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Working Group on Arctic Glaciology

MASS BALANCE OF ARCTIC GLACIERS

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1. INTRODUCTION

1.1. Objective

Present global climatic changes seem to be more discernible in the Northern Hemisphere's high latitudes than in any other area (Folland *et al.,* 1990; Wigley and Barnet, 1990). Reasons for the causes and scale of climatic warming are the subjects of considerable debate at present. Owing to the quick response of the land ice masses, the status of the Arctic glaciers can be used as a reliable indicator of the climatic changes. Regardless of the Greenland ice mass, these glaciers include a great variety of small ice caps and domes as well as mountain glaciers. About two-thirds of the Earth's small glaciers are located in the Arctic. If completely melted, these would raise sea level by about 50 cm (Meier, 1984). Their current rapid melting in some areas supplies the ocean with fresh water, which results in both local (desalination of the coastal sea water) and global (sea level) changes.

The uncertainty in identifying the causes of the observed sea level rise over the past century, and in forecasting future changes, is partly due to an incomplete knowledge of the mass balance of the Earth's ice bodies. A better knowledge of the mass balance components is critical for the determination of the overall balance of the ice masses and, thus, an understanding of the contribution to sea level rise. A dearth of continuous mass balance observations is the main cause of uncertainty in these calculations.

Most of the Arctic glaciers are warmer than those of Antarctica. further, as many of the Arctic ice masses are temperate, they might be expected to show a more rapid response to climatic warming than those of Antarctica. Circumpolar studies of Arctic glaciers are thus quite likely to give a measure of present-day climatic change and, by extrapolation, a warning of future changes.

The Working Group on Arctic Glaciology (WGAG), International Arctic Science Committee (IASC), is trying to co-ordinate research into the modern state and evolution of the Arctic glaciers and those of adjoining areas. The First Annual Meeting of the Working Group, which was combined with the Workshop on Mass Balance of Arctic Glaciers, took place in Wisla, Poland in 1994. At that meeting, it was decided that it would be useful to compile a report on the state of existing knowledge of glacier mass balance; this is to be regarded as the first step in understanding glacier reaction to climatic change.

The mass balance of some glaciers of high latitudes is listed in the publications of the World Glacier Monitoring Service (Müller, 1977; Haeberli and Müller, 1988; Haeberli *et al.*, 1993, 1994) and some glaciers are reviewed in separate papers. No review concerning the mass balance of all the Arctic glaciers is yet available. The aim of this report is to fill this gap between the published and original data from members of the Working Group and to synthesise, as completely as possible, our knowledge of the mass balance of the Arctic ice masses. The sole object of this report is to present all the available data and to give a general interpretation of its significance. Deeper analyses are beyond the scope of the present work. This kind of study has been supported by the IASC-WGAG since the Wisla meeting. The first such interpretation of the data collected has recently been prepared by Dowdeswell *et al.* (in press). The Editors and Authors hope that the report will be useful to all specialists who currently study problems of the recent and current global climatic changes.

1.2. General description of the land ice masses in the Arctic

The report concerns the glaciers of the Arctic, defined as glaciers developed within the northern Polar Circle; however, owing to the direct interaction with the adjacent areas, glaciers situated beyond the Arctic Circle are also included. The area of interest is shown in Fig. 1.1.

A complete inventory of Arctic glaciers has yet to be made; therefore, data on the number of glaciers, their area, the methods of data acquisition, their distribution, accuracy and times of collection are extremely patchy. Only for Svalbard (Hagen *et al.*, 1993), northern Scandinavia (Østrem *et al.*, 1973), some areas of Russia (cf Govorukha, 1989; Dolgushin and Osipova, 1989) and parts of Greenland (Weidick *et al.*, 1992) is there a comprehensive list of glaciers. By contrast, the data sets for the Canadian Arctic, the Russian Arctic, Iceland, Alaska and the greater part of Greenland are somewhat limited. The completion of the list of glaciers is not the principal objective of this report; nevertheless, it remains a proper objective for a complete picture of mass balance for the glaciers of this area and it is hoped that it will not be too long before this is achieved.

Fig. 1.1

Land ice masses in the northern circumpolar region cover more than 2 075 000 km^2 (including Greenland). They are not equally distributed in the Arctic territories (Tables 1.1, 1.2 and 1.3). The largest portion of Arctic ice by far lies in Greenland (1 726 400 km^2). The volume of the Greenland Ice Sheet, together with the ice caps and glaciers of the island, is estimated to be about $3*10^6$ km^3, whereas the volume of all the other Arctic glaciers is about 60 000 km^3. Similarly, the available data concerning the mass balance of the glaciers are, themselves, not equally distributed in the Arctic (curiously, the weakest data set is that relating to the largest ice mass, i.e. that in Greenland (Fig. 1.1). The best sets of data are those relating to northern Scandinavia, the Canadian Arctic and Svalbard. The periods during which the data were collected also vary from place to place, likewise the methods of measurement on individual glaciers. Nevertheless, the set of collected data, as presented here, may be regarded as a reliable basis for studies on mass balance changes in the Circum-Polar region.

The Arctic glaciers comprise various morphological types and it is possible to find a complete range of size and shape between the extremes of the continental ice sheet of Greenland, on the one hand, to the glacierets and firn or snow patches typical, for example, of the Wrangel Island glaciation on the other. The hydrothermal structure of glaciers also varies widely, from the temperate glaciers of Iceland to the cold-based glaciers of the Northern Urals and northern Alaska and in numerous places in other regions. It is also possible to distinguish a large variety of structures within the polythermal type; indeed, polythermality of glacier ice seems to be the commonest feature of all the Arctic glaciers. The dynamics of the ice masses also varies within the area of interest. The fastest ice stream on Earth - the Jakobshavn Glacier (Greenland) flows 200-400 times faster than a typical outlet-glacier in the Canadian Arctic or in Svalbard. Many glaciers in Arctic areas are of the surge type, with periodic sudden acceleration of flow. By contrast, it is possible that some small ice caps and glaciers are virtually inactive; their flow rate is close to zero. In general, such features of the ice masses are related to local climatic conditions (with the exception of the surge type glaciers).

The major source of moisture for the Arctic region is, of course, the Atlantic Ocean. Influences of the Pacific air masses are important, and then to a very limited extent, only for the glaciers of the Alaskan and Brookes Ranges. Glaciers in the Atlantic sector of the Arctic are warmer and wetter and their velocities are faster than those in the more continental environment (i.e. those in Asia and the western Canadian Arctic). Mass exchange in the oceanic climate is much more intensive that that in the continental High-Arctic areas. Nevertheless, mass balance of such different glaciers is an indicator of climatic change, both in the milder oceanic regions and in regions which have a severe continental climate. The report attempts to give background data for more detailed studies of the relations between mass balance and glacier types and fluctuations of climatic conditions.

Tab. 1.1 1.2 1.3

1.3. Remarks on methods

Studies of mass balance of ice masses are always time-consuming, very often logistically difficult and sometimes even dangerous. In particular countries, there is a long tradition of glacier mass balance measurement; but the method of collection, the field techniques and data calculation and presentation differ greatly. Owing to these factors, glaciologists from various countries (and sometimes even from different institutions from the same country) have used slightly different terms in their mass balance reports. Therefore, comparison of results from different data sources is often difficult.

During the International Hydrological Decade (1965-1975) definitions of glacier mass budget terms were proposed and internationally accepted (Meier, 1962; UNESCO, 1970). Nevertheless, such differences still exist, but they are not as distinct as before. The issue is thoroughly discussed by Østrem and Brugman (1991).

The principal terms relating to mass balance measurement are explained in the "Glossary" of this report. The greatest difficulty and/or inaccuracy in the comparison of the various data sets results from the varying application of measurement and reporting methods i.e. the "traditional" stratigraphic system, fixed date and the combined systems.

The Authors of the regional chapters in this report have described the methods and systems used in their own areas. For some, the methodology is unclear. Therefore, in tables which report the data, the original Author's terms are used (i.e. winter balance or accumulation, net balance or annual balance, etc.). In this report, all the balance data are expressed in metres of water equivalent (w.e.). Balances for the glaciological years (from the beginning of the accumulation season to the end of the ablation season) are denoted by year subsequent to the winter season (e.g. 1986 means the balance year 1985/1986). It must be emphasised that, for some glaciers, this work presents data recently and carefully recalculated by the Authors or the responsible agencies. These may differ from previously published results.

The Third International Geophysical Year (1957/1958) was very important for the initiation of studies on a number of glaciers, including mass balance measurements for some of them. Therefore, presentation of diagrams of mass balance results from glaciers representative of particular sectors of the Arctic relates to the period 1958-1995. This represents the longest series of observations for the

High-Arctic glaciers. The only notable exception in the Sub-Arctic area is the mass balance series for Storglaciären (Sweden).

Despite the efforts in trying to achieve a complete set of accurate data, the Editors are only too aware of the likelihood of many deficiencies in this report.

2. REGIONAL OVERVIEW

2.1. Alaska

(by Edward G. Josberger)

Introduction

The north western flank of the North American Cordillera is covered by vast snow and ice masses. The Rocky Mountain System lies entirely within the Arctic Circle in Alaska and contains the glaciated Brooks Range. The heavily glaciated Alaska Range is the northern portion of the Pacific Mountain System. The Alaska Range lies outside of the Arctic Circle but is included in this report because of the important glacier mass balance data that has been collected there. The largest glaciers in Alaska lie along the maritime southern and western shores of the Pacific Mountain System. Only one of these glaciers is included in this report, the well studied Wolverine Glacier in the Kenai Mountains of south-central Alaska which has a long time series of mass balance observations (cf Table 2.1). The cited glaciers and locations outside of the Arctic Circle are considered important for the purposes of this compilation. The Brooks Range glaciers represent Arctic continental conditions, glaciers in the Alaska Range are mostly continental, because of one or two orographic barriers that most storms must pass over. Wolverine Glacier represents the Circum-Arctic maritime climatic conditions of this sector of the Arctic. Despite the vast number and size of the Alaska glaciers, mass balance data are available for only very few glaciers (Fig. 2.1). Mass balance data are obtained by direct measurements and by reconstruction from analysis of changes in geometry.

Fig. 2.1

Mass balance data results

ALASKA RANGE

Gulkana Glacier

Gulkana Glacier is a valley glacier located on the south facing side of the eastern Alaska Range (Table 2.1). The glacier covers an area of 19.3 km^2 within the drainage basin (31.6 km^2) lies several smaller glaciers and perennial snowfields (2.9 km^2). There is some evidence that the glacier may have surged in the 1940's (Meier *et al.,* 1971). The glacier terminus retreat has been reported in the last decades. Mass balance studies began in 1965, during the International Hydrological Decade (Meier *et al.,* 1971) and carried out by the United States Geological Survey (USGS). The stratigraphic system of measurement was used and reported for the periods: 1966-1990 (Müller, 1977; Haeberli, 1985) and presented in Table 2.2. Combined system mass balances have been reported elsewhere including both net (stratigraphic) balances and annual (fixed-date) balances. The mass balance components and the cumulative net balance curve are shown in Fig. 2.2 and 2.3 respectively.

Fig.2.2 2.3

Other glaciers

There are mass balance data for four other glaciers in the Central Alaska Range for the period 1981-1983 (Table 2.1). The fixed date measurement system results are listed in Table 2.3. It is worth noting that West Fork Glacier began a major surge in fall/winter 1987 and continued in 1988. The surge caused the terminus to advance to a position near a moraine produced by the previous surge.

BROOKS RANGE

McCall Glacier

McCall Glacier lies in the northern most part of the Romanzof Mountains, northeastern part of the Eastern Brooks Range (Table 2.1). McCall Glacier resides in a mountain climate dominated by the proximity of the Arctic front. Approximate average annual air temperatures were about -12^{o}C at 1700 m a.s.l. The glacier occupies a north-facing valley and covers an area of 7.0 km^2. A polythermal ice temperature structure is reported for McCall Glacier. It was studied during the International Geophysical Year in 1957/1958 and from 1969 to 1972 during the International Hydrological Decade (Table 2.4). Recent studies focused on surface geometry changes along the longitudinal profile in 1993. McCall Glacier has a low mass-exchange rate. Annual accumulation and ablation averaged from 1970 to 1972, were +0.16 and -0.30 m respectively. Mass balance data for 1969-1972 were published by Trabant and Benson (1986) and are summarized in Table 2.4. The combined balance methods were applied and annual (fixed date) values reported. The mean ELA for that period was 2050 m a.s.l. The terminus retreat between 1958-1993 has been measured.

Analysis of photogrammetric and GPS surveys of glacier surface elevation changes support reconstruction of long term mean mass balance (Rabus *et al.*,1995). Mean mass balance during 1958-1971 was -0.13 m/year and -0.33 m/year for the period 1972-1993. Negative net balance is noted in a majority of the years when records were kept. Glacier thinning and terminus recession are notable features for the area. The only terminus advances are due to surge type behavior of some glaciers, which are noted.

KENAI MOUNTAINS

Wolverine Glacier

Wolverine Glacier is a valley glacier in the Kenai Mountains on the Kenai Peninsula, south-central Alaska (Table 2.1). The glacier lies 12 km southwest of Kings Bay, a fjord extending inland from the Gulf of Alaska. The Kenai Mountains are fairly low, but host an extensive ice field including hundreds of smaller glaciers. The glacier and perennial snowfields constitute *c.* 72% of the Wolverine Glacier basin area. The accumulation area of the glacier lies in a gently sloping basin of *c.* 4 km wide. From the basin the ice descends by a steep icefall to *c.* 5 km long valley tongue that is 1.5 km width. Despite being located in the precipitation shadow of the Sargent Icefield, Wolverine Glacier has a maritime climate characterized by fairly high precipitation (Meier *et al.*, 1971). The glacier mass balance seems to be fairly representative of valley glaciers of the maritime Circum Arctic Alaska (Table 2.5).

2.2. Canadian Arctic

(by Roy. M. Koerner)

Introduction

In context of this report, Arctic Canada is considered to include the Queen Elizabeth Islands and Baffin Island. The area contains the Earth's largest glacier cover in the northern hemisphere outside Greenland. Table 2.6 lists the ice caps and glaciers where mass balance measurements have been made, the years in which they were made and the elevations at which they were taken. The glaciers may be classified into four types as follows.

1. Dynamic ice caps and their outlet glaciers. These comprise the greater part of the ice cover, the largest ice caps each covering about 20 000 km^2. Thicknesses range between 300 and 800 m (Koerner, 1977). Velocities of the outlet glaciers vary seasonally according to the presence of basal meltwater during the summer (Iken, 1974). Mean velocities of 30 m/year are common.
2. Smaller ice caps (i.e. < 90 km^2) are stagnant and are mostly located on plateaux 500-800 m a.s.l. They vary in thickness between 20 and 60 m. The Meighen Ice Cap is the exception, as it lies at an elevation of only 130-250 m a.s.l. and reaches a thickness of 120 m. It owes its existence to the summer cooling effect of the nearby Arctic Ocean.
3. Ice shelves fringe the northern coast of Ellesmere Island, bordering the Arctic Ocean. The Ward Hunt is the most extensive, covering an area of 50 x 10 km with a thickness of 40 m (Jeffries, 1987).
4. Valley glaciers with catchments other than ice caps. There are many glaciers of this type and some have been centres of major glaciological research including continuous mass balance programmes (Table 2.6).

Fig. 2.4

Methods

The methodology used in the field for these ice caps varies according to the type of accumulation/ablation and/or the agencies involved in the measurements. All are covered by the stratigraphic method where the balance year is defined by the time of termination of melt rather than a fixed date for measurement. In most cases, mass balance measurements are made once a year, in the spring. At that time, measurements are made of snow depth and density (i.e. the winter balance) and of the previous year's mass balance (i.e. that which ended the previous summer). The time taken to make these measurements varies between two days and a week.

Stake height changes form the basis of measurements in all zones of the glacier or ice cap. However, while this method is satisfactory in the ablation zone, it can be used only as a guide in the firn zone. This is because compression of firn between the base of the pole and the snow surface effects a change in height of the pole without any mass change. The deeper the pole base, the greater the error. For example, the same pole sites have now been used for 30 years on the Devon Ice Cap. Before a pole becomes buried, another is tied to it. Thus some poles are now buried over 10 m deep. Errors caused by simply measuring the pole height would be extreme in this case. In the percolation zone, i.e. where meltwater percolates no deeper than the surface balance year, layer measurements can be made by probing to a board near the marker pole. Density measurements at each site convert the depth to water equivalent accumulation. However, wherever percolation penetrates deeper than the surface balance year layer, mass balance is measured either with the use of percolation trays (in the case of the Devon Ice Cap) or by repeated vertical density measurements from the surface to a depth greater than the previous balance year (the White Glacier). In the first case, a 30 x 30 cm aluminum tray is buried between two marker poles in the spring of each year. The tray is placed on the previous summer surface under the winter snow. Percolating meltwater in the following summer is caught by the tray where it refreezes and its mass is measured the following spring. The method is used to ensure that meltwater does not percolate out of range of the annual measurements. In the second case, density measurements are repeated each year to depths considered below the range of percolation. Measurements made in the current year, when compared with those made the previous year, allow for calculation of meltwater which percolated below the recognizable balance year firn layer. In the upper parts of the superimposed ice zone, both these methods may prove inadequate. This is because parts of this zone accumulate solid ice only when viewed over several years. In many years, the zone accumulates firn. A sequence of such years, with a much percolation, usually causes the development of a series of thick ice layers and even thicker firn layers. The spatial variability is very high. Thus, in some years, the balance in this zone is assessed by interpolation between the firn accumulation zone above and the lower parts of the superimposed ice zone below (i.e. where there is either accumulation by superimposed ice or ablation). Pole height changes within the superimposed ice zone may be used to "fine-tune" the interpolation. The lower areas of the zone of superimposed ice zone pose no problem, as the changes from year to year involve ice rather than firn on an annual basis. Mass balance in the ablation zone is much simpler and is accomplished by measuring pole height changes to the ice surface. The Geological Survey of Canada (GSC) has automatic meteorological stations on two ice caps. The autostation at the top of the Devon Ice Cap records year-round air and snow temperature. There are now three autostations on the Agassiz Ice Cap. That at the top of the ice cap has a complete array of sensors recording short-wave solar radiation, wind speed and direction, air and snow temperature, and changing snow surface level. The station in the superimposed ice zone records air and snow temperature and changing snow or ice surface level (up in winter, down in summer). The logger in the ablation zone is of interest mainly for its melt season records of ice level lowering and air temperature. All will be used to develop transfer functions to relate climate and mass balance and for the interpretation of ice core records.

An algorithm is used in data reduction from the ice caps monitored by the GSC (Table 2.6). The algorithm estimates the balance of poles that have melted out or have disappeared. This is done as poles which melt out are usually those in the area of highest melt. If not included in the final calculation, the balance will be less negative than the real value.

Mass balance data results

DEVON ISLAND

Devon Ice Cap

Mass balance measurements have been conducted on the northwest side of this ice cap since 1961 (Table 2.7). No measurement was made in the summer of 1969 so that a two year balance for the years ending in the summers of 1968 and 1969 only is available. Over the period of measurements, the firn line has occasionally fallen below the ice cap edge so that the rock plateau surrounding the ice cap has entered the accumulation zone. Conversely, the equilibrium line has, on two occasions, risen above the long-period firn line so that run-off emerged from the firn zone in excess of the annual snow accumulation. The altitude versus balance relationship, developed from a regression analysis of the pole measurements, is used to calculate balance in the ablation zone; an elevation interval of 100 m is used. The mean of the pole/tray measurements at each 100 m elevation interval is used to calculate the balance in the accumulation zone. The mass balance components and the cumulative net balance are presented on Fig. 2.5 and Fig.2.6 respectively.

Fig. 2.5 2.6

ELLESMERE ISLAND

Agassiz Ice Cap

Values of annual mass balance for a part of Agassiz Ice Cap have been calculated for each altitude interval using the same techniques as on Devon Ice Cap. As an accurate map is not available to compute the areas, the final step (area * balance) is not presented. Thus, the values each year are the sum of values derived from the regression analysis of pole values versus elevation (Table 2.8). The network extends only into the superimposed ice zone. Measurements above this elevation are not considered accurate enough for presentation.

Ward Hunt Ice Rise and Ice Shelf

The most extensive ice shelves in the northern hemisphere occur along the north coast of Ellesmere Island, adjoining the Arctic Ocean. Like the Meighen Ice Cap, survival of these ice bodies is heavily dependent on the cool summers generated by the melting ice cover and cold sea water of the Arctic Ocean. Stakes have been measured on both the ice shelf and ice rise of Ward Hunt Island on an intermittent basis between 1958 and 1986 (Table 2.9).

MEIGHEN ISLAND

Meighen Ice Cap

This ice cap is stagnant and only a small part at the top of the ice cap has an overall positive balance for the 34 year period (Table 2.10). Accumulation is usually in the form of superimposed ice but also, in some years, as firn overlying new superimposed ice. The area of the ice cap has diminished but the extent of this is not known. As the central part has gained very slightly in thickness and the margins have retreated, the slope has increased. Because of the decreasing area, some of the original pole sites are no longer applicable as the areas are now exposed rock. The true mass balance is, therefore, affected by shedding of high ablation zones.

Fig. 2.7 2.8

MELVILLE ISLAND

Melville South Ice Cap

This ice cap is also stagnant but although at a higher elevation than Meighen Ice Cap, has a completely negative balance over its entirity (Table 2.11). Measurements on this ice cap have not been made as regularly as on the others so that there is only the overall balance for the 1975-1980 period.

AXEL HEIBERG ISLAND

The largest ice bodies on Axel Heiberg Island are the Müller Ice Cap and Steacie Ice Cap. No measurements of the balance of an entire ice cap have ever been completed, but a long series of measurements is available from a valley glacier, the White Glacier and a shorter series from a niche glacier, the Baby Glacier (Table 2.12). These programmes were initiated by McGill University in 1959-60, and continued, first by the ETH, Zürich and later by the Trent University. Cogley *et al.* (1995) describe in detail the techniques used and the problems encountered. Uncertainty in annual mass-balance estimates for the White Glacier is estimated therein as 0.20 - 0.25 m/year.

General trends and recomendations

No persistent trends are observed in any of the data. There is a trend to minimum snow accumulation in the seventies but this shows no effect on the mass balance on the same ice cap. It would appear from comparisons with ice core records (Hattersley-Smith *et al.*, 1975; Koerner, 1979) and some of the early glaciological works (Hattersley-Smith *et al.*, 1955; Hattersley-Smith, 1961) that the period of mass balance measurements (i.e. since the 1950's to present) has followed one of substantially greater negative balance which became most pronounced between the mid-1920's and late 1950's (Hattersley-Smith, 1963). Changes to the ice caps appear to have been most pronounced in the ablation zones because melting has increased, while accumulation rates have shown very little change (cf Fig. 2.5 and 2.7). Detection of persistent trends which might be driven by „Greenhouse warming" and used to detect its effect, is difficult due to the variability inherent in the data. Using the variability the strength of the signal trend needed to emerge through the noise should be calculated. Alternatively, the persistance of such a trend may also be calculated. However, cumulative net balance for selected glaciers show a decrease of the ice volume (Fig. 2.6 and 2.8). Variation in the acumulation data is much lower than that in the ablation data largely because it is affected by a much shorter period of time i.e. about 6 weeks in the Queen Elisabeth Island compared with the annual values of snow accumulation.

The continuity of mass balance programmes in the Canadian Arctic is highly dependent on the principal investigator. In the past, with the clear exception of White Glacier, retirement or transfer of the principal investigator has meant the end of the mass balance measurement in that area. To ensure better continuity, the use of modern technology should be investigated. Airborne- and satellite-mounted sensors might be utilised in this respect. At present, the most applicable technology consists of airborne laser altimetry for monitoring volume changes. The footprint from most satellite sensors is at present too large for application to Canadian ice caps but ground-based datalogger technology might be used (and improved) for such measurements as snow accumulation and snow or ice ablation. Aditionally, automatic meteorological stations should be used at each glacier studied.

2.3. Greenland

(compiled by Jacek Jania)

Introduction

The enormous volume of ice, the many types of glaciers, the great variation in glacier flow and the significant differences in the glaciology of south-western and north-eastern areas of the country make Greenland a challenging prospect for the glaciologists.

Greenland ice masses can be classified into three morphological groups.

1. The inland ice (the continental-type ice sheet),
2. Local ice domes and ice caps,
3. Local valley and mountain glaciers.

Many glaciers and the ice sheet seem to be polythermal, but cold-based mountain glaciers and ice sheet margins are also present. In terms of their dynamics, the Greenland glaciers may also be classified into four groups.

1. Fast-flowing ice streams and fast-flowing tide-water glaciers in a state of a permanent surge,
2. Active tide-water glaciers,
3. Quiet outlets,
4. Surge-type glaciers and outlets.

The western part of the island is better known than the eastern. A glacier inventory of this part of Greenland has been compiled by Weidick *et al.* (1992).

Fig. 2.9

Mass balance data results

Despite the recent increase of interest in the budget of the Greenland ice sheet as an important factor in sea level change, the mass balance data from the island are very unsatisfactory (Warrick and Oerlemans, 1990; Hutter *et al.*, 1990). Half of the mass balance measurement sites relates to the slopes of the inland ice (e.g. van der Wal *et. al.*, 1995), the other half to local glaciers. Some of these concern smaller ice caps and glaciers of West Greenland (Fig. 2.9). Various methods have been used in the studies (stratigraphic, fixed dates, hydrological) and mass balance components have been evaluated from meteorological data and energy balance models (Braithwaite and Olesen, 1989; Braithwaite *et al.,* 1992). Precise survey of the glacier geometry changes using the laser altimeter method (Zwally *et al*., 1989; Thomas *et al.*, 1995) and wider studies of the ice sheet margin position in recent decades (Weidick, 1991) are a source of the indirect data. Ohmura and Reeh (1991) have summarised existing estimates of snow accumulation over the whole ice sheet.

An important part of the mass loss in Greenland is due to calving of the fronts of the outlet tide-water glaciers (Bauer, 1968; Weidick *et al*., 1992). Major icebergs flux is confined to fjords with deep proglacial troughs which continue into and under the ice sheet margin. These drainage channels act as large sinks for extensive parts of the Inland Ice. The largest example is Jakobshavn Isbrae, where iceberg production has been estimated to be between 26 km^3/year and 40 km^3/year. The other tide-water glaciers have significantly lower rates of movement and calving flux, i.e. *c.* 2 km^3/year and less (Weidick *et al*, 1992). The mass lost by calving amounts to *c*. 50% of the total ablation.

The mass balance data from Greenland may be divided into two groups.

1. Direct measurements of mass bala nce components, using field and remote sensing methods.
2. Indirect estimates and models of the mass balance of the inland ice.

The avaiable mass balance data are shown in Table 2.13 (ice sheet margin) and Tables 2.14, 2.15, 2.16 (local glaciers) and on Fig. 2.10 (mass balance components) and Fig. 2.11 (cumulative net balance). A summary of published calculations of the ice sheet mass balance is contained in Table 2.17.

Fig. 2.10 2.11

2.4. Iceland

(by Helgi Björnsson)

Introduction

The present climatic conditions and topographic features in Iceland (63°30' - 66°30'N; 14°-24°W) result in high glacierization. About 11% (11 200 km^2) of Iceland is covered by ice at present and almost all forms of glaciers are represented, from cirque glaciers to extensive plateau ice caps. Iceland is a mountainous country located in a region of high cyclonic activity at the border of cold polar air masses and warm air masses of tropical origin. The tracks of the atmospheric depressions crossing the North Atlantic usually lie close to Iceland. Further, the climate is affected by the confluence of warm and cold oceanic currents, namely a branch of the Gulf Stream and the polar East Greenland Current. The climate is maritime, with low summer temperatures and heavy winter precipitation. Averaged over the whole country, the mean annual precipitation is about 2000 mm but the maximum is above 4000 mm. About 80% of the annual precipitation falls in the months from September through May. At high levels on the glaciers most of the precipitation falls as snow. The average temperature for the warmest summer months is about 11°C along the southern coast and 8-9°C on the northern. On the highest parts of the main ice caps the average temperature is close to or below freezing throughout the year. At the glacier snouts which terminate at 100 m elevation, the ablation is typically up to 10 m of ice per year and about 5-6 m on those terminating at 700-800 m a.s.l. The accumulation area is typically 1.5 times larger than the ablation area.

Three glacier regions may be distinguished (Fig.2.12). The southernmost region follows the southern and southeastern coast and includes the ice cap Myrdasjökull (590 km^2) and southern Vatnajökull (8 200 km^2), where the firn line lies at about 1100 m a.s.l. The central region incudes the ice caps Langjökull, Hofsjökull (925 km^2) and the central and northern part of Vatnajökull where the firn line is at about 1200-1300 m a.s.l. The northern glacier region comprises the North-West Peninsula where the lowest level of the firn line in Iceland is observed, about 600 m a.s.l., and central northern Iceland, which has a typical alpine landscape where over 100 valley glaciers are located and the firn line is at 900-1000 m elevation. All glaciers in Iceland are of the temperate types and they are dynamically active. The most active glaciers flow southwards from the high plateaux of Vatnajökull and Myrdalsjökull. Velocities of the order of 1 m/day are common.

Fig. 2.12

The glaciers are responsive to climatic fluctuations, although many of them periodically experience catastropic advance due to surge. A general recession of the glaciers started in the 1890's and became quite rapid after 1930, but began to slow down during the 1960's. During that period the volume of Vatnajökull was reduced by the order of 5-10%. Since about 1970, a number of the most active glacier outlets have advanced, suggesting a positive mass balance since the 1960's for the main ice caps. These general trends have been interrupted by local short-lived advances of individual glaciers (ranging from a few hundred meters to 10 km). Such periodic surges, with return periods of several decades, have been observed in most of the large outlets of Vatnajökull. Surges are also typical of many outlets from Hofsjökull, Langjökull and Myrdalsjökull and they have also been observed in valley glaciers in the northern region.

Mass balance investigations

The first mass balance measurements were done on Vatnajökull in 1919 using tephra layers as a reference (Wadell, 1920). During the years 1936-1939, detailed mass balance measurements were undertaken on Hoffellsjökull, a southeastern outlet of Vatnajökull (Ahlmann and Thorarinsson, 1937a, b, 1938, 1939; Ahlmann, 1937, 1939, 1940; Thorarinsson, 1939). In 1951 and 1960 the winter balance was measured at a number of sites on Vatnajökull (Rist, 1952, 1961). Since 1954, systematic measurements of accumulation have been made in the Grimsvötn area in the interior of Vatnajökull (Björnsson, 1985). Sporadic measurements of accumulation and melting have been done on various parts of Vatnajökull. Further, mass balance measurements were carried out in 1966-1968 on the valley glacier Baegisarjökull, in northern Iceland (Björnsson, 1971).

Regular annual mass balance measurements have been carried out on only a few outlets of the ice cap Hofsjökull (Sigurdsson, 1989, 1991, 1993) and Vatnajökull (Björnsson, 1988; Björnsson *et al.* 1995a, b) since the early 1990's. In the table 2.18 are indicated observed glaciers and years of the balance measurements. Both winter and summer balances have been monitored by stratigraphic methods (snow depth soundings, shallow core drillings, density measurements and stake readings) along central flowlines. The balance year has been defined by the termination of melt.

VATNAJÖKULL

Mass balance measurements have been conducted on the western and northern outlets since 1991 (cf Table 2.18, Fig.2.12). Average specific mass balance values are given in tables below.

Tungnaarjökull

This glacier is a western outlet of Vatnajökull which drains from an elevation of 1660 m to 690 m. For three of the four years of measurements, the mass balance was positive (Table 2.19). The AAR is about 56% for zero net balance and the ELA about 1155 m a.s.l. A surge of the glacier has hindered mass balance measuremets since 1994. The area distribution of the glacier and its mass balance in 1993/1994 is given in Table 2.20.

Köldukvislarjökull

The glacier is a western outlet of Vatnajökull which drains from an elevation of 2000 m to 850 m a.s.l. Mass balance observations for the period of 1992-1995 are given in Table 2.21.

Dyngjujökull

Dyngjujökull drains Vatnajökull northwards from an elevation of 2000 m to 700 m a.s.l. This glacier represents the central northern outlets of Vatnajökull. It is located within the active volcanic zone and an abundant ash cover enhances melting in the ablation area. The net mass balance has been positive for all four years of measurements since 1992 (Table 2.22). The mass balance components and cumulative net balance are presented on Fig. 2.13 and Fig. 2.14 respectively. This is also the case for the year 1995, when the neighbouring glaciers showed negative mass balance. The reason for this is an exceptional area distribution, with 36% of the total area located between 1500 m and 1700 m elevation. The mass balance components values for particular altitudinal zones are presented in Table 2.23.

Fig. 2.13 2.14

Bruarjökull

This glacier is the largest of the northern outlet of Vatnajökull. It drains from an elevation of 1800 m to 580 m a.s.l. The main outlet is fairly flat and fluctuations of the ELA affected large areas. This large outlet is located outside the active volcanic zone but receives heavy precipitation because of its proximity to the eastern coast of Iceland. The mass balance has been positive for two of the last three years (Table 2.24).The glacier net balance equals zero for values of AAR at about 60%.

Sidujökull

Sidujökull is a southern outlet of Vatnajökull which drains from about 1700 m to 600 m elevation. Mass balance measurements were made in 1992 but, since then, a surge has made further measurements impossible. The results for the glaciological year 1991/1992 are as follows: winter balance *c*. 2.10 m; summer balance *c*. -1.60; net balance *c*. +0.50; ELA = 1050 m a.s.l.; AAR = 63%

HOFSJÖKULL

Satujökull

Satujökull is a northern outlet of Hofsjökull which drains from 1700 m elevation down to 850 m a.s.l. It is representative of the central area of Iceland but in 1990 the glacier was covered by volcanic ash from the volcano Hecla and this markedly affected the summer balance of 1991 (cf Table 2.25).

Conclusions

The mass balance measurements from Vatnajökull and Hofsjökull show high interannual variability, influenced mostly by significant variations in the summer balance. A predominance of positive balance years is noted. On Vatnajökull, all the measured outlets had positive mass balance in 1992 and 1993. In 1994 the western outlets had slightly negative balance but snowfall during the summer slowed down the ablation on the northern outlets, so that they showed positive net balance. In 1995, all outlets had negative mass balance except Dyngjujökull due to its unique area distribution. On northern Hofsjökull, half of the years since 1987 have shown positive mass balance and one of the years which had a negative mass balance is not climatically representative, because the highly negative summer balance was due to volcanic ash being spread over the glacier, therby lowering the surface albedo.

The mass balance was, in general, negative up to the 1960's but the advance of some glacier outlets since the 1970's suggests a positive mass balance since the1960's for the main ice caps.

2.5. Svalbard

(by Jon Ove Hagen)

Introduction

The Svalbard archipelago is located between 76° and 80°N and 10° and 33°E (Fig.2.15). It is the northernmost landmass in the European Arctic and has a variety of small- and medium-sized glaciers. The total ice volume is *c*.11 000 km^3 (Hagen *et al.*, 1993). Due to its position at the northern extremity of a zone of rapid transfer of heat through the Norwegian Sea, Svalbard is particularly sensitive to climatic change. Climatic change at the beginning of the century, particularly a warming of the atmosphere, has had a profound effect on mass balances and retreat of calving fronts. The climate of the area is strongly influenced by the North Atlantic Current, a branch of the Gulf Stream. On the western coast of Spitsbergen, the average annual temperature is about -6°C; further inland, it is slightly colder and more continental. The warmest month, July, has an average temperature on the western coast of about 5-6°C whereas, in the coldest period, January-March, it is about -15°C. Precipitation is normally low, about 400 mm annually on the western coast, and half as much in the central inland areas. Precipitation is higher on the glaciers due to an orographic effect but it seldom exceeds 2-4 m of snow. The frequent easterly winds, caused by low pressure systems passing through the Barents Sea, bring the highest precipitation in the eastern central part of the archipelago. About 60% of Svalbard is covered by glaciers of various types. The ELA is only 200 m a.s.l. in the south-east part of Spitsbergen but more than 800 m in the central northern part; this reflects a more continental type of climate in the latter area.

Fig. 2.15

Mass balance investigations

In 1950, the Norwegian Polar Institute started the first systematic mass balance studies on Finsterwalderbreen on the southern side of Van Keulenfjorden. These expeditions took place every other year from 1950 to 1966. We therefore have only net mass balance data given as mean values for every second year during this period. In 1966, investigations were started in the Kongsfjord area on

Brøggerbreen (6.1 km^2) and, a year later, on Lovénbreen (5.5 km^2). Both basins are close to the Ny-Ålesund (79°N; 12°E) on the northwest coast of Spitsbergen. These measurements have been carried out yearly since 1966.

Both accumulation and ablation have been measured by the direct glaciological methods: snow sounding profiles, density measurements and stake readings. Russian glaciologists started systematic annual mass balance measurements in 1966 on Vöringbreen in Grønfjorden. In the period 1973-1976, they extended the programme to three other glaciers, two in west-central Spitsbergen and one on the east coast (Fig. 2.15; Table 2.26). The results correlate well with the Norwegian recordings. Polish researchers have studied the mass balance on Hansbreen (57 km^2) in Hornsund, on southern Spitsbergen, since 1989 and its front position has been mapped for 30 years (Jania 1988; 1994). French scientists, in co-operation with Norwegian, have also carried out indirect measurments of mass balance through shallow core drilling and detection of radioactive reference layers. These investigations indicate the mean annual accumulation at the drill sites since the layers were deposited. Several cores at different altitudes in the accumulation area will permit the calculation of the accumulation area ratio and thus indicate the net mass balance for the whole glacier (Pourchet *et al.*, 1994). Both the Norwegian and the Russian mass balance measurements have been carried out on relatively small (2-6 km^2) isolated cirque- or valley-glaciers close to the coast (cf Table 2.26). Mostly, these lie below 500 m a.s.l. Only sporadic meaurements have been made on the larger glaciers and ice caps. Therefore, in 1987, mass balance investigations were started on Kongsvegen (105 km^2).

Most of the glaciers in Svalbard are of the surge type. It is therefore difficult to use the front position of a single glacier as a climatic indicator. Since most glaciers in Svalbard are slow-moving, the front will shrink and retreat between surges. The front position, therefore, gives little information on whether the total ice mass is growing or shrinking. Mass balance measurements are therefore necessary to calculate the total volume change accurately.

Mass balance data results

Finsterwalderbreen

Measurements on Finsterwalderbreen have shown a steady decrease of the glaciers, with a mean net balance of -0.25 m/year (w.e.) during the period 1950-1968 (see also Table 2.27)

Brøggerbreen and Lovénbreen

Reliable spot measurments of precipitation are difficult because most of it is associated with strong winds and snow drifting. At Ny-Ålesund, the meteorological station is situated only 5-6 km from the glaciers. However, at the station, the correlation between the measured winter precipitation from September to June and the snow accumulation, as measured by sounding profiles over the entire glacier surface, is not close. During the 14-year period, 1974-75 to 1987-88, the correlation coefficient was 0.63 (Hagen and Liestøl, 1990).

The mean winter accumulation on Brøggerbreen during the period 1967-1993 is 0.71 ±0.16 m (w.e.) and, on Lovénbreen, 0.75 ±0.18 m (w.e.). As can be seen in Fig. 2.16, the annual variations are fairly small. The altitudinal increase of snow accumulation has a fairly constant gradient 0.10 m (w.e.) per 100 m. Trend analysis of the measured winter balance shows a slight increase of the winter accumulation during this period. During the observation period (1967-93), the mean summer ablation has been -1.15 ±0.31 m (w.e.) on Brøggerbreen and -1.09 ±0.29 on Lovénbreen.

Ablation values show greater fluctuations than winter balance values (Fig. 2.16). There is no evidence of increased melting. Moreover, there is no significant trend in the summer ablation during the whole observation period. Because the summer ablation has been greater than the winter accumulation in nearly all the observation years, the glaciers are not in balance with the existing climate; the result has been a steady decrease in the size of the ice mass.

The mean annual specific net mass balance is -0.43 m (w.e.) on Brøggerbreen and -0.35 on Lovénbreen. In only two balance years, 1986/87 and 1990/91 were there positive net balances during this 27-year period; these were +0.22 and +0.13 m respectively and they probably reflect the exceptionally cold summers in those years when less melting took place than in the case of the average year (cf Tables 2.28 and 2.29; Fig. 2.16).

The net balance deficit decreased slightly from 1967 to 1993 (Fig. 2.17), mainly owing to a slightly increasing trend in the winter balance but also due to a front retreat and decrease of the area in the lower altitudes of the glacier.

The decreasing area at lower altitudes is partly caused by the new climatic conditions which have resulted in faster melting and partly because the flow and the emergence velocity is very small (the latter is due to the low temperature of the ice). In the lower part of the glacier, i.e. below 200 m a.s.l., the horizontal velocity is only a few centimetres per year. Based on air photographs taken in 1977, a glacier map was constructed at a scale of 1:20 000 with a contour interval of 10 m. One of the ablation stakes was resurveyed in 1985. The vertical difference on the glacier surface was 5.2 m, when compared with the 1977 map. The cumulative mass balance at this point over the same period was 4.95 m w.e., which represents 5.45 m of ice. Direct measurements from the map and the surveying thus agree reasonably well with the annual mass balance measurements (Hagen and Liestøl, 1987). This is typical of these small subpolar valley glaciers in Svalbard, where the thin and outermost parts of the glacier are frozen to the ground. In the period 1967-1993, the average lowering of the surface of the two glaciers has been 11 and 8 m respectively.

For Brøggerbreen, this represents a reduction of more than 10% of the total volume of the glacier. The results from Brøggerbreen and Lovénbreen are given in Tables 2.28 and 2.29.

The average equilibrium line is about 100 m higher than the level which gives zero net balance. A steady state would be obtained if the average summer temperature was lowered by 1°C or if the winter precipitation increased by about 50% (Hagen and Liestøl, 1990). There is a strong correlation between the annual net mass balance and the equilibrium line altitude. This again correlates well with the mean summer temperature or the sum of positve temperature days during the melt season. Summer balance (b_s in m/year w.e.) as a function of positive degree days (PDD - the cumulative sum of daily above-freezing mean temperatures for the whole summer season) gives a high correlation coeficient and the following regressive equation (Hagen and Liestøl, 1990):

$b_s = 0.0046\ PDD_{6\text{-}9} - 0.6259$ (with $r = 0.88$).

Based on temperature recordings in Svalbard since 1912, this strong correlation has been used to reconstruct the net mass balance on Brøggerbreen since then (Lefauconnier and Hagen, 1990). The total ice mass lost in the period 1912-1988 was 34.35 m (w.e.), which corresponds to a mean value of -0.45 m per year. This is almost 30% of the present total ice volume of Brøggerbreen. These low-altitude glaciers are still not in balance with the existing climate.

The results from the other small glaciers, presented in Tables 2.30 - 2.37, correlate well with the recordings from Brøggerbreen and Lovénbreen.

Fig. 2.16 2.17

Kongsvegen and Hansbreen

The mass balance investigations on Kongsvegen (105 km2) started in 1987. Kongsvegen is situated in the inner part of Kongsfjorden, about 30 km east of Ny-Ålesund (cf Fig. 2.15). The glacier extends from sea level to 800 m a.s.l. The mean accumulation is 0.79±0.14 m (w.e.) and the mean summer ablation, -0.73 ±0.28 m. On average, the summer ablation includes 0.05 m (w.e.) of calving into the sea. Estimates of the calving rate have been made from velocity measurements in the lower part of the glacier, together with radio-echo soundings of profiles in the lower part. The summer balances have been lower than the values measured on Brøggerbreen and Lovénbreen, principally because the main part of Kongsvegen is more elevated. As a result, the mean net balance of Kongsvegen is slightly positive, b_n = +0.06 m. Thus, the results from the 7 year investigation period indicate that glaciers originating in the higher accumulation areas are closer to a steady state than the lower cirque-glaciers situated nearer to the coast. The results from Kongsvegen are given in Table 2.38.

The mass balance studies on Hansbreen were started in 1989. Hansbreen lies in the northern shore of Hornsund, South Spitsbergen in the vicinity of the Polish Polar Station (cf Fig. 2.15; Table 2.26). The glacier extends from the sea level to 600 m a.s.l. The mean mass loss by calving of Hansbreen is 0.35 m w.e., which is significantly higher than this of Kongsvegen. Mean winter accumulation has been 0.90 m w.e. and mean summer balance has been –1.14 m w.e. (Table 2.39).

Conclusions

In general, no dramatic changes seem to have occurred during the last 26 years. The winter accumulation is stable or slightly decreasing and annual variations are minimal. The mean summer ablation is stable and no significant trend is discernible; however, there are some large annual variations. There is no evidence of increased melting during the observation period. The net balance depends on the area/altitude distribution. The low altitude galciers are shrinking steadily but with a slightly smaller negative net balance than 26 years ago. Glaciers with high altitude accumulation areas are close to equilibrium or are growing.

2.6. Northern Scandinavia

(by Per Holmlund and Jon Ove Hagen)

Several mass balance studies have been carried out for variable periods in northern Scandinavia between 66° - 70°N in both Norway and Sweden. (Fig. 2.18; Table 2.40). On all the glaciers investigated, both accumulation and ablation have been measured by the stratigraphic method (snow sounding profiles, density measurements and stake readings). The climatic gradient along a latitudinal transect from the Atlantic Ocean to central Sweden is quite steep. The climate in western Norway is maritime, but at the watershed and east of the Scandinavian Mountains it is continental and only partly maritime. This climatic gradient also influences both the net balance gradients on glaciers and the glaciation level. Typical values of net balance gradients are 1.5 m per 100 m in western Norway and 0.5 m per 100 m of elevation in the eastern part of the mountains. Conversely, the glaciation level increases at a gradient of approximately 0.7 m per 1 km of the distance from the sea. On Storglaciären, in Sweden, the winter, summer and net balances have been measured annually since 1946 (Table 2.41). This is almost certainly the longest continuous series of measurements in the World, certainly two years longer than in the case of the Storbreen in South Norway.

The Storglaciaren, a well-defined cirque glacier, which lies between 750 and 1130 m a.s.l., is situated in the mountain ridge close to the Norwegian border. It has a continental climate. The mean annual air temperature at the equilbrium line (at about 1500 m a.s.l.) is about -6°C. The glacier is mainly temperate with a cold surface layer in its lower parts and ends in a discontinuous permafrost area. the average annual precipitation is about 1000 mm at the nearby Tarfala Research Station. Mass balance results have been published by Schytt (1981) and Holmlund (1987, 1993, 1995). During the 49-year period 1946-1995, the average annual winter preciptiation has shown a clear positive trend and has increased by about 0.5 m (w.e.); by contrast, the summer ablation has shown a negative trend and has decreased by about the same amount, resulting in a change in net balance from a negative to a positive value (Holmlund *et al.*, in press). Fig. 2.19 shows the annual values for the winter, summer and net balances and Fig. 2.20 the cumulative net balance for the observation period.

The second longest mass balance series available from northern Scandinavia is that from Engabreen, which is situated in a maritime climate, close to the Arctic Circle on the west coast of Norway. This glacier has been studied since 1970 (Table 2.42). Engabreen has shown a considerable positive mass balance which sum amounts to as much as 18 m (w.e.). However, it has not shown an increasing trend during the last several years, as has Storglaciären and the South Norwegian glaciers.

Mass balance components are shown in Fig. 2.21 (Haakensen, 1995), while the annual cumulative mass balance for the period 1970-1995 is shown in Fig. 2.22.

Fig. 2.18

Short measurement series from other glaciers around the circumpolar area (66° -67°N) indicate that those in the more continental areas are close to equilibrium or have slightly decreased. The Storsteinsfjellbreen has been studied in two periods, 1964-1968 and 1991-1993. The results of these correlate well with the Storglaciären, which is about 50 km further inland to the east. The trend is similar, indicating a more positive mass balance. In the first period, it was close to equilibrium (mean b_n = +0.06 m) whereas it has been growing in the last period (mean b_n = +0.65 m) (Haakensen, 1995). Data are presented in Table 2.43. Due to high winter precipitation, all glaciers have shown a surplus during the last five years. An exception, however, is Langfjordjøkulen, the northernmost glacier in Scandinavia on which mass balance measurements have been carried out. Langfjordjøkulen was studied over the period 1989-1993. Results show that the glacier is close to equilibrium, the cumulative net balance for the five-year period being -0.11 m (Table 2.44). The main trend for the glaciers in northern Scandinavia is towards a more positive net balance in the area between 66° and 68°N (mainly due to higher precipitation there). This trend has also been observed in southern Norway. However, at 70°N, on Langfjordjøkulen, there is no sign of a changing trend over the last several years.

Fig. 2.19 2.20 2.21 2.22

2.7 Russian Arctic

(by Andrey F. Glazovskiy)

General remarks

The distribution of glaciers in the Russian part of the Arctic (cf Table 1.3), clearly shows that glaciation decreases markedly eastwards. This reduction clearly relates to a decrease of precipitation and an increase in the continentality of the climate in that direction. The major sites of glaciation in the Russian archipalagos lie along the branches of the atmospheric trough which originates in the North Atlantic. The eastern end of the trough reaches Severnaya Zemlya, where there is still enough atmospheric moisture to support glaciation; this is also the case in respect of the Taymyr and De Long Islands (Fig. 2.23). An absence of glaciation on the New Siberian Islands results not only from low precipitation but also their low altitude.

The mesoscale distribution of ice masses on the archipelagos is also asymmetric. The larger ice caps, which have numerous outlet glaciers, higher activity indices and lower ELAs, occur in areas which are located closer to the atmospheric pressure trough (cyclonic activity tracks). The occurrence of ice masses in the Arctic is mainly controlled by a climatic factor. There are, however, two exceptions: the Polar Urals and the Byrranga Mountains (in the Taymyr Peninsula), where landscape is also important, being favourable for high snow concentration. The mean air temperature in July varies from -15^{o}C to -20^{o}C north-east of the Barents Sea to -32^{o}C to -36^{o}C in the Siberian Arctic. The mean air temperature in July is highest in the continental part (+2^{o}C to +3^{o}C) whereas, on the archipelagos, it is near zero. The maximum precipitation is in the southern part of the Atlantic sector (as much as 400 mm) whereas, in the Siberian Arctic, precipitation is as little as 150 mm. The summer temperature on the glaciers is lower than that at the nearest meteorological stations, as shown in Table 2.45. The precipitation is variable, and depends on the glacier morphology and position relative to the prevailing wind directions. The mean differences in the solid precipitation between the leeward and windward sides of glaciation systems are significant, being higher than the differences between particular archipelagos: on Franz Josef Land, 240 mm; Novaya Zemlya, 600 mm; Severnaya Zemlya, 140 mm; the Polar Urals, 620 mm.

The pattern of the ELA shows a general northwards decrease of altitude from 600-1000 m a.s.l. in the Polar Urals and Byrranga Mountains to ca 150 m on some of the islands in the Franz Josef

Land archipelago and Ushakov Island. There are local increases in the ELA on the leeward sides of Severnaya Zemlya, and, especially, Novaya Zemlya and the middle part of the Franz Josef Land archipelago. Regional variations of ELA are shown in Fig. 2.24 and Table 2.45. It is generally believed that the different zones of ice facies on the ice masses of the Russian Arctic show a high ratio of superimposed ice relative to firn (Table 2.46).

Fig. 2.23 2.24

Mass balance measurements

The mass balance of glaciers in the Russian sector of the Arctic relate to different observational periods and have used different methods. Reconstructions of long mass balance time series all indicate negative values for all Russian glaciers during the Twentieth Century (e.g. Koryakin, 1988; Kotlyakov, 1992). Observations of individual years and reconstructed series are shown in Tables 2.47 and 2.55. Some are represented as values of separate net balances for accumulation and ablation areas, which makes it difficult to compare them with the standard stratigaphic system. The data for the Sedov Glacier (Franz Josef Land) are available in the standard system for 1957/58 and 1958/59 but they are estimated for the area which does not coincide with glacier catchment. Nevertheless, it is generally possible to recalculate them using published maps. Mass balance measurements are traditionally expressed in g/cm^2 units but, in this report, they are presented in metres of water equivalent.

VICTORIA ISLAND

Victoria Island (80^{o}N; 37^{o}E) is covered by an ice cap which is 10.7 km^2 in area. The ice-free area is only 0.1 km^2. The crest of the cap is at 105 m a.s.l. Observations since 1953 show that the ice dome margins are retreating at about 2.5-3.0 m/year. Stakes and markers have melted out all over the ice dome. No firn has been observed here (Govorukha, 1989). All the evidence thus suggests a negative mass balance (cf Table 2.46 and Table 2.55).

FRANZ JOSEF LAND

Franz Josef Land is an archipelago of 191 islands from 79^{o}46' to 81^{o}52'N and 44^{o}45' to 62^{o}25'E and has a glaciated area of 13 735 ±14 km^2 (85% of the total area). The maximum ice surface elevation is 735 m a.s.l. on Vilchek Land where ice thickness is as much as 450 m. The main morphological types of ice masses are ice domes, outlet glaciers and snow-drift glaciers. The total area of the ice domes is 8 530 km^2. Ice cliffs, which regularly produce icebergs, form nearly 21% (2

655 km) of the total island coast line. Ice loss due to calving and wave action is estimated to be 2 300 $* 10^6$ tonnes annually.

Accumulation on the ice domes has been measured by snow survey only irregularly. The results are presented in Table 2.48. To the south and south-east of the archipelago, the precipitation is 1.5 m higher than to the north-west. Mass balance measurements were made on the Sedov Outlet Glacier and the Jackson Ice Cap on Hooker Island during the IGY (1958/59) (cf Table 2.47). The temperature of the glaciers at a depth of more than 10 m varies from -3^{o}C to -10^{o}C, depending on the elevation and the ice facies. In total, the cold firn and slush zones occupy an area of 3 400 km^2; they lie above 250 m a.s.l. in the north and above 350 m in the south of the archipelago (cf Table 2.46). The superimposed ice zone is 1 900 km^2 in area and occupies a 60-100 m altitudinal range below the firn zone (Krenke, 1982). The velocity of the Sedov and Yuri Outlet Glaciers has been measured as 50-60 m/year. Estimates of the mass balance for the whole of the archipelago (Tables 2.47 and 2,55) and observations on changes of the fronts of glaciers indicate that the ice masses have receded in the last 30-50 years.

NOVAYA ZEMLYA

The Novaya Zemlya archipelago consists of two large islands, the so-called Northern and Southern Islands, together with a number of smaller ones. Nearly half of the Northern Island is occupied by the Northern Ice Sheet which rises to as high as 1100 m a.s.l. This sheet is 413 km long and has a maximum width of 95 km. It is drained by 60 outlet glaciers, most of which reach sea level. The total area of the ice sheet and its valley glaciers is 19 330 km^2. The mountain glaciers in this region have an area of 1190 km^2. Southwards, there is an area of transfluent mountain glaciation which has an area of 1852 km^2. To the south of the Northern Island and on the Southern Island, valley and cirque glaciers dominate; these have a total area of 1272 km^2. Precipitation decreases southwards and eastwards. At sea level, the annual precipitation varies from 150 to 280 mm but, on the ice divide, it is as much as 640 mm (cf Table 2.45). Gales are very frequent in this area.

Mass balance measurements were taken in 1958/59 on the western slope of the Northern Ice Sheet, in the drainage basin of the Shokalskiy Outlet Glacier (cf Table 2.45) The mean snow accumulation in the upper part of the glacier catchment is 0.68 m (w.e.). The ice velocity of the glacier varies from 15-20 m/year at the ELA to 150 m/year at the calving front.

Of interest, it was observed that the change from percolation to superimposed ice facies took place in the same area on the ice sheet divide sometime between 1954 and 1969. In turn, the percolation zone there had also been temporal and appeared intermittently between 1932 and 1954. In total, the cold firn zone (of area 2450 km^2) lies above 600 m a.s.l. in the north and above 800 m south of the ice sheet. The slush facies area (of 5150 km^2) occupies an altitudinal range 100-200 m below the firn zone, whereas the superimposed ice zone is 3300 km^2 (Krenke, 1982).

Balance reconstruction and front variations indicate a negative mass balance for the Novaya Zemlya glaciation during the present century (Tables 2.45 and 2.55).

USHAKOV ISLAND

Ushakov Ice Cap (80°55'N; 70°00'E) is a simple ice cap, some 325.5 km^2 in area and of maximum elevation 294 m a.s.l. The bedrock is flat. In some places, it lies below sea level. The ice margin is a cliff, 20-30 m high, where ice blocks collapse into the sea. There are not more than 30 days each year which have a positive air temperature. The mean annual precipitation at 50 m a.s.l. is *c.* 200 mm and, at the crest, 350-400 mm (cf Table 2.45). Above *c*. 150 m, a cold firn zone is present. Accumulation is estimated to be 0.1 km^3 or 0.28-0.30 m (w.e.). Metling is *c*. 0.1 km^3 and calving 0.001 km^3 (Govorukha, 1989).

SEVERNAYA ZEMLYA

The Severnaya Zemlya archipelago consists of 4 large islands and a number of smaller ones. It is the northernmost archipelago in Asia and was discovered as late as 1913. Ice masses, forming 17 glacier systems are 17 180 km^2 in area. These include ice domes (13 781 km^2), 99 outlet glaciers (2985 km^2), 3 ice shelves (258 km^2) and 72 glaciers of other types (157 km^2). In addition, there are 62 glaciers with an area of 1145 km^2. The maximum elevation (of 965 m) is the ice surface of the Karpinskiy Ice Dome on October Revolution Island.

The annual precipitation at sea level varies from 100 to 230 mm (solid precipitation *c*. 90 mm). At the crests of the ice domes, precipitation rises to 450-500 mm. Accumulation on the crest of the Akademii Nauk Ice Dome (on Konsomolets Island) is 0.40-0.45 m (w.e.) whereas, to the south-west, on the Leningradskiy Ice Dome (Bolshevik Island), it is only 0.15-0.20 m (w.e.).

Observations in 1965 on the Dezhnev Ice Dome (October Revolution Island) show that ablation on the crest of the Dome (at 405 m a.s.l.) is 1.33 m (w.e.) and, at the margins, 2.50-3.00. The velocities of the ice domes seems never to be more than 10 m/year whereas some outlet glaciers of the Rusanov and Vavilov Ice Domes flow at 100-150 m/year. Measurement series on the vavilov Glacier are the longest on all the Russian archipelagos, though different values have been recorded in different publications for the same year. The latest re-estimated data set is given in Table 2.49 and presented in Figures 2.25 and 2.26.

Vavilov Glacier, in the south-western part of October Revolution Island, Severnaya Zemlya, has been observed since 1962. In 1974, a glaciological station was established there. The glacier is an ice dome with a maximum thickness of 610 m, as measured by RES in the period 1974/75 and 1980/81 and 556.5 m by drilling. The mass balance has been measured over 10 years in the period 1975-1981 and 1986-1988 (Barkov *et al*., 1992). The mean area of the accumulation zone is 838 km^2 (46% of the total). It seems that, between 1962 and 1978, the slush zone on the crest of the dome (728 m) was replaced by a superimposed ice zone (Govorukha, 1989). The temperature of the Vavilov Ice Dome at a depth of 18 m is -1.8ºC.

Fig. 2.25 2.26

A comparison of air photographs taken in 1952 and 1985 shows that the Vavilov Ice Dome has advanced on the southern and western sides whereas the northern margin has retreated. In the south and west the increase has been 14.6 km^2 whereas, in the north, it has decreased by 11 km^2. The net areal change is, therefore, +3.5 km^2. Meanwhile, in the last 30 years, some small glaciers have disappeared and the Kropotkin Glacier on Bolshevik Island has retreated by more than 1 km. Estimates of mass balance for the whole archipelago (Tables 2.47 and 2.55) indicate a recession of the ice masses during the last 30-50 years.

POLAR URALS

The mass balance of the IGAN Glacier (area, 0.9 km^2; length, 1.5 km; altitude range, 830-1216 m a.s.l.; ELA_o = 930 m) and the Obruchev Glacier (area, 0.3 km^2; length, 1.0 km; altitude range, 390-660 m a.s.l.; ELA_o = 530 m) is presented in Tables 2.50 and 2.51. Theere are the latest reliable data for the glaciers of the Polar Urals. The climatic snow line lies at 1240-1440 m a.s.l. Glaciers are present below this, owing to the high snow concentration. The ratio of glacier/background snow accumulation varies from 1.6 to 2.9 (mean 2.3) for the IGAN Glacier and from 1.7 to 3.0 (mean 2.6) for the Obruchev Glacier. Summer balance values are estimated as the difference between b_w and b_n, as measured annually at the end of the cold and warm periods along the longitudinal and transverse profiles. Mean weighted values are estimated by areal averaging. The total value of internal accumulation (re-freezing) is estimated from thermosounding and is considered by the author to be of the order of 0.15 m (w.e.) for the IGAN Glacier. Winter, summer and annual mass balances at various altitudes averaged for the period 1960-1977 are presented in Tables 2.52 and 2.53.

Fig. 2.27 2.28

The accumulation and ablation regimes and the net balance of the Obruchev Glacier (Figures 2.27 and 2.28) seem to be more typical for the Polar Urals, because 60% of them are the same, cirque type, and the area of 67 glaciers (out of a total of 143) are between 0.11 and 0.3 km^2 in area.

An attempt to correlate the IGAN Glacier with the Storglaciären mass balance data shows only a very weak correlation. A comparison of integral-difference curves of mass balance components for these glaciers reveals that (1) the periods of increased or decreased net balances are in counterphase on the glaciers, (2) the summer balance variations show qualitatively the same, but less pronounced conterphase patterns, and (3) the winter balance variations are rather irregular. This means that, when the high pressure systems dominate in summer over northern Europe, the cyclonic activity shifts to the Polar Urals and western Siberia; also, the converse is true - the high pressure situation over the Urals and western Siberia results in stabilisation of low pressure areas over Scandinavia.

BYRRANGA MOUNTAINS

There are 96 glaciers in the northern, highest part of the Byrranga Mountains in the Taymyr Peninsula; these have a total area of 30.5 km^2. Small valley glaciers predominate (28 glaciers, totalling 22.1 km^2 in area). The largest of these, Neozhidanny, is 4.3 km^2 in area. The tongues of the glaciers are at 600-900 m a.s.l. and the highest points at 700-1000 m. The annual precipitation on the mountain watershed is 400-500 mm. The mean annual accumulation on the surface of the valley glaciers is 0.4-0.7 m (w.e.). The mean annual melting is 1.0-1.2 m (w.e.). From 1960 to 1977, more than 10 glaciers have disappeared. The recession of tongues has been as much as 150 m. Some glaciers are disintegrating.

DE LONG ISLANDS

Three islands (Bennett, Genrietta and Zhannetta) in the De Long Islands archipelago are partially covered by ice caps and outlet glaciers, which, together, total 80.6 km^2 in area. The largest of these is the Tollya Ice Cap on Bennett Island which has an area of 54.2 km^2 and a maximum altitude of 384 m a.s.l. The mean annual precipitation varies from 100 mm at sea level to as much as 400 mm at the crest of the ice caps. Observations on the Tollya Ice Cap show that, at the start of the melting period, accumulation is 50-55 cm of snow with a density 0.33 g/cm^3 (i.e. 16.5-18.2 m w.e.). The ELA is at ca 200 m. Slush and superimposed ice zones are present here.

Conclusions

1. Mass balance reconstructions and available data on glacier margins indicate that the mass balance state of the Russian Arctic glaciers is negative in the Twentieth Century; however, the sparse mass balance data do not reveal any particular trend. In order to understand recent changes, direct measurements based on modern techniques are urgently required.
2. The re-freezing of melted snow and liquid precipitation water in snow/firn zones and on the ice surface is clearly an important component of the mass balance structure in the High Arctic. Available estimates (presented in Table 2.54) show that more than half the net accumulation is the result of this re-freezing process. On the other hand, internal accumulation reduces the potential run-off by 26%. This process should be studied much more thoroughly as an important factor in the determination of mass balance fluctuation, glacier thermal evolution and glacier impact on sea level. Our understanding of this process would be much improved by the application of remote sensing techniques, combined, of course, with ground-truth surveys.
3. The iceberg discharge of ice into the sea is also an important, if yet poorly understood factor in mass balance fluctuation and glacier dynamics. Nearly one quarter of the flux of Russian Arctic glacier flow is discharged as calving into sea water. Approximately 3.8 km^3 is iceberg flux (1.5 km^3 on Franz Josef Land - 60% of glacier run-off; 2.0 km^3 on Novaya Zemlya - 80%; 0.2 km^3 on Severnaya Zemlya - 25%) Additionally, 2.0 km^3 is lost because of the thermal decay and wave abrasion of the ice cliffs. Thus, the determination of the solid ice output should be one of the special aims of Arctic glacier mass balance study.
4. Frequent summer snowfalls have a strong impact on the rate of ablation of Arctic ice masses. This requires to be investigated further.

3. CONCLUDING REMARKS

Data on the mass balance of Arctic glaciers are somewhat patchy. They were obtained by slightly dfferent methods of field measurements and the observational time series are of very variable length. More than 40 glaciers have been measured but most only for short periods of a few years. As few as 14 have observation series longer than 20 years and less than 10 of these are still being surveyed. In the Canadian Arctic, seven glaciers have long observation series and five are still being investigated. Storglaciären, in northern Sweden, is the glacier which has the longest continuous series (since 1946). The mass balance studies on Meighen Ice Cap, White Glacier and Baby Glacier in the Canadian Arctic and also IGAN Glacier and Obruchev Glacier in the Polar Urals were started in years1958-1960. In 1967, measurements were started on Brøggerbreen in Svalbard. The second half of the 1960's (the International Hydrological Decade) saw the start of numerous other mass balance studies. At present, regular field measurements of mass balance using classical methods are being carried out on about 20 glaciers; however, for most, the measurement series are no longer than 10 years. Investigations are currently being carried out on four glaciers in Svalbard, six in the Canadian Arctic, three in Arctic Alaska and three in northern Scandinavia. The whole collected data set of net balances (or annual balances) are presented on Fig. 3.1.

Fig. 3.1

Despite the methodological differences and varying quality of data, it is now possible to formulate some general conclusions. Averaged data for glaciers for the whole of the Arctic indicate a stable negative net balance since the beginning of observations (Fig. 3.2). For such simple analysis, glaciers with longer mass balance data series were selected from particular sectors of the Arctic. No more than four glaciers from any particular part of the Arctic have been used; of course, the averaged series is not uniform statistically, because only one glacier (Storglaciären, in Sweden) represents the period 1945/46-1956/57. In the period 1957/58-1959/60 data on 4 glaciers have been averaged and after the glaciological year 1960/61 average values have been calculated from data on 11-17 glaciers. The most distinctive features about the mass balance of Arctic glaciers (as revealed from a plot of the averaged data and the three-year running mean) are: (1) a stable negative balance over long period, (2) strong interannual fluctuations, and (3) there is no significant trend in net balances.

It should be emphasised that there is, as yet, no evidence of increased melting due to the predicted (and observed) global warming. However, during the last decade, an increase of winter precipitation has been observed in Scandinavia and Iceland, resulting in a positive mass balance on the glaciers there.

Fig.3.2

After a relatively cold "Litle Ice Age", the climate warmed up significantly at the beginning of the Twentieth Century. However, the warming-up process was not homogeneous; there were important spatial, interdecadal and interannual fluctuations. As a result, a negative mass balance ensued and the glaciers tended to recede. A reconstruction of the mass balance series, together with the observed series, shows that that the general negative mass balance of Arctic glaciers has been consistent since the beginning of the century. The glaciers are still responding to a new equilibrium state.

For the majority of the glaciers studied, negative values of mass balance predominate over the last several decades. Additionally, the total balance of tide-water glaciers is more negative, owing to mass loss by calving. Most of the larger ice masses in the Arctic have calving ice-cliff margins. Calving as an ablation mechanism is plainly important in respect that roughly half the loss of ice from the Greenland Ice Sheet is due to calving. There are, however, only two glaciers for which the calving rate has accurately been plotted. Surge-type glaciers are frequent in the Arctic; some are polythermal, as those in Svalbard, some temperate, as in Iceland. The surge behaviour of the glaciers must eventually result in a general retreat of the glacier front during quiescent stages, regardless of the state of the mass balance. Thus, the glacier front position is not a good indicator of climatic change on these glaciers. During the active surge phase, the geometry and area/altitude distribution of the glacier may change considerably during a two-year or three-year period and thus influence the mass balance of the glacier in subsequent years.

Significantly, negative mass balance is a feature specific to the Arctic except in respect of the Greenland Ice Sheet. Greenland ice masses are still an unknown quantity with respect to its mass balance components and the total net budget. The Greenland data presented here refer only to small glaciers and the Inland Ice margin; thus , it can give only general impressions about relatively small areas of the island. It is clearly necessary to establish longer time series, with respect to both direct measurements and, especially, those from airborne laser and satellite radar altimetry.

The Greenland Ice Sheet is by far the most important of all the ice masses for sea level change but it is doubtless the smaller glaciers which will give the first detectable response. Future studies of the mass balance of the Arctic glaciers should have the following aims:

1) to try to predict the change in ice volume in the Arctic which is the result of possible climatic change (over periods ranging from a few decades to several centuries),
2) to try to estimate the future rates of sea level change,
3) to validate and predict freshwater inputs to the sea from the melting of glacier ice, and,
4) to validate and provide more data for global climate models (GCM).

A reliable understanding of the response of Arctic ice masses to climate change requires the study a mass balance components and their altitudinal and regional variations in selected representative glaciers and ice caps, especially in areas where data are lacking e.g. in large parts of the Greenland Ice Sheet, eastern Svalbard and the archipelagos of the Russian Arctic. In order to obtain longer homogeneous time series, it is very important that the existing mass balance measurements should be continued. Field work should be carried out using closely comparable methods and techniques. In order to relate the results to meterorological conditions, the research sites on the glaciers should be equipped with automatic recording stations. Associated meteorological elements must include the properties of the atmospheric boundary layer. Only through this sort of investigation will it be possible to integrate the case studies into climatic models. For some selected glaciers, it would be essential to combine studies on mass balance with accurate measurements of glacier geometry, their rates of change and dynamics using such differing field and remote sensing techniques as airborne laser altimetry, interferometry, photogrammetric methods and GPS (terrestrial and airborne) over 3- to 5-year intervals.

In this way, coherent data-bases of different places in the Arctic might be established which would then make it possible to create models of glacier behaviour, as influenced by a changing climate. Future monitoring of the glaciers will inevitably be based on remote sensing techniques, but the definition of some key areas on the ground will always be essential. This would help to detect the reactions of the Arctic ice masses to climatic change.

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REFERENCES

Ahlmann, H.W., 1937: Vatnajökull in relation to other present-day Icelandic glaciers. *Geografiska Annaler*, *19*, 212-229.

Ahlmann, H.W., 1939: The regime of Hoffellsjökull. *Geografiska Annaler*, 21, 171-188.

Ahlmann, H.W., 1940: The relative influence of precipitation and temperature on glacier regime. *Geografiska Annaler*, *22*, 188-205.

Ahlmann, H.W. and Thorarinsson, S., 1937a: Object, resources nad general progress of the Swedish-Icelandic investigations. *Geografiska Annaler*, *19*, 140-160.

Ahlmann, H.W. and Thorarinsson, S., 1937b: Previous investigations of Vatnajökull, marginal oscillations of its outlet-glaciers and general description of its morphology. *Geografiska Annaler*, *19*, 176-211.

Ahlmann, H.W. and Thorarinsson, S., 1938: Scientific results of the Swedish-Icelandic investigations 1936-37-38. The ablation. *Geografiska Annaler, 20*, 171-233.

Ahlmann, H.W. and Thorarinsson, S., 1939: Scientific results of the Swedish-Icelandic investigations 1936-37-38. The accumulation. *Geografiska Annaler, 21*, 39-66.

Barkov N. I., Bolshiyanov D. Yu., Gvozdik O. A., Klementyev O. L., Makeyev V. M., Maksimenko I. G., Potapenko V. Yu., Yunak R. I., 1992: Novye dannye o stroenii i razvitii lednika Vavilova na Severnoy Zemle [New data on structure and development of Vovilov Glacier on Severnaya Zemlya - English summary]. *Materialy Glatsiologicheskikh Issledovaniy, 75*, 35-41.

Bauer, A., 1968: Missions aeriennes de reconnaisance au Groenland 1957-68. *Meddeleser om Grrnland*, 173(3), 116 pp.

Bindschadler, R.A., 1985: Contribution if the Greenland Ice Cap to changing sea level: present and future. [In:] Glaciers, ice sheets, and sea level; effect of a CO_2 induced climatic change, Report of a Workshop held in Seatle, Washington, September 13-15, 1984. Report No. DOP/HR/60235-1 prepared by Ad Hoc committee on the relationship between Land Ice and Sea Level. Committee of Glaciology, Polar Research Board, National Research Council for, Office of Energy Research, U.S.Department of Energy, Washington, 258-266

Björnsson, H., 1971: Baegisarjökull, North-Iceland. Results of glaciological investigations 1967-68. Part I. Mass balance and general meteorology. *Jökull, 21*, 1-23.

Björnsson, H. 1979. Glaciers in Iceland. *Jökull, 29*, 74-80.

Björnsson, H., 1985: The winter balance of Grimsvötn 1954-1985. *Jökull, 35*, 107-109.

Björnsson, H., 1986: Surface and bedrock topography of icecaps in Iceland mapped by radio echo-sounding. *Annals of Glaciology, 8*, 11-18.

Björnsson, H., Pálsson, F. and Gudmundsson, M.T., 1995a: Afkoma hreyfing og afrennsli á vestan- og nordanverdum Vatnajökli jökularin 1992-1993 og 1993-1994. Report RH-95- 2.

Björnsson, H., Pálsson, F. and Gudmundsson, M.T., 1995b: Afkoma hreyfing og afrennsli á vestan- og nordanverdum Vatnajökli jökularin 1994-1995. Report RH-95- 25.

Björnsson, H. 1988. Hydrology of Ice Caps in Volcanic Regions. *Rit XLV*, Societas Scientarium Islandica. Reykjavik. 139 pp (and maps).

Braithwaite, R.J. and Olesen O.B., 1989: Calculation of glacier ablation from air temperature, West Greenland. [In:] Oerlemans, J. [Ed.], *Glacier fluctuations and climatic change,* Kluwer Academic Publishers, Dordrecht, 219-233.

Braithwaite, R.J., Reeh, N. and Weidick, A., 1992: Greenland glaciers and the „greenhouse effect", status 1991. *Grrnlands Geologiske Undersrgelse Rapport, 155,* 9-13.

Chizhov O.P. 1976: Oledenenie severnoy polyarnoy oblasti [Glaciation of the Northern Polar area]. Nauka, Moskva, 240 pp.

Cogley, J.G., Adams, W.P., Eccelestone, M.A., Jung-Rothenhäusler F. and Ommaney, C.S.L., 1995: Mass balance of Axel Heiberg Island glaciers, 1960-1991: a reassesment and discussion. National Hydrology Research Institute, Environment Canada, Saskatoon, (*NHRI Science Report 6*), 168 pp.

Dolgushin L.D. and Osipova G.B., 1989: Ledniki [Glaciers - in Russian], Mysl', Moskva, 448 pp.

Dowdeswell, J.A., Hagen, J.O., Björnsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Koerner, R.M., Lefauconnier, B., Ommaney, C.S.L. and Thomas, R.H., (in press): The mass balance of Circum-Arctic Glaciers and recent climate change. *Quaternary Research.*

Fleming, K.M., Dowdeswell, J.A., and Oerlemans, J., (in press): Modelling the mass balance of North-West Spitsbergen glaciers and responses to climate change. *Annals of Glaciology, 24.*

Folland, C.K., Karl, T. and Vinnikov, K.Ta., 1990: Observed climate variations and change. [In:] Climate Change. The IPCC Scientific Assessment, Cambridge University Press, Cambridge, 195-238.

Govorukha, L.S., 1970: Rasched srednego mnogoletnego budzheta l'da i sistema vneshnego massoobmena lednikovogo pokrova Severnoy Zemli [Estimation of mean multiannual ice budget system of external mass exchange on Severnaya Zemlya glaciers - in Russian]. *Proceedings of the Arcitc and Antarctic Research Institute, 294,* 12 - 27.

Govorukha, L.S., 1989: Sovremennoye oledeneniye sovetskoy Arktiki [Modern glaciation of the Soviet Arctic - in Russian]. Hydrometeoizdat, Leningrad, 256 pp.

Grosswald M.G., Krenke A.N., Vinogradov O.N., Markin V.A., Psariova T.V., Razumeiko N.G. and Sukhodrovskiy V.L., 1973: Oledeneniye Zemli Franza-Iosifa [Glaciation of Franz-Josef Land - in Russian]. - Nauka, Moskva, 352 pp.

Haakensen, N., 1995: Glasiologiske Undersokelser i Norge 1992 og 1993 [Glaciological Investigations in Norway 1992 and 1993 - English summary]. Norges Vassdrags og Energiverk, *Hydrologisk Avdeling Report, 8,*139 pp.

Haeberli, W. [Ed.], 1985: Fluctuations of Glaciers 1975-1980 (Vol. IV). IAHS(ICSI) - UNESCO, Paris, 265 pp.

Haeberli, W. and Hoelzle, M. [Eds.], 1993: Fluctuations of Glaciers 1985-1990 (Vol. VI). IAHS(ICSI) - UNEP - UNESCO, Paris, 322 pp.

Haeberli, W. and Müller, P. [Eds.], 1988: Fluctuations of Glaciers 1980-1985 (Vol. V). IAHS(ICSI) - UNEP - UNESCO, Paris, 288 pp.

Haeberli, W., Bösch, H., Scherler, K., Rstrem, G. and Wallén, C.C., 1989: World glacier inventory. Status 1988. IAHS(ICSI) - UNEP - UNESCO, Paris, 408 pp.

Haeberli, W. and Herren, E., [Eds.], 1991: *Glacier Mass Balance Bulletin. No. 1*, IAHS(ICSI) - UNEP - UNESCO, Zürich, 70 pp.

Haeberli, W., Herren, E. and Hoelzle M., [Eds.], 1993: *Glacier Mass Balance Bulletin. No. 2,* IAHS(ICSI) - UNEP - UNESCO, Zürich, 74 pp.

Haeberli, W., Hoelzle, M. and Bösch, H. [Eds.], 1994: *Glacier Mass Balance Bulletin. No. 3,* IAHS(ICSI) - UNEP - UNESCO, Zürich, 80 pp.

Hagen, J.O. (in press): Recent Trends in Mass Balance of Glaciers in Scandinavia and Svalbard. [In:] Proceedings: International Symposium on Environmental Research in the Arctic. NIPR, Tokyo, 19-21 July, 1995.

Hagen,J.O. and Liestøl, O. 1987: Glacier mass balance investigations in the balance years 1984-85 and 1985-86. *Polar Research, 5*, 261-265.

Hagen, J.O. and Liestøl, O. 1990: Long term glacier mass balance investigations in Svalbard 1950-1988. *Annals of Glaciology, 14,* 102-106.

Hagen, J.O., O.Liestøl, E. Roland and T. Jørgensen 1993: Glacier Atlas of Svalbard and Jan Mayen. *Norsk Polarinstitutt Meddelelser, 129,* 141pp.

Hattersley-Smith, G., 1961: Glaciological studies on Gilman Glacier, progress report 1960. Defence Research Board, Department of National Defence (Operation Hazen D Phys R(G), Hazen 16), Ottawa.

Hattersley-Smith, G., 1963. Climatic inferences from firn studies in northern Ellesmere Island. *Geografiska Annaler, 45*, 139-151.

Hattersley-Smith, G., Crary, A.P. and Christie, R.I., 1955: Northern Ellesmere Island, 1953 and 1954. *Arctic, 8,* 3-36.

Hattersley-Smith, G., Krouse, H.R. and West, K.R., 1975: Oxygen isotope analysis in accumulationstudies on an ice cap in northern Ellesmere Island, NWT. *IAHS Publication, 104,* Proceedings of the Moscow Symposium, Snow and Ice in Mountainous Areas, August 1971, 123-128.

Holmlund, P. 1987: Mass Balance of Storglaciären during the 20th century. *Geografiska Annaler. 69A*, 439-447.

Holmlund, P., 1993: Surveys of Post-Litle Ice Age glacier fluctuations in northern Sweden. *Zeitschrift für Gletscherkunde und Glazialgeologie, 29*, 1-13.

Holmlund, P., (in press): Mass balance studies in northern Sweden. *Zeitschrift für Gletscherkunde und Glazialgeologie.*

Hutter, K., Blatter, H., Ohmura, A., 1990: Climatic changes ice sheet dynamics and sea level variations. *Züricher Geographishe Schriften, 37,* 83 pp.

Iken A., 1974: Velocity fluctuations of an arctic valley glacier, a study of the White Glacier, Axel Heiberg Island, Canadian Arctic Archipelago. McGill University, (*Axel Heiberg Island Research Reports, Glaciology, 5*), Montreal

Jania, J., 1988: Dynamiczne procesy glacjalne na poludniowym Spitsbergenie [Dynamic glacial processes in south Spitsbergen - English summary]. *Prace Naukowe Uniwersytetu Slaskiego, 955,* Katowice, 258 pp.

Jania, J., 1994: Field investigations during the Glaciological Expeditions to Spitsbergen in the period of 1992-1994. Interim report. University of Silesia, Katowice, 40 pp.

Jeffries, M.O., 1987: The growth, structure and disintegration of arctic ice shelves. *Polar Record, 23*, 631-649.

Koerner, R.M., 1977: Ice thickness measurements and their implications with respect to past and present ice volumes in the Canadian High Arctic ice caps, Canada. *Canadian Journal of Earth Sciences, 14*, 2697-2705.

Koerner, R.M., 1979: Accumulation. ablation, and oxygen isoptope variations on the Queen Elizabeth Island ice caps, Canada. *Journal of Glaciology*, 22(86), 25-41

Koryakin, V.S., 1988: Ledniki Arktiki [Glaciers of Arctic - in Russian]. Nauka, Moskva, 158 pp.

Kotlyakov, V.M. [Ed.], 1992: Rezhim i evolutsiya polyarnykh lednikovykh pokrovov [Regime and evolution of polar ice sheets - in Russian], Hydrometeoizdat, Sankt-Peterburg, 231 pp.

Krenke A.N., 1982: Massoobmen v lednikovykh sistemakh na territorii SSSR [Mass-exchange in glacier systems over the territory of the USSR - in Russian]. Hydrometeoizdat, Leningrad, 288 pp.

Lefauconnier, B. and Hagen, J.O. 1990: Glaciers and Climate in Svalbard, statistical analysis and reconstruction of the Brøgger glacier mass balance for the last 77 years. *Annals of Glaciology, 14,* 148-152.

Lefauconnier, B., M. Vallon, J. Dowdeswell, J.O. Hagen, J.F. Pinglot and M. Pourchet 1993: Global Balance of Spitsbergen Ice Mass and predic tion of its change due to climatic change. EPOCH 0035 Scientific Report, 30pp.

Lefauconnier, B., J.O. Hagen, J.F. Pinglot and M. Pourchet 1994: Mass balance estimates on the glacier complex Kongsvegen and Sveabreen, Spitsbergen, Svalbard, using radioactive layers. *Journal of Glaciology, 40,* 135, 368-376.

Meier, M.F., 1962: Proposed definitions for glacier mass budget terms. *Journal of Glaciology, 4,* 252-263.

Meier, M.F., 1984: The contribution of small glaciers to global sea level. *Science, 226,* 1418-1421.

Meier, M.F., Tangborn, W.V., Mayo, L.R. and Post, A., 1971: Combined ice and water balances of Gulkana and Wolverine Glaciers, Alaska, and South Cascade Glacier, Washington, 1965 and 1966 hydrologic years. *Geological Survey Professional Paper, 715-A,* 23 pp. + maps.

Müller, F. [Ed.], 1977: Fluctuations of Glaciers 1970-1975 (Vol. III). IAHS(ICSI) - UNESCO, Paris, 269 pp.

Oerlemans, J., Van de Wal, R.S. and Conrads, L.A., 1993: A model for the surface balance of ice masses: part II. Application to the Greenland Ice Sheet. *Zetschrift für Gletscherkunde und Glazialgeologie, 27/28* (1991/1992), 85-96.

Ohmura, A. and Reeh, N., 1991: New precipitation and accumulation maps for Greenland. *Journal of Glaciology, 37,* 140-148.

Rstrem, G. and Brugman, M., 1991: Glacier mass-balance measurements. A manual for field and office work. Norwegian Water Resources and Energy Administration and National Hydrology Research Institute, Environment Canada, Saskatoon (*NHRI Science Report 4*), 224 pp.

Rstrem, G., Haakensen, N. and Melander, O., 1973: Atlas over breer i Nord-Scandinavia [Atlas of glaciers of Northern Scandinavia]. Norwegian Water Resources and Electricity Board, *Hydrology Division Meddelese, 22,* 315 pp.

Rabus, B., Echelmeyer, K., Trabant, D. and Benson, C., 1995: Recent changes of McCall Glacier Alaska. *Annals of Glaciology, 21,* 231-239.

Reeh, N. [Ed.], 1985: Hans Tavsen Ice Cap project - glacier and climate change research, North Greenland. Report on activities and results 1993-1995. Nodisk Ministerrld, Miljrforskningsprogram. Klimaforskning, 52 pp.

Reeh, N., 1985: Greenland Ice-Sheet mass balance and sea-level change. [In:] Glaciers, ice sheets, and sea level; effect of a CO_2 induced climatic change, Report of a Workshop held in Seatle, Washington, September 13-15, 1984. Report No. DOP/HR/60235-1 prepared by Ad Hoc committee on the relationship between Land Ice and Sea Level. Committee of Glaciology, Polar Research Board, National Research Council for, Office of Energy Research, U.S.Department of Energy, Washington, 155-171.

Rist, S., 1952: Snow measurement on the Vatnajökull from March 27 to April 24, 1951. *Jökull, 2,* 6-7.

Rist, S., 1961: Rannsokrúr a Vatnajöki, 1960. *Jökull, 11*, 1-11.

Schytt, V. 1981, The net mass balance of Storglaciären, Kebnekaise, Sweden, related to the height of the equilibrium line and to the height of the 500 mb surface. *Geografiska Annaler, 63A*, 219-223.

Sigurdsson, O. 1989. Afkoma Hofsjökuls 1987-1988. Report OS-89005/VOD-02B.

Sigurdsson, O. 1991. Afkoma Hofsjökuls 1988-1989. Report OS-911052/VOD-08B.

Sigurdsson, O. 1993. Afkoma nokkurra jökla á Islandi 1989-1992. Report OS-93032/VOD-02.

Sigurdsson, O. and T. Jónsson, 1995. Glacier variations and climate changes in Iceland. *Annals of Glaciology, 21*, 263-270.

Thomas, R., Krabill, W., Frederick, E. and Jezek, K., 1995: Thickenning of Jakobshavns Isbrae, West Greenland, measured by airborne laser altimetry. *Annals of Glaciology, 21*, 259-262.

Thorarinsson, S., 1939: Hoffellsjökull, its movement and drainage. *Geografiska Annaler, 21,* 189-215.

Trabant, D.C. and Benson, C.S., 1986: Influence of internal accumulation and superimposed ice formation on the mass balance of McCall Glacier, an Arctic glacier in Alaska. *Materialy Glatsiologicheskikh Issledovaniy, 58,* 157-165 [Russian text with figures, p. 40-49].

Troitskiy, L.S., Guskov, A.S., Zinger, E.M. and Mikhalev, V.I., 1985: Balans massy lednikov (analiz fakticheskikh dannych) [Glacier mass balance(interpretation of actual data) - in Russian]. [In:] Kotlyakov, V.M. [Ed.], Glatsiologiya Spitsbergena [Glaciology of Spitsbergen], Nauka, Moskva, 47-61.

UNESCO, 1970: Combined heat, ice and water balances at selected glacier basins, a guide to measurement and data compilation. *Technical Papers in Hydrology, 5,* Paris, 20 pp.

Van der Wal, R.S.W., Bintanja, R., Boot, W., van den Broeke, M.R., Conrads, L.A., Duynkerke, P.G., Fortuin, P., Henneken, E.A.C., Knap, W.H., Portanger, M., Fugts, H.F., and Oerlemans, J., 1995: Mass balance measurements in the S!ondre Str!omfjord area in the period 1990-1994. *Zeitschrift für Gletscherkunde und Glazialgeologie,* 31, 57-63.

Voloshina, A.P., 1988: Nekotorye itogi issledovaniy balansa massy lednikov Polyarnogo Urala [Some results of glacier mass-balance studies in the Polar Urals - in Russian]. *Materialy Glyatsiologicheskikh Issledovaniy, 61*, 44-51.

Wadell, H., 1920: Vatnajökull. Some studies and observations from the greatest glacial area in Island. *Geografiska Annaler, 4*, 300-323.

Warrick, R.A., Oerlemans, H., 1990: Sea level rise. [In:] Climate Change. The IPCC Scientific Assessment, Cambridge University Press, Cambridge, 257-282.

Weidick, A., 1984: Studies of glacier behaviour and glacier mass balance in Greenland - a revuiew. *Geografiska Annaler, 66A*, 183-195.

Weidick, A., 1990: Investigating Greenland's glaciers. *Grrnlands Geologiske Undersrgelse Rapport, 148,* 46-51.

Weidick, A., 1991: A change in status of the Greenland Inland Ice. *Grrnlands Geologiske Undersrgelse Rapport, 152,* 39-41.

Weidick, A., Boggild, C.E. and Knudsen, N.T., 1992: Glacier inventory and atlas of West Greenland. *Grrnlands Geologiske Undersrgelse Rapport, 158*.

Wigley, T.M.L., Barnett, T.P., 1990: Detection of the greenhouse effect in the observations. [In:] Climate Change. The IPCC Scientific Assessment, Cambridge University Press, Cambridge, 239-256.

Zwally, H.J., Brenner, A.C., Major, J.A., Bindshadler, R. and Marsh, J.G., 1989: Growth of the Greenland Ice Sheet: measurements and interpretation. *Science, 246*, 1587-1591.

GLOSSARY

The mass balance of a glacier is measured at selected points on its surface; these points should be representative of its overall form. The results are integrated for the entire glacier surface and reported as a value averaged for the total surface, rather than as the sum of the total mass increase or decrease. This is in order that comparisons may be made between glaciers of different size. For this purpose, values of the mas balance and its components are usually expressed as an equivalent of a water layer (in metres thickness). The water equivalent, (w.e.) enables comparisons to be made between particular components of the glacier budget which are of different specific gravity (density), i.e. snow cover and polycrystalline ice.

This report presents data on the mass balance of the entire glacier surface. Only in a few cases, which are treated as special cases, are the balances for particular altitudinal zones of glaciers given. Therefore, the glossary contains only simplified explanations of the mass balance terms relating to the entire glacier rather than with respect to specific points of measurement or elevation zones. Definitions are based on the standardized terminology defined and explained in the UNESCO (1970) report, the "Manual of Mass Balance Measurements" (Østrem and Brugman, 1991) and in most textbooks on glaciology (e.g. Paterson, 1994). For a better understanding of the terms relating to the "stratigraphic" and "fixed date" measuring and reporting systems, two diagrams which illustrate the terms described in this glossary are appended (Fig. 5.1). In the explanatory text, terms which are written in bold script are also defined herein.

Fig. 5.1

Ablation - all processes which reduce the glacier mass. Most of the mass loss of Arctic glaciers is caused by snow and ice melting and **calving**.

Ablation zone - the part of the glacier where summer melt exceeds winter accumulation. Not only does this include the total melting of the snow cover of the last winter, but also a layer of glacier ice. A deficit of mass appears in that area. The zone lies at lower altitudes of the glacier surface. The ablation zone meets the **accumulation zone** at the **equilibrium line**.

Accumulation - all processes which increase the glacier mass. Winter snowfalls are the most important source of mass gain. Redeposition of snow by wind and avalanche is an important factor in certain topographic conditions.

Accumulation area ratio (AAR) - the ratio of the **accumulation zone** to the entire glacier with respect to any particular year. AAR is an indicator of the glacier balance state in the observation year. The ratio is expressed as a proportion of the total area of the glacier, presented herein as a percentage.

Accumulation zone - that part of a glacier where snow which has accumulated in winter does not totally melt in the subsequent summer. An increase of mass is observed in this area. The zone lies in the upper altitudes of the glacier. The accumulation zone meets the **ablation zone** at the **equilibrium line** .

Annual ablation - the mass loss during one **measurement year** in the **fixed date system** (see Fig. 5.1).

Annual accumulation - the mass gain to the glacier during one **measurement year** in the **fixed date system** (see Fig. 5.1).

Annual balance - the sum of the **annual accumulation** (positive) and the **annual ablation** (negative) at the end of the **measurement year** („glaciological year") of observations. This term is used in the **fixed date system** of measuring and reporting of mass balance (cf Fig. 5.1). Total values are averaged over the entire glacier surface and presented in terms of an equivalent water layer (in metres).

Balance year - the time between dates of formation of two consecutive **summer surfaces**; commonly understood to be the time between the beginning of the winter accumulation and the end of ablation in the subsequent summer (the date of the minimum **summer balance**). The balance year is very seldom equal to one calendar year (cf Fig. 5.1).

Calving - an important process of ablation in respect of tide-water glaciers (glaciers which terminate in the sea or a lake) by the detachment of icebergs.

Combined system - system of mass balance studies based on combination of the **fixed date system**, **stratigraphic system** and other direct data to obtain a measure of glacier **summer balance**, **winter balance** and **net balance.**

Cumulative balance - the balances summed from particular years of an observation period, which indicate a general tendency of the glacier mass to have either grown or shrunk.

Equilibrium line - a line joining points on a glacier surface where **winter balance** equals **summer balance**. Usually this is a line or narrow zone where the summer melting entirely removes the winter snow cover but not any older ice or firn below this. The line separates the **accumulation zone** from the **ablation zone**.

Equilibrium line altitude (ELA) - the altitude at which the **equilbrium line** is noted at the end of any particular **balance year**. Normally, it is an averaged value with respect to the whole glacier. ELA is used as an indicator of the glacier balance state; when it is higher, the **net balance** is lower and *vice versa*.

Firn - old, coarse-grained snow that has survived at least one summer melt season.

Fixed date system - a system of mass balance study, based on field measurements on the same date in consecutive years.

Internal accumulation - the water melted out at times of ablation usually drains from the glacier and its mass is thereby reduced. However, in areas with snow or **firn** temperatures below zero, melt water percolating through the **summer surface** can re-freeze and thereby add mass to the lower layers of snow or **firn**.

Mass balance - the change in mass at any point on a glacier surface at any time (this may be positive or negative). Usually, and in this report, it means a change in the mass of the entire glacier in a standard unit of time (normally one year - the **"balance year"** or **"measurement year"**).

Measurement year - the unit of time used in the fixed date system of mass balance study, which is usually taken at the end of the summer or the beginning of winter and lasts 365 days. In some countries, it is the same as the hydrological year („glaciological year"), which differs from that of the Julian calendar year.

Net balance (b_n) - the sum of the **winter balance** (positive) and the **summer balance** (negative) through the **balance year** ($b_n = b_w + b_s$). The term is used in the **stratigraphic system** of measurement and reporting of mass balance (cf Fig. 5.1). Total values are averaged over the entire glacier area and presented in terms of an equivalent of water layer (in metres thickness).

Stratigraphic system - a system of mass balance study based on recognition of the glacier **summer surface** and the maximum values of accumulation (**winter balance**) and maximum values of ablation (**summer balance**) during the **balance year**.

Summer balance (b_s) - the change in mass (negative) during the **summer season** (a term used in the **stratigraphic system**). It is usually measured at the end of the **summer season** and time of formation of the **summer surface** (minimum balance). The term is often used synonymously with "summer ablation". However, in Arctic conditions, accumulation has been observed to have taken place on many glaciers during the summer season also.

Summer surface - the glacier surface is formed as a result of the **summer balance** (i.e the product of melting during the **summer season**). This represents the surface of the minimum glacier volume during the **balance year** (see Fig. 5.1).

Winter balance (b_w) - the maximum balance value (positive) during one **balance year** in the **stratigraphic system**. Very often, this is regarded as being synonymous with the term "winter accumulation", but this can be higher, because, during the Arctic winter, **ablation** (i.e. melting and **calving**) may sometimes take place. The time when the maximum balance is observed divides the **balance year** into the winter and summer seasons.

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