

GLACIO-METEOROLOGICAL INVESTIGATIONS ON VATNAJÖKULL, ICELAND, SUMMER 1996: AN OVERVIEW

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Abstract. We give an overview of a glacio-meteorological experiment carried out in the summer (melt season) of 1996 on the largest European ice cap, Vatnajökull, Iceland (area 8000 km²; altitude range: from sea level to about 2000 m). The main goal was to understand how the energy used in the melting of snow and ice is delivered to the surface. Many meteorological stations were operated simultaneously on the ice cap, at almost all of which profile measurements were made. Cable balloons and radiosondes were used to probe the vertical structure of the boundary layer. It appears that the flow near the surface is katabatic most of the time, with the height of the wind maximum varying between a few metres and a few tens of metres. It is only during the passage of intense storms that the katabatic wind in the melt zone disappears. Global radiation increases significantly with altitude. Surface albedo varies enormously in space and time, with very low values (≈ 0.1) being found at many places because of the melt out of volcanic ash layers. If we consider the total melt in the period 22 May–31 August 1996, we conclude that radiation typically provides two-thirds of the melt energy, and turbulent exchange of heat one-third. At locations high on the glacier, turbulent exchange becomes less significant.

Keywords: Glacier melt, Ice melt, Katabatic flow, Mass balance, Energy balance, Ablation.

1. Introduction and Background

The role of the cryosphere in the global climate system has gained increasing attention, and the paleoclimatic record has demonstrated that ice masses are sensitive to relatively small changes in climate. Ice sheets affect sea level, generate part of the albedo feedback enhancing climate sensitivity, and store unique information on past climate and atmospheric composition. Outlet glaciers and valley glaciers, on the other hand, affect life on a more regional scale (hydro power, irrigation, road and railway construction, tourism). The last decade has seen considerable progress in the modelling of glaciers and ice sheets, especially with regard to the mathematical description of ice flow and numerical techniques for solving the related initial value problems. It has become clear, however, that in many applications the way in which the surface mass balance is specified is the most crucial aspect. The relation between mass balance and meteorological conditions is understood only broadly,



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and improvements are needed so that reliable projections can be made of the future behaviour of ice sheets and glaciers.

For clarity we recall that the mass balance, B , or specific balance, is defined as the annual amount of mass gained (+) or lost (−) per unit area (plan view) of the glacier surface. The mean specific balance, B_m , is the specific balance averaged over a glacier; the mass balance is normally expressed in kg m^{-2} or m of water equivalent.

With regard to glaciers in ‘warm’ climates (this currently encompasses all land ice outside the Antarctic interior, but includes a significant part of the Antarctic Peninsula), the surface energy balance is the most important factor determining mass balance. In view of this, recent attempts to model glacier mass balance have taken this energy balance as the starting point (e.g., Ambach and Kuhn, 1985; Greuell and Oerlemans, 1987; Oerlemans and Fortuin, 1992; Van de Wal and Oerlemans, 1994). A first quantity needed to characterize the sensitivity of a glacier to climate change is the change in mean specific balance for a spatially and seasonally uniform change in air temperature T (i.e., $\partial B_m / \partial T$). Calculations suggest differences of a factor of 10 in climate sensitivity, depending on the climatic setting of a particular glacier.

For a given ice mass, the surface energy balance depends to first order on surface elevation. Consequently, for mass balance modelling, information on altitudinal gradients of meteorological quantities is of particular importance. In recent years a few glacio-meteorological experiments have been undertaken to obtain this type of information, and during the melt season meteorological stations have been operated along transects on glaciers (e.g., central West Greenland: Oerlemans and Vugts, 1993; Pasterze, Austria: Greuell et al., 1994). The Vatnajökull experiment was designed to complement and extend the data sets obtained in these studies; four research institutions were involved in this experiment, namely, the Institute for Marine and Atmospheric Research, Utrecht University; the Science Institute, University of Iceland; the Department of Earth Sciences, Free University Amsterdam; and the Institute for Meteorology and Geophysics, University of Innsbruck.

The field work comprised mass balance measurements along many transects covering the entire ice cap, a detailed meteorological experiment in the summer of 1996, and the operation of a number of automatic weather stations for a longer period of time. Computer modelling and satellite images were used to aggregate and extrapolate data.

The specific scientific goals are to:

- obtain a good estimate of the mass balance of the ice cap and its spatial variability;
- measure the surface energy balance during summer over the entire ice cap;
- determine the strength and persistence of the katabatic wind system;
- understand the significant gradients of climate and mass balance across the ice cap;

- obtain a data set for the validation of surface parameters determined from satellite data;
- construct a calibrated energy balance model for the entire ice sheet;
- determine the sensitivity of the ice cap's mass balance to climate change.

In this paper an overview is given of the detailed meteorological experiment carried out in the summer of 1996. After describing the experiment we will discuss a selection of the results, focussing on the global characteristics of the glacier surface and the overlying atmospheric boundary layer.

2. Set-Up of the Meteorological Experiment

Vatnajökull was selected for this experiment for several reasons. First of all, it is a large ice cap (about 8000 km²; Björnsson, 1988) in a country with a well-developed infrastructure, making access not too difficult. Secondly, because of its size, the ice cap interferes with the (sub)synoptic-scale weather systems, creating a tremendous gradient in climatic conditions across the ice cap. For example, annual precipitation in the south-eastern parts of the ice cap is five to ten times as high as in the north-western parts.

The obvious drawback of working on Vatnajökull, as compared with west Greenland or glaciers in the Alps, is the poor weather. Low cloud occurs so frequently that it is very hard to use helicopters for placing and visiting weather stations. Fortunately, this drawback could be partly overcome by making extensive use of jeeps and snow scooters. In the course of the summer this becomes increasingly difficult, however, as water-saturated snow and melt water lakes, and later very unevenly melting ice facies, form large obstacles.

The set-up of the 1996-experiment is best explained by means of a map (see Figure 1). The upper part shows a map of Vatnajökull, on which the meteorological stations are indicated; basically, the stations are aligned along north-south and east-west transects. Station labels refer to the research group that operated them: R: University of Iceland; U: University of Utrecht; A: Free University, Amsterdam; I: University of Innsbruck. The station R2 was planned originally between R1 and R3, but had to be moved northwards because the part of the ice cap between R1 and R3 was surging and therefore inaccessible. Station R6 is not within the transects, but is placed close to a mountain hut from where many visits were made to the stations by snow scooters.

In March 1996 an extensive intercalibration experiment was carried out at Cabauw, in the Netherlands. Most of the sensors used by the participating groups were mounted there and measurements compared. Equipment was shipped to the ice cap in April. Three camps were established: at I6, R5, and close to U2 (base camp Breida), making use of existing huts owned by the Iceland Glaciological Society and the Icelandic Power Company. The equipment was transported to the appropriate locations by jeeps and snow scooters and stations were erected, and in

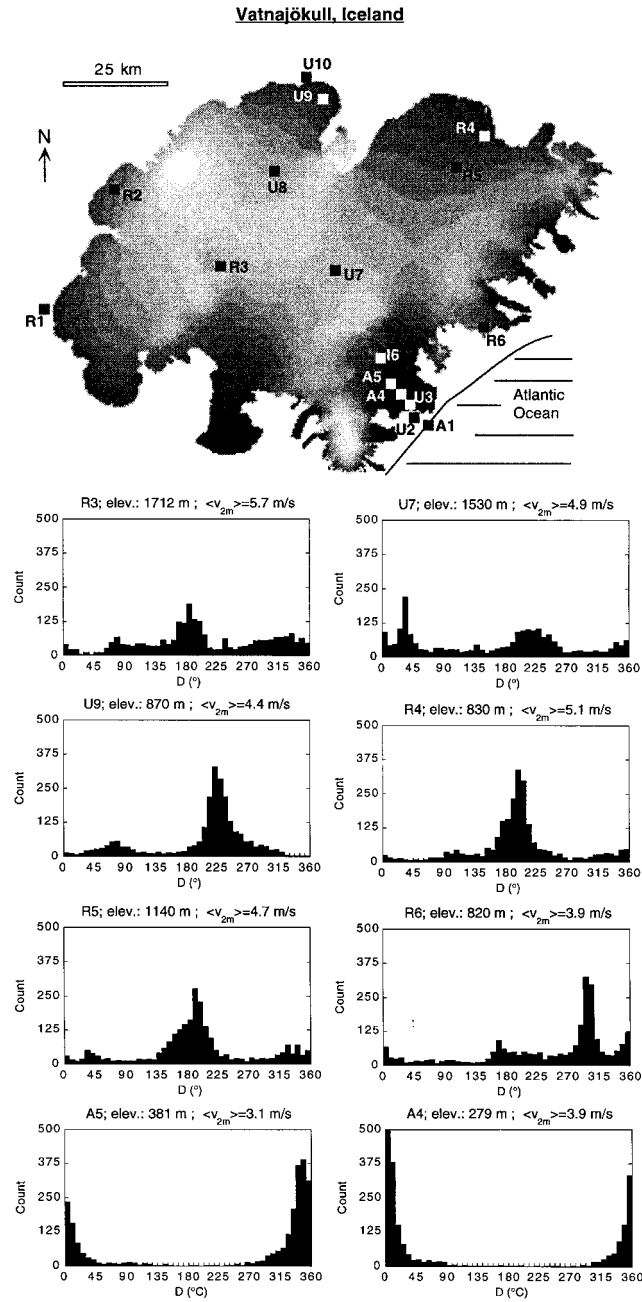


Figure 1. The map of Vatnajökull shows the locations of the meteorological stations that were operated during the 1996 summer field experiment. Camps were established at U2, I6 and R5. The largest density of stations (transect A1–U7) is on Breidamerkurjökull, a large outlet glacier extending down to sea level. Grey tones reflect surface elevation that runs from sea level (black) to over 2000 m (white). The eight graphs show histograms of wind direction D for selected stations (period: 22 May–31 August 1996). Station number, elevation and mean wind speed over the period are given at the top of each graph.

early May virtually all stations were working properly. The detailed experiment ran until September 1, after which most of the stations were dismantled, except for a few robust automatic weather stations. The intercalibration of sensors was repeated in October 1996, again at Cabauw.

Appendix A provides an overview of the location of the stations and the quantities measured. Apart from some additional measurements carried out by the individual research groups, 248 sensors were logged. At almost all sites wind, temperature and humidity profiles were measured, in most cases by having sensors at three heights.

Apart from the logistic problems involved in gaining and maintaining access to the ice cap, there are two conditions that make meteorological work difficult. First of all, the glacier surface is unstable. In the lowest part of the ice cap summer melt amounts up to 8 m of ice. To maintain sensors at approximately constant height, a mast construction is used that stands freely on the surface and sinks with the surface as melting proceeds. We used masts supported by four long legs that make a small (10°) angle with the ice surface and have a sharp vertical pin at the end. The use of such constructions in earlier field experiments has shown that the system works well. Over a few weeks, the tilt of the masts rarely exceeds a few degrees, and measuring the tilt during all visits makes it possible to correct the radiation measurements.

The second difficulty is related to power. All instruments have to be designed or modified in such a way that power consumption is kept to a minimum. Lithium batteries, in combination with a solar panel, perform adequately even at stations unattended for a month or so. The consequence is that mechanical ventilation is only possible for the temperature/humidity sensors; for radiation one has to rely on unventilated sensors.

As can be seen in Figure 1, the largest density of stations is on Breidamerkjökull, the large outlet glacier flowing down to the Atlantic Ocean. The camp at U2 served as ‘headquarters’, and from here the stations A1, U2, U3, A4 and A5 could be visited regularly on foot. At U2, three containers served as working space for computers and for launching a radiosonde twice a day. In addition to the standard profile observations, eddy correlation measurements were carried out at A4, A5 and U3.

A 12 m^3 helium balloon (Airborne K-65, AIR sonde) was used for profiling the lowest 500 m of the atmosphere. Air pressure, temperature, humidity, wind speed and wind direction were sampled every 10 seconds and transmitted to the receiving station. Great care was taken in maintaining a very low speed of ascent/descent close to the surface, as this is necessary to resolve the detailed structure of the katabatic flow in the lowest 20 metres. The balloon was operated at U2 for some weeks, and was later brought onto the ice and used at U3 until it was destroyed, together with its shelter, in a severe gale. After that the spare balloon and sonde were used. In all about 150 soundings were made. Observations with a smaller cable balloon (with an AIR-3A sonde) were also made at I6, where 174 soundings were

successful. Radiosondes were launched twice a day at basecamp Breida (close to U2), using standard weather balloons (TA-100), Marwin 12 V sounding equipment and Vaisala RS80-15N Omega radiosondes.

Most sites were visited regularly, that is, at least once each fortnight. During visits, data loggers were downloaded and the position of the sensors was remeasured; stake readings of ablation were taken and at the higher stations snow profiles were made. Also, at some locations, the spatial variability of albedo was measured by means of a portable albedometer.

As listed in Appendix A, at a number of stations the surface height was measured with an acoustic sounder, mounted in a frame drilled into the ice. The changes in surface height thus measured contain information on loss or gain of mass if the density of the upper layers can be estimated (it should be noted that these changes in height are not absolute). Changes associated with convergence or divergence of the large-scale ice flow are not detected with this method.

3. The Occurrence of Katabatic Flow

Iceland is in the heart of the Atlantic storm track and well-developed weather systems pass by frequently, and one would expect that ice caps here would have difficulty developing their own microclimate. A first impression of how frequently a well-developed katabatic layer occurs can be obtained from an inspection of wind direction at the various stations. This is based on the notion that, in katabatic flows with a horizontal length scale of up to some tens of kilometres, the dominant forces are buoyancy and friction (Van den Broeke, 1996). The consequence is that the flow follows the slope of the surface. In a second-order approximation the Coriolis force plays a role, but even in the melting zone in central West Greenland the katabatic flow does not deviate from the flow line by more than 15 to 20° (Oerlemans and Vugts, 1993). So, it seems useful to investigate wind direction first, and in Figure 1 histograms of wind direction are shown for eight stations, for the period 22 May–31 August 1996. The graphs have been produced from hourly mean data, and it is clear that the histograms show little coherence over the ice cap.

Stations R3 and U7 are in the high central part of the ice cap and most probably have a wind regime that is determined mainly by the synoptic- and meso-scale flow. It is obvious that the wind direction at these stations has a relatively flat distribution, whilst at the other stations there is a marked preference for wind direction. It is easily verified in the figure that the direction at which the distribution peaks is always along the local slope of the glacier surface. The most marked distribution is for A4 and A5 on Breidamerkurjökull, where the flow is always downslope.

Mean wind speeds are also indicated in the figure, though there is no clear pattern in these. The highest value is found at R3, which is a very exposed site. As a first conclusion we can say that on Vatnajökull, in spite of its location in the North Atlantic storm track, *a katabatic flow is present most of the time.*

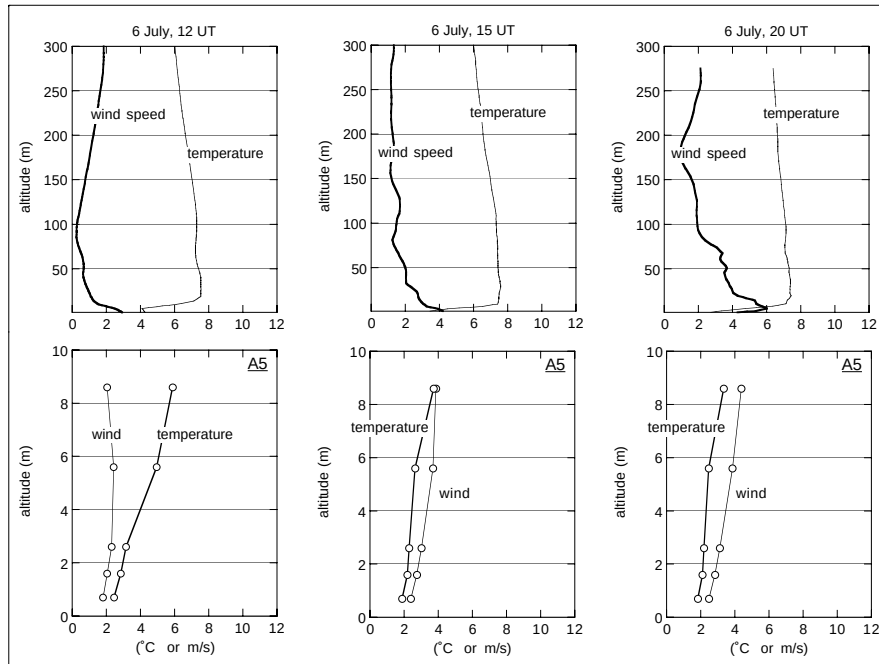


Figure 2. Vertical structure of the glacier wind as observed at A5 (see Figure 1) on July 6, 1996. The upper graphs show smoothed data from the cable balloon. The lower graphs give hourly mean values from a profile mast at five levels as indicated.

4. The Vertical Structure of the Katabatic Flow

The structure of the katabatic flow as observed at station A5 (for location see Figure 1) is illustrated for two cases in Figures 2 and 3. In case 1 (Figure 2) the wind maximum is observed close to the surface, at a typical height of 10 m. In such cases, which occur frequently, the balloon data (smoothed) do not resolve the structure of the katabatic jet, but the profile data do (sensors were mounted at heights of 0.7, 1.6, 2.6, 5.6 and 8.6 m). It appears that at 1200 UTC the wind maximum is found at a height of about 5 m. Later on this day its height increases. The balloon data show a sharp inversion of about 8 K over 20 m, whilst above this height a near-constant lapse rate is found (-0.0055 K m^{-1} averaged over the three ascents shown). The flow is purely katabatic, in the sense that upper air winds are weak.

In the second case discussed here (Figure 3) the wind maximum is found at greater heights, and there is a great deal of variability in the structure of the katabatic flow during the night and early morning. An inspection of wind direction from these soundings (not shown) reveals advection from the east to southeast. In the course of the day the katabatic flow attains its well-defined shape with a low-level jet again, although winds at higher altitudes remain of the same order of

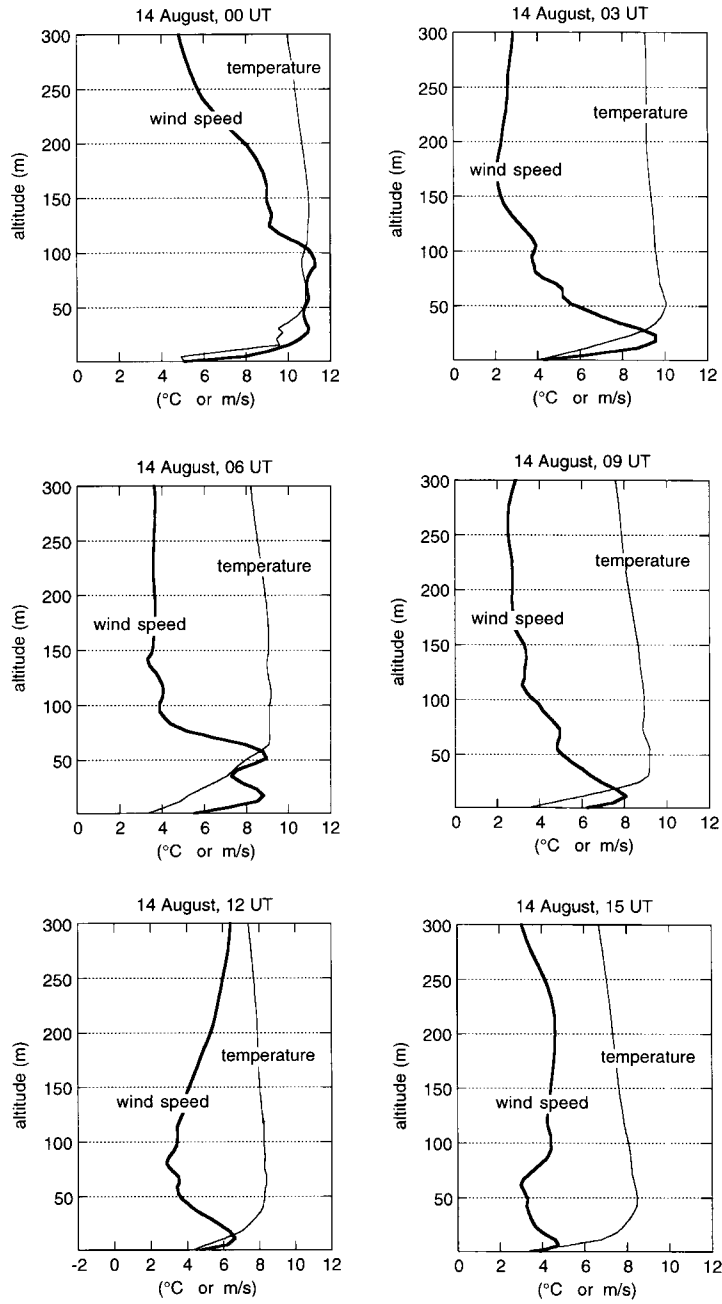


Figure 3. A second example of the structure of the glacier wind. As compared to Figure 2, the wind maximum is at greater height now and resolved by the balloon measurements. Also, the temperature profile varies more over the day.

magnitude. It is hard to determine the reason for the differences seen at the various times. On theoretical grounds (Prandtl, 1942) one has to expect that, for a given slope, the height of the wind maximum will increase with decreasing potential temperature lapse rate. Other factors may play a role, however [notably, differences in turbulence intensity, not dealt with in the Prandtl model].

5. Temperature

Here we discuss air temperature as measured at 2 m. All sensors were ventilated and calibrated before and after the experiment, so that accuracy should be good to 0.1 °C. In view of the large temperature gradients encountered in the lowest few metres of the boundary layer, it is likely that the error associated with uncertainty in sensor height is larger than the instrumental error. First of all it is difficult to define a zero reference level when the surface is very bumpy and irregular, and secondly, the height of the sensors could not be measured on a continuous basis. We estimate the error in sensor height to be ± 0.1 m, though it should be noted, however, that the resulting temperature error is not relevant for profile studies, as the relative height of sensors mounted on the same mast is not subject to significant changes.

Figure 4 shows mean temperature and potential temperature (with respect to sea level) for all ice stations for the period 22 May–31 August 1996. Except for the two stations high on the plateau (R3 and U7), mean air temperature is well above the melting point. We note that the altitudinal temperature gradient is remarkably small (-0.0036 K m $^{-1}$), which is only about half the lapse rate typical for the mid-latitude atmosphere in summer. The small temperature gradient is, of course, due to diabatic cooling of the air at the melting glacier surface; the closer to the surface, the smaller the temperature gradient. Although all data from the cable balloons and radiosondes have yet to be analysed in detail, a preliminary analysis shows that most of the time the temperature lapse rate is close to the typical mid-latitude value (i.e., between 0.005 and 0.007 K m $^{-1}$).

Temperature variations at 2 m are remarkably small, the standard deviation in the hourly mean data set varying from about 3 K for the higher stations to only 1.5 K for the stations on the glacier tongues. It is only during periods with high wind speeds that significant deviations occur, when entrainment of warm air from aloft apparently becomes significant. Figure 5 shows an example when, during the anticyclonic circulation over the western North Atlantic, with the jet stream running from north-west to south-east over Iceland, a downslope storm developed over the ice cap. As can be seen from the record of global radiation, clear skies prevailed at this time. During the gale the only cloud type observed was altocumulus lenticularis. The 2-m temperature at A4 rose to 7 °C, probably due to the strong adiabatic heating in the air descending on the lee side of the ice cap and the strong turbulent mixing in this air.

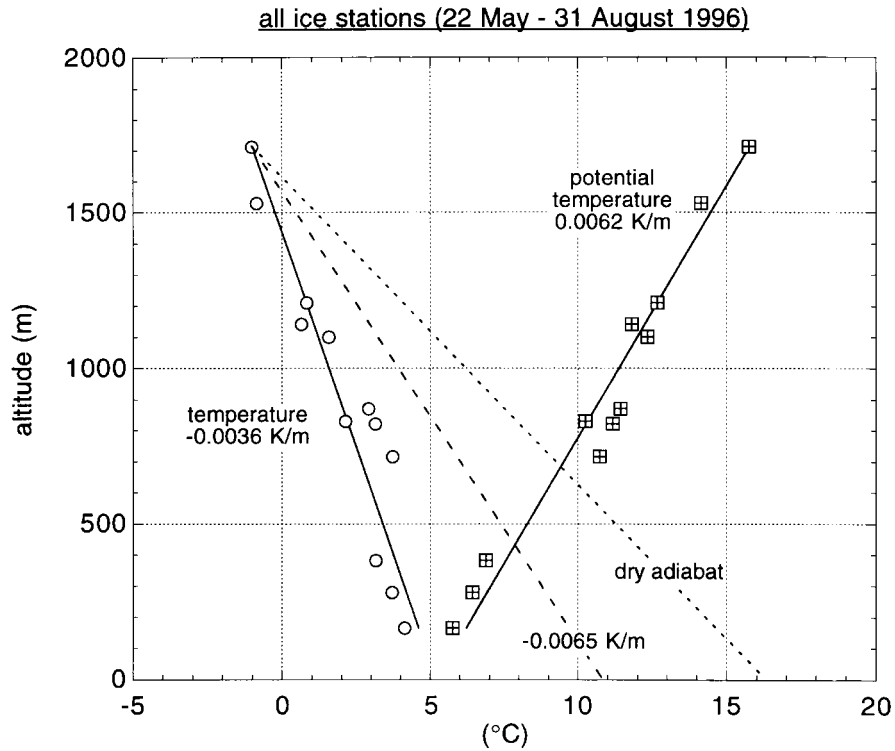


Figure 4. Mean temperature (circles) and potential temperature (squares) at 2 m for all stations located on the ice cap, plotted against station altitude. Dry adiabat (-0.01 K m^{-1}) and a standard atmospheric lapse rate (-0.0065 K m^{-1}) are shown for comparison.

6. Föhn

Because of its size and shape, Vatnajökull will have a significant influence on the atmospheric flow impinging upon it. Föhn-type flows have been observed frequently, and in some cases these take the form of a severe gale. The case shown in Figure 5 was a striking example, and inspection of ECMWF analyses reveals that in this case a deep depression passed south-east of Iceland, moving in an easterly direction. The rapid build-up of high pressure behind this storm forced cold air southwards across Iceland, where the flow was obstructed by the ice cap, and, with the jetstream running north-west to south-east, created conditions for a downslope wind storm.

In Figure 6 wind speed records are shown from all stations along a north-west to south-east transect, and it can be seen that at the upflow side (U10–U8) winds were not very strong. The first station to experience strong winds was U7, in the middle of the ice cap. When the gale reached full force at the leeside, with hourly mean wind speeds of almost 20 m s^{-1} at A4 and U3, winds on the north-western part of the ice cap were weak, notably at U8. At I6 there is a calm period within the storm,

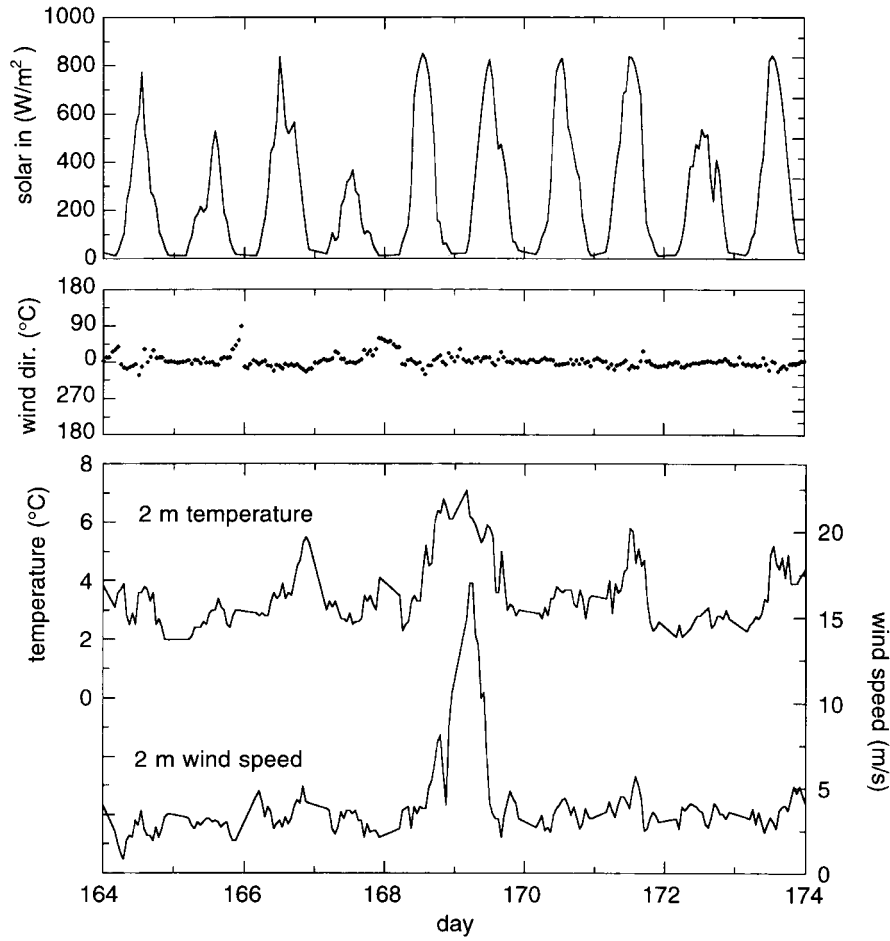


Figure 5. A 10-day close-up of hourly mean data from A4, showing the gale that occurred under a clear sky on day 169 (June 17). During the event, the 2-m temperature increased by several degrees.

which is attributed to local orographic effects; I6 is just downslope of mountain ranges protruding through the ice cap. The gale lasted about half a day, and in the afternoon of June 17 winds were weak at all stations. Unfortunately, during this gale profile masts and the balloon system at U3 were seriously damaged.

7. Radiation

The configuration of the radiation sensors was not the same at all stations (see Appendix), but the data are sufficiently comprehensive to reveal general patterns. Figure 7 shows global radiation and net radiation as a function of altitude for all stations on the ice cap. The increase in global radiation, from about 195 W m^{-2}

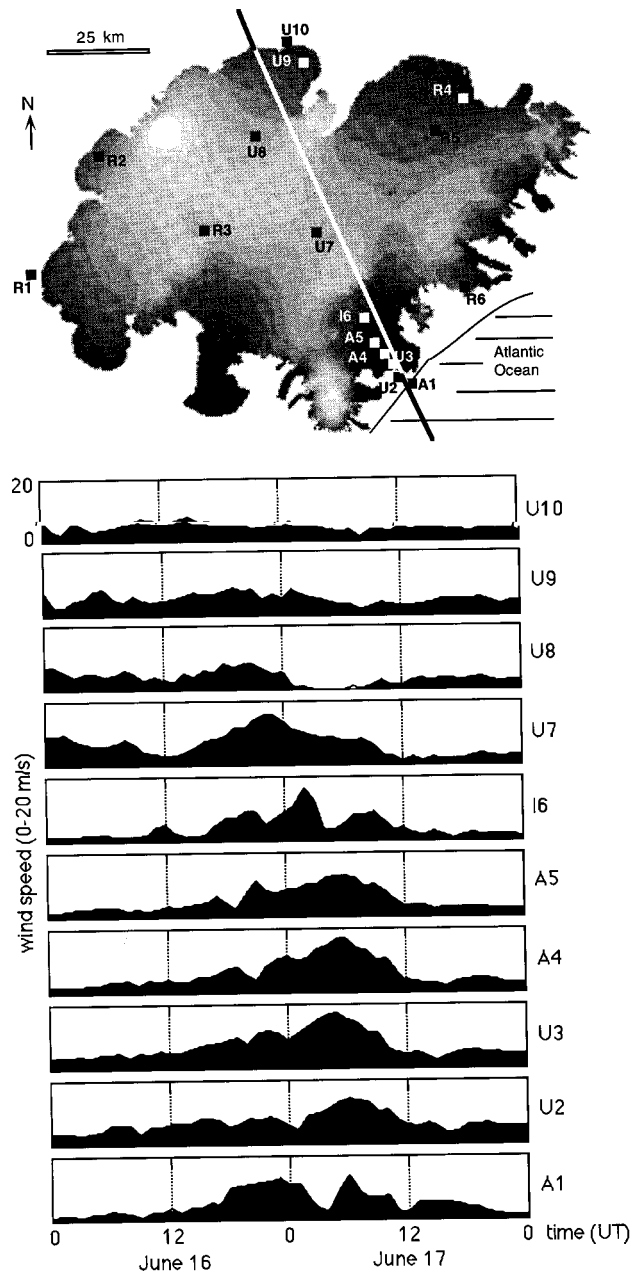


Figure 6. Wind speed records during a föhn. In the 2-day period shown, the synoptic-scale flow is changing from south-west to north; in the evening of June 16 the gale strikes. Hourly mean wind speed is shown for the stations more or less aligned along the transect shown on the map.

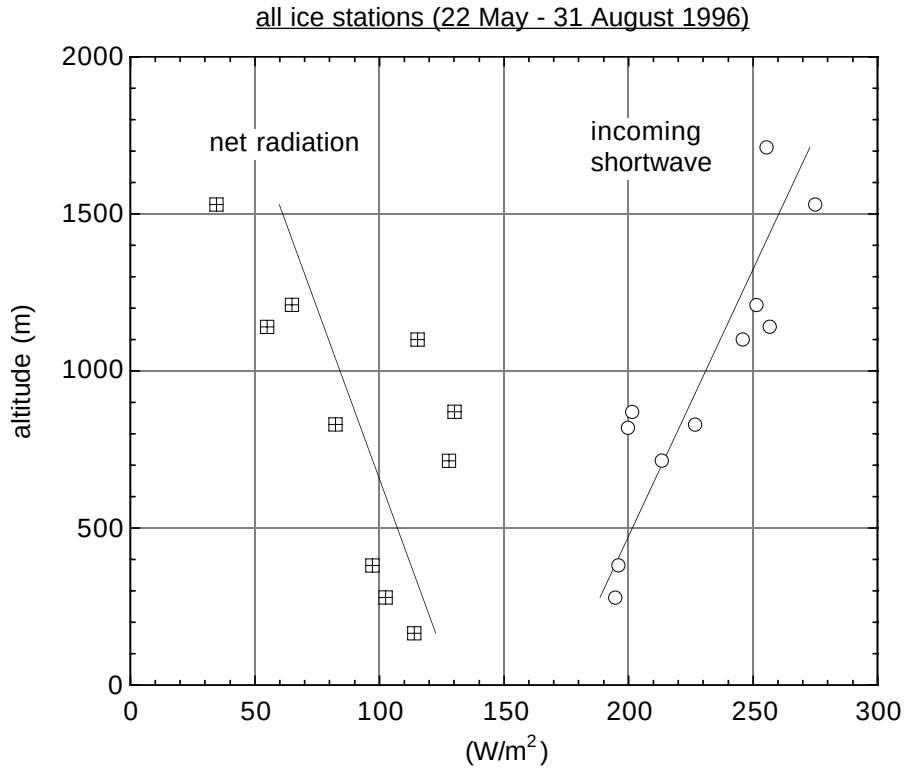


Figure 7. Mean global radiation (incoming shortwave, circles) and net radiation (squares) for all ice stations plotted against station altitude.

in the lower reaches to 265 W m^{-2} on the plateau, is striking, and is significantly larger than the increase observed in the earlier experiments on the Greenland ice sheet (Oerlemans and Vugts, 1993) and on the Pasterze, Austria (Greuell et al., 1994). We suggest that this is due to the frequent occurrence of low-level clouds with large optical thickness over Vatnajökull. The net radiation decreases with altitude, although here the scatter is larger, with the decrease due to the increasing albedo, discussed in more detail shortly, and the decreasing longwave radiation from the atmosphere. It should be noted that, in the period considered for the stations below 1000 m a.s.l., the surface was melting most of the time, fixing the outgoing longwave radiation at about 315 W m^{-2} .

The most important factor leading to a large spatial and temporal variability in the radiation balance is the surface albedo. Figure 8 shows a histogram of all hourly mean albedo values observed at the ice stations; the full range from 0 to 1 is observed [in fact, some erroneous values larger than 1 also occur; this happens when snow adheres to the upward facing radiation sensor and not to the downward facing sensor]. A noticeable feature on Vatnajökull is the presence of black volcanic ash layers that were deposited on the snow during eruptions. These layers

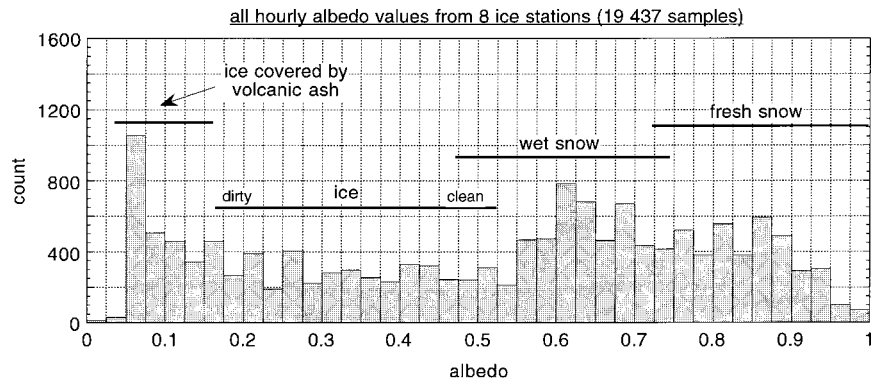


Figure 8. Histogram of hourly albedos from the eight ice stations where shortwave radiation was measured. Ranges of characteristic albedo for different facies are indicated by horizontal bars.

melt out in the ablation regions, and when the glacier surface is totally covered by volcanic ash, the albedo is about 0.1; this happened later in the melt season at site U9. Ice albedos range from 0.15 to 0.5, depending on the amount of (volcanic) dust, morainic material and melt water running across the surface. Fresh dry snow has an albedo of about 0.9, but this rapidly decreases when crystals grow and/or when surface melting occurs. In the relatively warm and moist conditions on Iceland in summer, dry snow does not persist very long. The albedo of old wet snow reduces down to 0.5, or even lower when a significant amount of dust accumulates at the surface.

More detail on the temporal variation of the albedo is given in Figure 9. For five selected stations, roughly aligned in a north-south transect, albedo is shown for the period 22 May–31 August 1996. At A4, where only a few snow patches were present at the beginning of the period, albedo steadily decreases to a value typical for ice with a moderate amount of dust (0.3). At I6 the changes are more pronounced. At the start of the record the glacier surface consists of a snow pack, and occasionally new snow is added to the surface, creating peaks in the albedo. Between days 160 and 180 all the snow melts away and a dark irregular ice surface remains; U7 is located above the equilibrium line and ice does not appear at the surface. The albedo of the snow varies depending on the amount of fresh snow that is added. At U8, which is lower down than U7, the ice does not appear at the surface until day 225, and at day 238 a significant amount of snow increased the albedo to 0.7. Finally, the record from U9 shows the transition from snow cover to ice totally covered by volcanic ash.

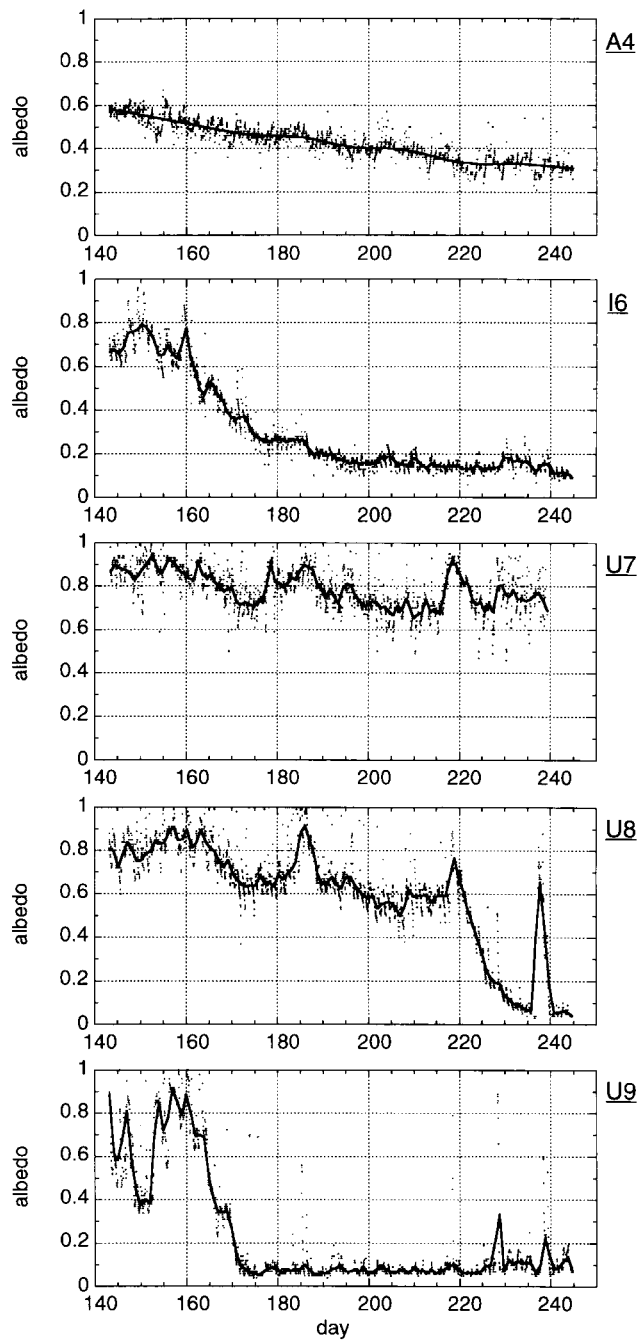


Figure 9. Temporal evolution of albedo at a selection of sites. Each dot represents an hourly mean value. Smooth curves from 12-point filtering are also shown.

8. Energy Balance and Melting

One of the primary goals of this study is to investigate how the melt energy is delivered to the surface. In spring or early summer, when the energy budget of the surface becomes positive, melt water is formed and it percolates into the winter snow. There it refreezes and heats the snow quickly up to the melting point. The amount of energy involved is significant for dry subpolar glaciers, but for maritime glaciers such as Vatnajökull the energy released in refreezing is very low compared to other components of the energy budget over a summer. Once the old snow has been heated up and the surface remains at the melting point, the energy and mass budgets take a simple form:

$$F = R + H_S + H_L, \quad (1)$$

$$\frac{F}{L_m} = A - \frac{H_L}{L_v}. \quad (2)$$

Here F is the energy budget of the surface (in W m^{-2}), R the net radiation, H_S the turbulent sensible heat flux, H_L the turbulent latent heat flux, A the amount of ablation (kg m^{-2}), L_m the latent heat of melt and L_v the latent heat of vaporisation.

In principle all the terms in Equations (2) and (3) can be evaluated from the data obtained in the field, although because of the irregularity of the surface and the occurrence of melt just below the surface, the measurement of A is inaccurate for short periods of time (e.g., 12 hours). However, it becomes accurate when periods of a few days or more are considered.

The major difficulty is with the evaluation of the turbulent fluxes. With a wind maximum at 10-m height the constant flux layer cannot be much deeper than 1 m, which is comparable to the characteristic obstacle size once the snow has melted and ice emerges (see Figure 10). So it is no surprise that problems are encountered when standard profile analysis is applied to the boundary layer over melting glaciers (e.g., Munro and Davies, 1978; Kuhn, 1978; Hay and Fitzharris, 1988; Munro, 1989; Van den Broeke 1996). The scatter of aerodynamic roughness values found from profile analysis is generally very large. In fact, there is a zero-referencing problem that cannot be solved (Munro, 1989). Van den Broeke (1996) and Munro (1989) have argued that it is better to determine the roughness length from a microtopographical survey (e.g., Lettau, 1969) and estimate the fluxes from a bulk formula.

The problem of determining turbulent fluxes and drawing a comparison between eddy correlation measurements and profile analysis will be discussed in more detail elsewhere. Here we take advantage of the fact that the melt and radiation balance have been measured accurately. The difference in melt energy and net radiation then provides an estimate of the turbulent fluxes. In making this estimate, we neglect the last term in Equation (3). For typical conditions on Vatnajökull this can safely be done. Figure 11 shows the melt and energy budgets for the eight ice



Figure 10. A picture of the glacier surface in the ablation zone (August 1996). Ice hummocks are typically 2 m high; there is a person standing just above the middle of the picture. Photo taken by Paul Smeets.

stations at which the net radiation was measured. Again, the data are for the period 22 May–31 August 1996. Although the amount of melt is related to the station altitude, the correlation coefficient is rather small (0.57). Note, for instance, the large difference in the melt at R2 and R5, although these stations are at about the same altitude; this appears to be related to lower albedo and higher air temperature at R2. At all stations radiation supplies more melt energy than the turbulent flux,

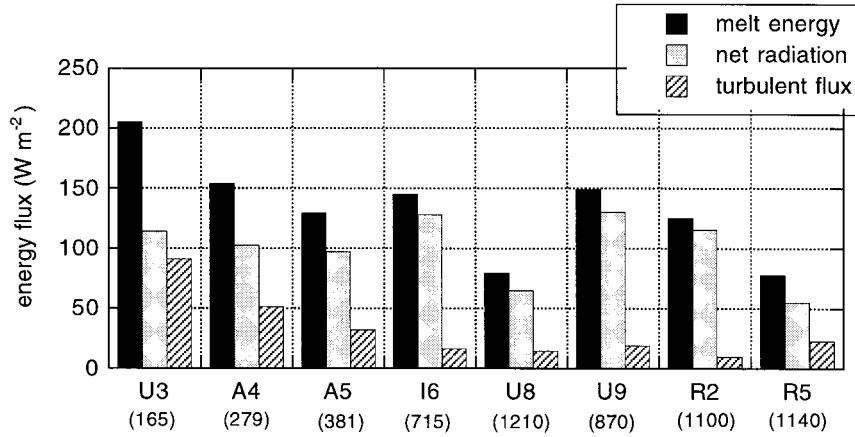


Figure 11. Total energy (black) absorbed to melt snow and ice at the stations indicated. The contributions from radiation and turbulent exchange are shown separately. Numbers in brackets below station identification give station altitudes in m a.s.l.

and typically, the contribution from the turbulent flux is half the contribution from radiation. The turbulent heat flux is more important at the lower stations, where mean air temperature is higher.

9. Conclusions

First of all, it is obvious that in summer, katabatic flows determine the microclimate of the glacier to a large extent. The height of the wind maximum varies between a few metres and a few tens of metres, and it is only during intense storms that the glacier wind in the ablation zone disappears. In this respect Vatnajökull is not much different from glaciers in more sheltered alpine valleys (e.g., Obleitner, 1994; Greuell et al., 1994). The presence of the glacier wind has implications for the turbulent exchange between surface and atmosphere, though it is difficult to apply standard profile analysis since it is hard to demonstrate that the basic assumptions on which profile analysis is based are fulfilled here.

The increase in global radiation with altitude is remarkable, and is much larger than has been observed on glaciers and ice sheets so far. We suggest that the frequent occurrence of dense low clouds is the primary cause of this.

Spatial and temporal variation of albedo is very large, and will be a difficult feature so far as modelling the energy balance of the ice cap is concerned. We believe that the data obtained in this experiment will be useful in the validation of satellite-derived albedo. The analysis of energy sources for melt emphasises the clear key role played by solar radiation, and by albedo.

The data set obtained on Vatnajökull is large and many aspects will be treated in detail in subsequent papers. We expect to obtain more insight into the vertical structure of the glacier wind and associated fluxes from the balloon and radiosonde data, involving, in part, a comparison between fluxes from profile analysis and eddy correlation measurements. Also, the surface energy budget at some individual stations will be investigated in great detail.

In the course of time, a better climatology will become available from a limited number of automatic stations that will be kept operating on the ice cap. Altogether, the data from the detailed summer experiment and the automatic stations will be used to calibrate a grid-point energy-balance model for the entire ice cap, which is currently being developed. Sensitivity studies with this model may help clarify the way in which the mass balance of Vatnajökull might respond to climate change.

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Appendix A

During the 1996 summer experiment on Vatnajökull, 16 meteorological stations were operated on and near the ice cap. Below, the geographical coordinates, altitude, period for which good data were acquired, and the instrumentation are summarised.

No.	Location	Height (m a.s.l.)	Data obtained	Quantities	Sensor heights (m)
R1	64° 19.03 N, 18° 13.24 W	730 (on land)	Day 122–262	Temperature Humidity Wind speed Wind direction Global radiation Pressure	2 2 2 2 2 2
R2	64° 35.31 N, 17° 51.73 W	1100 (on ice)	Day 120–274	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Net longwave Pressure Ablation (acoustic)	0.5, 2, 4 0.5, 2, 4 0.5, 2, 4 2 2 2 2 2 2
R3	64° 24.49 N, 17° 16.24 W	1712 (on ice)	Day 121–244	Temperature Humidity Wind speed Wind direction Global radiation	2 2 2 2 2
R4	64° 40.98 N, 15° 52.99 W	830 (on ice)	Day 124–249	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Net radiation Ablation (acoustic)	0.5, 2, 4 0.5, 2, 4 0.5, 2, 4 2 2 2 2 2
R5	64° 35.95 N, 15° 59.88 W	1140 (on ice)	Day 124–250	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Longwave in Longwave out Ablation (acoustic) Snow temperature	0.5, 2, 4, 6 0.5, 2, 4, 6 0.5, 2, 4 2 2 2 2 2 2 At 3 levels

No.	Location	Height (m a.s.l.)	Data obtained	Quantities	Sensor heights (m)
R6	64° 19.03 N, 18° 13.24 W	820 (on ice)	Day 121–244	Temperature Humidity Wind speed Wind direction Global radiation Ablation (acoustic)	0.5, 2 0.5, 2 2 2 2
I6	64° 12.13 N, 16° 25.30 W	715 (on ice)	Day 132–244	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Ablation (acoustic) Snow temperature	0.2, 0.5, 1, 2, 3, 5 0.2, 0.5, 1, 2, 3, 5 0.2, 0.5, 1, 2, 3, 5 2 1.2 1.2 At 5 levels
U2	64° 04.57 N, 16° 18.91 W	50 (on land)	Day 132–244	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Longwave in Longwave out Precipitation Soil temperature	1, 2, 6 1, 2 1, 2, 6 6 –0.1, –0.2, –0.4, –0.6
U3	64° 05.03 N, 16° 18.98 W	165 (on ice)	Day 132–244	Temperature Humidity Wind speed Wind direction Net radiation Turbulent heat flux Turbulent mom. flux	1, 2, 3, 6, 9 1, 2, 3, 6, 9 1, 2, 3, 6, 9 2, 9 3 3
U7	64° 23.57 N, 16° 42.03 W	1530 (on ice)	Day 132–244	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Longwave in Longwave out Ablation (acoustic)	0.5, 2, 6 0.5, 2, 6 0.5, 2, 6 6

No.	Location	Height (m a.s.l.)	Data obtained	Quantities	Sensor heights (m)
U8	64° 42.65 N, 16° 53.96 W	1210 (on ice)	Day 132–244	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Longwave in Longwave out Ablation (acoustic)	0.5, 2, 6 0.5, 2, 6 0.5, 2, 6 6
U9	64° 47.35 N, 16° 43.82 W	870 (on ice)	Day 132–244	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Longwave in Longwave out Ablation (acoustic)	1, 2, 6 1, 2 1, 2, 6 6
U10	64° 49.71 N, 16° 50.02 W	770 (on land)	Day 132–244	Temperature Humidity Wind speed Wind direction Global radiation Reflected solar Pressure Precipitation	2, 4 2 4 4
A1	64° 01.56 N, 16° 15.56 W	4 (on land)	Day 142–248	Temperature Humidity Wind speed Wind direction Temp. fluctuations Wt. bulb temp. fluct. Global radiation Net radiation Pressure Precipitation Soil temperature	1, 3 1, 3 1, 3 3 1.5 1.5
					–0.02, –0.1

No.	Location	Height (m a.s.l.)	Data obtained	Quantities	Sensor heights (m)
A4	64° 05.27 N, 16° 19.44 W	279 (on ice)	Day 139–245	Temperature Humidity Wind speed Wind direction Turb. flux momentum Turb. flux heat Turb. flux moisture IR surface temp. Global radiation Reflected solar Longwave in Longwave out Precipitation	1, 2, 3, 6, 9 1, 2, 3, 6, 9 1, 2, 3, 6, 9 3, 9 3 3 3
A5	64° 07.22 N, 16° 22.08 W	381 (on ice)	Day 143–244	Temperature Humidity Wind speed Wind direction Turb. flux momentum Turb. flux heat Turb. flux moisture IR surface temp. Global radiation Reflected solar Longwave in Longwave out Precipitation	1, 2, 3, 6, 9 1, 2, 3, 6, 9 1, 2, 3, 6, 9 3, 9 3 3 3

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