centuries of rapid increase growth was slower until the thirteenth or fourteenth centuries when it again accelerated and so far has reached its climax in most districts between the first half of the eighteenth century and about 1900.*

However, in front of some glaciers, for example some of Vatnajökull and Myrdalsjökull in Iceland, there are terminal moraines which might indicate that in early "subatlantic" time (the first centuries about the beginning of our era) these glaciers advanced a little further than during the last few centuries.[75] In front of several glaciers in the high mountains of Sweden there also is one morainic ridge just outside those representing the maximum extension about 1750 and much older. Similar examples occur in southern Norway[76] and in the central Alps.[77]

I have tried in this lecture to give you a brief outline of our present knowledge of recent glacier variations and the present climatic fluctuation, based chiefly on facts established in the Nordic countries and to a lesser extent in North America. I have also tried to project these phenomena against the background of what Scandinavian students consider the most likely progress of the melting of the inland ice and the most likely local glacier variations in the last 10,000 years. Our results are most certainly incomplete and in some, perhaps many, respects may prove to be erroneous. But in the treatment of these and of many other problems a new epoch is now opening before us. A few examples will suffice.

Its new-found geophysical basis has made glaciology better able to explain the reactions of glaciers to meteorological factors. We hope to be able to organize international cooperation for the purpose of getting accurate values of representative glacier regimes for elucidating glaciological-climatic development in the subarctic zone. The glaciers ought to be not too big but should be well defined. So far the following glaciers have been selected: Lemon Creek Glacier in southern Alaska (near Juneau), a glacier in the Tindfjallajökull group in southern Iceland, Stor Glacier in Jotunheim in southern Norway, and Stor Glacier in the Kebnekajse Massif, northern Swedish Lapland. If possible we want to include a glacier in northernmost Greenland. The investigations and measurements are planned to be of the same kind as those of Stor Glacier in Kebnekajse.

Improved statistical methods of analysis will eventually provide a more assured and detailed picture of long-range climatic fluctuations. New methods of age determina-

Pl. I A—Kårsa Glacier, south of Abisko Tourist Station in Swedish Lapland (68° 20′N.). Photo C. C. Wallén, 1948.

Pl. I B—Stor Glacier, Kebnekajse Massif, Swedish Lapland (67°50′N., 2117 meters above sea level). In the background the highest elevation, Sydtopp, covered by a small glacier. Photo G. Lundquist, August, 1951.

Pl. II A—Bukkhö Glacier, Jotunheim, Norway (61° 40′N.), 1949. The dotted line shows the glacier extension in about 1750. Photo O. Liestöl, 1949.

Pl. II B—Engabre Glacier, an outlet glacier from the Svartisen glacier cap, Norway (66° 40′), in 1949; in 1930 the glacier still covered most of the lake.

Pl. III A—Twenty-three year old and younger pines in the mountain birch forest at Enontekiö in Finland (68° 30′N.). Photo by P. Mikola, 1949.

Pl. III B—A mature *pals* (called *rúst* in Iceland), in a *flá* south of Hofsjökull Iceland (64° 30′N.); it is 600 m. above sea level, 10 m. long, and nearly 2 m. high. Photo by F. Gudmundsson, 1951.

Pl. IV A—Timber line on the eastern slope of Njulja, Abisko, Swedish Lapland (68° 20′N.), in 1937; B) in 1948. Photo G. Sandberg.

tion, notably by radiocarbon content, will in conjunction with continued paleobotanical research throw a new and stronger light on the climatic changes of the past thirty thousand years. The results of the Swedish Oceanographic Expedition of 1947–1948 promise to be of great importance to our understanding of the same phenomena throughout a much longer period of the world's history.

I have claimed your attention in order to sum up some of my thoughts on the state of our knowledge of snow, ice, and climate in selected areas of the world, as well as some scattered features of changes in the flora and fauna due to the present climatic fluctuation. I have done so not only because an account ought to be given of our observations and results, even though the conclusions may soon be out-of-date, but also—and of greater moment for this gathering—to direct your attention to the many relevant problems, and to stimulate continued work towards their solution by the newer and better methods which this constantly developing science brings forth. For climate, its changes and fluctuations, is, as Isaiah Bowman has said, a fundamental factor in physical geography and one of the most important influences on the phenomena to which human geography is devoting its attention.

FOOTNOTES

[1] Isaiah Bowman: Geography in the Creative Experiment, *Geogr. Rev.*, Vol. 28, 1938, pp. 1–19.

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[3] H. W:son Ahlmann: The Contribution of Polar Expeditions to the Science of Glaciology, *Polar Record*, Vol. 5, 1949, pp. 324–331.

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[5] Popular narratives of the expedition are: John Giæver: Maudheim: To år i Antarktis Oslo, 1952); John Giæver och Valter Schytt: Antarktisboken: Med Norsel till Maudheim och Antarktis (Stockholm, 1952). English and American editions will follow. Preliminary scientific reports are: E. F. Roots: The Norwegian-British-Swedish Expedition 1949–52, *Science News*, No. 26, Penguin Books, 1952, pp. 9–32; G. de Q. Robin: Measurements of Ice Thickness in Dronning Maud Land, Antarctica, *Nature*, Vol. 171, 1953, pp. 55–58; The Norwegian-British-Swedish Antarctic Expedition, 1949–52. I. Valter Schytt: Summary of the Glaciological Work; II. G. de Q. Robin: Summary of Seismic Shooting Investigations in Dronning Maud Land, *Journ. of Glaciol*, Vol. 2, No. 13, 1953, pp. 204–205; 205–213.

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[9] H. U. Sverdrup: The Scientific Results of the Norwegian-Swedish Spitsbergen Expedition in 1934, Part IV, The Ablation on Isachsen's Plateau and on the Fourteenth of July Glacier in Relation to Radiation and Meteorological Conditions, *Geografiska Annaler*, Vol. 17, 1935, pp. 145–166.

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[11] *Idem:* Influences Affecting Glacier Extension in Northern Sweden, *Union Géodésique et Géophysique internationale, Assoc. Internatl. d'Hydrologie Sci., Assemblée Gén. de Bruxelles 1951*, Vol. 1, Louvain, 1952.

[12] H. W:son Ahlmann and Sigurdur Thorarinsson: Vatnajökull: Scientific Results of the Swedish-Icelandic Investigations 1936–37–38, Chapter V, The Ablation, *Geografiska Annaler*, Vol. 20, 1938, pp. 171–233 (see also the *Geogr. Rev.*, Vol. 28, 1938, pp. 412–438); H. W:son Ahlmann: Vatnajökull, Ch. VII, The Regime of Hoffellsjökull, *Geografiska Annaler*, Vol. 21, 1939, pp. 171–188.

[13] Børge Fristrup: Climate and Glaciology of Peary Land, North Greenland, *Union Géodésique et Géophysique internationale, Assoc. Internatl. d'Hydro-*

logie Sci., Assemblée Gén. de Bruxelles 1951, Vol. 1, Louvain, 1952; *idem:* Danish Expedition to Peary Land, 1947–1950, *Geogr. Rev.,* Vol. 42, 1952, pp. 87–97.

[14] H. W:son Ahlmann: Scientific Results of the Swedish-Norwegian Arctic Expedition in the Summer of 1931, Part VIII, Glaciology, *Geografiska Annaler,* Vol. 15, 1933, pp. 161–216 and 261–295, reference on pp. 181–186 (Marginal Movements in the Spitsbergen Glaciers); *idem:* Scientific Results of the Norwegian-Swedish Spitsbergen Expedition in 1934, Part V, The Fourteenth of July Glacier, *ibid.,* Vol. 17, 1935, pp. 167–218.

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The Norwegian curve relates to the Nigardsbre, an outlet glacier from Jostedalsbre, which may be regarded as being representative of the glaciers of southern Norway. The values are plotted by O. Liestöl, of the Norwegian Polar Institute, from Knut Faegri: Über die Längenvariationen einiger Gletscher des Jostedalsbre und die dadurch bedingten Pflanzensukzessionen, *Bergens*

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22 The Drangajökull curve is based upon Jón Eythórsson: On the Variations of Glaciers in Iceland, I, Drangajökull, *Geografiska Annaler,* Vol. 17, 1935, pp. 121–136, and for later years on Eythórsson's measurement of four outlet glaciers from the ice cap, plotted together by Sigurdur Thorarinsson. The Vatnajökull curve is based upon Eythórsson's measurements of about 18 of the southern outlet glaciers on the ice cap, summarized to the year 1930, by Thorarinsson in Vatnajökull, Chapter XI, Oscillations of the Iceland Glaciers in the Last 250 Years, *ibid.,* Vol. 25, 1943, pp. 1–54, and after that year supplemented by him.

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[32] W. O. Field, Jr.: Glacier Recession in Muir Inlet, Glacier Bay, Alaska, *Geogr. Rev.,* Vol. 37, 1947, pp. 369–399.

[33] See also R. L. Nichols and M. M. Miller: The Moreno Glacier, Lago Argentino, Patagonia, *Journ. of Glaciol.,* Vol. 2, No. 11, 1952, pp. 41–50.

[34] See also P. D. Baird: Report on the Northern American Glaciers, *Union Géodésique et Géophysique internationale, Assoc. Internatl. d'Hydrologie Sci., Assemblée Gén. de Bruxelles 1951,* Vol. 1, Louvain, 1952. A. E. Harrison (personal communication) says that "the terrific recession characteristic of the twenties and thirties seems to have passed a climax."

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[50] G. H. Liljequist: On Fluctuations of the Summer Mean Temperature, *op. cit.*

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[52] D. F. Rex: Blocking Action in the Middle Troposphere and Its Effect Upon Regional Climate, *Tellus,* Vol. 2, 1950, pp. 196–211 and 275–301; Vol. 3, 1951, pp. 3–16.

[53] Sverre Petterssen: Some Aspects of the General Circulation of the Atmosphere, *Centenary Proc. Royal Meteorol. Soc.,* 1950, pp. 120–155.

[54] C. E. P. Brooks: Climate Through the Ages (rev. edit., London, 1949).

[55] Ad. S. Jensen and Børge Fristrup: Den Arktiske klimaforandring, *op. cit.*

[56] Hans Hedtoft: Grønlands Fremtid, *Det Grønlandske Selskabs Aarsskrift,* 1949, pp. 22–42. In a lecture at Oslo in February, 1953, Director P. Rosendahl of the Greenland State Department in Copenhagen pointed out that the principal reason for the new era in Greenland has been the present climatic fluctuation with the associated disappearance of the seals and the northern migration of cod.

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