CHAPTER 15

GLACIAL METEOROLOGY

Herfried C. Hoinkes

1. Introduction

In 1773, as most glaciers in the European Alps were at or near their maximum extension in historic times, it was stated for the first time by Walcher, after a visit to the advancing Vernagtferner in the Oetztal Alps, that glacier variations are caused by variations in climatic conditions [212]. In the same year Bordier [22] suggested the systematic control of glaciers, which was adopted on a wide scale only after the establishment of the International Commission of Glaciers in 1894. Together with the younger Commission of Snow, I. A. S. H. (Lisbon, 1933), the joint Commission of Snow and Glaciers (Washington, 1939) continued to encourage the permanent measurements of glaciers. Later (Oslo, 1948), the name was changed to Commission of Snow and Ice. At Helsinki in 1960 again "it was agreed that the commission shall undertake the permanent task of recording the variations of existing glaciers."

From about 1894 the changing length (but little else) of an increasing number of glaciers was kept under observation. For example, in 1957–1958 a total of 304 glaciers in Europe (including Iceland) had been observed, 93 per cent of which were retreating; in 1958–1959 the number was 247 with 91 per cent retreating [155]. Observations of this simple type give a very general summary of the behavior of glaciers but are of little use for a detailed analysis of glaciometeorological relations.

Much more valuable information can be acquired by repeated surveys of certain profiles or even better by photogrammetric surveys of certain glaciers, giving the volumetric changes for specific periods. Photogrammetric surveys were carried out during the IGY–IGC in different glacierized regions, for instance of several glaciers in the Eastern Alps [50], of the Aletschgletscher [97], of the Fedchenko Glacier in the North-West Pamir

[173], of the Werenskjold Glacier in Spitsbergen [107], of the Salmon Glacier, British Columbia [75], or of several glaciers in Alaska [16] and in the western United States [26]. The maps produced are invaluable documents for future studies. Comparisons with existing older maps (e.g., for the Aletschgletscher from 1926–1927 or for the Fedchenko Glacier from 1928) make calculations of the total ice loss possible. The accuracy achieved is sufficient for periods of several years, which again is of less interest for the purpose of detailed glaciometeorological analysis. For annually repeated photogrammetric surveys another difficulty arises, because the glacier surface consists to a varying portion of material of different densities, viz., old snow, firn, and ice. The deduced changes in volume are therefore not easily converted to changes in mass, even if the relatively small changes in the height of the whole glacier's surface from year to year could be determined with sufficient precision. Variations in height of specific parts of the glacier's surface are influenced by the vertical component of glacier movement, and are therefore not identical with the specific mass budget of that point [150].

Only the net mass budget of a glacier, specific or total, is clearly related to the climatic environment. Pioneering investigations of mass budget and heat budget were accomplished in different glacierized areas surrounding the North Atlantic Ocean by Ahlmann and collaborators since 1918. Ahlmann (1948) expressed the hope "that these investigations and their results will encourage further extensive and systematic research into the nature and causes of glaciers. For this research international cooperation is desirable" [4]. Only dilatorily studies in glacial meteorology were carried out in other parts of the earth, e.g., the Antarctic in 1949–1952 [128, 129, 182], the Alps beginning from 1950 [77], Baffin Island in 1950 and 1953 [162], Alaska in 1953–1954 [91], and the Karakorum in 1955 [205]. As a part of the IGY efforts, 30 nations announced programs in glaciology, which took place with few exceptions in glacierized regions of very different character: in the Antarctic, 11 nations combined their efforts; in the Arctic, 10; on mountain glaciers of subpolar, temperate, and subtropical latitudes, 10; and in the tropics, 5. Judging from the number of entries in the final catalogue of data, this work has been highly successful, yielding a wealth of new data due to the unprecedented international cooperation.

2. Mass Budget

During the IGY and the years following considerable effort went into the measuring of net mass budgets of glaciers. As yet there is neither general agreement with respect to the methods nor to the terminology; consequently not all of the results are of equally high standard. Meier's proposed definitions for glacier mass budget terms [150] will be used in the following.

Contrary to the opinion of many glaciologists, measurement of accumulation is more difficult than measurement of ablation [185]. This is especially so if the net budget total is to be calculated from observations of cumulative accumulation and cumulative ablation, requiring permanent work on the glacier, but providing the data necessary to correlate the net mass budget total to the net heat budget total of the glacier. Year-round activity was maintained at ten glaciological stations in the Soviet Union [18, 156] but also in other programs (e.g., Blue Glacier [116]). For complete information the best approach is to measure apparent accumulation and apparent ablation, the difference being the net budget. This method has been applied on Storglaciären in the Kebnekajse-Massif by Schytt [183].

It is easier and less time-consuming to measure only the specific net budget of numerous points, and to calculate the net budget total by integrating over the total area of the glacier. This method has been used, for instance, on the South Cascade Glacier [148]. On the Hintereisferner and Kesselwandferner [86] it was preferred to calculate the total net accumulation and the total net ablation for the areas above and below the firn edge or zero line of ice ablation [88]. This subdivision is justified by the appreciable differences in albedo as well as in the roughness parameter between the glacier surface covered with old snow and firn (above the firn edge) and that showing bare ice at the end of the budget year (below the firn edge). Without further information, knowledge of the net budget total is of somewhat limited value, giving first of all an indication of the "state of health" of a glacier [188]. This additional information can be gained by measuring precipitation in and discharge from the drainage area [29, 85, 86, 102, 152]. The mass budget determinations of the Grosser Aletschgletscher [96] are based mainly on hydrological methods. The net mass budget total of the glacier is the relatively small difference of two large quantities: total precipitation and discharge. Evaporation from glacierized areas is comparably small—and therefore an erroneous estimate does not debase the result—but the applicability of the mass balance equation is limited by the well-known difficulties in measuring solid precipitation. If, however, precipitation, discharge, and net mass budget total are measured at the same time, the correction for the rain gauges can be found, and the dependence of precipitation on altitude can be determined for that drainage area [85].

The increase of solid precipitation with altitude, though important, is not sufficient for understanding glacier formation. Owing to the action of wind, blowing snow is frequent during snowstorms, and drifting snow is observed on slopes even in fine weather, caused by the katabatic winds. The resulting deposition of the snow shows typical deviations from the precipitation-altitude relation; i.e., snow is removed from exposed ridges and deposited in basins, where Alpine-type glaciers are situated. Painstaking observations of apparent accumulation on the Tuyuksu Glaciers in the Zailiysky Alatau [64, 141, 142, 195, 196] led to the conclusion that on an average 15 to 20 per cent, and in some altitudes even more, of the snow accumulated on the glaciers was brought in from the surrounding slopes. The same order of magnitude was found in the course of snow surveys, carried out since 1954 on the Hintereisferner [85]. In some glacierized regions the transport and redistribution of snow by the wind is of vital importance for existing glaciers. This is the case for instance in the Kodar Range, Transbaykalia [171], and even more so in the Polar Urals [45, 200], where numerous cirque-glaciers were found to exist on leeward slopes well below the theoretical snow line. The intensity of the snow transport was analyzed as a function of wind speed and snow surface conditions in the Urals [101] and the Caucasus [170].

The importance of the phenomenon of blowing and drifting snow for the mass budget has fostered detailed studies on the Antarctic continent. Different types of drift snow gauges were used [54, 130, 153], which makes comparisons of the results difficult. Lister [130] found the amount of drifting snow at South Ice proportional to the wind speed and inversely proportional to the height, the threshold being at about 12 knots, provided that soft snow to form drift was available. By applying Bagnold's formula for the process of saltation, somewhat higher values were obtained as calculated by Vickers [208]. Based on Loewe's theory of stationary turbulent snow drift [133], Dingle and Radok [44] arrived at much higher values in analyzing snow drift measurements from Wilkes Station, in accordance with earlier measurements carried out at Mawson [154]. The analysis of data collected at Station Charcot in 1958 [136] again revealed quantities of drifting snow close to the values of Vickers and Lister. Apparently near the coast turbulent snow drift is much more effective at high wind speeds, because of larger precipitation and therefore more snow available to form drifts. Even though mass loss due to drifting snow is highly important in areas of strong katabatic winds, it should be pointed out that in other regions strongest winds are from the North, for instance at Little America [79]. Lister [130] arrives at the conclusion that mass loss is less than 1 $gm/cm^2/yr$ over the area of the Antarctic continent, compared to an annual accumulation of approximately 13 gm/cm^2. Kotlyakov analyzed observations of drifting snow with respect to surface hardness [108], and states likewise [109] that drifting snow is not of essential importance for the mass budget. Many more year-round measurements of drifting snow with standardized equipment are needed, taking into account the direction of wind and its state of "saturation" [130], before a final solution to the problem can be expected.

Owing to the action of the wind a very typical microrelief develops on the snow surface [110]. Snow dunes and barchanes are chiefly deposition forms, whereas sastrugi are caused by erosion. Both processes are frequently active at the same time, causing the dunes to move downwind with speeds up to 1 m/hr [80, 209]. This continuously changing surface becomes expressed in the usually very high standard deviation of accumulation values, which in itself is indicative of accumulation conditions. Much could be learned from observations of sastrugi about the drainage patterns of katabatic winds [19, 146, 147, 194], which are strongly influenced by the main surface topography. According to Dolgushin's schematic picture [46], the peripheral zone of katabatic winds (up to 800 km wide) is characterized by a hard surface of high density and a great number of sastrugi, whereas in the central zone of the continent, owing to lower winds, a loose snow cover predominates. The excellent work by Crary and collaborators [36] revealed the interesting fact that even on an ideally flat and uniform snow field as the Ross Ice Shelf clear patterns of snow characteristics are distinctive of certain atmospheric processes. Moderate density, hardness, and sastrugi, but high net accumulation and temperature around Little America are typical of cyclonic activity with moderate to strong on-shore winds and only weak katabatic flow from Marie Byrd Land. High density, hardness, and prominent sastrugi, but likewise high net accumulation and temperature between Beardmore and Liv Glaciers show the influence of strong katabatic winds with mostly snowdrift accumulation and possibly orographic precipitation caused by the Queen Maud Range. The central part of the Ross Ice Shelf has low density and hardness, a smooth surface, rather low precipitation, and lowest annual temperature. Apparently it is an area only rarely invaded by active cyclonic disturbances and out of reach for the katabatic winds from the Horst range. This distribution would fit in with the picture of a predominant clockwise circulation in the area of Ross Ice Shelf, derived by Alt [5] and Astapenko [17], based on rather sparse meteorological observations. This is a fine example of how glaciological data can supply details, which with the present station-density are out of reach for meteorology.

Information on net accumulation is based either on stake observations or preferably on pit studies. On mountain glaciers with regular summer melting, it is no problem to analyze annual layers by conventional methods. A discoloration of late summer snow and a characteristic pollen content [204] can be utilized for additional proof. Within the dry snow facies, particularly on the higher parts of the Antarctic ice cap, where snow due to drifting becomes redistributed frequently, and where the originally faint horizons are obliterated by sublimation, the interpretation of the stratigraphic record from pits becomes difficult and rather doubtful. Snow from different years mingles, because the micro-relief caused by the wind is in considerable excess of the annual accumulation. A very valuable means of possible identification of annual layers became available during the IGY, viz., the isotopic methods. Seasonal variations of the isotopic composition of oxygen in snow or ice samples have been used by Gonfiantini and Picciotto [62] in the Antarctic, and by Epstein and Sharp [49] for different sites in the Antarctic, in Greenland, and on the Blue Glacier. Picciotto *et al.* [168] and Lorius [135] made use of the variations of the isotopic composition of hydrogen in Antarctic snow. A variation of 1°C in cloud temperature was found to correspond to a relative variation of 0.1 per cent in the ratio oxygen-18: oxygen-16, and of 0.8 per cent in the ratio deuterium: hydrogen, both values being well above the experimental error. Oeschger and colleagues [160] determined the age of firn by means of the amount of radioactive tritium on the Jungfraufirn (Switzerland) in 1957, in order to apply this method during the International Greenland Expedition (EGIG 1957–1960).

Whereas stratigraphic methods yield satisfying results even in North Greenland [123], which compare almost perfectly with the isotopic method [49], this is not the case in the Antarctic [189]. In more than 500 samples from US-IGY stations in the Antarctic, O^{18}/O^{16} ratios have been analyzed and both methods compared. The variations in the oxygen isotope ratio suggest annual rates of accumulation about twice as large for stations on the inland-ice (Byrd and South Pole), and about 13 to 50 per cent larger at Wilkes and Little America Stations. This is rather unfortunate, since a recent and very competent analysis by Giovinetto of snow pits dug during the McMurdo-South Pole Traverse 1960–1961 [59] justifies the cutting in half of previously determined accumulation values. The reason for this discrepancy is not yet understood, but it should be kept in mind that annual variations of tropospheric temperatures are much smaller in the Antarctic, compared to the Arctic [214], and that heavy precipitation usually occurs at comparably high temperatures throughout the year. Three heavy falls of snow at Little America V in May, June, and November, 1957 began with freezing drizzle at average daily surface temperatures of −7.6, −6.5, and −4.8°C, respectively; the blizzard of May, 1957, has been analyzed by Alvarez and Lieske [6]. According to Kotlyakov [110], the main accumulation season in Antarctica is autumn, with a secondary peak in spring. This annual variation of accumulation was also found by Crary [34] and by the present author [79]. Prominent "summer peaks" in O^{18}/O^{16} ratios therefore might mean a record of storms associated with heavy precipitation but not necessarily a record of seasons. Therefore, good stratigraphic interpretations seem to give more reliable information at present.

In general, no unequivocal mass budget history can be reconstructed solely from stratigraphic evidence, some years being removed from the profile either by exceptional ablation, or by wind corrosion. An apparent accumulation hiatus of about annual duration has frequently been observed in the Antarctic [33, 194], and the chance of missing an annual layer in a particular stratigraphic section has been estimated as 5 to 15 per cent [59]. Only a reference horizon of known date could help to solve the problem. The only known and accessible man-made horizon, viz., Little America III, (1939–1940) has been utilized for accumulation studies [81, 209], but is no longer of use because it has been reported broken off [207]. Another man-made horizon, formed by the fallout of radioactive debris from thermonuclear bomb tests, marking early 1955 and 1962 layers [169], will soon become important, because it probably extends over the entire Antarctic continent, thus providing a check on the hitherto obtained results [210].

During and after the IGY so many observations of net accumulation have been carried out, carefully analyzed, and published (e.g., Ohio State Research Foundation, 1958–1961 [161], Academy of Sciences of the U.S.S.R., 1960 [1]) that it becomes possible to construct accumulation maps of Antarctica with some confidence. The first two maps were presented at the Symposium on Antarctic Glaciology, Helsinki, 1960, showing essentially the same features, but different mean values: Cameron and Goldthwait [24] obtained an average net accumulation of 12.5 cm of water, whereas Kotlyakov [109, 110] arrived at 19 cm of water. A very detailed accumulation map was compiled by Rubin [174], giving an average value of 14.5 cm of water. A similar picture is shown in Giovinetto's map [59], with some important deductions in Victoria Land and additions south of Bellingshausen Sea [58]. The observed accumulation patterns in West Antarctica have been explained by Rubin and Giovinetto [175] by the interaction of the topographic features with circulation patterns and associated atmospheric moisture transport, and lifting condensation level. More studies of this type are necessary for a closer understanding of the mass budget of Antarctica on a regional scale. The evolution of glaciers in the Arctic has been studied likewise in terms of atmospheric circulation patterns by Krenke [113]. According to Loewe, in the interior of Antarctica, evaporation and hoarfrost formation contribute only insignificantly to the mass economy [134]. The same was found to be true in the Arctic [40]. By adding estimates of the mass loss due to drifting snow to the observed net accumulation, the total precipitation over Antarctica may be obtained. Rubin arrives at a value between 15 and 19 cm/yr, depending on whether minimum or maximum values are used for drifting snow [174]. This is a very remarkable result, indeed equally important for glaciology as for meteorology.

Another exciting aspect of accumulation studies in deep pits or boreholes is the possibility of revealing the accumulation history. At Site 2 on the Greenland Ice Sheet a hole was drilled to a depth of 411 m in 1957 [124], and there is some indication that net accumulation has increased there since about 1783. The same result was obtained at the South Pole Station since 1760 [57], and near Wilkes Station since 1783 [25], the increase being more pronounced within the last century in both places. This might be interpreted as an indication of a world-wide change in atmospheric circulation. Even minor fluctuations in net accumulation as a tendency toward higher values between about 1910 and 1930 were reported similar for stations South Ice and North Ice by Lister [130]. It would be rewarding to check this result in other boreholes or deep pits [21, 63, 145].

The transition zone between the dry snow line and the equilibrium line offers more difficulties for mean budget studies than any other area on glaciers. The subdivision of this zone into percolation zones A and B and superimposed ice zone has been outlined very clearly by Müller [158]. In percolation zone B, which is predominant on most Alpine-type glaciers, some meltwater may percolate into the firn layers of previous years and refreeze; therefore budget values are most difficult to assess [72, 74, 103]. The formation of ice in the accumulation zone by refreezing of meltwater takes different times depending mainly on the amount of winter snow [142]. Highly interesting conditions were found on the glaciers of the Nan-Shan in Central Asia, where nourishment takes place almost entirely in summer. Owing to the dry and intensely cold winter the Nan-Shan glaciers are among the coldest of the temperate zone, and refreezing of meltwater takes place in summer; the glaciers therefore consist of ice also in the area of nourishment [47]. Both types of nourishment were found closely associated on Franz-Josef Land [65], where the higher glacier domes still retain firn areas, whereas slightly lower ones belong to the Baffin type and are nourished only by superimposed ice. As Krenke points out [112], this small difference in accumulation conditions leads to essentially different temperature regimes within the ice. The heat of fusion, deliberated in the process of freezing of percolating meltwater, keeps the firn-covered parts of the higher domes at a much higher temperature than the average air temperature, which again is very nearly reached by the ice of the lower domes. Reports on intense firn-type nourishment and consequently high ice temperatures also became available from Novaya Zemlya [198], and from Nordaustlandet [165]. The Hurlbut glacier, North Greenland, according to Fristrup [52] is nourished mainly by superimposed ice, which was found in a borehole down to at least 15 m. Indications of annual layering in superimposed ice were observed at Wilkes Station by Hollin and collaborators [90]. In the ablation area superimposed ice deserves consideration as well, and measurements of apparent accumulation should always be made prior to the formation of superimposed ice. This was studied in detail in the ablation area of Hintereisferner in 1957–1958 [9] and in the ablation area of the Greenland Ice Cap in 1959 by Ambach [10], and the energies involved computed. On glaciers with high ablation rates there is no problem in measuring ablation with stakes, provided the stakes are kept deep enough in the ice. Daily mean specific ablation values within 10 per cent of the true mean, with a probability of 90 per cent, can be expected from about 10 measuring points. But, as Untersteiner pointed out [206], this requirement cannot be met with an acceptable number of points when ablation rates are as small as on Drifting Station A. Ablation

TABLE 1

NET MASS BUDGET QUANTITIES IGY 1957–1958, IGC 1959.

Glacier	Approximate Geogr. Position		Approximate Height of Equilibrium Line	Approximate Surface	Net Budget 1957–1958		Net Budget 1958–1959		Reference
					Total	Mean Specific	Total	Mean Specific	
			m	km²	× 10⁶ m³	mm	× 10⁶ m³	mm	
Gilman	82°N	71°W	1200	481	−33	−69	"Near balance"		Lotz and Sagar [139]
Jackson				50	−12	−240	—		
Churlyanis	80°N	53°E	300	5.5	−2.8	−510	—		Grosswald and Krenke [66]
Franz-Josef-Land				14300	−5300	−370	—		
Shokalskiy				545	−51	−94	−96	−176	
Novaya Zemlya	76°N	63°E	680	20575	−6260	−304	−12270	−597	Chizhov [31]
Stor	68°N	19°E	1500	3.2	−2.0	−626	−3.0	−938	Schytt [186]
Lemon Creek	59°N	134°W	960	10	−9.0	−900	—		Crary, Field, Meier [35]
Blue	48°N	124°W	2050	4.2	−7.1	−1690	−0.2	−60	LaChapelle [116, 119]
South Cascade	48°N	121°W	2040	2.6	−5.6	−2164	+1.8	+690	Meier [148]
Hintereis	47°N	11°E	3120	10.0	−9.8	−981	−7.6	−763	Hoinkes and Lang [86]
Kesselwand			3150	4.1	−1.6	−382	−1.5	−372	
Aletsch	46°N	08°E	3000	~136	−88	−650	−145	−1070	Kasser, pers. comm.
Zentralny Tuyuksu	43°N	77°E	3660	3.0	+0.3	+100	−1.8	−594	Makarevich [141]
Tasman	44°S	170°E	1800	55	—	—	−42	−764	Goldthwait and McKellar [60]
Hamberg	54°S	37°W	500	11.4	−2.9	−254	—	—	Smith [193]
Hodges				0.27	−0.04	−150	—	—	

rates over longer periods of time are usually much better, but even then single stakes should be controlled by auxiliary boreholes as on the Hintereisferner [86] or by supplementary stakes, as in Greenland [20] in order to reduce the error.

In Table 1 results of mass budget investigations during the IGY-IGC periods have been summarized. In fact, many more glaciers were the object of studies, but the results are either not yet published, or the data obtained are not sufficient for a mass budget calculation. It is certainly a pity that no mass budget values have become known from the tropics. In equatorial Africa the displacements of the intertropical convergence zone apparently cause two accumulation and two ablation seasons within one year [27, 92, 215]. The contents of numerous more descriptive papers, and the information put together in Table 1 indicate that with very few exceptions [197] glaciers were shrinking in most glacierized regions during the IGY-IGC period, with the probable exception of two, where almost all of the ice on earth is concentrated: the Greenland Ice Sheet [123] and the Antarctic Ice Sheet [48], both of which were found to have a slightly positive mass budget or else are in equilibrium [167], to all appearance.

3. Heat Budget

Meteorological observations were carried out during the IGY-IGC in many remote places on or near glaciers in connection with mass budget studies. The observations included for the most part solar radiation, net radiation, and vertical gradients of wind, temperature, and humidity within the lowest ten meters of the atmosphere, as well as subsurface temperatures. Most of the data are processed, and some are accessible in tabulated form, and are ready for investigations of the complex interrelations between glaciers and the climatic environment [e.g., 2, 38, 43]. However, in heat balance studies, one should be very careful in making use of data obtained with instruments, whose calibrations and servicing are not known. In a certain case, because of incorrect calculation, the daily totals of albedo and of some other radiation elements were found wrong [163].

The great variety of radiation instruments in use during the IGY-IGC proved to be a disadvantage because only in some cases could calibrations be made during field work. At low sun elevations with a clear sky the calibration factor of all thermopiles shows a dependence on solar elevation, which is partly due to the cosine error, or caused by the catacaustics of the covering glass bulb. In addition the EMF generated depends on ambient air temperature which in polar regions is usually much below calibration temperature. The errors thus caused might be tolerated if only daily or monthly totals are wanted [199], but must be corrected if an analysis of hourly variations of the components of net radiation is attempted. The widely used ventilated Gier and Dunkle net-radiometers operate properly only as long as the blower is facing downwind, and the blower louvers are not blocked by rime or drifting snow. Formation of frost crystals on the receiver plate or rain makes the meaning of the output uncertain, and at low solar altitudes the supports cast a shadow across the top plate. The Schulze net-radiometer with polythene-covered thermopiles became available just shortly before the IGY, and insufficient knowledge of the properties of polythene was available, but the material was thought to be about equally transparent in all wavelengths. After the IGY-IGC thorough calibration tests revealed the fact that the Schulze net-radiometer was appreciably less sensitive for long-wave radiation [11], thus leaving some former calculations of net radiation with an error of about 50 per cent [79]. The evaluation of data is now extremely time-consuming, for all recorded scale parts must be separated into short- and long-wave components, using different calibration factors. As long as these difficulties are not overcome, automatic integration devices will render little help, and some recalculations of IGY radiation data will be unavoidable.

In some investigations attention has been paid to the fact that short-wave radiation is not absorbed at the surface, but penetrates into snow and ice to a certain extent, thus causing internal heating or melting. Ambach and Mocker used a specially designed very small radiation receiver [15], to render the shading effect a minimum, for measurements of the extinction coefficient in ice and firn snow on the Hintereisferner. A net-radiometer of only 7.5 mm diameter was developed by Ambach and Habicht [12] which allowed a nearly undisturbed measurement of the net radiation below the glacier surface. The spatial distribution of scattered radiation was measured in three wavelengths on the Hintereisferner and in Greenland by means of small directional receivers with filters [10, 13]; these investigations led to a new explanation of the daily variation of albedo. A different theoretical approach to examining radiation distribution in snow was utilized by Giddings and LaChapelle [56]; and field data to check the derived equations for albedo were obtained on the Blue Glacier. The problem was also investigated by Karol [95] on the Fedchenko Glacier, by Untersteiner [206] on Drifting Station A, and by Koptev and Pyatnenkov [106] on drifting station "North Pole 6." Theoretical considerations of horizontal visual range in dependence of albedo were substantiated by measurements in the visual and the near-infrared spectral range on the Greenland Ice Cap by Kasten [98, 99] in connection with polar whiteout research.

Results of radiation observations carried out during the IGY-IGC reveal high intensities in most glacierized regions. For instance, normal incidence values, observed at Little America V, Antarctica, at 44 m. a. s. l. [53, 78, 82] and on the Kesselwandferner, Oetztal Alps, at 3240 m a. s. l. [14], if reduced to mean solar distance and sea level pressure, compare exactly at identical optical air masses. Ångström's turbidity coefficient yields equally low on both places, i.e., between 0.01 and 0.02 for monthly averages. Total short-wave radiation of sun and sky on a horizontal surface depends largely on cloudiness, possible duration of sunshine and percentage of diffuse radiation, which again is strongly influenced by albedo; therefore comparisons are not readily made. Surprisingly, large average daily totals have been reported, e.g., 770 ly/day at the South Pole Station in January, 1958 [69], and 865 ly/day on the Fedchenko Glacier (38°N, 4900 m) in June, 1958, where the yearly total of 194,300 ly rates amongst the largest observed [55]. Under favorable conditions the total short-wave radiation may reach or even exceed the extraterrestrial radiation, as observed at the South Pole Station on 4 October 1958 [68]. Rusin has summarized observations of various stations in Antarctica and calculated the dependence of total short-wave radiation upon solar altitude [179]. Again, there were no radiation measurements on glaciers in the tropics, which is most deplorable indeed. To speak of "solar radiation measurements," when only readings on a Weston exposure meter or of a black bulb thermometer were taken, is somewhat behind the times [216].

Because of the high amount of energy offered by radiation, the most important quantity to know in glacial meteorology is the albedo, which is known to vary in a wide range. Highest albedo values were obtained on the Antarctic snowfields, where the range, depending on snow characteristics, was found to be between 75 and 93 per cent [68, 78, 192] for instantaneous measurements, and between 81 and 91 per cent for monthly totals. The average weighted annual albedo at Little America was 86 per cent, at Charcot 84 per cent, and at Mirnyi 84 per cent [82, 104, 137]. At the South Pole Station a yearly average albedo of 82 per cent [69] seems rather low. In addition to the explanation offered by Hanson [68], the different response of thermopiles for direct and isotropic radiation at low sun elevations should be considered. Albedo of Arctic sea ice was reported much lower by Untersteiner [206], who in July, 1957 measured daily totals between 56 and 70 per cent. The average value of 66 per cent adopted for heat balance calculations was confirmed as representative by Hanson [70], who arrived at a mean value of 65 per cent by means of airborne measurements in the summer of 1958. Briazgin reported a slightly lower value of 60 per cent [23], probably because of more pools of meltwater on the ice floes. An "atlas of mean monthly albedo of Arctic surfaces," prepared by Larsson and Orvig [125] will prove valuable in extensive calculations. In the firn basin of Fedchenko Glacier the annual albedo averaged 76 per cent [55], which seems to be typical of high snowfields of mountain glaciers [14]. Somewhat lower albedo values (55 to 65 per cent) for old snow (from the running budget year) were observed on the ground and from an aircraft on the Blue Glacier by LaChapelle [116], owing to much lower altitude and therefore different snow structure. Large variations of albedo (36 to 86 per cent) with respect to time and locality in the ablation area of the Greenland Ice Cap were observed by Ambach [10], which caused considerable difficulties in heat budget calculations.

Total short-wave radiation, albedo and terrestrial long-wave radiation, including radiation from the atmosphere and from the surface are the controlling factors of net radiation. On temperate glaciers, where during the melting season radiation from the surface remains constant, albedo becomes the decisive factor. This has been pointed out frequently by several authors [76]. Voloshina [211] reported high positive net radiation from glacier tongues (albedo 20–30 per cent), and about balanced net radiation on the Elbrus saddle (5300 m a. s. l., albedo 70 to 80 per cent). Skeib [190] observed a distinct relation between net radiation, albedo, and cloudiness on the Zentralny Tuyuksu Glacier, Tien Shan. An empirical equation was found, which might prove useful for calculations of net radiation, if only observations of total short-wave radiation, albedo, and cloudiness are available [191]. The relation between net long-wave radiation of a melting snow or ice surface and cloudiness has also been studied by Ambach in Greenland [10], and by Ambach and Hoinkes on the Kesselwandferner [14]. In both cases a slightly nonlinear relation was obtained, similar to the one found in Little America [79], and at Scott Base [199]. Markin [143, 144], from extensive measurements of albedo on Franz-Josef Land, concluded that the ice domes retain a negative average radiation balance because of high albedo, in contrast to the surrounding ice-free areas whose average net radiation is positive. The same has been reported from the ice-free areas on the fringe of the Antarctic continent [110]. At Scott Base on Ross Island unbelievably large positive net radiation is recorded between November and February, when the albedo drops to about 15 per cent [199] and even the yearly total remains positive. This is in sharp contrast to the observations at Little America V on the Ross Ice Shelf, where during the same year (February, 1957 to January, 1958) a moderately positive net radiation was observed only in December (+31 ly/day) and in January (+4 ly/day), and the yearly total was at least −6000 ly (Hoinkes, not yet published). This is only about half as much as the −35 ly/day at the South Pole Station in 1958 [69]. At Mirnyi net radiation remained positive during four months, with a yearly total of −2100 ly [177], whereas for Halley Bay, according to MacDowall [140], the yearly total resulted as −1000 ly for 1958, with positive net radiation from November through February. Some earlier net radiation data for the Antarctic are summarized in a report by Rusin [178], and for the Soviet Arctic by Chernigovsky [30].

Eddy flux of sensible and latent heat was ascertained in most investigations by conventional methods from vertical profiles of wind velocity, potential temperature, and specific humidity. Frequently difficulties arose from irregular profiles in connection with very shallow drainage winds

[3, 114, 191, 120]. Skeib [191] successfully used gradients from the lowest 100 cm, where strictly logarithmic profiles were obtained, to calculate the eddy heat fluxes on the Zentralny Tuyuksu glacier. Kuhlman [114], on the other hand, had the lowest measuring level at 150 cm at Sermikavsak glacier; therefore he missed the most important layer, and no quantitative data resulted. LaChapelle [116, 119, 120] found anomalous temperature profiles on the Snowdome of Blue Glacier and, since he had taken great care in measuring the water vapor exchange, decided to obtain the sensible heat flux as the residual in the heat budget. To do so, ablation has to be measured rather carefully.

LaChapelle [117], on Blue Glacier, analyzed the errors in short-time measurements of snow ablation caused by settling and subsurface melting owing to the penetration of radiation into the snow cover. To avoid the error, profiles of ice density of snow are required instead of bulk density, which together with measured changes in surface level allow one to determine the ablation. Adkins [3] on Salmon Glacier did not even measure bulk density each time, but instead applied an average density to convert 4-hour values of surface lowering in mm of snow to mm of water. It is certainly no surprise that the agreement between ablation as calculated from the heat budget and measured ablation was rather poor. LaChapelle [115] advocated centrifugal separation of free water from melting snow for ready use in the field. Yosida [217] recently developed a new handy calorimeter, and presented highly interesting results on meltwater penetration and subsurface melting [218]. Radok and colleagues [172] introduced a new type of freezing calorimeter, where only the relatively small amount of heat released in the process of freezing of the free water has to be measured. Ambach [7] designed a condenser, which was suitable for measuring the dielectric constant and therefore the free water content of rather large wet snow samples of about 1000 cm^3. The instrument was used in heat budget investigations on the Kesselwandferner [14] and in the ablation zone of the Greenland Ice Cap [10].

In Antarctic heat budget investigations the latent heat flux was treated as a residual of the net radiation, the heat flux in the snow, and the sensible heat exchange with the atmosphere [79, 127], because no water vapor profiles could be measured. The sensible heat flux, as calculated by Hoinkes [79] for the winter night 1957 at Little America from vertical differences of temperature and wind speed was admittedly a rather rough estimate, leaving the deposition term probably too large. Lettau's calculation of sensible heat flux in the South Pole heat budget study [127] was based on material of wind and temperature profiles unique of its kind, collected in 1958 by Dalrymple [38]. The thorough analysis of the data [39] may safely be said to be the most remarkable contribution to glacial micrometeorology during the IGY-IGC. Curvature characteristics of wind and temperature profiles were analyzed in great detail, and were found to differ at high stabilities, indicating a difference in thickness of the surface layer of the wind and temperature field, the latter being significantly thicker. A new method was developed to compute the aerodynamic roughness length from diabatic wind profiles. The value obtained, viz., 0.014 cm, is of the same order of magnitude as that found on the snowfields of Hintereis- and Kesselwandferner, viz., 0.012 cm [14]. Eddy heat flux was computed from surface stress and vertical differences of potential temperature and wind speed, using for Kármán's constant $k = 0.428$ instead of 0.40. A reasonable deposition rate at the South Pole was obtained, but the authors felt that the uncertainty of all terms in the heat budget equation might be such that the latent heat flux, when computed as a remainder, is accurate only within ±10 ly/day. Hanson and Rubin [71] treated sensible and latent heat exchange as a residual of net radiation and subsurface heat flux in an estimate of the semiannual heat budget at the South Pole Station for 1958. The same was done by Lorius [137] in computing the heat balance for the period 15 July to 31 August 1957, at Charcot Station. Kopanev [105] at Mirnyi also computed the net radiation. No other Antarctic heat budget investigations have become known to the present author, but undoubtedly they will appear in the near future.

Valuable data have been collected from the many investigations on certain glaciometeorological parameters, but for lack of proper instrumentation only qualitative relations between ablation and single meteorological parameters have been obtained. Daily maximum temperatures were found in "almost perfect correlation" with ice ablation on Gilman Glacier by Sagar [181], but this could not be confirmed by Lotz [138] on Ward Hunt Island. Only the consideration of all components of the total heat budget leads to a physical understanding of the ablation process. In Table 2 a summary is given of some results of heat budget studies, carried out during the IGY-IGC periods. Some of the original data had to be recalculated for easier comparison. The main results of pre-IGY investigations, i.e., the predominance of solar radiation as heat source for ablation and the general insignificance of evaporation [28, 29], could be confirmed. The relative importance of net radiation increases with increasing altitude and latitude [131, 206], and the same is true for evaporation. Whenever atmospheric conditions favor evaporation, the amount of heat available for melting remains small, and snow or ice are rather preserved. On these occasions net radiation supplies more energy than is needed to explain the observed wastage, including internal melting and heating. This was observed by Ambach [8, 10] on the Greenland Ice Cap, by Untersteiner [206] on Drifting Station A, and shows even better on the upper snowfields of Fedchenko Glacier [55], where net radiation supplies 113 per cent of the energy needed for melting. In the lower regions of glaciers eddy heat flux becomes more effective, and condensation of water vapor prevails; consequently the relative contribution of net radiation to ablation diminishes.

TABLE 2

RESULTS OF HEAT BUDGET INVESTIGATIONS FOR SELECTED PERIODS (ABLATION ONLY), IGY 1957–58, IGC 1959.

	Zentralny Tuyuksu Glacier, 3475 m 43°N, 77°E 10 July–9 Sept. 1958, 62 Days Snow and Ice		Kesselwandferner, 3240 m 47°N, 11°E 11–19 Aug. 28 Aug.–8 Sept. 1958, 20 Days Snow		Blue Glacier 2050 m 48°N, 124°W 12 July–20 Aug. 1958, 37 Days Snow		Moscow University Glacier, 750 m 68°N, 66°E 21 July–3 Aug. 1958, 14 Days Snow and Ice		Greenland Ice Cap 70°N, 50°W, 1004 m				U.S. Drifting Station A 82°N, 165°W 10–23 July, 1957, 14 Days Ice	
									26 May–23 June 1959, 29 Days Snow		24 June–7 July 12–29 July 2–7 Aug. 1959, 38 Days Ice			
	ly/day	per cent	ly/day	per cent	ly/day	per cent	ly/day	per cent	ly/day	per cent	ly/day	per cent	ly/day	per cent
Sources:														
Net short-wave radiation	307	89	158	79	292	69	208	47	192	80	323	80	142	94
Sensible heat	38*	11	43†	21	104	25	166	37	42	18	74	18	9	6
Condensation					26	6	69	16	6	2	9	2	—	—
Sum of sources	345	100	201	100	422	100	443	100	240	100	406	100	151	100
Sinks:														
Net long-wave radiation	−170	49	−69	34	−118	28	−48	11	−38§	16	−61§	15	−8	5
Evaporation	−25	7	−1‡	1	−32	8	−5	1	−50	21	−36	9	−11	7
Melting	−150	44	−131	65	−272	64	−390	88	−122	51	−285	70	−82	55
Heating									−30	12	−24	6	−50	33
Sum of sinks	−345	100	−201	100	−422	100	−443	100	−240	100	−406	100	−151	100
Melting and heating	150	100	131	100	272	100	390	100	152	100	309	100	132	100
Net radiation	137	91	89	68	174	64	160	41	153	101	262	85	134	102
Net convection	13	9	42	32	98	36	230	59	−2	−1	47	15	−2	−2
Reference	Skeib [191]		Ambach and Hoinkes [14]		LaChapelle [118]		Lebedeva [126]		Ambach [10]				Untersteiner [206]	

* Sensible and latent heat.

† Net convective heat.

‡ Frozen layer.

§ Preliminary value.

This was measured on the lower parts of Alpine glaciers [77], at the middle and lower parts of Fedchenko Glacier [55], and resulted even more clearly on Moscow University Glacier in the Polar Urals [126] situated at an exceptionally low altitude. On Hodges Glacier, South Georgia, radiation accounted for only 35 per cent of ablation [193].

However, great care should be observed in comparing results of heat budget investigations, because they are representative of selected periods only. In the summer of 1960 an additional heat budget investigation was carried out on the Blue Glacier for a period of 19 days with essentially identical results. But because of instrument difficulties in storm conditions the record is weighted in favor of fair weather [119]; nevertheless, 24-hour intervals were always considered. Adkins, on Salmon Glacier [3], selected only daylight periods of two to four hours' duration without rain, again because of difficulties with the net radiometer. He arrived at a relative contribution of net radiation to ablation of 75 per cent. This number is not comparable with any of the values given in Table 2. If on the Kesselwandferner only daylight hours with melting conditions, but including rain, are considered, the relative contribution of net radiation to melting results as 88 per cent [14] instead of the 68 per cent (Table 2) valid for 24-hour intervals.

Heat budget estimates of stations in Antarctica, based on observations during the IGY, are summarized in Table 3. A comparison of the results is

TABLE 3

HEAT BUDGET ESTIMATES OF STATIONS IN ANTARCTICA, IGY 1957–1958.

	South Pole Station 90°S 2800 m				Charcot 70°S 139°E 2400 m	Little America V 78°S 162°W 44 m	Mirnyi 67°S 93°E 35 m	
	June–July 1958	21 March– 22 Sept. 1958	22 Sept.– 21 March 1958	April 1958	15 July– 31 Aug. 1957	June–July 1957	June–July 1957	Nov.–Dec. 1957
	ly/day	ly/day	ly/day	ly/day	ly/day	ly/day	ly/day	ly/day
Net radiation	−56.5	−53	−17	−54	−37.1	−32.5	−51	+57
Snow heat flux	2.5	7	−7	11	2.4	2.6	3	−3.5
Eddy heat flux	51.0					13.1	77	29.5
Deposition	3.0	46*	24*	43*	34.7*	16.8		
Evaporation							−29	−83
Reference	Lettau *et al.* [127]	Hanson and Rubin [71]		Hanson [69]	Lorius [137]	Hoinkes [79] revised: Lettau *et al.* [127]	Kopanev [105] after Dalrymple *et al.* [39]	

* Sensible and latent heat exchange.

confined to orders of magnitude, because of instrumental difficulties and different methods of computing. Average net radiation in winter is negative at all stations, even though at Little America V about one quarter of the winter night had incoming long-wave radiation due to a dense cloud cover under inversion conditions [79]. In summer, on an average, net radiation becomes positive only in the coastal zone. Snow heat flux in all investigations is the smallest term which can be asserted with least difficulties for longer periods. The sensible and latent heat exchange, if treated as a residual, is also in fair agreement; so it seems the right orders of magnitude could be obtained. Only at Mirnyi did extremely high values for eddy heat and latent heat flux result, the latter indicating strong evaporation even in winter. It should be kept in mind, however, that net radiation at Mirnyi was computed rather than measured [104, 105]. Rusin [180], based on further computations of turbulent flux, divided Antarctica into three zones: the coastal zone under the influence of katabatic winds, with evaporation during the entire year; the coastal zone outside the influence of katabatic winds, i.e., the ice shelves, with predominance of evaporation in summer and deposition in winter, and the intracontinental zone with deposition of water vapor during the entire year. These results await further confirmation with respect to the magnitudes involved. It would be highly rewarding to measure the heat budget of glaciers ending on land, and of their surroundings, in order to find out the significance of ablation in keeping the ice edge stationary [84]. Evaporation might be very important, but pure mechanical erosion of ice by either drifting snow or sand should also be considered. Only then would it become possible to decide whether Hollin [89] is right in stating that limits of the ice in the "oases" are practically independent of direct climatic control. According to calculations by Rubin [174] the influx of sensible and latent heat as deduced from radiosonde ascents from ten stations on the Antarctic coast, less the heat used in melting and evaporation, equals the net radiative heat loss through the top of the atmosphere over Antarctica, assuming a balanced annual heat budget for Antarctica. Allowing for the uncertainties involved, this result is rather satisfying.

4. Discussion

It is not easy to relate mass budget quantities, as given in Table 1, to heat budget quantities, as shown in Table 2. A comparison of 1958 data of Blue Glacier and Kesselwandferner, both of which have about the same size and are situated at the same latitude, shows a negative mean specific net mass budget which for the Blue Glacier exceeds the one for the Kesselwandferner by a factor of about 4.4. At the same time the average heat budget on the Blue Glacier is bigger by a factor of only about 2.1, which can be accounted for by the differences in albedo, cloudiness, horizon, and altitude of both micrometeorological stations. Apparently both study sites, even though they were on snow, did not equally represent the whole glacier's surface, whose heat budget we ought to know. The area covered with old snow from the budget year 1957–1958 at the end of the budget year was 1.3 km^2 on Blue Glacier, as measured by planimeter from the map of LaChapelle's report [116], but 2.4 km^2 on Kesselwandferner [86]. This is again a factor of about 2, which helps to understand the difference in the mass budget total, which, if properly established, is a measure of the heat budget total.

Because albedo is the main controlling factor for net radiation, the average albedo of the glacier surface should be roughly indicative of the amount of absorbed radiation. This relationship was formulated by Meier [148] as "ablation is not independent of accumulation," and shows clearly in the difference between the mean specific mass budget (see Table 1) of Jackson Dome with firn accumulation and of Churlyanis Dome with ice accumulation on Franz-Josef Land [66]. A definite dependence of average ablation on average albedo was observed on the Zentralny Tuyuksu Glacier by Golovkova and Tkachuk [61]. This is one of the main difficulties in all attempts to correlate glacier variations to variations of climatic elements, when only data of precipitation and air temperature are available from stations in the neighborhood. As a very rough indicator of heat budget, air temperature has frequently been used, because it can easily be reduced to glacierized altitudes, but the relations deduced between ice melt and air temperature were never satisfactory [28]. The only relative assessment of albedo from routine observations is given by the amount of winter snow, and even better by the number of days with fresh snow in summer [77]. As pointed out by Tronov [202, 203] the late summer snowfalls are of greatest influence, because large areas of bare ice become snow-covered, and the ablation period is shortened. On the Hintereisferner from 1952 to 1961 the effective duration of the ablation period varied between 85 and 140 days, in close correlation to the measured ablation total [87]. A rather insignificant drop of temperature might decide whether rain or snow is falling on glaciers during periods of bad weather in summer, thus causing a very pronounced difference in albedo. The heat budget of a temperate glacier, therefore, is extremely sensitive to changes of temperature around freezing only during periods of bad weather. The duration of the effective ablation period apparently is a useful description of the varying complex of weather conditions, and as an element of dynamic climatology deserves more attention. Sometimes albedo might be changed by other influences brought about by meteorological processes. Windblown dust, originating either locally [73] or transported over long distances, e.g., from North Africa to the Alps during periods of strong foehn, as in April, 1962, gives rise to early or exceptionally heavy ablation in the course of the following summer [84]. On such occasions the relation between the ablation total and the effective duration of the ablation period is disturbed.

The old snow line [88], which for temperate mountain glaciers is nearly identical with the equilibrium line, separates at the end of the budget year two areas with appreciably different albedo. From observations on the Zentralny Tuyuksu Glacier, Palgov [164] found with balanced mass budget a height of the old snow line such that the ratio of the accumulation area to the ablation area became 2.64. The same order of magnitude was obtained on the Hintereisferner [84], and on Axel Heiberg Island [157], i.e., with very different climatic conditions. This is rather promising as a means for simple glacier control, and could help to extend information into remote areas or into a great number of glaciers. The method was applied successfully by Meier and Post [151] on a large scale, using the ratio accumulation area to the total area of 475 glaciers in Western North America, as measured from aerial photographs. Accumulation area ratios greater than 0.5 should indicate balanced net budgets; on the Hintereisferner and Kesselwandferner this is indicated by a ratio greater than 0.7 in fair agreement with Meier's results. The ratio accumulation to ablation area permits us to estimate to what degree a glacier is in balance with the average present climatic environment [86]. On the Hintereisferner nine budget years 1952/53–1960/61 gave an average area ratio of about 1.5 (area of nourishment 6 km^2, area of wastage 4 km^2). Therefore, with the present climatic conditions, i.e., no change in the average height of the old snow line, the area of wastage would need to be reduced to about 2 km^2. If the glacier would be removed somehow, it would certainly reestablish itself under present-day climatic conditions [84].

Recently LaChapelle [121] suggested a method whereby quantitative mass budget data might be obtained from aerial photography, if only the position of the equilibrium line is known at the end of the budget year, a topographic map exists, and the vertical gradient of net specific mass budget has been studied in the respective area. As yet, no detailed study of the vertical variation of net budget is available, but certain relations with latitude [67], and with continentality [151] are indicated. The lowest value obtained so far was found on McCall Glacier [100] in a subpolar continental environment. Different values of net budget gradients below and above the old snow line were reported from the Blue Glacier, and found on the Hintereisferner in a very similar way (Table 4, Fig. 1). This is apart from the different duration of ablation largely caused by differences in albedo, the area of nourishment having only one type of surface, whereas in the area of wastage albedo decreases sharply as ice appears on the surface. An intermediate gradient value is indicated on old firn snow, which becomes exposed in years with strongly negative mass budget. The value of the net budget gradient in the ablation zone of Hintereisferner, viz., about 1 m of

TABLE 4

HINTEREISFERNER, NET BUDGET GRADIENTS
(Average value of $\bar{b}$ for 100-m altitude increments)

	Ice Ablation m/100 m	Firn Ablation m/100 m	Accumulation m/100 m	Mean Specific Budget mm
Year 1955	1.05	—	0.25	+76
1958	1.05	0.57	0.20	−981
Average 1953–1959	1.00	0.58	0.23	−423
Blue Glacier 1958	1.00	—	0.30	−1700

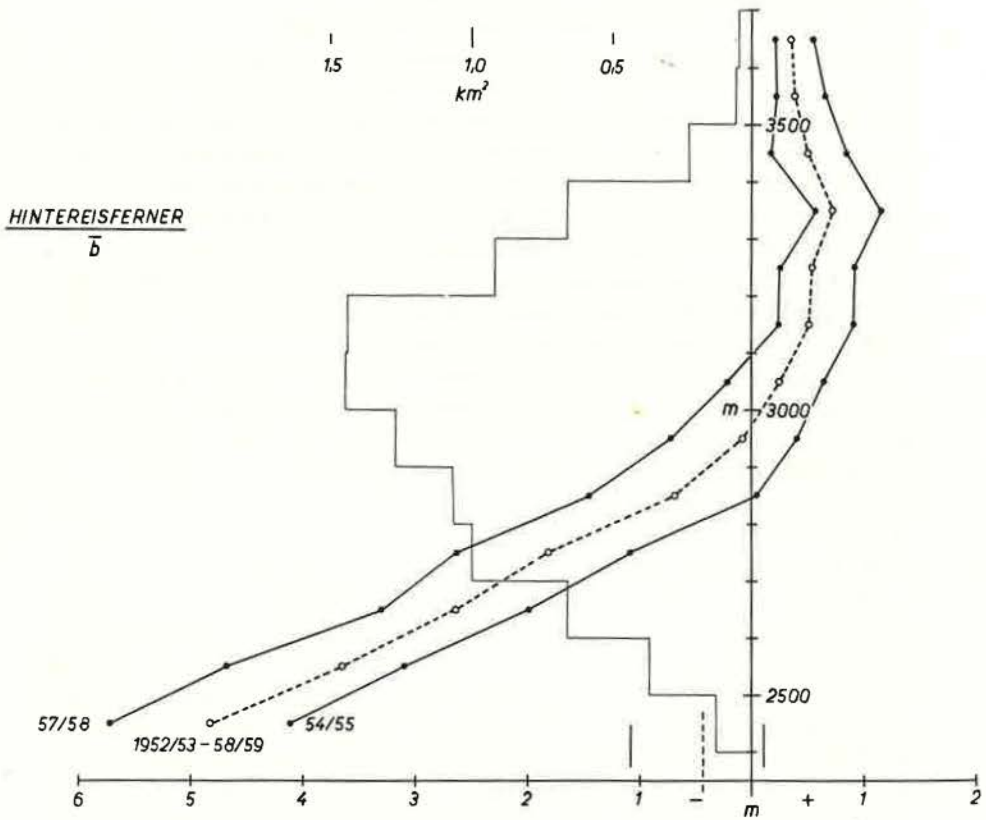

FIG. 1. Hintereisferner, Oetztal Alps. Specific net mass budget gradients, average values in meters of water for 100-m altitude increments. Most negative budget year: 1957/58. Only positive budget year: 1954/55. Average for 7 budget years: 1952/53–1958/59. Area distribution, km² for 100-m altitude increments.

water-equivalent per 100 m, is in agreement with Haefeli's value from the Aletschgletscher, and with the value reported by Lliboutry and his colleagues [132] for the Mer de Glace. There seems to be less variation from year to year in the gradient values obtained on Hintereisferner, than reported by LaChapelle [121] and Kalmynkina [94].

It should be mentioned that according to observations from the Hintereisferner the vertical ablation gradient proper, as measured during the main ablation period along profiles of similar albedo, i.e., either ice or snow, amounts to only about one-tenth of the vertical net budget gradient [176]. This should be expected if absorption of solar radiation is the main source of energy for ablation. The same was observed in the ablation zone of the Greenland Ice Cap [10].

Comparatively little has been done to relate glacier mass budget variations to variations of atmospheric circulation patterns. Even though the contemporaneous observations carried out during the IGY-IGC period proved highly valuable for a general understanding, for some problems this period was too short. Schytt [185] compared the regime programme on Storglaciären with a meteorological station: "one year's observations are useful, a ten-year period is very valuable, but it is not until it covers some periods with glacier advance and glacier retreat that it appears to full advantage." We should not restrict ourselves to insufficient cognition, merely because the data are troublesome to get, and what we need most urgently are mass budget observations covering periods of many years, and applying different methods, including hydrological ones, at least on a few glaciers. The best series available, based on uninterrupted direct observations without doubtful assumptions was initiated in 1946 on Storglaciären in Kebnekajse. It is quite interesting to compare the results from Storglaciären with mass budget data from the Hintereisferner, collected since 1953 (Fig. 2). The seven budget years 1952/53–1958/59 agree fairly well, but then both curves diverge sharply. In 1959/60 the mass budget total of Storglaciären was the second lowest observed, mainly due to smallest accumulation on record [184], but also caused by fourth strongest ablation. During the same budget year the Hintereisferner was nearly balanced, with an ablation period of only 95 days, and on Aletschgletscher a positive net budget was obtained [83]. Whereas the Alps between July and September 1960 were influenced by a well-developed frontal zone in a too southerly position, Scandinavia experienced a rather hot summer, and in general pressure in high latitudes was too high. This is a typical "low index" situation, shown in Figure 2 by means of deviations from the average height of the 500-mb level. In 1961–1962 the mass budget of Storglaciären went positive for the first time since 1948–1949, because of extremely low ablation [187] under the influence of cyclonic activity. At the same time the mass budget of Hintereisferner became seriously low, clearly exceeded only by 1957–1958, because of a dry summer with long duration of bright sunshine. This again shows clearly from anomalies of the height of the 500-mb level, which indicate increased zonal flow. The most pronounced deviations in both mass budget series appear therefore clearly related to anomalous patterns of atmospheric circulation, lasting through the ablation period.

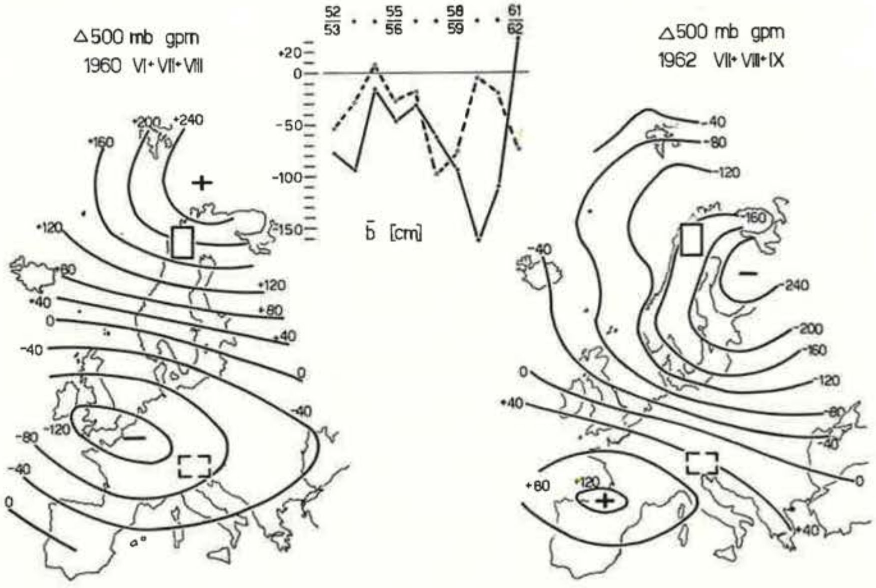

FIG. 2. Comparison of specific net mass budgets for Storglaciären and Hintereisferner, budget years 1952/53–1961/62. Atmospheric circulation anomalies for the summers of 1960 (left) and of 1962 (right) are shown as deviations from the average (1949–1958) height of the 500-mb level in geopotential meters.

On these lines characteristic differences in net mass budget figures, as observed during the IGY-IGC periods (Table 1) might be explained. The summer of 1958 was one of abnormally heavy ablation in western North America [149], as well as in the Alps [86], but not so much on Storglaciären [185], and was reported cool in the Altai [202] and on the Zentralny Tuyuksu Glacier, whose mass budget was found slightly positive [141]. On the contrary, most glaciers in western North America experienced balanced or positive net budgets in 1958–1959, whereas in Europe, the Soviet Arctic, and Central Asia negative net budget values prevailed. At the same time glaciers of Jan Mayen were reported advancing [51] because of increased precipitation, in connection with increased atmospheric activity [122]. Increased accumulation also caused an advance of Hans Glacier, South West Spitsbergen [107], and stationary glacier fronts were found dominant in Peary Land [42]. Changes in the accumulation regime on Novaya Zemlya from firn-type to ice-type nourishment were shown to be related to temperature fluctuations, introduced by fluctuations of circulation patterns [41, 166, 198]. Based on rather doubtful assumptions with respect to the height of the firn line, and on insufficiently proved correlations between ablation and average summer temperature, and between accumulation and average winter temperature, changes in the regime of the Novaya Zemlya Ice Sheet were traced back until 1896 by Chizhov and Koryakin [32]. Predominant negative net mass budget was found, but little more should be deduced from this paper.

Another important point indicated by the mass budget investigations on Hintereisferner is the dependence of one year's mass budget on that of the previous year [87]. If after a summer with a strongly negative mass budget the accumulation area ratio is low, then the same amount of heat supplied by the atmospheric conditions during the following year will be utilized to a higher degree because of lower average albedo, and consequently a greater mass loss will be found, provided the amount of winter snow remains the same. In this way some sort of an amplification factor is introduced if years with deviations of the same sign follow each other for any length of time. This acts in addition to the consequences of Nye's important theory [159] which finally will lead to a quantitative understanding of the response of glaciers to climatic changes, provided appropriate field data can be collected in future. As pointed out by Tronov [201, 202], there are elements of "self-evolution" to be considered, i.e., the budget of a glacier should be treated as a function of climate, relief, and of the glacier itself. With ice sheets of the size of Antarctica the difficult problem of glaciers influencing the climate becomes important. In all calculations of build-up times the mass budget rate should be taken rather than the accumulation rate [89], and in calculations of shrinking times the amount of heat necessary to melt the ice should be considered. Then it might prove more difficult to build up or remove an ice sheet in short periods of time without appreciably changing the climate [213]. At least for the first stages of building up of an ice cap a rather sharp deterioration in climatic conditions seems necessary in order to get high budget rates. Shrinking certainly becomes accelerated, if albedo is lowered. Therefore ice caps surrounded by dry land consume more heat during the same warming period than ice caps which retain a high albedo, because they are surrounded by the sea. This might help to understand the still existing Antarctic and Greenland Ice Caps [80]. As Kotlyakov pointed out [111], the evolution of glaciers on earth is rather complicated at present, different in intensity and possibly in sign, even though the changes of climate have the same tendency.

ACKNOWLEDGMENTS

The author is indebted to World Data Centers A, B, C (glaciology) and to numerous colleagues and friends who contributed to the paper by sending reprints and information. I. Lauffer, Dr. R. Rudolph, and I. Vergeiner assisted in preparing the manuscript.

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CHAPTER 16

ICE AND ITS CHANGES

P. A. Shumskiy, A. N. Krenke, and I. A. Zotikov

During the IGY–IGC period great progress was made in glaciology owing to simultaneous observations over most of the iced areas according to the single program, to studies of all interdependent geophysical processes, and to a considerable extension of a physical theory of ice phenomena. A full analysis of the IGY–IGC glaciological data will require more time, but it is possible even now to draw a number of general conclusions. Main attention here is drawn to the role of ice in the geophysical processes and to general laws of its distribution and changes.

1. Ice and External Heat Exchange

Temperatures lower than the melting point of ice are limited by radiation processes to, at an average, a 100-km spherical belt between warm thermosphere above and the hydro- and lithospheres below. The lower approximately 10-km boundary layer of this cold belt, or cryosphere, is characterized by higher density, temperature gradient, and conductive and convective heat exchange rate. Here phase transformation of H_2O and its transfer, forming a part of the "water" circulation on the earth, play a substantial role. This lower part of cryosphere is the area of ice distribution. (In a narrower sense, cryosphere is meant only as a sphere of ice distribution.) Below it there are no thermodynamic conditions for ice existence; above it there are practically no H_2O molecules (their concentration is of the order of 10^{-6}), for the tropopause with its very low temperatures acts as "a trap for water vapor" (Bates [5]).

Atmospheric precipitation is usually connected with condensation of water vapor from supercooled droplets into ice crystals that fall out of clouds [8, 9]. Whether they reach the earth surface in the form of solid