Greenland Ice Margin EXperiment (GIMEX)

GIMEX-90 Field Report

Institute of Meteorology and Oceanography
University of Utrecht

GIMEX-90 Field Report

R. Bintanja, W. Boot, M. van de Broeke, L. Conrads, P. Fortuin, J. Oerlemans,
M. Portanger, A. Russell, R. van de Wal, J. de Weger

1. INTRODUCTION

The GIMEX (Greenland Ice Margin EXperiment) campaigns form part of a research project on *Land Ice and Sea-Level Change*, carried out at the Institute of Meteorology and Oceanography, University of Utrecht. The overall aim of this project is to reduce the current uncertainty in prediction of future sea level on the century time scale, and to better understand sea-level variations that have occurred in the immediate past.

Apart from major input by the University of Utrecht, the project is funded by a number of bodies/institutions: the European Commission, NWO (the Netherlands Organization for Scientific Research), VROM (the Netherlands Ministry of Housing, Physical Planning and Environment).

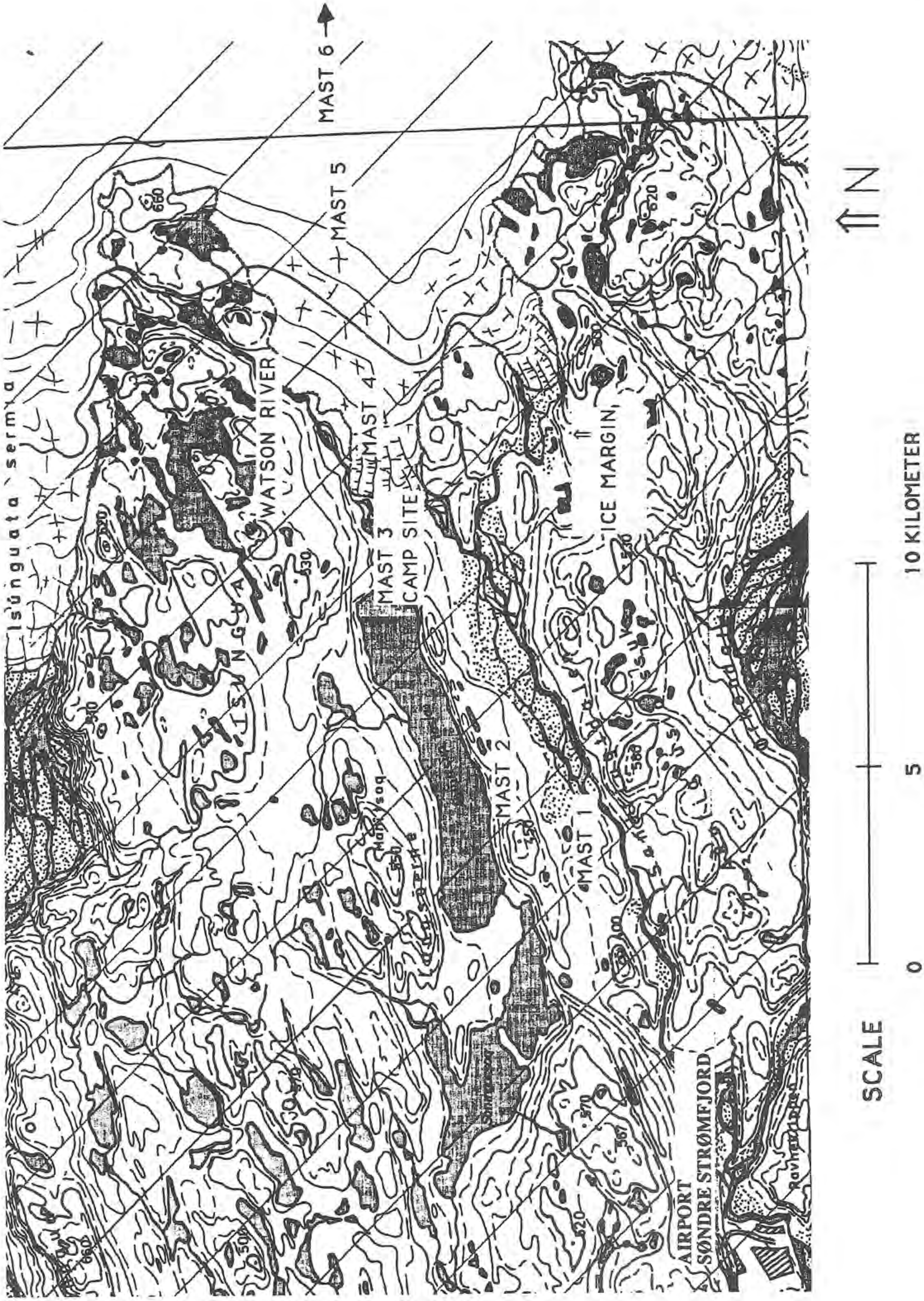
There is a close scientific collaboration with the Geological Survey of Greenland (Copenhagen), the Eidgenossische Technische Hochschule in Zürich, and the Alfred-Wegener-Institut für Polar- und Meeresforschung (Bremerhaven), in the framework of a *European Programme on the Greenland Ice Sheet and Climatic Change*.

The more specific scientific goals of the meteorological experiments near and on the ice margin in West Greenland, GIMEX-90 and GIMEX-91, are:

(1) To obtain a better understanding of how glacier mass balance is related to meteorological conditions.
(2) To investigate how the large thermal contrast between the ice-free tundra and the ablation zone of the ice sheet affects local circulations and associated heat transport.
(3) To make a detailed study of the atmospheric boundary layer over a melting ice/snow surface.

The most important aspect of the experiment is to support further modelling studies in which the physical process close to and on the surface are treated as explicitly as possible. For this reason it was decided to carry out a detailed experiment of relatively short duration, rather than aiming to obtain a 'climatology'.

The area of Søndre Strømfjord was, to a large extent, selected for logistic reasons: close to an international airport and relatively easy access to the ice sheet. In addition, the mass-balance transect (established in 1989) nicely fills the gap between the measurements made by the Geological Survey of Greenland in the south and those made near Jakobshavn.


Isunguata sermia
ISUNGUA
WATSON RIVER
MAST 6
MAST 5
MAST 4
MAST 3
CAMP SITE
MAST 2
MAST 1
ICE MARGIN
AIRPORT
SØNDRE STRØMFJORD
660
620
530
550
580
500
570
567
520
SCALE
0
5
10 KILOMETER
N

2. LOGISTICS

Survey in 1989

In August 1989 a survey of the field area was made by car and helicopter. Stakes were placed on the ice sheet at six locations, in an east-west transect just south of Insunguate Sermia (see map).
Radio contact was tested for audio connections and telemetric data assimilation. In fact, a visit was made to all locations where meteorological masts were to be placed in 1990. The survey was carried out by L. Conrads, W. Boot and R. v.d. Wal, with assistance from P. Tollerup.

It was decided that during GIMEX-90 and GIMEX-91 a base camp would be set up close to the ice margin ('barbecue place'), which could be reached by the two small trucs available. One of these trucs could serve as data communication center (referred to as the 'communication truck' in the following) and contains the radio receivers and computers, the other one could then be used for transport in the area. It became also obvious that a boat would be needed to cross the major glacial river.

Experiment in 1990

Shipping of the equipment turned out to have its difficulties. A 10-day delay was encountered before the equipment actually was onshore in Søndre Strømfjord. Because of this, it was decided to shift the measuring period further in time, which unfortunately implied that materials could not be send back by ship. The necessary equipment (sensors and electronics) were finally send back by plane, while storing as much as possible (masts, trucks, boat, camp gear, etc.) in Søndre Strømfjord for GIMEX-91. The following timetable provides an idea of how the work was organized.

The trucks used in GIMEX-90. One is for transportation mainly, the other contains the data communication centre (receivers / computers / power).

June, 5	loading of equipment in 10 ft container at University of Utrecht
June, 7/8	transport of container and two trucks to Aalborg
June, 13	departure ship from Aalborg
July, 3	departure of *group 1* (Boot, v.d. Broeke, Conrads, Fortuin, Russell)
July, 4	arrival of ship in Søndre Strømfjord, arrival of group 1
July, 6-8	transport of equipment to basecamp
July, 8-17	installation of the six masts, placing stakes, GPS
July, 18	first day on which all equipment worked
July, 20	departure of *group 2* (Bintanja, Portanger,v/d Wal, de Weger)
July, 21/22	changing the guard
August, 17	last day of experiment
August, 18-22	transport of equipment to Søndre Strømfjord
August, 24	departure of group 2/transport of a part of the equipment by air to Schiphol, Amsterdam

A camp was erected close to the ice margin, consisting of one large cooking/working/sitting tent (heated), one tent for storage of food and other goods, one tent to serve as electronic laboratory, and a number of small sleeping tents (basically, each expedition member has his private sleeping tent). All materials were brought from the harbour to the camp site, from where it was lifted by helicopter to the actual mast locations.

Reliable power supply at the camp is essential for the whole experiment, so particular attention was paid to it. Normally a generator was run continuously. In case of a break-down, a spare generator was available. As additional safety, a large battery capacity was stored in the communication truck. In the event that this source would be almost empty, the engine of the truck could still be used to generate power.

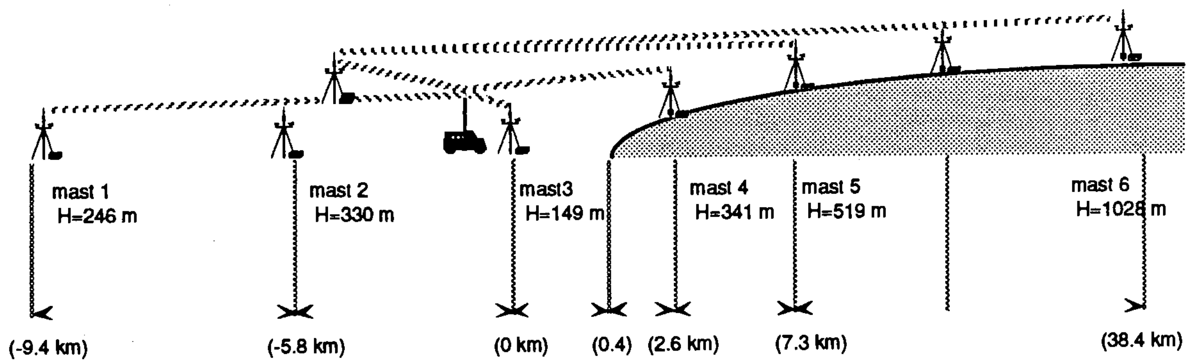
The camp site close to the ice edge

3. EQUIPMENT

Meteorological instruments on the masts

Six masts were erected along a line perpendicular to the ice edge. Two additional masts were installed to improve the audio and data-communication. This set-up is shown in the figure below. The instrumentation was as follows:

mast 1:	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
mast 2:	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
mast 3:	temperature at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	humidity at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	shortwave up and down at 1.5 m:	Kipp CM14
	total rad up and down at 1.5 m:	Aanderaa 2811
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
mast 4:	temperature at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	humidity at 0.5, 2 and 6 m:	ventilated Rotronic YA-100
	shortwave up and down at 1.5 m:	Kipp CM14
	shortwave up and down at 1.5 m:	Aanderaa 2811
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
mast 5:	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	shortwave up and down at 1.5 m:	Kipp CM14
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750
mast 6:	temperature at 2 and 6 m:	ventilated Aanderaa 2775
	shortwave up and down at 1.5 m:	Kipp CM14
	wind speed at 2 and 6 m:	Aanderaa 2740
	wind direction at 6 m:	Aanderaa 2750



Some specifications of the sensors:

sensor	type		range	unit.	precision
air temperature	Aanderaa	2775	-44 to +49	°C	0.1
air temperature	Rotronic	YA-100	-20 to +28	°C	0.05
humidity	Rotronic	YA-100	0 to 100	%	2
wind speed	Aanderaa	2740	0.2 to 60	m/sec.	0.2
wind direction	Aanderaa	2750	0 to 360	°	4

sensor	type		spectral range	precision
pyranometer	Aanderaa	2811	300 to 2500 nm	3 W/m2
pyrradiometer	Aanderaa	2770	300 to 60000 nm	3 W/m2
pyranometer	Kipp	CM14	305 to 2800 nm	2 W/m2

A count of the sensors:

	number of sensors	transmitting power (Watt)	distance to base camp (km)
Station 1	5	5	9.4
Station 2	5	0.5	5.8
Station 3	13	0.5	0.2
Station 4	13	5	2.6
Station 5	7	5	7.3
Station 6	7	20	40
total	50		

Picture of a mast in upper ablation zone

The use of unguarded masts in a region where melting rates are high (several meters in the measuring period) poses some special problems. A construction fixed to the ice could be made, but this would imply very large changes in the height of the sensors. This is undesirable, in particular since turbulent fluxes have to be calculated. Instead a construction was designed that stands freely on the ice surface. It consists of a regular aluminum mast, with four long lags at the base, making a small angle (10°) with the surface. At the end of these lags sharp pins are attached to keep the construction in place. A mast of this type was tested in a field campaign on the Hintereisferner (summer 1989) and appeared to work well. It was then decided to use this design on Greenland as well, for masts 4, 5 and 6. At least during GIMEX-90, the masts behaved in a satisfactory way. At the end of the field campaign, the tilt was small. As the pins/legs melt in the ice, the sensors gradually came closer to the surface. This is a small effect, however: not more than 0.1 m in the course of the whole period.

Data assimilation

The system of registration was telemetric (RIDAS, Radio Interfacing Data Aquisition System). A reliable protocol for this was developed. The sampling frequency for all sensors is 2 minutes; to this time, date, voltage of battery, load current of solar panel, and a dummy sensor are added.
First data are stored locally at the mast, and after some time send in packets to the receiving station in the base camp. In practice, a disturbance in the radio connection during up to 28 hours can be handled with this system without loosing data. The sequential accumulation of data from all the stations is done in a fully computer-steered procedure. The total volume of data per day (excluding the cable balloon) amounts to about 45000 numbers.
Further equipment/specifications:

radio receiver, Kenwood TM431A/TH45
radio-telemetry with Packet Radio, Protocol AX25, 1200 bit/s, 451 MHz
computers: 2 x MacIntosh IIcx, removeable drives.

Each mast has its own power unit (for ventilation of the temperature sensor and local computer/ transmitter), consisting of a solar panel(Siemens, 12 Watt) in combination with a regular battery , and a lithium battery to overcome periods with extremely low insolation. Only for mast 4 the lithium battery was actually used, after a cloudy/rainy period of several days.

The balloon

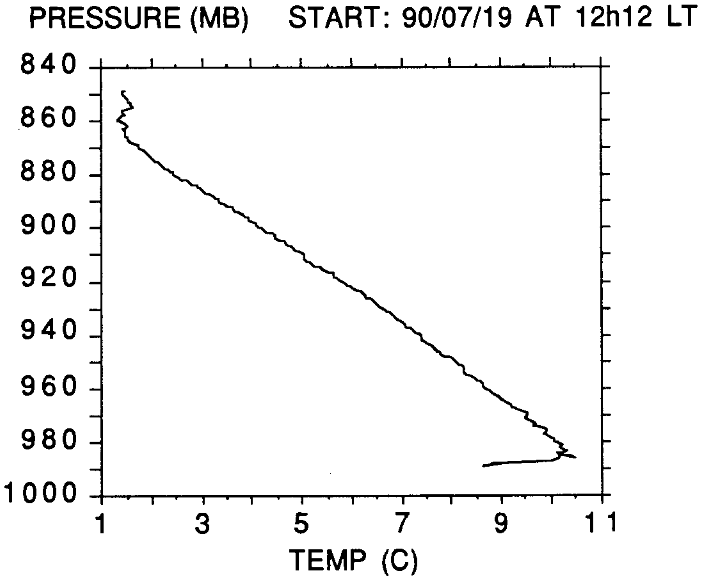
In addition to the masts, a cable-balloon system (with ADAS, Airborne Data Aquisition System) was used at the camp site to obtain wind, temperature and humidity profiles up to a height of 1500 m. A 12 m^3 balloon was used, requiring slighty more than one bottle of helium for one filling. Seven bottles thus appeared to be sufficient for the whole period.
Some specifications:

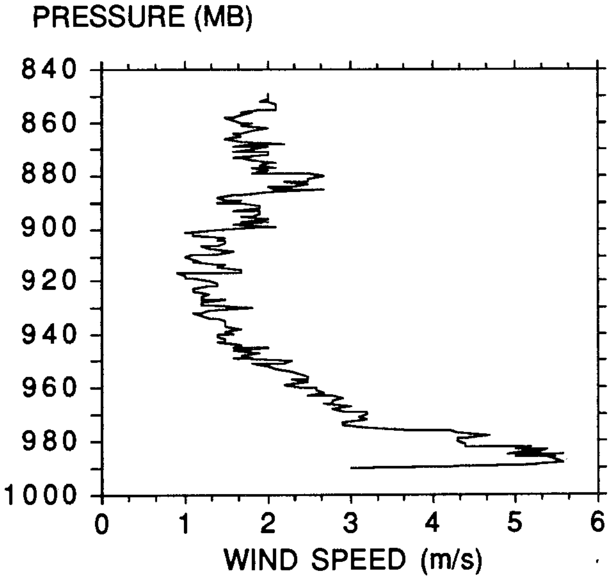
- 11.3 m^3 balloon, helium, type Airborne K-65, weight 7.3 kg
- cable: 2000 m Kevlar, 1 g/m.
- winch: electric, 750 Watt, especially made
- sonde 1: tethersonde
    air temperature
    wet-bulb temperature
    wind speed
    wind direction
    pressure
- sonde 2: tethersonde
    air temperature
    humidity from a carbon hygristor
    wind speed
    wind direction
    pressure

- data assimilation: ADAS (Atmospheric Data Acquisition System).
  The ground station is a basic ADAS-receiver, which receives eight variables by telemetry: elapsed time, pressure, temperature, wet-bulb tempereerature, wind speed, wind direction. The ADAS then sends the data to a Macintoch IIcx computer in the 'communication truck'. Operating frequency: 404 MHz.

Soundings were made every day at 07, 10, 13, 16, 19, 22, 01 and 04 local time, subject to the condition that it was not raining and wind speed at the surface was not exceeding 10 m/s. High priority was given to the 04, 10, 16 and 22 hour soundings. In total, 140 ascents were made in 31 days.

As an example, the output from one ascent is shown below. This is a case with a pronounced but shallow katabatic flow shooting off the ice sheet.





Mass balance measurements

Two portable hot-water drills were used to drill holes for placing stakes. This did not give any problems, although the drills are still not as light and convenient as one would wish.
Unfortunately, most of the stakes placed in the summer of 1989 could not be found back. In spite of the fact that they were made of strong aluminum, they all broke off, supposingly due to ice accretion and extreme high winds. Probably, the flags attached to the stakes were too large. Flags on the new stakes have been made smaller, and all stakes have been positioned accurately by GPS (see below).

Positioning and navigation

GPS was used for positioning stakes as well as navigation in the helicopter. Two instruments of the type Magellan GPS NAV-1000 were used for this purpose. In the Netherlands a test with a helicopter (at Soesterberg air base) had already been made and showed that a single instrument can be used efficiently in a small helicopter. For navigation on the ice sheet, this type of instrument turned out to be of great value.
Positioning of stakes was done by using the instruments in differential mode. This requires two instruments, but leads to a larger accuracy (estimated error amounts to about 5m in the 2 dimensional, i.e. horizontal, mode). Comparing stake positions at the beginning and at the end of the field campaign gave estimates of ice velocities that looked quite reasonable.
Using the instruments required some planning, however. As not all planned satellites are yet in orbit, positioning could not be done through the whole day. A program had to be run to find out the availability of satellites, and to plan a trip accordingly. It is expected that in the coming years the situation will improve considerably.

Runoff measurements

In the glacial river emerging from the ice edge measurements of discharge were carried out. These measurements formed a continutaion of work done on Jökulhlaupts by A. Russell in earlier years, and the availability of abundant meteorological data for the 1990 summer season promised an interesting comparison between calculated ablation and river discharge.
A pressure transducer was placed in a plastic pipe, and pressure was logged by a simple Squirrel data logger. The river was profiled with a boat several times. Flow measurements were done to obtain a reliable relation between discharge and water depth.

4. SOME PRELIMINARY RESULTS

Global characteristic of temperature and wind at the six masts

The data set obtained in the experiment is large, and it is not feasible to give a full description here. Instead, a few examples of output are given, which give a first impression of the typical local meteorological conditions in summer.

Figure 1 shows daily mean values of air temperature (at 2m) and global radiation as measured at the base camp. The weather conditions were good, particularly in the beginning of the period, but with some noticable weather break downs (e.g. on day 10). Some days had exceptionally high mean temperature (e.g. almost 16 °C on day 9)

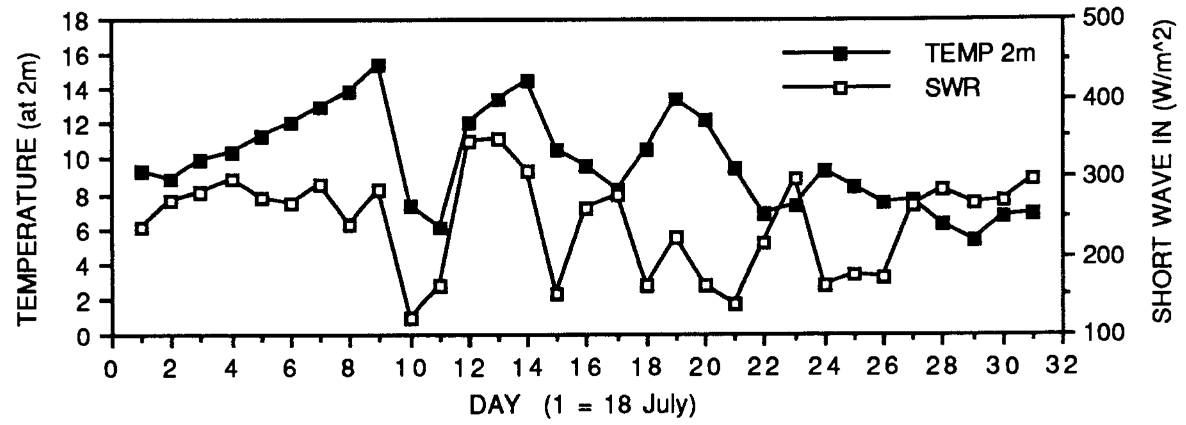


Figure 1. Global radiation (SWR) en air temperature at 2 m, at mast 3 (base camp).

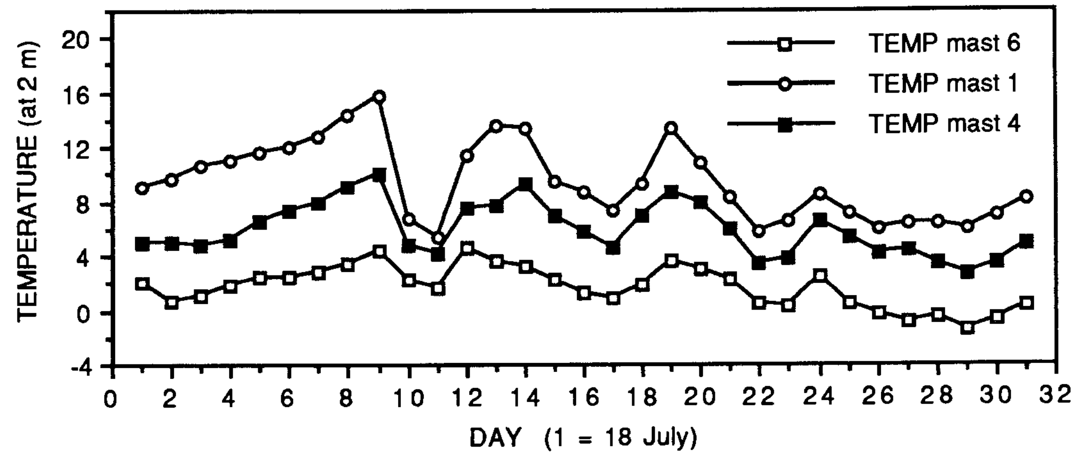


Figure 2. Daily air temperature at 2 m, at masts 1, 6 and 4. The temperature at mast 1 is very similar to that at mast 3 (base camp, see figure 1).

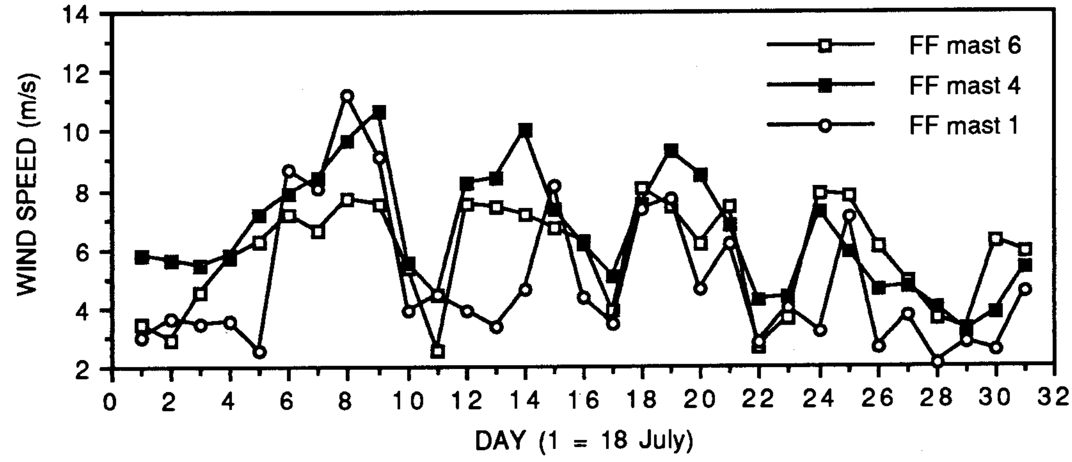


Figure 3. Daily mean wind speed at 6 m, at masts 1, 6 and 4. The winds on the ice sheet are generally stronger than in the tundra (even on the hills). This reflects the strong katabatic component, particularly at mast 4.

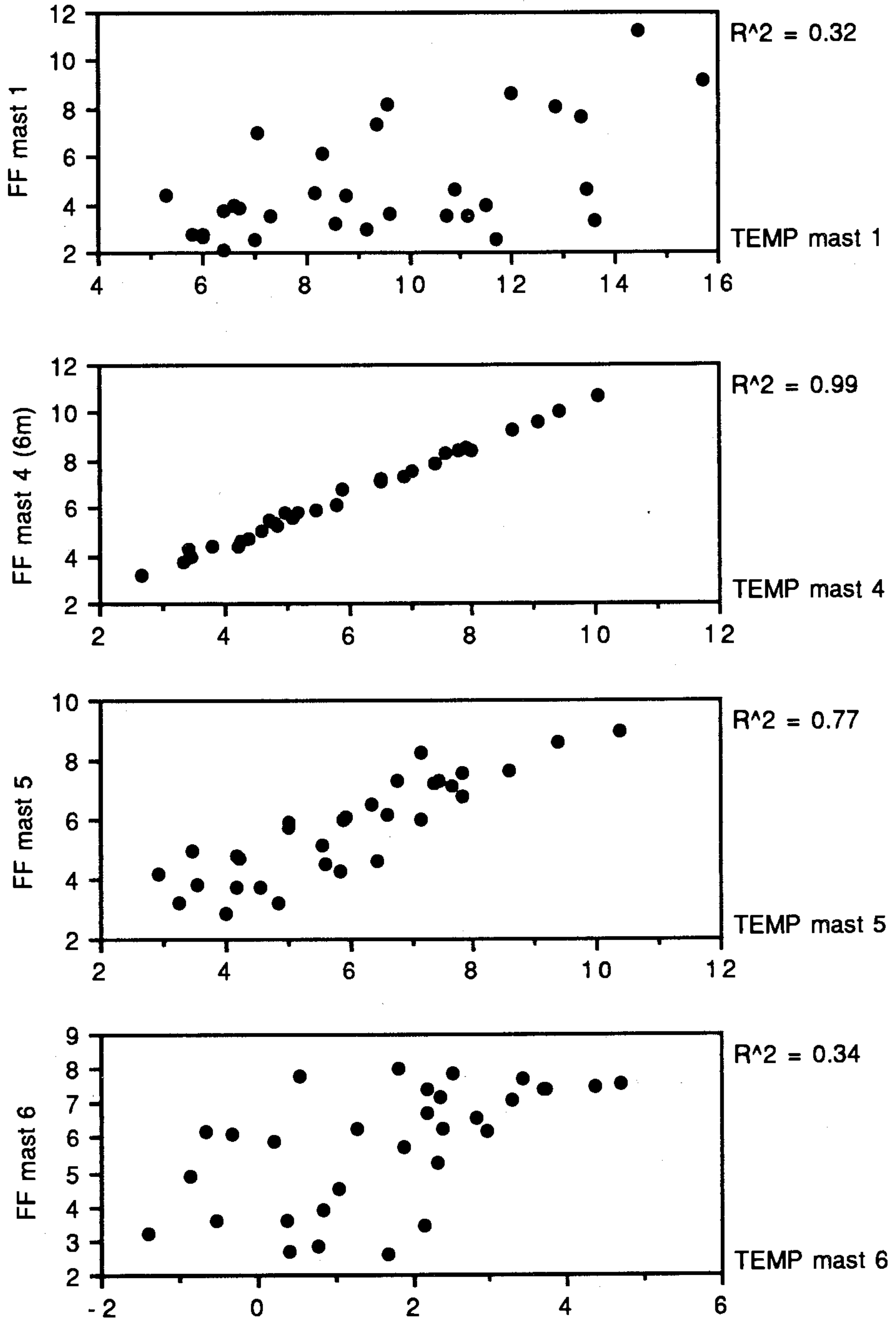
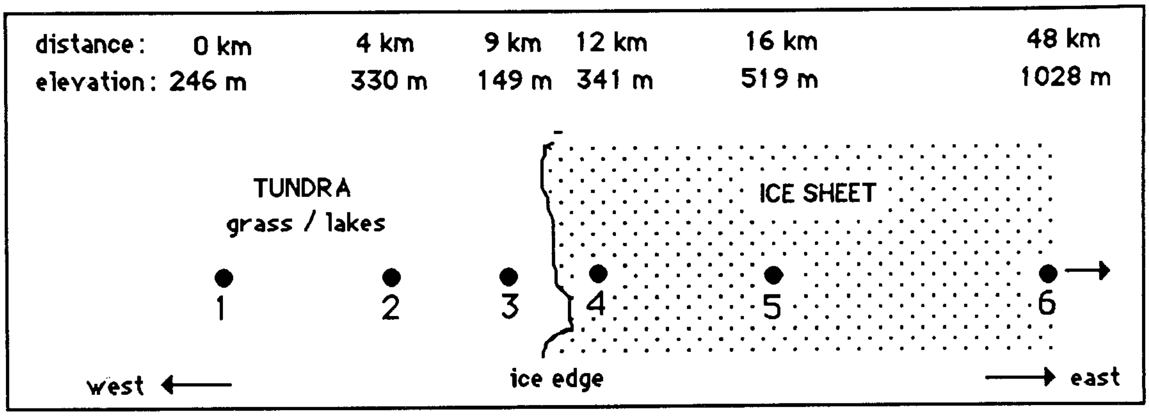


Figure 4. Scatter diagrams of daily wind speed and daily mean temperature at masts 1, 4, 5 and 6. The perfect relation for mast 4 is very striking (0.99 correlation coefficient). This demonstrates that the wind at mast 4 is totally driven by the local excess buoyancy. Correlation of temperature at mast 1 and wind speed at mast 4, not displayed here, also gives a high, though somewhat smaller, correlation coefficient. A closer look at the data shows that there is a pronounced daily cycle in the katabatic flow down the ice sheet, with maximum wind speed in the early afternoon.

Wind direction is not considered in these figures, but on the ice sheet easterly flow dominates. At mast 6, the wind was easterly during the entire period of 31 days.



An additional sketch of the experimental set-up for reference

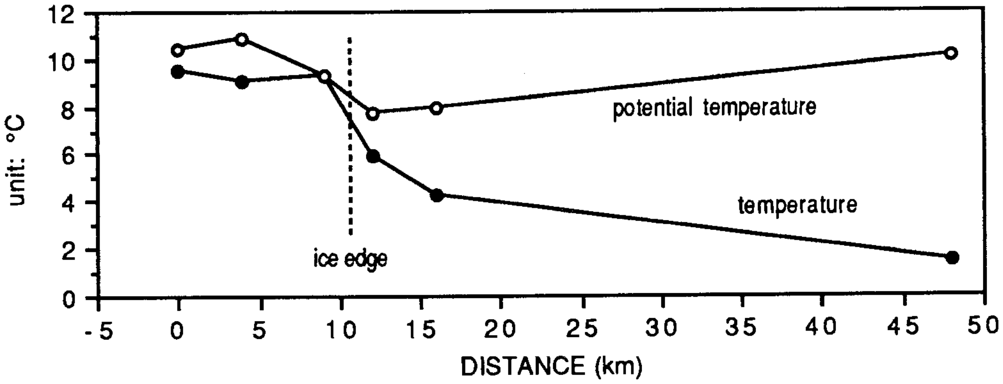


Figure 5. Temperature (at 2 m) and potential temperature (with reference to base-camp elevation) averaged over the entire 31-day period. Mean temperature difference between masts 4 and 6 corresponds to a 0.0064 K/m lapse rate. For temperature at 6 m this rate is larger, namely 0.0070 K/m.

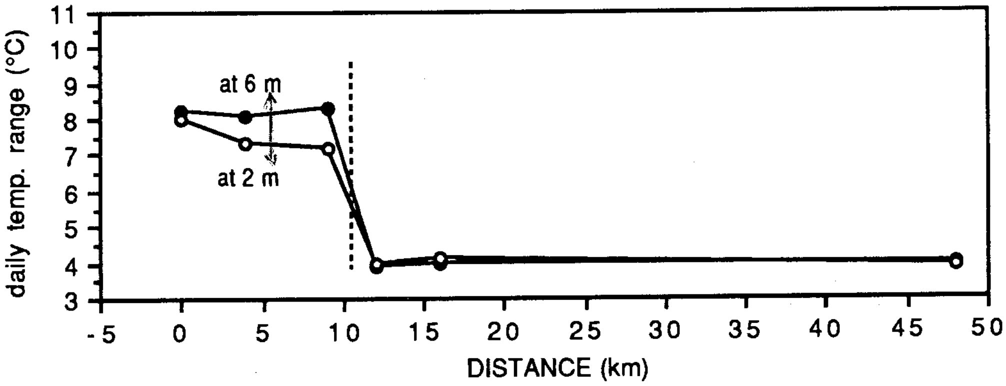


Figure 6. Daily temperature range averaged over the 31-day period. Note the remarkable constancy of the range both over the tundra and over the ice sheet. It should be added, however, that there is no clear daily cycle on the ice sheet. In many cases, the signal is dominated by a temperature trend increasing or decreasing during the whole day. On calm and sunny days, the temperature range in the tundra is about 14 K.

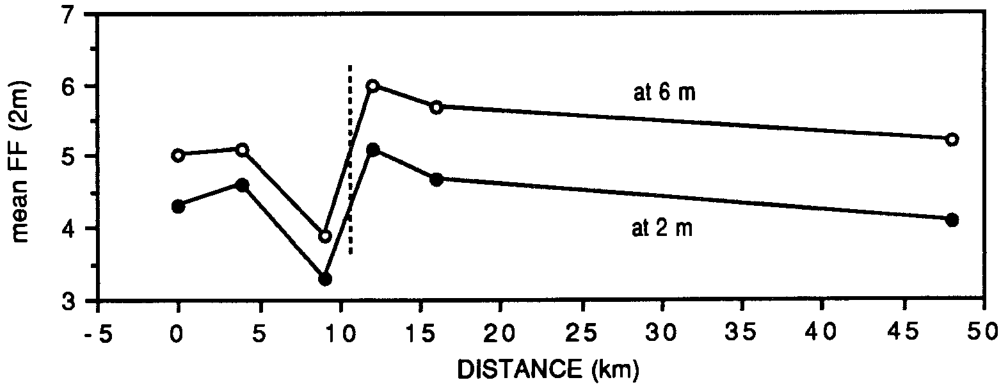


Figure 7. Wind speed averaged over the 31-day period. Apparently, the increase with height is somewhat larger over the ice sheet.

Typical daily cycle in fair weather

The differences between the tundra and ice sheet are most pronounced during sunny weather, of course. Such a sunny period, with weak synoptic-scale flow, was 18-22 July. To obtain a smoothed characteristic pattern, the daily cycles were superposed, both for the measurements at the masts and with the balloon. In this five-day period, 30 ascents/descents were made, on average up to 1200 m. Most interesting features were found in the lower few hundred meters. At the base camp, an inversion is present during most of the day. During the (short) night, the katabatic wind is weak and the inversion develops due to local radiative cooling. In the morning the surface layer heats very rapidly and conditions become more uniform with height (see 6am curve in *figure 9*). However, as the boundary layer heats up during the day, the katabatic flow from the ice sheet strengthens and creates a sharp inversion over the nearby tundra. This is shown in more detail in *figure 9*. This sequence of events occurs on all sunny days with a large-scale flow that is not too strong. In fact, the inversions in *figure 8 and 9* appear remarkably sharp even in 5-day means.

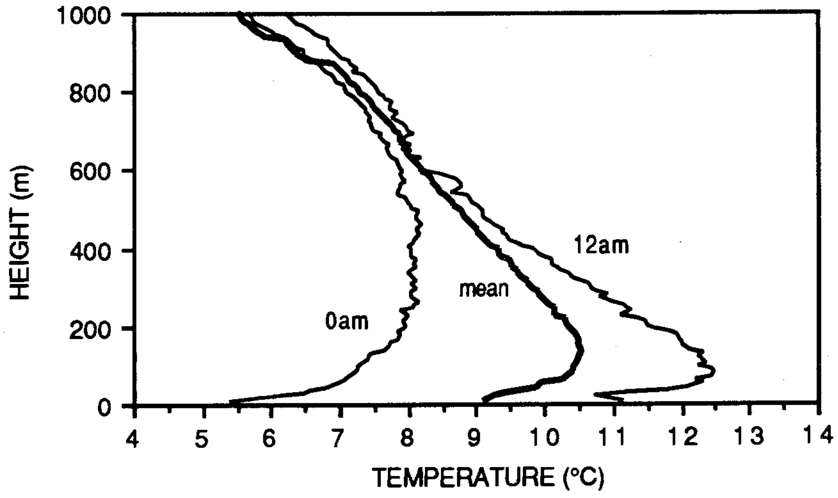


Figure 8. Five-day mean soundings for a fair weather period. Mean refers to the average taken over the sample of 30 soundings made during this period. The inversion during the night is mainly due to radiative cooling, whereas the inversion at noon is entirely caused by the katabatic wind flowing from the ice sheet. Very close to the surface the temperature gradient changes sign again, so that there is still an upward net heat flux from the surface. More detail about the development of the katabatic wind layer is shown in the next figure.

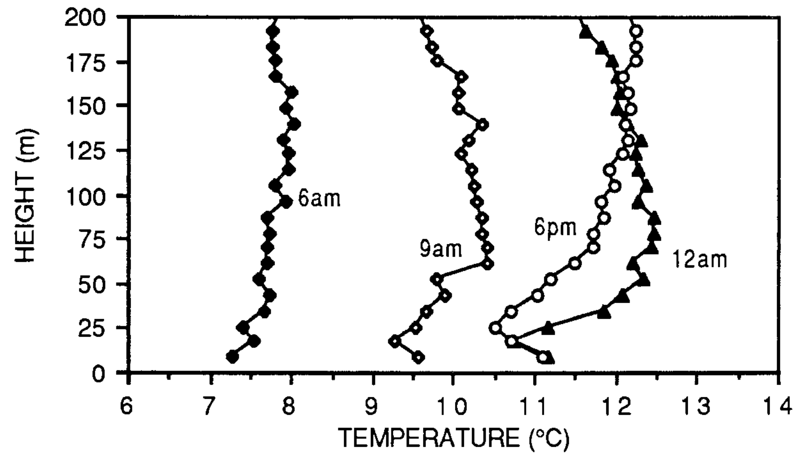


Figure 9. A close-up of mean temperature profiles for the indicated times averaged over 18-22 July 1990.

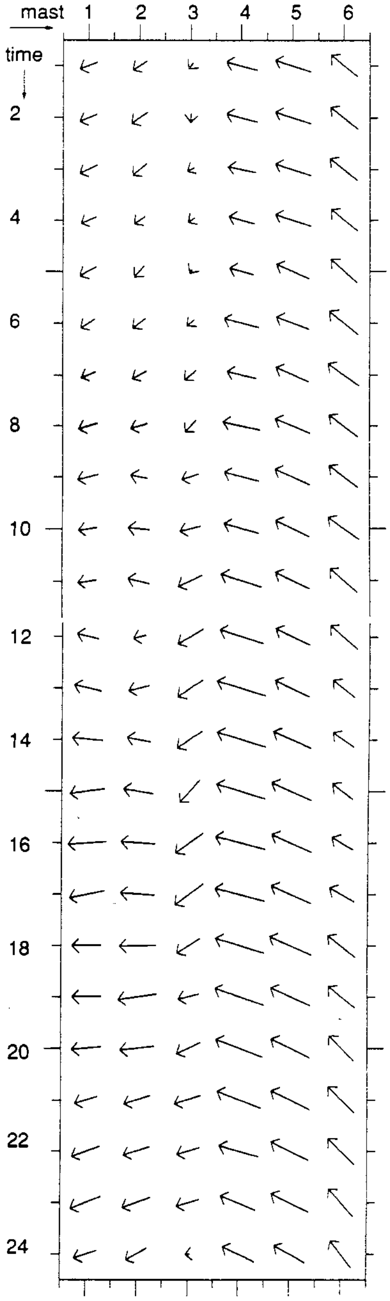


Figure 10. Mean wind vectors at the six masts, obtained by superposition of the five days (18-22 July) with fair weather. Orientation of windvectors as usual (up=north; right=east). The discontonuity at the edge of the ice sheet (between masts 3 and 4) is striking. Note that the katabatic flow is strongest and close to the fall line at mast 4, and that it turns to southeast further on the ice sheet (mast 6).

Water discharge in the glacial river

Although the catchment of the glacial river in which the pressure transducer was placed is not very well known, a comparison between discharge and the energy balance of the ice surface in the ablation area appears interesting. Comparing variations in these elements may give useful information on the drainage system of the ice-sheet sector in study.

River stage data was converted to discharge at five minute intervals using the previously derived rating curve. Discharge figures were averaged into hourly and daily mean values for comparison with energy balance calculations. All the hourly discharge data for the period 10 July - 18 August are shown in *figure 11.*

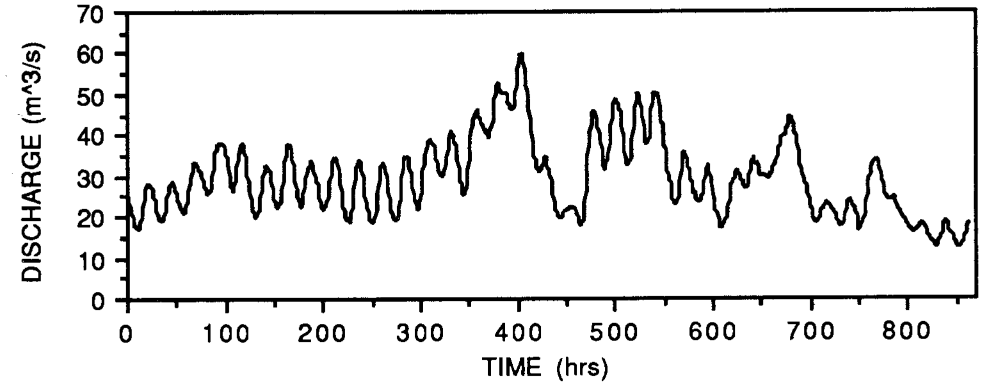


Figure 11. A plot of all hourly mean discharge values, starting on 10 July. Note that the daily cycle is, on average, about one third of the base flow.

Physically it might be expected that discharge would lag behind the energy balance of the ice surface, the magnitude of the lag being dependent upon meltwater transit times. Statistical analyses for hourly mean values revealed *a lag time of approximately six hours* as expressed by maximum correlation coefficients. This in agreement with the concept of a relatively small catchment area with a well developed glacial drainage system. The relation between discharge and energy balance on a daily basis is shown in *figure 12.* There still seems to be a lag of approximately one day. A more detailed interpretation will require the use of a model for the hydraulic system of the ice-sheet sector.

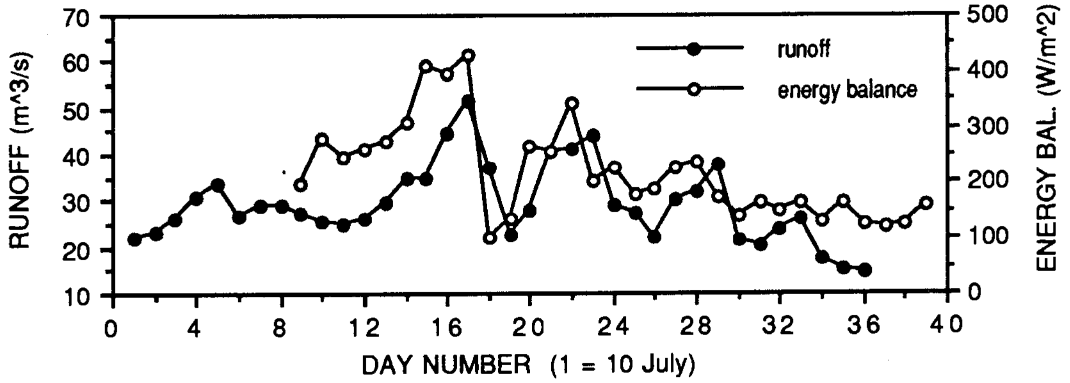


Figure 12. Daily mean values of river discharge compared to daily mean values of the surface energy balance at mast 4.

Surface albedo

As mentioned earlier, there were logging problems with the Kipp sensors. Fortunately, on mast 4 both Aanderaa and Kipp radiometers were used, which provided a possibility to analyse the problems in detail. So reliable albedo measurements are only available from mast 4, although at the other locations on the ice sheet measurements were done several times with a hand-held fotocel type of albedometer. This suggested that there is little variation in the lower ablation zone between masts 4 and 5. ***Figure 13*** gives an impression of variability in suface albedo at mast 4 (from the Aanderaa sensors, which were also used in the Hintereisferner-experiment in 1989).

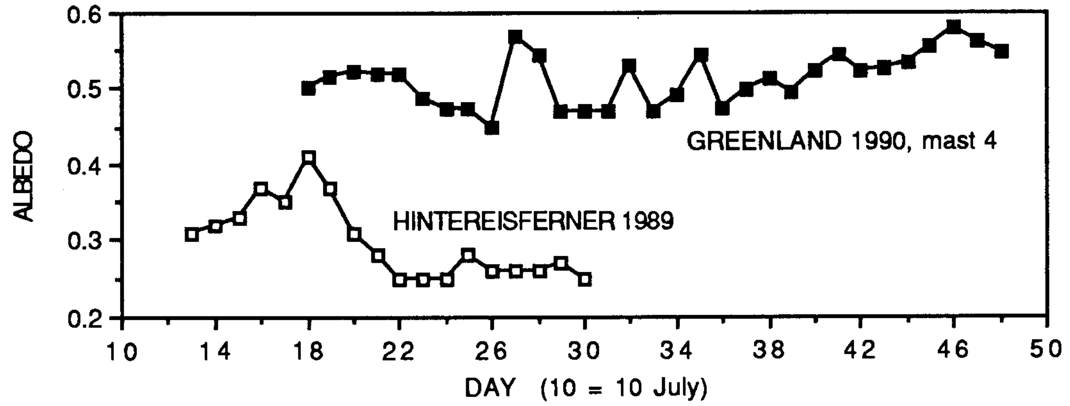


Figure 13. Daily albedo as measured at mast 4. A comparison is made with albedo measured with the same equipment on the Hintereisferner in 1989, also in the ablation zone.

Ablation and pdd (sum of positive daily mean temperatures)

At 4 locations ablation was measured: mast 4, mast 5, relais station, mast 6. As these places were not visited on exactly the same days, the duration of the period over which the ablation was measured differs somewhat. A summary of the data:

location	elevation (m)	ablation (cm *ice*)	period (days)	rate (cm day^{-1})	pdd (K)	ddf (cm day^{-1} K^{-1})
mast 4	355	195	43	4.53	184	1.06
mast 5	519	170	42	4.05	133	1.28
relais	738	147	37	3.97	-	-
mast 6	1028	113	34	3.32	51	2.21

The decrease of ablation with surface elevation is of the order of 0.11 m water equivalent per 100 m. In comparison with usual ablation gradients found on glaciers, this is very small. However, one should realize that normally a considerable part of the ablation gradient stems from difference in the *length* of the ablation season. As the values presented here refer to part of the ablation season only, firm conclusions cannot yet been drawn. Nevertheless, it appears that decreasing cloudiness and the associated increase in the net radiation balance when going up the ice sheet explains the small ablation gradient.

The degree-day factor (ddf; defined here as cm of ice melt per pdd) appears to increase significantly when going higher up. This points to a large importance of radiation (relative to turbulent flux) in providing the melt energy.

5. CONCLUSIONS

Much of the scientific work based on the data set acquired during GIMEX-90 still has to be carried out and/or written up. Publication of results will mainly be after the GIMEX-91 experiment, which is very similar in character to GIMEX-90. A number of conclusions, or points of interest, can nevertheless be listed.

Equipment and experimental set-up:

* The types of sensors in use now have sufficient accuracy and reliability.
* Logging of the Kipp's gave problems and the absolute values of the data are not reliable. This problem has meanwhile been solved in the laboratory.
* Powers supply with solar panels at the masts is satisfactory for summer experiments.
* RIDAS works well; much of the data handling has been done at the base camp during the experiment.
* The balloon data are of good quality, and many ascents were made. This is a direct consequence of the very good weather conditions in the region, and cannot be expected to work everywhere. Sooner or later all balloons start to leak. This requires further attention. The winch also showed some deficiencies, but it could be kept working for the whole period. Having a spare winch in future experiments is a necessity.
* Ablation stakes have to be placed carefully. Only one 1989 stake was found back; probably the flags were too large.
* GPS is of great help in navigation and finding masts. It can be expected that some useful ice velocity data become available at the end of GIMEX-91.

Preliminary results:

* Calculated energy balance is in agreement with measured ablation.
* The ablation decreased surprisingly little with altitude during the measuring period.
* Day-to-day fluctuations in the energy balance of the ablating ice surface correlate well with variations in run-off in the glacial river. The base flow is relatively large, however.
* Over the ice margin the katabatic wind regime dominates. The correlation of temperature and (downslope) wind on the ice sheet is very high.
* In the tundra wind direction was variable, while on mast 6 (40 km from the ice edge) the wind was always easterly.
* On sunny days the daily temperature range in the tundra is 15 K, on the ice sheet 4 K.
* The balloon soundings showed that maximum temperature at 1000 m above the tundra occurs a few hours later than at the surface. No shift in time of maximum temperature at masts 5 and 6 was found, indicating little energy transport on a daily time scale.
* The katabatic flow layer shooting off the ice sheet is some tens to a few hundred meters deep.
* Typical surface albedo in the ablation zone is 0.5, which seems higher than on most mountain glaciers.
* It is difficult to determine the temperature lapse rate along the ice surface. At 6 m above the surface it appears to be 0.0070 K/m, at 2 m above the surface 0.0064 K/m.

6. PARTICIPANTS

Group 1: L. Conrads (field leader)
W. Boot (technician)
M. van de Broeke (student)
P. Fortuin (Ph.D. student)
A. Russell (University of Edinburgh)

Group 2: R. van de Wal (field leader)
M. Portanger (technician)
R. Bintanja (Ph.D. student)
J. de Weger (student)

General project leader: J. Oerlemans
General expedition leader: L. Conrads

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