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OROGRAPHIC PRECIPITATION AT THE GLACIER AUSTRE BRØGGERBREEN, SVALBARD

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REPORT NR. 02/97 KLIMA

DNMI - RAPPORT

ISSN 0805-9918

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REPORT NO.
2/97 KLIMA

DATE
06.01.97

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PROJECT CONTRACTORS

Norwegian Research Council and Norwegian Meteorological institute.

Abstract

During the summer seasons 1994-95, seven recording raingauges were operated in a profile across the glacier Austre Brøggerbreen near Ny-Ålesund, Spitsbergen. The results indicate that the precipitation in central areas of the glacier is 45% higher than in Ny-Ålesund, and that the precipitation distribution in the Ny-Ålesund area is strongly dependent on the large-scale wind direction.

The high precipitation amounts recorded at the glacier are probably caused by a combination of spillover and seeder/feeder effects. A rough altitude-precipitation increase is estimated to 20 % per 100m, at least up to 300 m a.s.l. The orographic precipitation enhancement, and catch deficiency of conventional precipitation gauges may fully explain the apparent discrepancy between precipitation measured in Ny-Ålesund and runoff/massbalance estimates for the Bayelva catchment. The precipitation conditions in Ny-Ålesund and at the glacier are very vulnerable for changes in circulation pattern. For a «climate change» scenario of 30% increase of winds from sector S-W, the precipitation in Ny-Ålesund would increase by 8% and at the glacier by 19%. The precipitation at the glacier would for this scenario be 60% higher than in Ny-Ålesund.

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FOREWORD AND ACKNOWLEDGEMENT

During the years 1993-96, the Climatology Division at the Norwegian Meteorological Institute (DNMI) has performed three projects in the Norwegian Arctic. The projects are partly financed by DNMI and partly by the Norwegian Research Council (NRC).

In the project «Climate Studies in the Norwegian Arctic» (NRC-No 101612/410) one of the subprojects was to study precipitation distribution in a profile across the glacier Austre Brøggerbreen near Ny-Ålesund, Spitsbergen. This report summarizes the main results from this subproject.

The second project «Long term variations in atmospheric circulation and climate in Norwegian Arctic» (NRC-No 112890/720) deals with e.g. comprehensive surveys of climatological statistics for Norwegian Arctic, and relationships between circulation patterns and climate. In chapter 3 and 4 some preliminary results are given on the influence of circulation on the local precipitation distribution.

In the third project, «Climatological Scenarios in two Catchments at Svalbard» (NRC-No110648/730), one of the aims was to give climatological scenarios for Ny-Ålesund, with special emphasis on hydrological consequences. Some scenario-considerations of influences of changes in frequencies of circulation types on the precipitation distribution in the Ny-Ålesund area, are discussed in ch. 4.2.

The authors are indebted to
Sverre N.Thon, Geir Åsebøstøl, Lars Inge Sæther and Even Moldstad, Norwegian Polar Institute for assistance in Ny-Ålesund, and to Ellen Viste, UNIS/UiB for assistance in the field.

Nils Langgård, Per Ove Kjensli, Ragnar Brækkan, Egil Kragstad, Leif Gunnar Olonkin, DNMI for assistance in the field and preparing the instruments. Nils Langgård and Martin Iden, DNMI for excellent assistance in the preparing and statistical handling of the dataset.

Dr. Tadeusz Niedzwiedz, Institute of Meteorology and Water Management in Cracow, Poland for permission to use his circulation type classification in this study.

A special thank to our good friend, the late Elias Davidsen, Faeroe Islands, who designed the recording precipitation equipment used at the glacier and who encouraged the project.

1. Introduction

1.1 Background

The knowledge of precipitation distribution at Spitsbergen is rather limited. The available station network is sparse, presently just consisting of the 5 weather stations: Hornsund, Sveagruva, Barentsburg, Svalbard Airport and Ny-Ålesund (Nordli et al.,1996). All these stations are situated at the western coast of Spitsbergen, and all stations (except Barentsburg, height 73 m a.s.l.) are located lower than 30 m a.s.l. The highest mountains on Spitsbergen are more than 1700 m a.s.l., and very little is known about precipitation conditions in the mountain areas.

Maps of annual precipitation distribution at Spitsbergen have been based mainly on snow depth measurements, glacier accumulation studies and scattered streamflow measurements. In addition it is extremely difficult to perform accurate precipitation measurements in Arctic areas (Hanssen-Bauer et al.,1996). A large proportion of the precipitation falls as snow during high wind speeds, and under such conditions the conventional precipitation gauges just catch a small fraction of the "ground true" precipitation (Førland et.al.,1996).

Because of lifting and consequent cooling of airmasses over hills and mountains, precipitation is usually increasing with increasing altitude (see e.g. Førland, 1979). Scattered measurements indicate that the annual precipitation in the mountain areas of Spitsbergen is substantially larger than the measured amounts at the regular weather stations (see e.g. Steffensen, 1982; Jania & Pulina, 1994; Osokin et al.,1994). This discrepancy is partly caused by the catch deficiency in precipitation gauges. But even at Spitsbergen, orographic effects will cause enhanced precipitation at higher altitudes.

The main aim of this study was to estimate the orographic precipitation effects across the glacier Austre Brøggerbreen near Ny-Ålesund (Figure 1.1). Precipitation was measured during the summer seasons 1994 and 1995 in a N-S profile (cf. Figure 2) from Ny-Ålesund (8 m a.s.l.) to a pass of Austre Brøggerbreen, (about 400 m a.s.l.) and towards the shores of Engelskbukta (50 m a.s.l.). To be able to study the precipitation distribution within different precipitation events, recording rain gauges were used.

Austre Brøggerbreen is situated in the watershed of the river Bayelva. One of the reasons for choosing this glacier as model area, was that the Norwegian Water and Energy Board (NVE) is operating a streamflow station at the outlet of this river. Even after subtracting contribution from glacier ablation, the streamflow measurements are indicating substantially higher river discharge than can be explained by the precipitation measured at the weather station in Ny-Ålesund (Killingtveit et al.,1994; Pettersson, 1994). Hagen & Lefauconnier (1995) found that the mean *winter* snow accumulation on Brøggerbreen during the period 1967-1991 was 720±160 mm in water equivalent. On the other hand the mean *annual* precipitation (1961-90) measured at the weather station in Ny-Ålesund is just 370 mm/year (Førland, 1993). In this report it will be discussed whether parts of this discrepancy between measured precipitation on one hand and runoff/massbalance on the other hand, may be explained by orographic precipitation enhancement over the Austre Brøggerbreen.

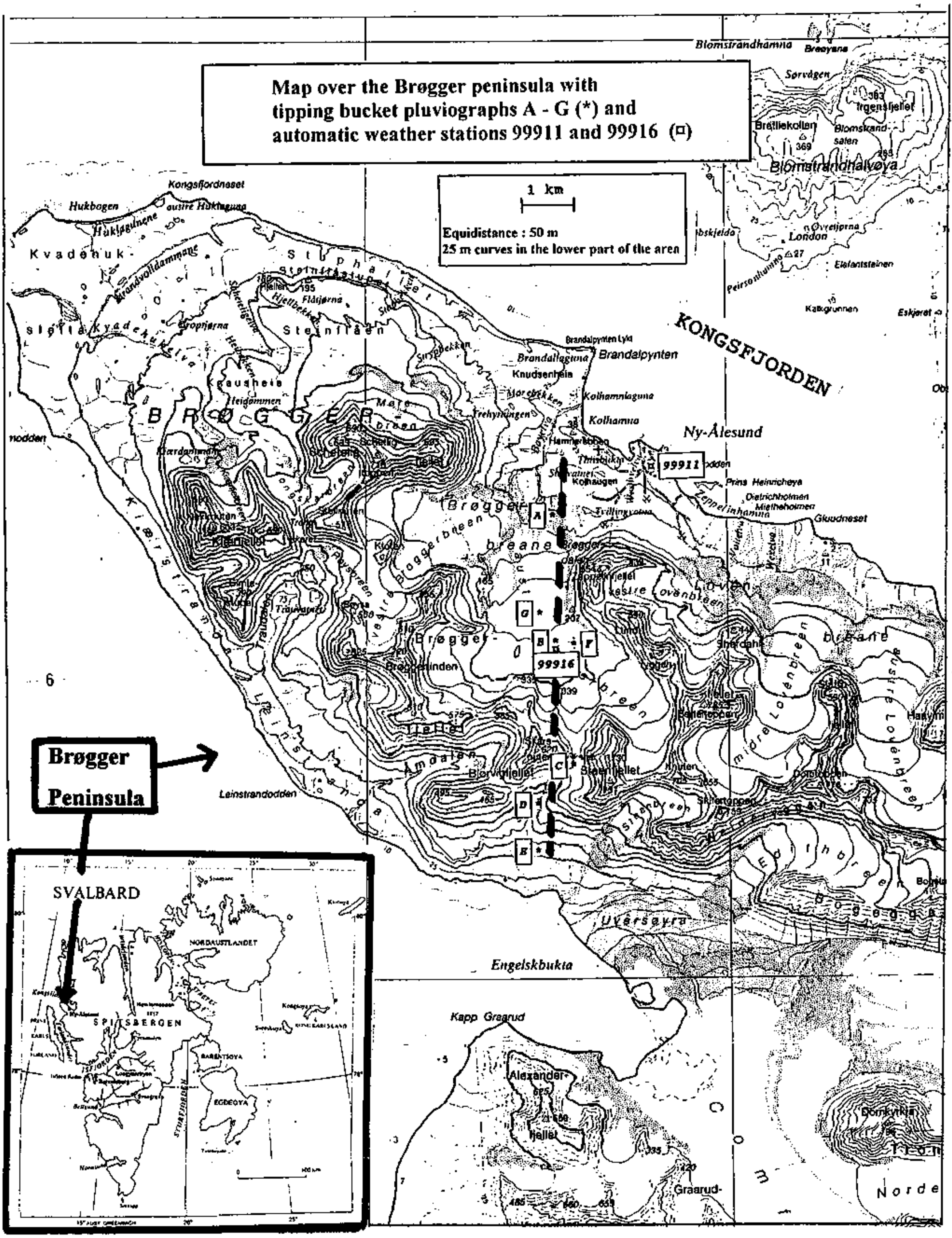

Figure 1.1 Map of Svalbard and model area at the Brøgger Peninsula

1.2 Orographic precipitation

The precipitation pattern in a watershed is influenced by a number of factors, both meteorological and physiographic. The most important physiographic factors affecting the precipitation pattern are elevation, exposure, steepness and the orientation of the terrain slope. But many other physiographic features may also significantly influence the precipitation pattern (see e.g. Nordenson, 1968).

It is important to stress that orographic precipitation is not just caused by lifting (and condensation) of high-level precipitation (nimbus) clouds. Lifting, increased friction and turbulence in the air near the ground often leads to formation of low-level clouds (stratus) even over small hills. The droplets in these "feeder" clouds are too small to fall out in their own right, but may be washed out in significant amounts by raindrops falling from a "seeder" cloud at higher level.

The lower distance between cloud base and ground in mountain areas may cause an additional orographic effect by reduced evaporation of falling raindrops. On the other hand, the atmospheric water content decreases with increasing elevation. At low temperatures and/or great altitudes this reduced water content may lead to decreasing precipitation with increasing elevation above a certain level (Singh et al., 1995. Loukas & Quick, 1996).

In Western Norway annual precipitation is increasing by about 30% per 100 m, and in the mountain areas in central Norway by about 10% per 100 m (Førland,1979). On the Faeroe Islands a similar gradient as in Western Norway was found (Davidsen et al.,1994), i.e. the precipitation increased from about 1000 mm/yr on the outermost coastal islands to more than 3000 mm/yr in the mountains in the central parts of the main islands.

Preliminary analyses of precipitation distribution in Spitsbergen based on an extended network of gauges, indicated a 5-10% increase in measured summer precipitation for each 100 m (Killingtveit et al., 1994). Based on snow surveys in two catchments, a probable vertical gradient of 14% per 100 m was assumed (Tveit & Killingtveit, 1994)

In the Ny-Ålesund/Brøggerbreen area, Hagen & Lefauconnier (1995) found that the altitudinal increase of snow accumulation had a fairly constant gradient of 100 mm per 100 m. This is equivalent to a 25% increase per 100 m altitude. In their runoff modelling, Hagen & Lefauconnier (op.cit.) pointed out that this linear gradient may give too high values in the uppermost areas of the basin.

Under some atmospheric conditions, orographic precipitation is transferred to the leeward side of hills and mountains. This so-called «spillover effect» is caused by:

- For certain vertical temperature gradients in the atmosphere, the lifting of the precipitation clouds continues also a short distance on the leeward side of a mountain ridge

- Raindrops, and especially snowflakes are carried by the wind during the fall from cloudbase to the ground

The distance hydrometeors are transferred to the leeward side, is dependent on the distance from the cloudbase to the ground, the terminal velocity of the hydrometeors, and the horizontal windspeed along the trajectory of the hydrometeors. For raindrops and moderate windspeeds, a typical «spill-over» transfer is 2-4 km (Aune & Førland, 1986). Because of the lower fall velocity, the horizontal transfer of snowflakes may be substantially larger.

2. Data

2.1 Profile measuring sites

The intention of the measurements was to study precipitation amounts over a glacier profile across the Austre Brøggerbreen for winds from different sectors. Five localities were chosen along a N-S oriented profile (see Figure 1.1). To avoid additional wind errors because of vertical wind components in a sloping terrain, flat areas of at least 3x3 m around each gauge was a minimum requirement. The highest altitude station , C was at 380 m a.s.l., and it was attempted to find suitable locations at about 50 and 200 m a.s.l. at both sides of station C.

Station A was established on a flat part of the moraine on the NE side of the glacier. The station height was 30 m a.s.l. The gauge was placed on a wooden foundation (see Figure 2.1), with gauge orifice about 1.4 m above the ground. This station operated without problems during both seasons.

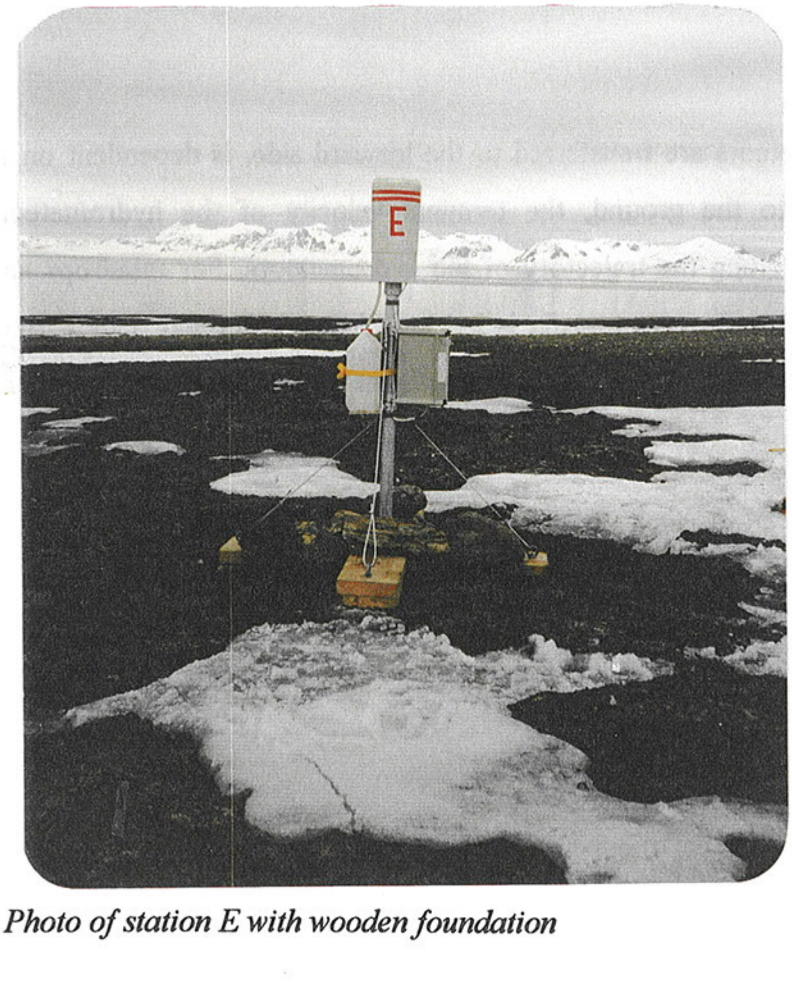

Figure 2.1 Photo of station E with wooden foundation

Station B (see Figure 2.2) was placed in a flat part of the glacier, about 200 m a.s.l. The gauge was installed on top of a pipe drilled into the ice. The gauge orifice was about 1.50 m above the glacier surface at the start of the season. When the gauge was installed, more than 1 m snow was lying on the glacier; consequently the gauge orifice was at the «ground-level» during the first part of the season. Because of rapid snowmelt, and subsequent glacier melting the gauge orifice above the «ground» was increasing during the summer season. Particularly during the 1995 season, the melting from the glacier was heavy, and consequently the gauge height was about 2 m above the surface when the station was closed down in early September 1995. However the gauge orifice remained horizontal, and the station was operating without problems during both seasons.

Station C was installed in a moraine higher up than the glacier, in the pass towards Engelskbukta. The altitude was 380 m a.s.l., and the foundation pipes were dug down in the moraine. The gauge was placed in a small, flat area. But this pass is heavy wind exposed, and very vulnerable for small scale turbulence generated by the rugged terrain. The station was running without problems in both seasons.

Station D was placed at about the same altitude as station B, i.e. about 200 m a.s.l., but on the leeward side of the glacier. The terrain is falling rather steep down towards Engelskbukta in this area, but the gauge was placed on a 3x3 m flat shelf. A wooden foundation as on station A was used. The station was running without problems during both seasons.

Station E (see Figure 2.1) was established 55 m a.s.l. near the shore at Engelskbukta. The area around the gauge was flat, and a wooden foundation was used. The environment of the station was ideal, with a flat moor in all directions. However reindeers perceived the station as an enemy. At the end of the 1994 season, the station was «attacked» and partly destroyed. But the collector and the PSION-organiser was not damaged, and all data were recovered. In the 1995 season the attacks were fiercer and more violent. When the station was visited at the end of the season, it was found to be completely destroyed. The recordings in the PSION-organiser indicated that the station was demolished just a few days after the initiation on 13. June 1995. Consequently no data for the 1995 season is available for this station.

Station F and G (see Figure 2.2) were installed to check eventual horizontal precipitation gradients at the same altitude level of the glacier. Both stations were founded on pipes drilled into the ice. Because of melting, these two gauges tilted at the end of the measuring seasons. At station G the logger malfunctioned quite early in the 1994-season, and these data had to be rejected.

Figure 2.2 Photos of stations B and G

2.2 Recording raingauges

Orographic precipitation enhancement is depending on the wind direction. In the Austre Brøggerbreen catchment, precipitation may fall for winds from all directional sectors. Usually the wind direction is changing from day to day, and also within a precipitation event. As it was practical impossible to execute frequent manual readings of precipitation gauges in this large and rather inaccessible basin, it was decided to use gauges with automatic registration of precipitation intensity.

In a similar study on the Faeroe Islands (Davidsen et al., 1994), the Rainomatic tipping bucket gauge manufactured by PRONAMIC in Denmark was applied. The gauges were connected to PSION-organizers in a special design constructed by Elias Davidsen, E.D. Verkfrødi (Tórshavn, Faeroe Islands). In this special arrangement, the exact time of each tipping was registered in the PSION-logger. The tipping bucket system in the Rainomatic gauges was consisting of a «tea spoon» bucket, tipping for each 0.2 mm of precipitation. The battery operated logger had a capacity of storing data equivalent to 800 mm precipitation. The gauges were carefully tested both at the Faeroes, at DNMI in Oslo and during the summer 1993 in Ny-Ålesund. All tests were successful, but showed that individual calibrations of each gauge were necessary.

The tipping bucket gauges were unheated, and were just used during the «warm» season from mid June to ultimo August. Some episodes with snowfall were excluded from the dataset. To reduce the deficit caused by wind effects around the gauge, the gauges were placed as close to the ground level as possible. At the glacier stations, 2 m long metal pipes (3.8 cm diameter) were drilled down into the ice. The precipitation gauge was installed on top of the pipe, and 4 guys were used to keep the gauge orifice horizontal (Figure 2.2). On the tundra outside the glacier, a special wooden foundation was used (Figure 2.1).

Totally 7 automatic raingauges were installed in the Brøggerbreen profile (Figure 1.1). A survey of the 7 stations is given in Table 2.2.

In case of logger failure, additional recordings of total precipitation was provided for. The total number of tips were recorded on an independent digital display, and also the total amount of water draining through the gauge was accumulated in a plastic bottle connected to the outlet of the raingauge.

The exact time of each tip, as well as the total amount of precipitation recorded could be read on the display of the PSION-organizers. The data storing units (EPROMS) of the PSION-Organizers were read at DNMI after each seasons measurements were terminated.

The capacity of the «bucket» in the tipping bucket gauge was 0.2 mm. The PSION-organiser registered the exact time of each «tipping». An example of some of the registrations at 5 of the stations during 11/7-1994 are shown in Table 2.1. Cumulative precipitation amounts for the five stations for the episode 11.07.1994 1400-2000 are illustrated in Figure 2.3.

Table 2.1 Example of recordings in the PSION-organiser at station A, 11.07.1994 Each point of time indicate a «tipping» equivalent to 0.2 mm.

Date	A	B	C	D	E
11/07/94	14:50:12	15:08:25	16:44:06	15:37:41	15:18:52
11/07/94	15:12:50	15:22:05	16:57:41	15:54:35	15:45:52
11/07/94	15:28:16	15:35:29	17:00:54	16:19:19	16:13:21
11/07/94	15:44:42	15:45:08	17:07:57	16:41:08	16:37:09
11/07/94	15:50:21	15:51:15	17:08:58	17:33:41	17:50:07
11/07/94	15:53:56	15:56:10	17:11:52	18:05:53	18:12:24
11/07/94	15:58:47	16:03:19	17:15:19	18:29:11	18:38:48
11/07/94	16:07:47	16:11:11	17:16:46	18:56:45	19:03:27

Figure 2.3 shows that the precipitation starts between 14 and 15h and first at station A. In the first part of the episode the stations A and B records about the same amounts, while station B records the highest intensities after 1730h. The precipitation starts later at stations D and E on

the leeward side of the glacier, and the total amounts are substantially lower at these two stations than on the glacier side of the pass.

In the current dataset just daily precipitation amounts are studied. The daily amounts are calculated for the calendar day, i.e. between 00-24h.

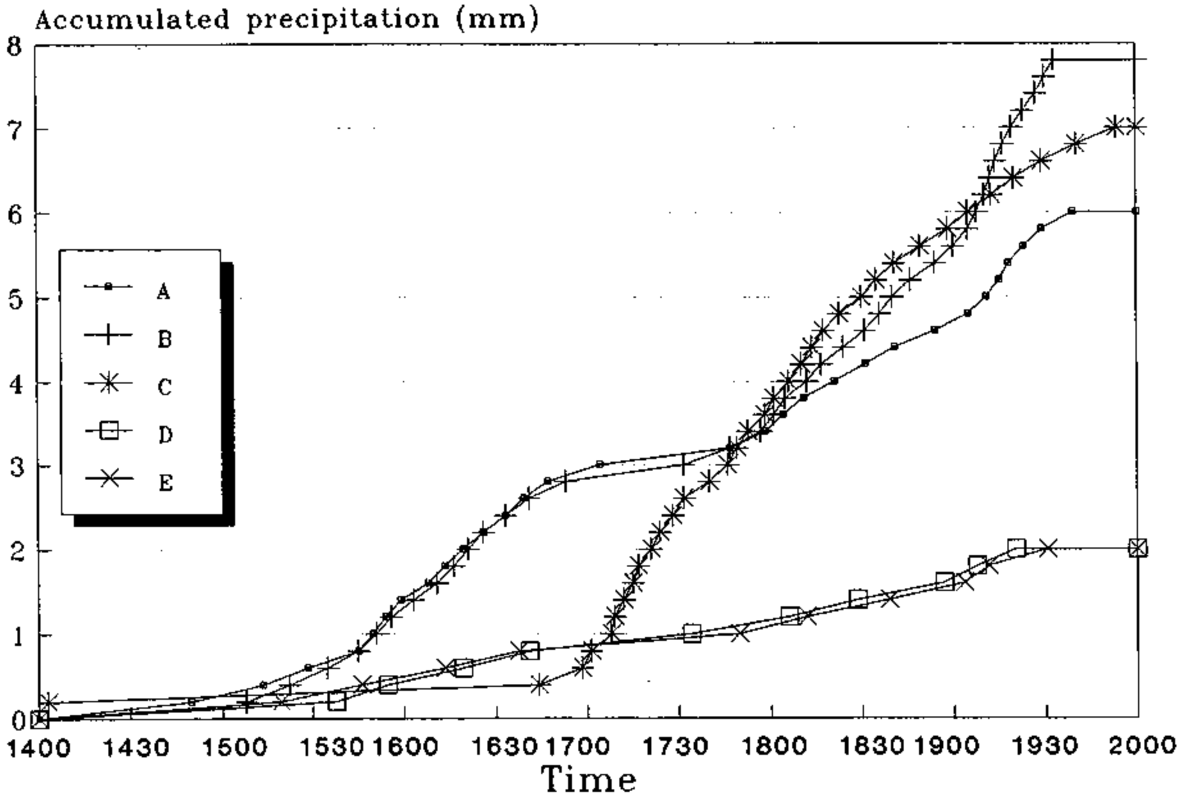

Figure 2.3 Accumulated precipitation at 5 profile stations (A-E) on 11. July 1994

Snow. Figure 2.3 indicates that the precipitation on the 11. July is starting later at station C than on the other stations. The reason is probably that the precipitation started as snow at this station. In fact sleet was reported in the weather observations from Ny-Ålesund, and the temperature was rising from 2 °C in the morning to about +5 °C in the evening. Because of the higher altitude, the temperature at station C will be about 3 °C lower than in Ny-Ålesund, and thus the first part of the precipitation was snow that accumulated in the gauge collector. The graph in Figure 2.3 indicates that this snow started to melt during the rainfall after about

1645h. The rather high intensity at this station between 1700h and 1900h is thus probably due to a combination of rainfall and melting of snow in the collector.

Even during mid-summer, some events with snowfall occur also in the coastal areas of Spitsbergen. By use of temperature and precipitation type observations from Ny-Ålesund, temperatures at an automatic weather station near station B, and suggested temperature gradients within the field, some episodes with snowfall at all stations late in the season of 1995 were rejected from the final dataset. (Air temperature may be used as an indicator of precipitation type, as more than 50% of the precipitation falls as snow for temperatures lower than 1°C and more than 50% falls as rain for temperatures higher than 1°C (Førland, 1994)).

Some episodes with snowfall just at the higher altitude stations were kept in the dataset. As the snow in these cases was stored in the collector part of the gauge and accordingly was not recorded by the «tipping bucket» until it melted, the precipitation recorded during the melting phase was distributed to the previous precipitation day. The total precipitation amounts in the dataset were however not changed, i.e. except for station F on 23. and 24. August 1994 (Appendix A), no precipitation amounts were interpolated.

Measuring errors. No corrections for measuring errors were done. Concerning *wetting* and *evaporation* it was anticipated that the conditions were quite the same at all seven locations. Thus corrections for evaporation and wetting would just give minor influences on the relative precipitation distribution in the basin. It should however be recognised that because of the low precipitation intensity in the area, precipitation loss because of wetting and subsequent evaporation from the inner walls (and from water remaining in the bucket) in the gauge will cause underestimation of the real precipitation.

The collector part of the Rainomatic gauge is of exactly the same design as the commonly used Hellmann gauge. The opening area is 200 cm^2. It is well known that during snowfall and strong wind, the unshielded Hellmann gauge just catches a small fraction of the «ground true precipitation» (Sevruk,1982; Førland et al.,1996). Also for rainfall at low intensities the Hellmann gauge gives a substantial underestimation of the true precipitation.

The aerodynamic measuring error for the Hellmann gauge is illustrated by the correction factor k in Figure 2.4. For snowfall at a temperature of -10 °C and wind speed at gauge level of 5 m/s, Figure 2.4a shows that the measured precipitation has to be multiplied by a factor of about 6 to give the «true» precipitation. For rainfall, the correction factor is substantially lower (Figure 2.4b). At an intensity of 1.0 mm/h and wind speed at gauge level of 5 m/s, the correction factor is about 1.2. Even at low rain intensities (0.1 mm/h) the correction factor is lower than 1.4 for wind speeds lower than 5 m/s.

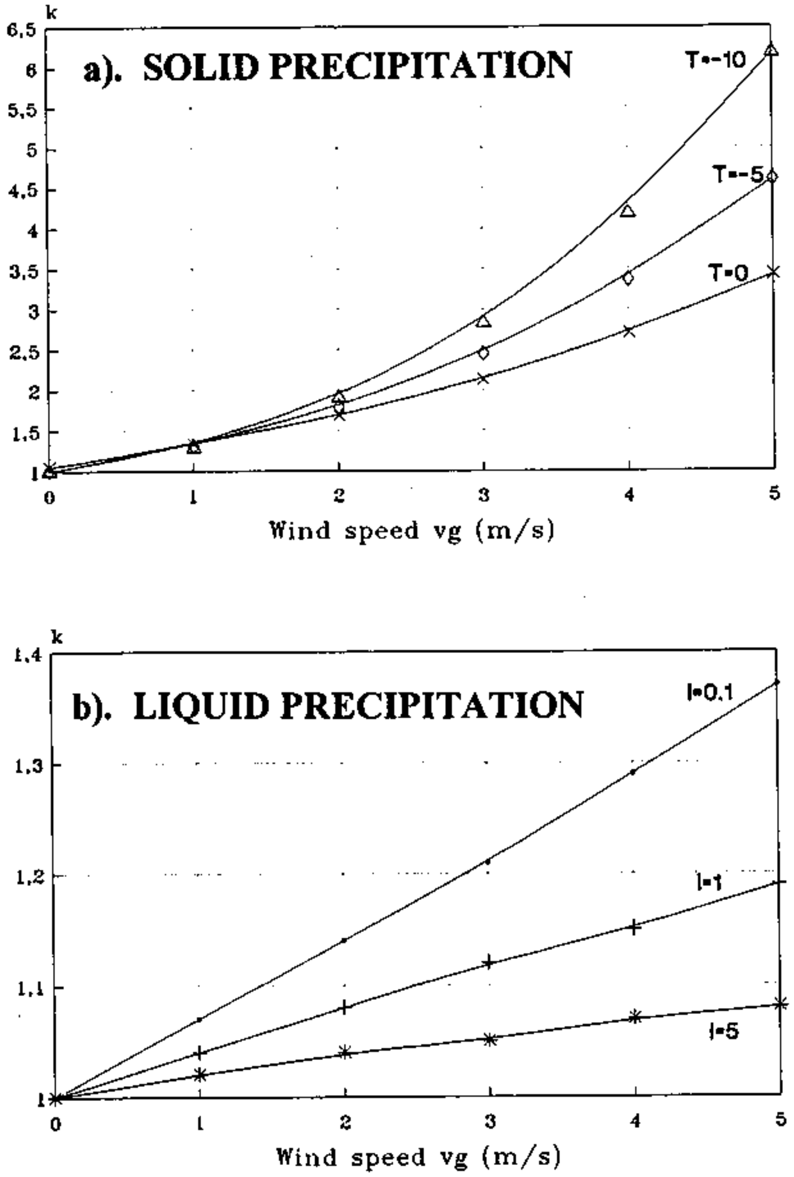

Figure 2.4 Correction factors for Hellmann gauge (from Førland et al., 1996)

(Correction factor k is ratio between true and measured precipitation)

To reduce the aerodynamic measuring error, the tipping bucket gauges were placed as close to the ground as possible. At 1.5 m height above the ground, the wind speed over level ground is about 67% of the wind speed at 10 m level and just 93% of the wind speed at the 2 m level of the regular DNMI precipitation gauges (Førland et al.,1996).

As for evaporation and wetting, all gauges will be exposed to aerodynamic measuring errors, and thus the influence on the relative precipitation distribution in the area will be reduced. However, the stations at higher altitudes, and in particular the gauge C at the pass, will probably be more influenced by aerodynamic errors than the stations as lower altitudes. The wind speed is higher in this area, and a larger proportion of the precipitation falls as snow. In the event illustrated in Figure 2.3, the precipitation registered at station C is probably too low compared to the other stations due to solid precipitation during the first part of the event.

Wind speed and temperature were not measured at the profile stations. Consequently, it is not possible to quantify the aerodynamic measuring error at the different localities. It should thus be kept in mind that the measured precipitation gradients within the area may to some degree be influenced by differences in aerodynamic measuring errors.

The measurements at the automatic precipitation stations are compared to the manual DNMI gauge and the automatic Geonor gauge in Ny-Ålesund. Both these gauges are equipped with wind shield. As the orifice of these gauges are 2 m above the ground, the wind speed is 7% higher than at the orifice level of the automatic gauges. This higher level partly compensates the increased catch efficiency caused by the wind screen.

Calibration. The automatic tipping bucket gauges were calibrated to «tip» for each 0.2 mm precipitation. The calibration for each gauge was checked when they were installed in the field, and in 1995 also at the end of the season. It turned out to be important to run the calibration tests when the gauge was placed in its proper position in the field. The calibration was performed by slowly pouring water equivalent to 10 mm into the gauge, and counting the number of tippings. The results from the calibration tests are presented in Table 2.2.

Table 2.2 Site descriptions and calibration factors for tipping bucket gauges
(The calibration factor has to be multiplied to the recorded amounts)

				Calibration factors			
Station	Altitude m a.s.l.	Height above ground *(m)	Surface type	1994 June	1995 June	1995 Aug.	Mean
A	30	1.43	Tundra	0.91	0.98	0.95	0.97
B	200	1.40	Glacier	1.02	1.02	1.05	1.03
C	380	1.38	Moraine	1.00	0.97	0.92	0.95
D	190	1.45	Tundra	1.00	1.03	1.03	1.03
E	50	1.45	Moor	1.02	1.04	-	1.04
F	202	1.50	Glacier	0.73	0.89	-	0.89
G	170	1.50	Glacier	0.93	1.01	-	1.01

** On the glacier: Above the glacier surface*

According to Table 2.2 there were some deviations from the prescribed calibration, and it was decided to adjust all recordings by using the field calibrations. For the 1994 season the calibration correction from June was used for the whole season, while in 1995 the mean values of the June and August calibrations were used. Table 2.2 shows that for gauge B, C, D and E the corrections for deviating calibration was less than ± 5%. For station F the recordings in the 1994 season was reduced by 27%, and also in the 1995 season this gauge had a quite large calibration correction.

2.3 Supplementary data

Automatic weather station at Austre Brøggerbreen.

As a part of the project, an Aanderaa automatic weather stations was established next to station B (see Figure 2.2). At this weather station, the following weather elements were logged hourly: Temperature, humidity, precipitation amount, wind speed and wind direction. The station was in operation from 5.September 1994 to 28.July 1995. The station was mounted on pipes drilled into the ice. During the heavy melting of the glacier in the summer of 1995, the ice around the pipes melted and the pipes gradually tilted. At the end of July the station overturned. This station gave very important informations on the wintertime weather conditions at the glacier 1994/95.

Automatic weather station in Ny-Ålesund.

As a part of the project, an Aanderaa automatic weather station was established in Ny-Ålesund in June 1993, side by side of the regular DNMI weather station. At the automatic station hourly registrations were taken of temperature, humidity, precipitation amount, wind speed and wind direction. The station was running without problems during the whole project period.

Synoptic weather station at Ny-Ålesund.

In Ny-Ålesund, DNMI has operated a manual weather station since 1969. Three times a day (at 06,12 and 18 UTC) observations of pressure, temperature, humidity, wind direction, wind speed, precipitation amount, visibility, clouds and weather phenomena are taken.

Observations at the Zeppelin mountain.

The Norwegian Institute for Air Research is operating a station near the top of the Zeppelin mountain (554 m a.s.l.) close to Ny-Ålesund. At this station also some meteorological elements are monitored.

2.4 Large scale wind direction

Dr. Tadeusz Niedzwiedz at the Institute of Meteorology and Water Management in Cracow has used the pressure on regular weather maps to indicate the main daily wind directions and whether it was cyclonic or anticyclonic conditions over Spitsbergen. Dr. Niedzwiedz kindly gave permission to use his circulation classification also for this study.

Table 2.3 Classification of circulation types according to Dr. Niedzwiedz

Direction	Anticyclonic	Cyclonic
North	01 - Na	11-Nc
Northeast	02 - NEa	12-NEc
East	03 - Ea	13-Ec
Southeast	04 - SEa	14-SEc
South	05 - Sa	15-Sc
Southwest	06 - SWa	16-SWc
West	07 - Wa	17-Wc
Northwest	08 - NWa	18-NWc
	09 - Ca central anticyclonic situation	19-Cc Centre of cyclone above or very near Spitsbergen
	10 - Ka anticyclonic ridge,etc. (Only local air flow)	20-Bc Three-dimensional cyclonic trough
	21- Three-dimensional situation or situation which cannot be classified	

Dr. Niedzwiedz distinguished between 21 «Circulation types» (see Table 2.3). The advection directions are marked by capital letters. Anticyclonic and cyclonic circulation is marked by the subscript "a" and "c" respectively. For example, Wa and Wc denote anticyclonic and cyclonic situations with airmass advection from west. Thus, there are 16 circulation types with definite directions of the air masses. The other four situations are characterised either by lack of advection or by variable directions of the air masses coming to Spitsbergen.

3. Results

3.1 Total precipitation amounts

During the 1994 season all gauges were in operation from 26. June to 3. September. In 1995 the season lasted from 14. June to 4. September. Because of the gradual tilting of some of the gauges, and episodes with snowfall at the end of each season, the data after 25. August 1994 and 26. August 1995 were rejected. The daily amounts for each day in the two seasons are given in Appendix A, and the total amounts are presented in Table 3.1.

Table 3.1 Precipitation amounts (mm) during the 1994 and 1995 summer seasons. Ratios relative to gauge A are also presented
Stations A-G are tipping bucket stations, 99911 is recording Geonor gauge in Ny-Ålesund, and 99910 is manual gauge at the Ny-Ålesund weather station

	A	B	C	D	E	F	G	99911	99910
Altitude (m a.s.l.)	30	200	380	190	50	202	170	8	8
26.06-25.08.1994	114.4	158.4	155.2	112.8	109.0	151.6	-	116.3	131.0
Ratio to gauge A	1.00	1.39	1.36	0.99	0.95	1.33	-	1.02	1.14
14.06-26.08.1995	34.5	50.6	50.1	38.6	-	61.3	49.9	28.2	31.9
Ratio to gauge A	1.00	1.47	1.45	1.12	-	1.78	1.45	0.82	0.93
Total 1994+1995	148.9	209.0	205.3	151.4	-	212.9	-	144.5	162.9
Ratio to gauge A	1.00	1.40	1.38	1.02	-	1.43	-	0.97	1.09

The normal (1961-90) precipitation amounts in Ny-Ålesund is in June:19 mm, July: 29 mm, August: 40 mm (Førland, 1993), that is totally 80 mm during the «field period» mid-June to ultimo August. The precipitation during the summer season 1994 was thus substantially higher than the normal value, in 1995 substantially lower. Table 3.1 shows that the precipitation at the glacier was 40 % higher than at station A and at 99911 Ny-Ålesund.

In Figure 3.1 the distribution of precipitation during the two seasons is shown as total amounts and as ratios relative to the «reference» station A. The precipitation amounts at the glacier stations are about 40% higher than at station A. At station D the precipitation is about the same as on station A. The total amount recorded in Ny-Ålesund is lower than at all the profile stations.

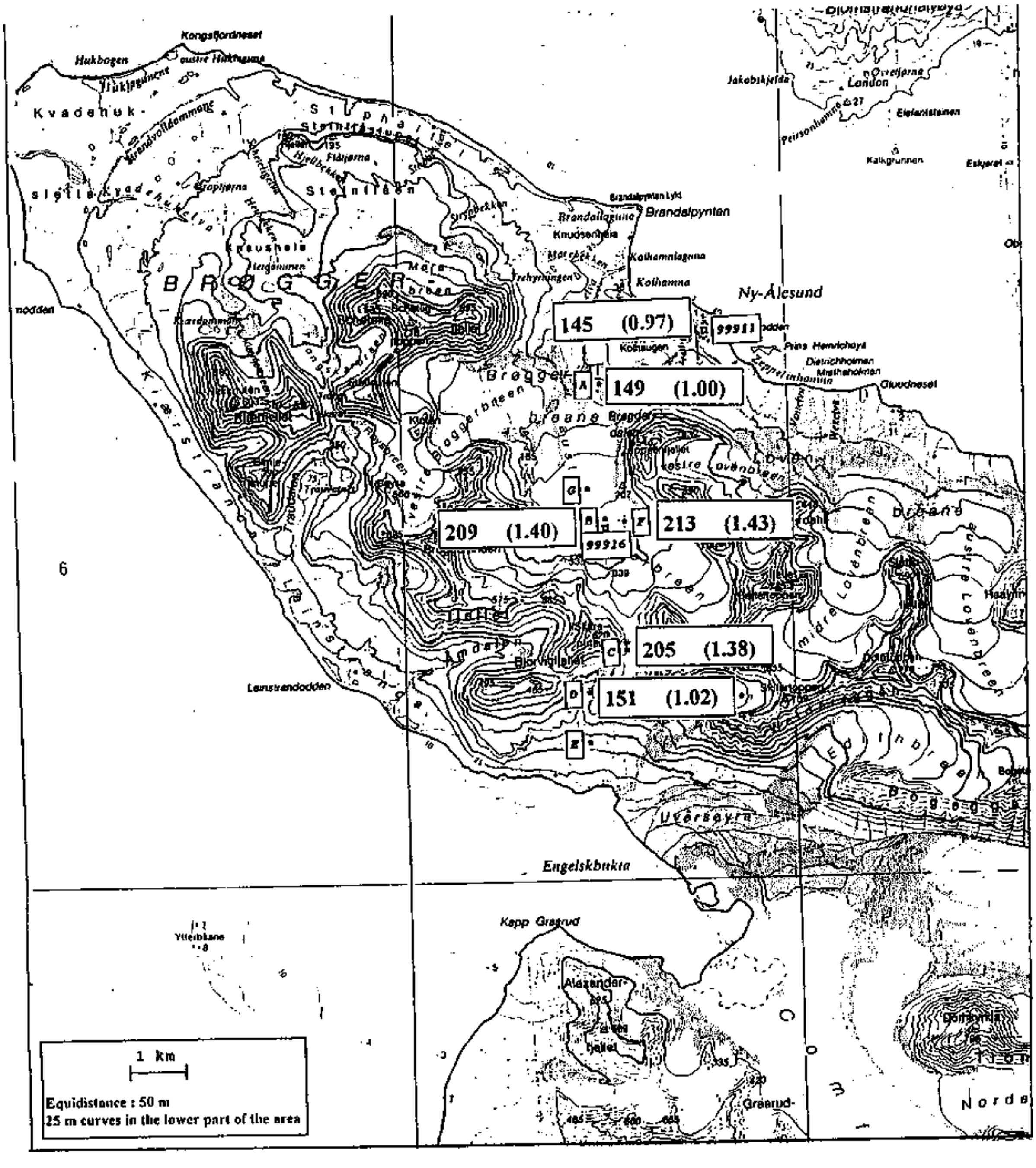

Figure 3.1 Total precipitation (mm) during the 1994 and 1995 summer seasons. Values in brackets are ratios relative to station A.

3.2 Choice of indicator for wind direction in the profile area

Orographic precipitation enhancement is dependent on the wind direction (see section 1.2). Several indicators of wind direction were considered.

Wind direction at the 10 m level is measured at the weather station in Ny-Ålesund three times a day. At the automatic weather station in Ny-Ålesund, wind direction 3 m above the ground was recorded on an hourly basis. However, the topography in Ny-Ålesund has a major influence on the local wind direction. The most common wind direction is from Southeast parallel to Kongsfjorden. This is partly caused by the topography's channelling effect on the large scale windfield (which often has an easterly component), and partly by drainage winds transporting cold, heavy air from the inland glaciers to the warmer sea (Hanssen-Bauer et. al, 1990). Wind roses for Ny-Ålesund are reproduced in Figure 3.2.

This channelling effect of the large scale windfield is illustrated in Figure 3.3a. For all days during the summer seasons 1994 and 1995, the wind direction in Ny-Ålesund is compared to the circulation types, CT (see Table 2.3). Anticyclonic and cyclonic situations are combined in the figure. It appears that whatever the large scale wind direction is, the local wind direction in Ny-Ålesund is channelled in two bands along the direction of Kongsfjorden.

This channelling effect is even more evident in Figure 3.3b, showing median wind direction in Ny-Ålesund for different large scale wind directions (CT) for days with precipitation. For winds from NE, E and SE there are just 1,1 and 2 cases respectively, and these are not included in the graph. For the other CTs the tendency is evident: For large scale wind direction from the sector S-W, the wind in Ny-Ålesund is blowing out of Kongsfjorden (130-160 degrees). For large scale wind direction from NW and N, the wind is blowing inwards along Kongsfjorden (310 degrees).

The channelling of wind shown in Figure 3.2 and 3.3 is just valid for Ny-Ålesund. Consequently the wind directions reported in Ny-Ålesund are not representative for the wind direction in the precipitation gauge profile, and are not appropriate as basic data for studying

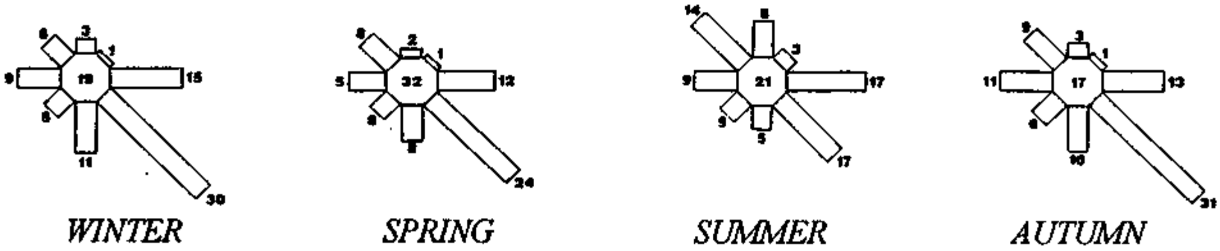

Figure 3.2 Seasonal percentage frequencies of different wind directions in Ny-Ålesund (from Hanssen-Bauer et al., 1990)

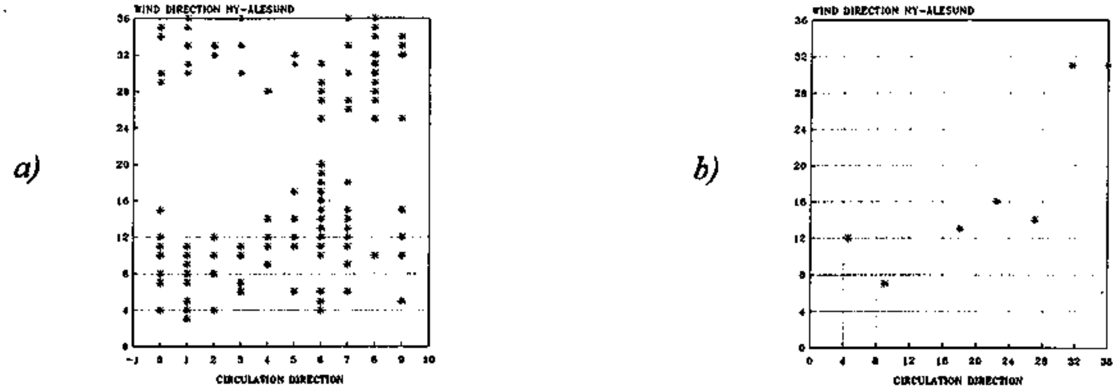

Figure 3.3 Scatter plot of large-scale and local wind directions in Ny-Ålesund
a). Single values b). Group mean values
(Wind direction in dekadegrees, Circulation direction CT code (excl. first digit)

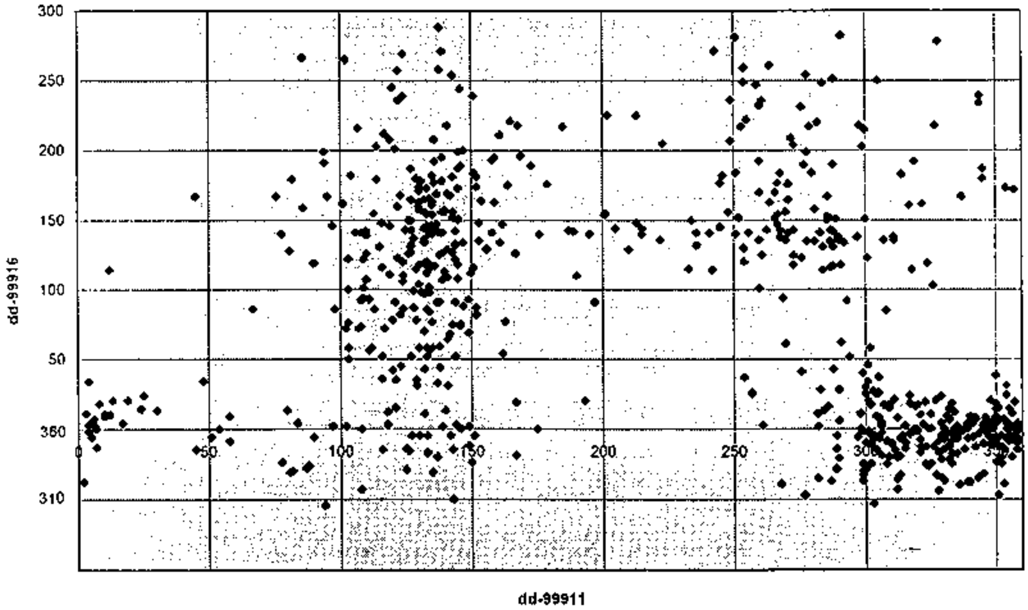

Figure 3.4 Scatter plot of simultaneous wind directions at the automatic weather stations 99911 Ny-Ålesund and 99916 Austre Brøggerbreen, 06.09.-18.10.1994
Criteria: Wind speed Ny-Ålesund higher than 1.0 m/s

orographic effects at the Austre Brøggerbreen. The local wind conditions in Ny-Ålesund was known before the project started (Hanssen-Bauer et. al., 1990). One of the reasons for establishing the automatic weather station near gauge B was thus to get more representative measurements for the glacier area. Unfortunately it was not possible to get this station in operation before at the end of the summer season of 1994. Because of the tilting fundaments in July 1995 (see section 2.3), the wind direction measurements from this station just covers a small part of the profile measurement period.

Figure 3.4 shows a scatter plot of simultaneous wind direction recordings at the automatic weather stations in Ny-Ålesund and at Brøggerbreen during the period 06.09-18.10.1994. The channelling effect in Ny-Ålesund is evident also in this graph, with a concentration of wind directions in the sectors 100-150 degrees and 270-360 degrees. But it seems as if a channelling effect is present even at the glacier station, with a concentration of wind directions in the sectors 130-200 and 310-020 degrees.

The orographic precipitation enhancement is partly caused by lifting of the nimbostratus (precipitation) clouds at medium levels, and partly by washout from stratus clouds below (see section 1.2). These low stratus clouds may be enhanced by the cooling effect of the glacier acting on airmasses close to the surface, and by local lifting of low-level airmasses. Because of the wash-out of droplets from fog and low-level stratus clouds, the local low-level wind direction across the profile may be vital to explain the orographic precipitation enhancement.

By considering the local channelling effects in Ny-Ålesund and at the automatic station at the glacier, as well as the rather short wind direction record from the glaciers station, it was decided to use the Niedzwiedz circulation types (CT) as indicators of the large-scale wind direction. It should however be recognised that some noise is introduced by using these CT-values. Firstly they are «typical» for the whole Spitsbergen area, and not in particular just for Ny-Ålesund. Thus slightly different conditions may be prevailing in the Ny-Ålesund area. Secondly the CT's are based on regular weather maps and are covering whole calendar days, while the major part of the daily precipitation may have fallen within a few hours with a different circulation type.

3.3 Precipitation as a function of large-scale wind direction

Each of the 135 days in the measuring periods in 1994 and 1995 was classified by a circulation type. The CTs are valid for calendar days, and accordingly the 00-24h precipitation amount in the recording gauges in the profile was calculated. As the manual gauge in Ny-Ålesund is measured at 07h and 19h, it was not convenient to use these values in a calendar-day comparison. Therefore, for Ny-Ålesund the 00-24h precipitation values from the Geonor gauge at the automatic weather station was used.

Table 3.1 shows that the precipitation in the manual gauge (99910) in Ny-Ålesund was higher than at the automatic station (99911). A large part of this discrepancy may be explained by differences in wetting and evaporation losses in the manual and automatic gauges. In a detailed analysis of precipitation data from Ny-Ålesund, Hanssen-Bauer et al. (1996) found the wetting loss in the automatic Geonor gauge to be about 0.2 mm per event larger than in the manual DNMI-gauge. Considering the number of precipitation days in the 1994 and 1995 summer seasons, the difference between the DNMI and Geonor gauge may be explained by differences in wetting and evaporation loss. (It should be noted that the manual gauge is emptied twice a day. The total loss caused by evaporation and wetting depends on the weather conditions, and whether the manual gauge is exchanged or just emptied at the measurement).

Table 3.2 gives a survey of the distribution of circulation types within the two summer seasons. For more than half of the days, the large scale wind direction is from the sector SW-N. In Table 3.2 also some statistics from station A are included. During the two seasons, 63 days with precipitation at station A was recorded. For 40 (64%) of these precipitation days, the large scale circulation direction was from the sector SW-NW. This sector also contributed to 74% of the total precipitation amount (149 mm) at station A.

Table 3.2 Frequency of circulation types and precipitation at station A during the 1994 & 1995 seasons

Circulation type (CT)	Number of days	Days with precip at st. A	Total precip. (mm)	Mean prec (mm/day)	Mean prec. per precip. day (mm/day)	Fraction of total precip. (%)
01+11 N	10	1	4.9	0.5	4.9	3.3
02+12 NE	6	0	0	0	0	0
03+13 E	9	2	0.6	0	0.3	0.4
04+14 SE	5	1	0.8	0.2	0.8	0.5
05+15 S	9	7	13.2	1.5	1.9	8.9
06+16 SW	25	19	61.0	2.4	3.2	41.0
07+17 W	17	11	25.9	1.5	2.4	17.4
08+18 NW	18	10	22.9	1.3	2.3	15.4
10 AC	7	0	0	0	0	0
19 C	9	6	13.4	1.5	2.2	9.0
20 C-TR	8	3	2.3	0.3	0.8	1.5
21 UCL	12	3	3.9	0.3	1.3	2.6
Total	135	63	148.9	1.10	2.36	100.0

For large scale winds from the sectors N, NE, E and SE precipitation was recorded on just 4 out of totally 30 days. For the seven days with an anticyclone centred over Spitsbergen (CT=10) no precipitation was recorded.

The precipitation distribution across the profile is presented in Table 3.3 and Figures 3.5-3.8. Station G is excluded because of limited data, and even the statistics for station E is based on a reduced dataset. The distribution is described by the ratio between the various stations and the reference station A. Three types of ratios are presented in Table 3.3. The first type is ratio of total amounts, but these ratios are to a large extent influenced by a few events with high precipitation. The second type is the median of all ratios within each group, but these ratios are influenced by several episodes with small precipitation amounts. The third type is therefore the median ratio for days with more than 0.5 mm precipitation at station A. These latter ratios are used in the plots in Figures 3.5-3.8.

3.3.1 Winds from south

The precipitation on the windward side of the profile (station D and E) is about 80% of the precipitation at station A (Figure 3.5). The ratios at station C and B is about 1.4, i.e. the precipitation is almost 75% higher than on the two windward stations. The rather high values at stations B and F is partly caused by «spillover-effect» (see section 1.2), and at station F also by lifting and convergence against the mountain ridge Zeppelinfjellet-Lundryggen. Ny-Ålesund is in the leeward-shadow of the mountain Zeppelinfjellet, and just gets about 60% of the precipitation at station A.

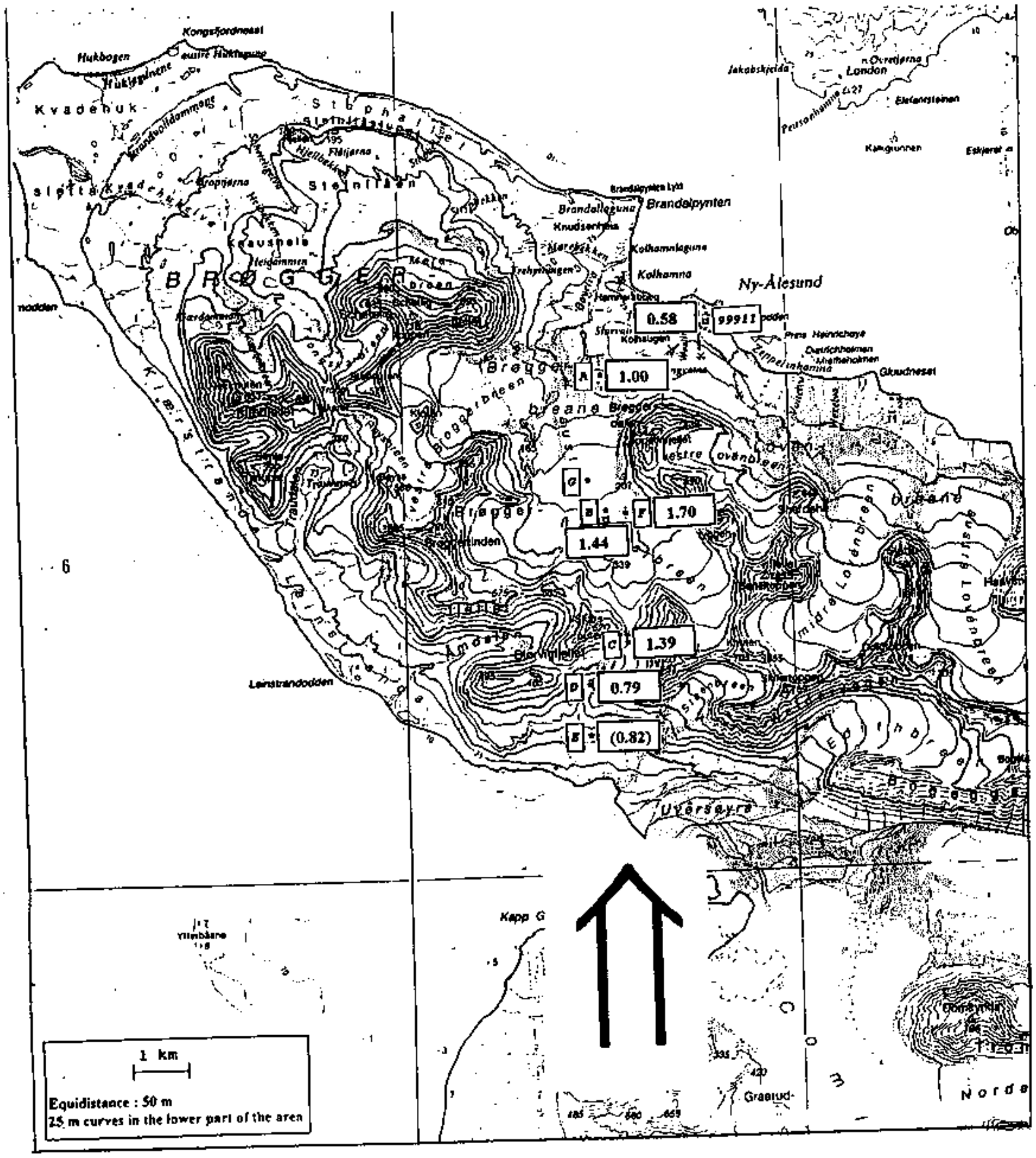

Figure 3.5 Precipitation distribution (relative to station A) for large-scale winds from South

Table 3.3 Precipitation for different large scale wind directions.
(The last row is median ratio relative to gauge A for days with precipitation amounts > 0.5 mm at station A)

Circulation direction: S (CT = 5 or 15)

	A	B	C	D	E	F	99911
No. of days with precip.	7	8	7	8	(4)	8	7
Precip. amount (mm)	13.2	19.1	16.5	11.0	(7.3)	21.2	8.0
Ratio to gauge A	1.00	1.45	1.25	0.83	(0.84)	1.61	0.61
Median ratio	1.00	1.42	1.14	0.71	(0.82)	1.59	0.56
Median ratio RRA>0.5mm	1.00	1.44	1.39	0.79	(0.82)	1.70	0.58

Circulation direction: SW (CT = 6 or 16)

	A	B	C	D	E	F	99911
No. of days with precip.	19	22	22	21	(18)	22	18
Precip. amount (mm)	61.0	98.6	84.5	59.3	(52.1)	94.2	49.9
Ratio to gauge A	1.00	1.62	1.39	0.97	(0.98)	1.54	0.82
Median ratio	1.00	1.74	1.47	1.06	(0.82)	1.80	0.77
Median ratio RRA>0.5mm	1.00	1.68	1.24	0.79	(0.92)	1.61	0.77

Circulation direction: W (CT = 7 or 17)

	A	B	C	D	E	F	99911
No. of days with precip.	11	13	14	13	(8)	14	13
Precip. amount (mm)	25.9	42.0	44.0	29.3	(17.2)	47.6	28.2
Ratio to gauge A	1.00	1.62	1.70	1.13	(0.86)	1.84	1.09
Median ratio	1.00	1.68	1.65	1.10	(0.94)	1.61	1.00
Median ratio RRA>0.5mm	1.00	1.37	1.38	0.98	(0.94)	1.43	1.05

Circulation direction: NW (CT = 8 or 18)

	A	B	C	D	E	F	99911
No. of days with precip.	10	12	12	11	(4)	11	13
Precip. amount (mm)	22.9	16.4	21.3	16.4	(18.7)	15.7	32.9
Ratio to gauge A	1.00	0.72	0.93	0.72	(1.06)	0.69	1.44
Median ratio	1.00	0.78	0.81	0.76	(0.75)	0.96	1.36
Median ratio RRA>0.5mm	1.00	0.78	0.81	0.77	(0.92)	0.82	1.21

3.3.2 Winds from Southwest

This is the dominating winddirection for precipitation in the Ny-Ålesund area, and Figure 3.6 shows that the glacier stations B and F get more than 60% more precipitation than station A (and more than twice the amount in Ny-Ålesund) for this direction. The ratio at station C is 1.24, i.e. substantially lower than at station B and F. The reason is partly larger catch deficiency at station C, but most important is probably the spillover effect transferring the area of maximum precipitation to the leeward side of the mountains. This effect was also very distinct at the Faeroes (Davidsen et al., 1994). In Ny-Ålesund and at station D on the windward side, the precipitation amount is about 20% lower than at station A.

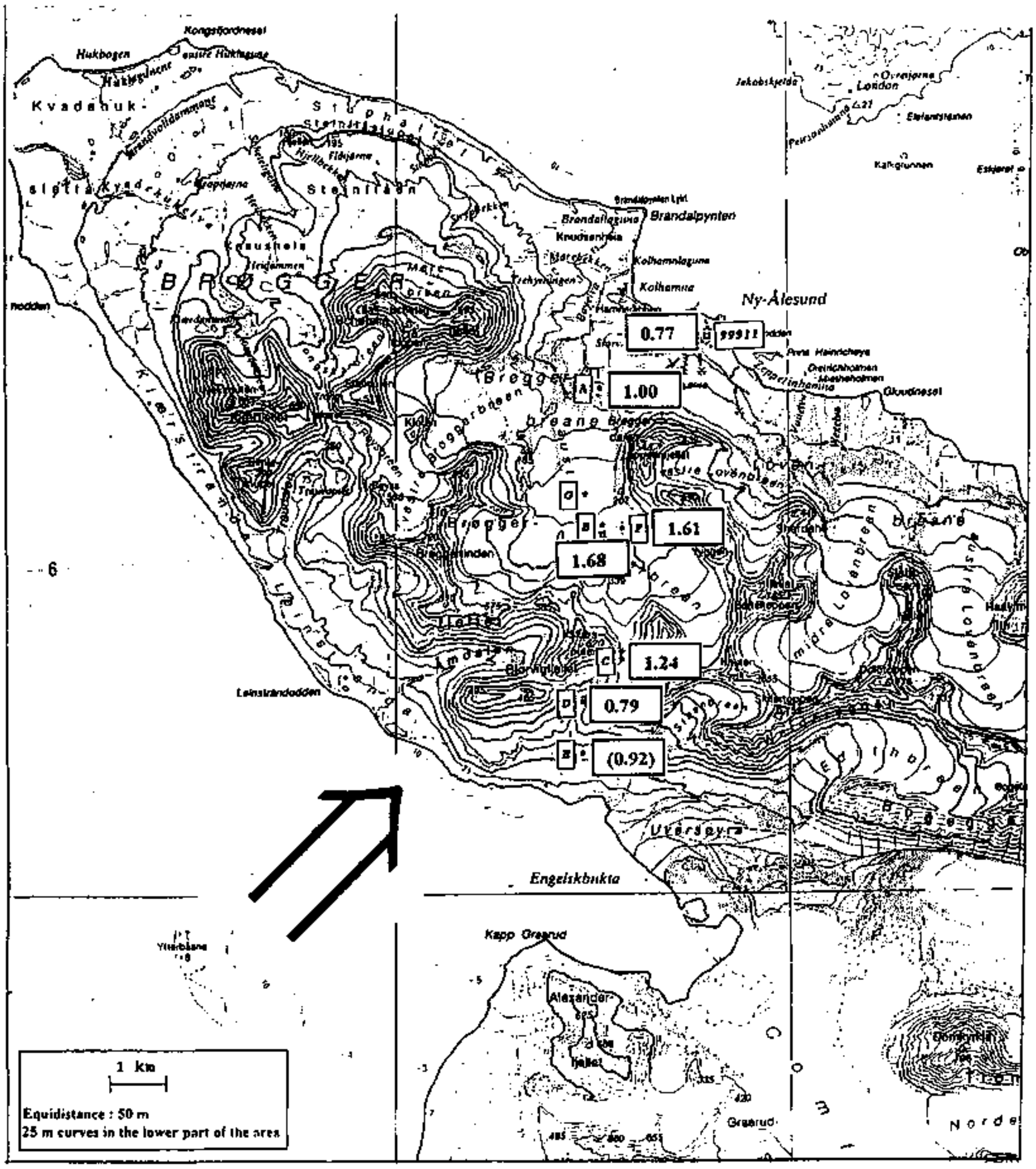

Figure 3.6 Precipitation distribution (relative to station A) for large-scale winds from SW

3.3.3 Winds from west

The precipitation at the glacier stations B, F and C is about 40% higher than at station A (Figure 3.7). On the windward side (D, E) the precipitation is at about the same level as on station A. In contrast to winds from S and SW, the precipitation in Ny-Ålesund for winds from W is higher than at station A. For this wind direction some of the airmasses may be channelled inwards the fjord Kongsfjorden, and may thus reach Ny-Ålesund without passing over the mountains.

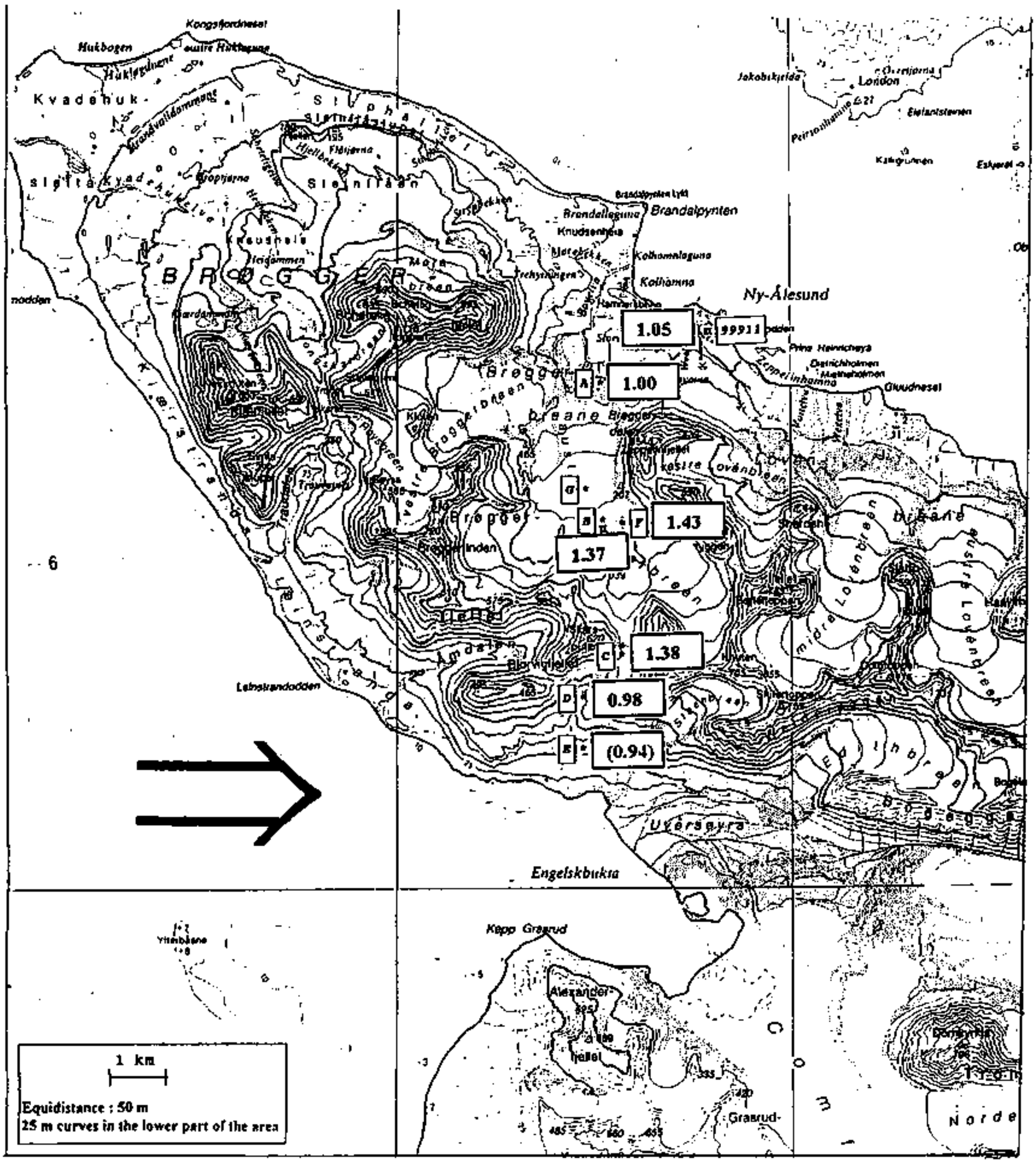

Figure 3.7 Precipitation distribution (relative to station A) for large-scale winds from W

3.3.4 Winds from Northwest

For winds from Northwest, the precipitation in Ny-Ålesund is higher than at all the profile stations (Figure 3.8). The glacier stations get just about 65 percent of the Ny-Ålesund value. (For the total amounts (Table 3.1) about 50%). As the winds for this direction are blowing parallel to the Brøgger peninsula, there is probably insignificant lifting against the mountains Northwest on the peninsula. The wind is diverted to both sides of the peninsula, and against the north-eastern shores (incl. Ny-Ålesund) there is a precipitation enhancement because of convergence-effects when the airmasses are «trapped» in the Kongsfjorden basin.

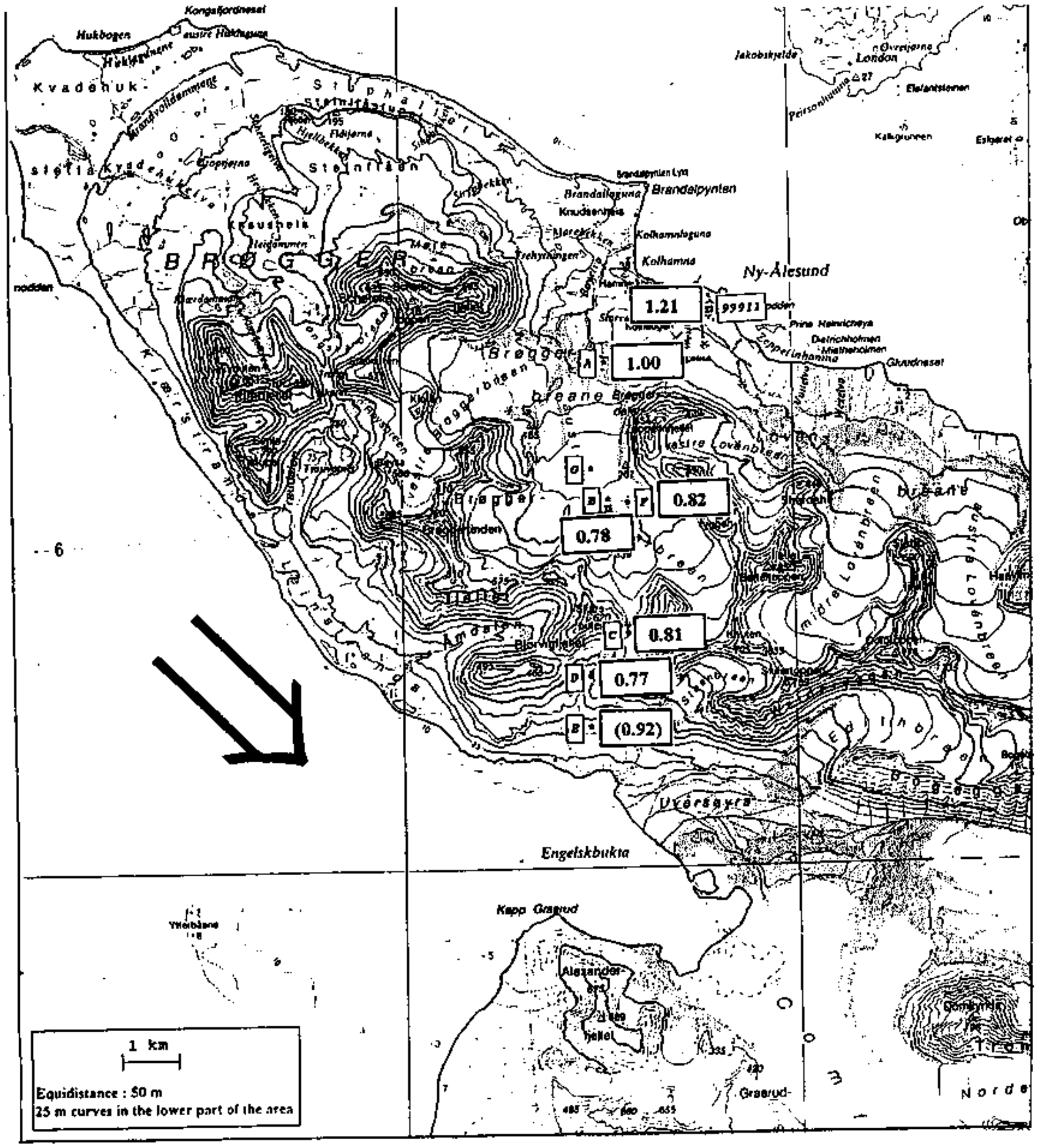

Figure 3.8 Precipitation distribution (relative to station A) for large-scale winds from NW

3.3.5 Distribution of ratios for different circulation types

The distinct different distribution of ratios for circulation sectors S-W and sectors NW-N are demonstrated in Figure 3.9 for days with more than 0.5 mm/day precipitation at station A. For the two glacier stations B and F all ratios are larger than 1.0 for winds from sectors S-W, while just 2 (out of 9) are larger than 1.0 for winds from sectors NW-N. Also for Ny-Ålesund there is a distinct shift in ratios for wind from different sectors.

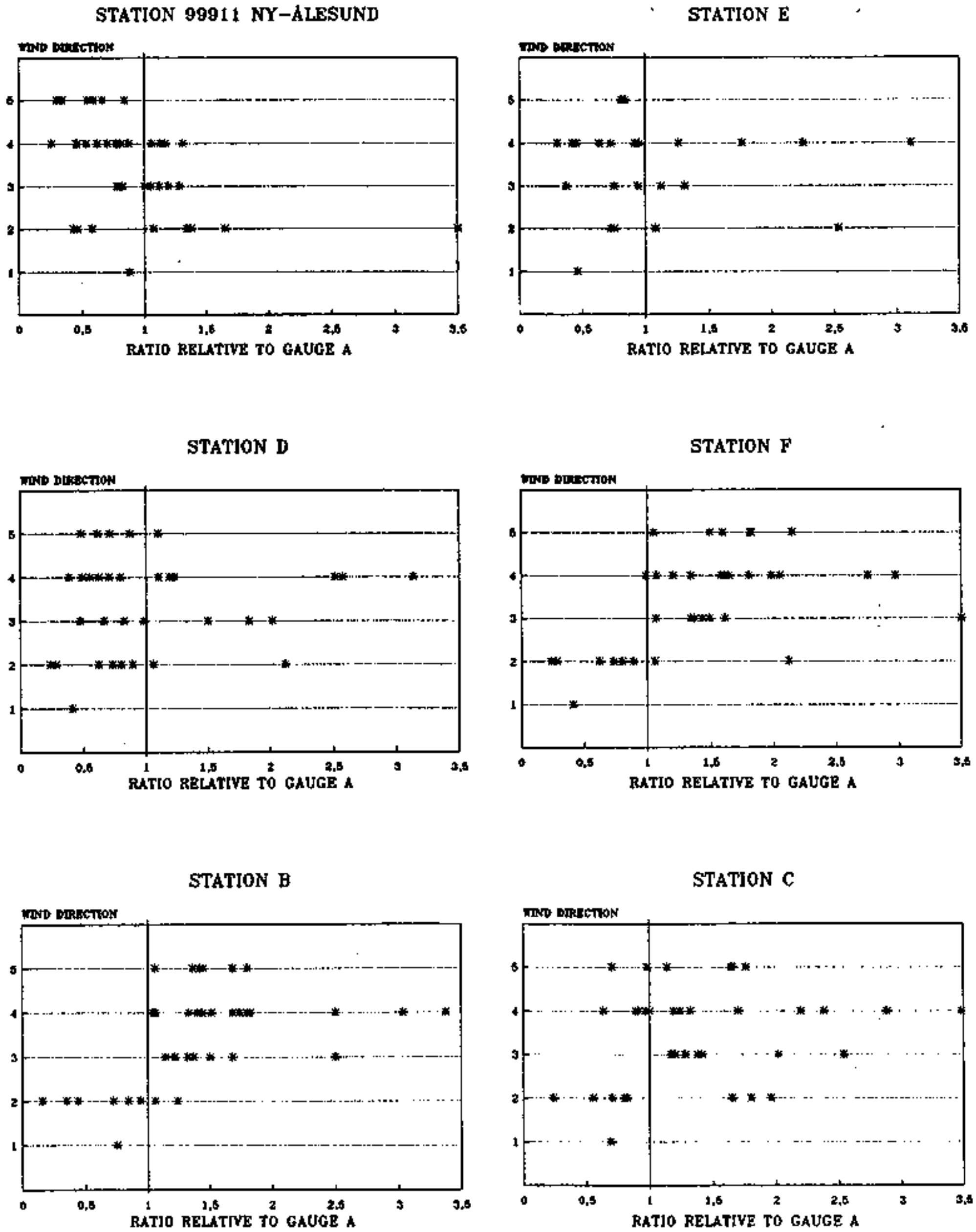

Figure 3.9 Precipitation ratios (relative to station A) for large scale winds from sector S (5) SW (4), W (3), NW (2) and N (1).

4. Discussion

4.1 Precipitation gradients at the glacier Austre Brøggerbreen.

To generalise the results, it would be useful to indicate a «typical» altitudinal precipitation gradient for the Ny-Ålesund area. For this purpose the total annual precipitation values presented in Table 3.1 are expressed as ratios to the automatic gauge in Ny-Ålesund (station 99911). As mentioned in section 2.1, station C is exposed to stronger winds than the other stations, and also a larger proportion of the summer precipitation falls as snow. If it e.g. is assumed that the wind speed at this station is 3 m/s higher than at the other stations, that this station has 10% higher proportion of solid precipitation than the other stations, and that the mean rainfall intensity was about 0.5 mm/h, the correction factor (cf. Figure 2.4) for this station will be about 20% higher than at the other stations. By using a correction factor of this magnitude, the ratio between station C and Ny-Ålesund will be increased from 1.42 to 1.70.

Station D was situated at a flat 3x3 m shelf in a rather steep hillside (cf. Figure 1.1). The size of this shelf is so small, that at this station the winds will usually have a vertical component. In the basin Dyrdalen outside Bergen in Western Norway, it was found that in steep terrain there was significantly more precipitation caught in gauges with orifice parallel to the hillside than in gauges with horizontal orifice (Abildsnes, 1980). The largest differences (up to 50%) were found on the windward side of a ridge. The rather low precipitation amounts at the station D may thus to a large extent be the result of too steep terrain in the gauge area. Figures 3.5-3.7 confirm that this station gets lower precipitation value than the glacier stations when it is on the windward side (upslope winds from sectors S, SW and W), while it (cf. Figure 3.8) records about the same amounts when it is on the leeward side (downslope winds from NW). By using a correction factor of e.g. 1.30 for this «hillside effect», the corrected ratio for station D would be 1.35 i.e. about the same as for the two glacier stations B and F. However, this «correction» is rather speculative.

The rainfall-altitude relation for the profile (Figure 4.1) indicates a precipitation increase of about 20% per 100m, i.e. about the same magnitude as the 25% per 100m found by Hagen &

Lefauconnier (1995). By considering the tentative corrections above, the recorded amounts at stations C and D are not in contradiction to this estimate.

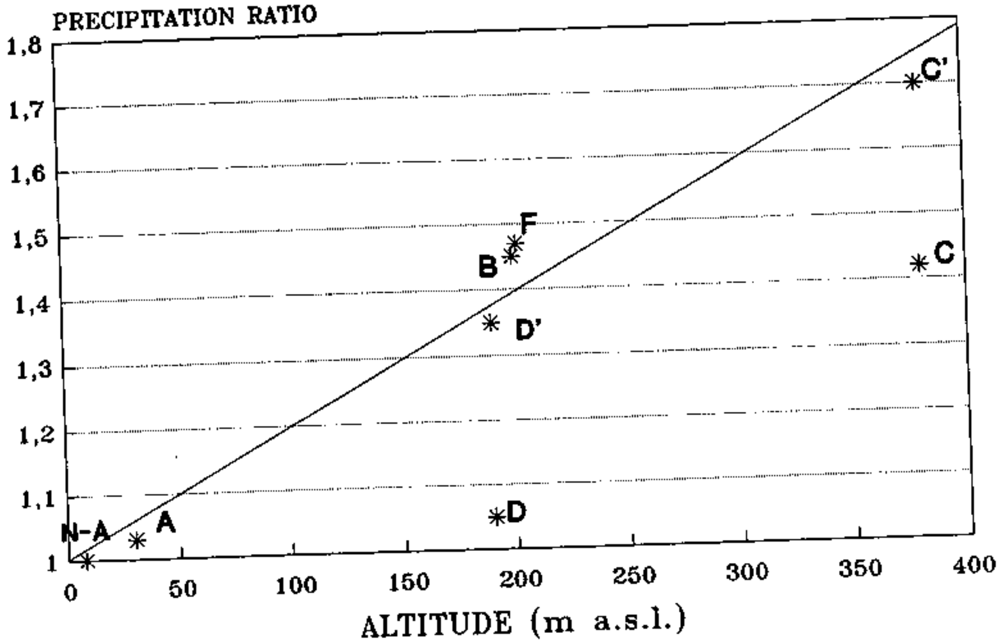

Figure 4.1 Precipitation ratio (relative to Ny-Ålesund) as a function of altitude
(C' and D' are values for stations C and D «adjusted» for resp. catch deficiency and «hillside effects» (See text)

However as shown in Figures 3.5-3.9, the precipitation distribution in the Ny-Ålesund area is strongly influenced by the large scale wind direction. For winds from sectors S, SW and W the precipitation at the glacier is distinctly higher than at the lower altitude stations both on the windward and leeward side (Figure 4.2). For winds from S and SW the precipitation at the glacier is even higher than at the highest altitude station C. As mentioned above, the precipitation at station C may be underestimated because of large measuring errors at this station. But it is also possible that the maximum precipitation area at the glacier is a real feature. Also Hagen & Lefauconnier (1995) pointed out that a linear gradient of 25% per 100 m might give too high values in the uppermost areas.

The high precipitation amounts at the glacier may be caused by spillover effects and seeder/feeder effects (See section 1.2). The spillover effects cause a displacement of the maximum precipitation area some 2-4 km to the leeward side of the mountains. Over the glacier, with a wet surface at about 0°C, there are favourable conditions for formation of ground fog and low level stratus clouds during precipitation events in the summer season. When the additional raindrops from spillover are falling through this fog/stratus layer, washout of small droplets (seeder/feeder effect) will cause a further enhancement of the precipitation.

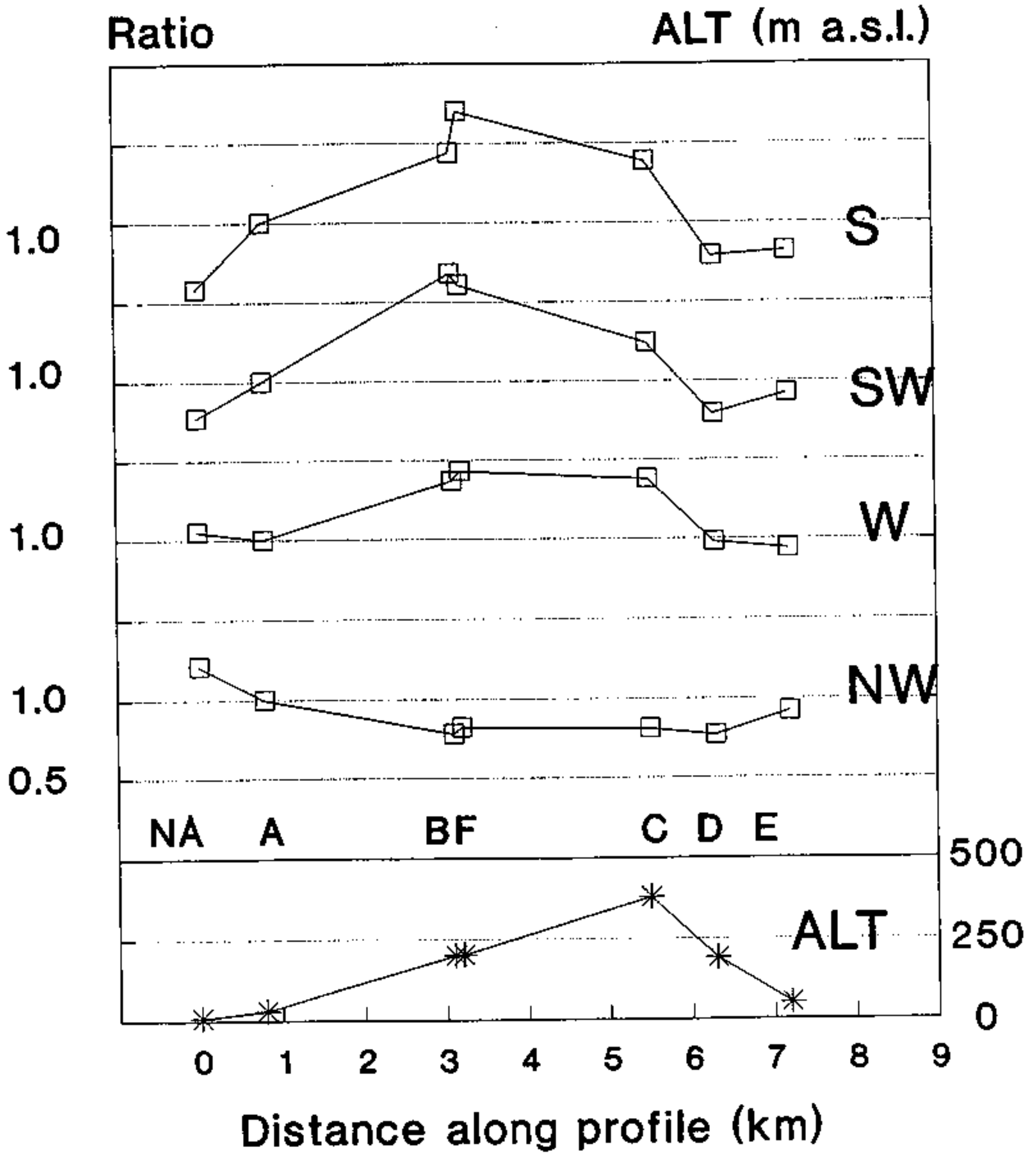

Figure 4.2 Precipitation gradients along profile A-E (cf. Figure 1.1) for large scale winds from sectors S, SW, W and NW. Bottom: ALTitudes along the profile

Thus the maximum precipitation at the glacier stations B and F (and station G in 1995) may be real, and the linear altitude-precipitation relationship (Figure 4.1) may be misleading. Some of the profile stations are continued in another project in 1996 (Sand, 1996), and these supplementary data may indicate which hypothesis is the correct one.

Based on the 1994-95 seasons, the most likely conclusion is that the maximum precipitation at the central parts of the glacier is real, and that spillover combined with seeder/feeder effects are the dominant features. These effects will vary with e.g. wind direction and wind speed. Accordingly the ratio between glacier precipitation and measured precipitation in Ny-Ålesund will vary from year to year, depending on the dominating wind conditions. This may be one of the reasons why Hagen & Liestøl (1990) found that the correlation between the measured precipitation in Ny-Ålesund and the snow accumulation measured by sounding profiles over the glacier surface was as low as 0.63 for the period 1974-1988.

4.2 Precipitation scenarios for changes in wind directions.

Table 3.2 and 3.3 present the number of days and precipitation amounts for the different circulation types. The results are summarized in Table 4.1. The precipitation ratios relative to station A and Ny-Ålesund are also presented.

Table 4.1 Number of days (No) and precipitation amounts (mm) at stations A-E and Ny-Ålesund (N-Å) for different circulation types.

	No	A	B	C	D	F	N-Å
S	9	13.2	19.1	16.5	11.0	21.2	8.0
SW	25	61.0	98.6	84.5	59.3	94.2	49.9
W	17	25.9	42.0	44.0	29.3	47.6	28.2
NW	18	22.9	16.4	21.3	16.4	15.7	32.9
Others	66	25.9	32.9	39.0	35.4	34.2	25.5
Total	135	148.9	209.0	205.3	151.4	212.9	144.5
Ratio to A		1.00	1.40	1.38	1.02	1.43	0.97
Ratio to N-Å		1.03	1.45	1.42	1.05	1.47	1.00

In Table 4.2 the mean precipitation intensities (mm/day) for each station and circulation type are presented. The highest intensities (about 4 mm/day) are found for the two glacier stations B and F for winds from SW. In Ny-Ålesund the intensity is 2 mm/day for winds from SW.

Table 4.2 Number of days (No) and precipitation intensities (mm/day) at stations A-E and Ny-Ålesund (N-Å) for different circulation types.

	No	A	B	C	D	F	N-Å
S	9	1.47	2.12	1.83	1.22	2.36	0.89
SW	25	2.44	3.94	3.38	2.37	3.77	2.00
W	17	1.52	2.47	2.59	1.72	2.80	1.66
NW	18	1.27	0.91	1.18	0.91	0.87	1.83
Others	66	0.39	0.50	0.59	0.54	0.52	0.39
Total	135	1.10	1.55	1.52	1.12	1.58	1.07

IPCC-95 (Houghton et al.,1996 p.307) states that on increasing CO2, all models produce an increase in global mean precipitation. Precipitation increases in high latitudes in winter. The warming of the atmosphere leads to higher atmospheric water vapour content, enhanced poleward water vapour transport into the northern high latitudes and hence enhanced water vapour convergence and precipitation. For the Norwegian Arctic, the climate is very vulnerable for changes in frequencies of circulation types. Nothing is stated by IPCC concerning regional changes of atmospheric circulation or cyclone tracks in these areas. However, the circulation pattern will most probably be changed by the predicted changes in temperature gradients in the northern latitudes. The results from this study may be used to illustrate how dependent the precipitation in the Ny-Ålesund area is of the circulation pattern.

In the following «scenario» it is as an example assumed that there is an increase of 30% for frequencies of circulation directions S, SW and W, and a similar decrease for the other circulation types. I.e. the frequency of winds from S increase from 9 (Table 4.1 and 4.2) to 12 etc. If it further is assumed that the precipitation intensities for each circulation type is unchanged, the resulting amounts for each station and circulation type would be as shown in Table 4.3. For e.g. station A, the total amount for winds from sector S would increase to 17.6 mm. The total amount at station A would increase from 148.9 m (Table 4.1) to 168.9 mm (Table 4.3), i.e. by 13%. For station B, the total precipitation would increase by 19%, and in Ny-Ålesund by some 8%.

Table 4.3 Number of days (No) and precipitation amounts (mm) at stations A-E and Ny-Ålesund (N-Å) for different circulation types **for Scenario** 1 (30% increase of frequency of winds from sector S-W)

	No	A	B	C	D	F	N-Å
S	12	17.6	25.5	22.0	14.7	28.3	10.7
SW	33	80.5	130.2	111.5	78.3	124.3	65.9
W	22	33.5	54.4	56.9	37.9	61.6	36.5
NW	12	15.3	10.9	14.2	10.9	10.5	21.9
Others	56	22.0	27.9	33.1	30.0	29.0	21.6
Total	135	168.9	248.8	237.8	171.8	253.7	156.6
Scenario1/present		1.13	1.19	1.16	1.13	1.19	1.08
Ratio to A		1.00	1.47	1.41	1.02	1.50	0.93
Ratio to N-Å		1.08	1.59	1.52	1.10	1.62	1.00

Table 4.3 also shows that the precipitation gradients in the area would change. While station B during the observation period had 45% higher precipitation than Ny-Ålesund (Table 4.1), Scenario-1 would imply an almost 60% higher precipitation amount in this area of the glacier compared to Ny-Ålesund.

In addition to influences of probable changes in circulation patterns, the precipitation regime in Norwegian Arctic would be affected by other aspects of the climate change issue. IPCC-95 (Houghton et al.,1996 p.308) indicates an increase of 0.0-0.5 mm/day for Spitsbergen both for summer and winter, and a temperature increase of about 4°C during winter and about 1°C during summer. (IPCC also stress that the regional estimates are uncertain and that some models imply that an area around the Norwegian Sea may experience a cooling and a reduction in precipitation). Hanssen-Bauer et al (1996) have shown that the measuring errors for precipitation would be reduced by increasing temperatures. For a general increase in temperature of 4 °C all year, the measured precipitation would increase by 10%.

These simple scenario considerations are made just to illustrate how crucially important changes in circulation patterns are for the precipitation conditions in Ny-Ålesund. The analysis will be elaborated further by DNMI for a larger dataset where also temperature is included.

Conclusions

- Recording tipping buckets were successful in mapping the precipitation in the glacier area near Ny-Ålesund. The fine time resolution of the precipitation recordings made it possible to study the precipitation distribution as a function of wind direction.

- The total precipitation amount at the glacier Austre Brøggerbreen during the summer seasons 1994-95 was about 45% higher than in Ny-Ålesund

- The precipitation distribution in the Ny-Ålesund area is strongly dependent on the wind direction. For large-scale winds from South and Southwest, the precipitation at the glacier is about 60% higher than in Ny-Ålesund, while for winds from Northwest Ny-Ålesund gets more precipitation than all the glacier stations.

- The high precipitation amounts recorded at the central areas of the glacier are probably caused by a combination of spillover and seeder/feeder effects.

- A rough altitude-precipitation increase may be estimated to 20 % per 100m, at least up to 300 m a.s.l.

- The orographic precipitation enhancement, and catch deficiency of conventional precipitation gauges may fully explain the apparent discrepancy between precipitation measured in Ny-Ålesund and runoff/massbalance estimates for the Bayelva catchment.

- The precipitation conditions in Ny-Ålesund and at the glacier are very vulnerable for changes in circulation pattern. A 30% increase of winds from sector S-W would increase the precipitation in Ny-Ålesund by 8% and at the glacier by 19%. The precipitation at the glacier would be 60% higher than in Ny-Ålesund.

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APPENDIX A. Daily precipitation amounts (mm) and circulation type (CT).

The recorded values are adjusted according to the calibration factors in Table 2.2.
*** indicates interpolated values.**

Dates	A	B	C	D	E	F	G	99931	99930	CT
26.jun.94	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.9	0.0	13
27.jun.94	2.0	2.0	2.4	2.0	1.6	2.0		1.6	3.0	19
28.jun.94	0.0	0.2	0.2	0.4	0.0	0.0		0.0	0.0	19
29.jun.94	1.3	4.3	4.8	3.2	2.2	3.5		1.4	1.9	16
30.jun.94	0.4	1.4	1.8	1.2	1.0	1.5		0.2	0.6	20
01.jul.94	1.8	1.6	2.4	2.0	1.6	1.8		2.0	2.5	19
02.jul.94	3.8	4.5	5.2	5.8	4.1	4.4		3.6	4.0	19
03.jul.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.4	7
04.jul.94	10.4	11.0	9.2	6.4	6.5	12.4		13.6	15.1	6
05.jul.94	8.2	10.8	9.6	5.4	9.2	11.2		10.4	9.4	17
06.jul.94	13.3	9.6	10.6	8.2	14.3	7.2		14.3	12.6	18
07.jul.94	4.9	3.7	3.4	2.0	2.2	3.1		4.3	7.2	11
08.jul.94	0.5	1.0	1.0	0.6	0.4	1.2		1.4	1.4	19
09.jul.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	11
10.jul.94	1.1	1.0	1.8	0.8	0.8	1.2		1.8	0.8	18
11.jul.94	6.0	9.0	7.2	2.8	2.2	9.6		6.3	7.8	17
12.jul.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.7	16
13.jul.94	0.0	0.2	0.0	0.2	0.2	0.4		0.1	0.2	15
14.jul.94	1.8	5.5	4.0	2.0	0.8	5.4		0.8	1.1	16
15.jul.94	5.3	7.1	6.0	4.6	4.3	7.9		3.0	2.2	15
16.jul.94	4.5	8.2	6.0	3.6	3.3	8.2		1.2	3.1	16
17.jul.94	0.4	0.6	0.6	0.2	0.0	0.7		0.1	0.5	17
18.jul.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	16
19.jul.94	0.4	0.6	0.8	0.0	0.0	0.7		0.7	1.0	16
20.jul.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	10
21.jul.94	0.4	2.0	3.0	1.8	1.0	2.3		0.0	0.1	6
22.jul.94	0.0	0.2	0.8	1.2	0.2	0.3		0.0	0.1	6
23.jul.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	4
24.jul.94	0.0	0.4	0.8	0.2	0.4	0.3		0.2	0.0	16
25.jul.94	0.2	0.2	0.2	0.4	0.2	0.3		0.0	0.4	16
26.jul.94	0.0	0.2	1.0	0.4	0.2	0.3		0.0	0.1	6
27.jul.94	2.7	4.9	4.8	3.0	2.2	5.0		2.3	1.8	15
28.jul.94	4.7	8.0	4.6	1.8	1.4	7.4		5.6	4.1	16
29.jul.94	2.2	3.1	5.2	5.6	4.9	2.9		1.7	2.2	16
30.jul.94	0.0	0.0	0.0	0.0	0.2	0.0		0.1	0.1	7
31.jul.94	2.4	2.4	2.8	2.8	2.2	2.3		1.7	0.4	6
01.aug.94	6.0	8.0	10.2	7.4	7.6	8.0		5.2	8.0	16
02.aug.94	0.2	1.0	1.8	0.8	0.2	1.0		0.2	0.8	17
03.aug.94	0.2	0.6	0.4	0.0	0.0	0.7		1.1	1.6	18
04.aug.94	0.0	0.0	0.2	0.0	0.0	0.1		0.0	0.4	7
05.aug.94	1.5	2.7	1.8	0.8	0.6	2.3		0.9	1.2	16
06.aug.94	0.7	0.6	0.4	0.2	1.8	0.7		1.0	0.2	18
07.aug.94	1.1	1.6	4.0	3.4	2.4	1.5		1.2	2.7	20
08.aug.94	1.6	2.2	2.3	1.6	1.2	2.3		1.8	2.5	17
09.aug.94	2.5	0.4	0.6	0.6	1.8	0.9		10.9	7.1	18
10.aug.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	1.7	18
11.aug.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	18
12.aug.94	0.2	1.4	2.1	2.0	0.4	1.9		0.5	0.1	21
13.aug.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	21
14.aug.94	2.2	2.7	3.0	4.0	2.0	2.3		2.6	3.6	17
15.aug.94	0.2	1.0	0.4	0.2	0.0	1.0		0.2	0.3	7
16.aug.94	1.1	1.8	2.2	2.2	1.4	1.5		1.1	2.4	17
17.aug.94	0.4	1.6	0.6	0.6	0.2	1.5		0.1	0.1	16
18.aug.94	2.4	5.9	6.8	7.4	7.3	4.7		1.9	2.6	16
19.aug.94	0.2	0.4	2.2	2.2	0.8	0.4		0.1	0.4	17
20.aug.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	10
21.aug.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	10
22.aug.94	0.7	1.2	1.2	0.8	0.6	1.3		0.2	0.1	15
23.aug.94	14.0	20.2	14.0	9.8	12.9	15.0*		6.3	7.7	16
24.aug.94	0.5	1.4	0.8	0.2	0.2	1.0*		1.7	2.6	16
25.aug.94	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.1	20
TOTAL(1994)	114.4	158.4	155.2	112.8	109.0	151.6		116.3	131.0	

(Continuation)

Dates	A	B	C	D	E	F	G	99911	99910	CT
14.jun.95	0.0	0.2	0.0	0.0		0.2	0.0	0.1	0.0	10
15.jun.95	0.0	0.0	0.8	0.0		0.0	0.0	0.1	0.0	19
16.jun.95	0.0	0.0	0.4	0.0		0.2	0.0	0.0	0.0	20
17.jun.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	10
18.jun.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	3
19.jun.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	3
20.jun.95	0.0	0.2	0.2	0.0		0.2	0.2	0.0	0.0	4
21.jun.95	1.4	1.4	1.0	0.8		1.4	2.0	0.8	0.1	15
22.jun.95	2.7	4.7	1.7	1.0		4.5	5.7	1.4	2.4	16
23.jun.95	5.0	7.6	4.6	2.5		10.4	9.3	5.3	5.1	16
24.jun.95	2.5	2.9	3.2	2.1		3.7	3.6	2.0	4.3	17
25.jun.95	0.0	0.2	0.2	0.2		0.0	0.0	0.1	0.1	18
26.jun.95	0.0	0.0	0.0	0.0		0.0	0.0	0.1	0.0	18
27.jun.95	0.2	0.0	0.0	0.4		0.2	0.2	0.4	0.6	18
28.jun.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
29.jun.95	0.0	0.4	0.8	0.2		0.5	0.4	0.2	0.1	18
30.jun.95	0.6	0.2	0.5	0.6		0.4	0.2	0.3	0.1	18
01.jul.95	2.3	1.0	1.6	2.1		1.4	1.4	1.3	1.2	18
02.jul.95	1.2	1.4	2.1	2.5		1.4	1.2	0.5	0.4	18
03.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.1	14
04.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	13
05.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	13
06.jul.95	0.8	1.2	2.3	2.3		1.6	1.2	1.3	1.2	20
07.jul.95	0.4	0.4	0.4	0.2		0.5	0.4	0.0	0.7	15
08.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	14
09.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	20
10.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	12
11.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.1	1
12.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	2
13.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	2
14.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	1
15.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	10
16.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	1
17.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
18.jul.95	0.4	0.4	1.0	0.6		0.4	0.4	0.6	0.1	21
19.jul.95	0.0	0.2	0.4	0.4		0.2	0.0	0.3	0.9	20
20.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
21.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	11
22.jul.95	3.3	3.5	0.8	0.6		4.1	4.6	1.1	1.2	21
23.jul.95	0.4	0.4	0.6	0.4		0.5	0.6	0.3	0.3	13
24.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	13
25.jul.95	3.7	4.7	5.9	7.0		4.5	4.4	3.6	3.5	19
26.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	19
27.jul.95	0.8	0.8	1.5	0.6		1.1	0.8	1.0	1.2	18
28.jul.95	0.0	0.2	0.8	0.0		0.0	0.2	0.0	0.0	18
29.jul.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	6
30.jul.95	3.3	8.2	8.4	4.9		11.8	8.7	2.7	3.2	17
31.jul.95	0.0	1.0	1.9	2.7		1.1	0.4	0.6	1.1	17
01.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	7
02.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
03.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
04.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
05.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
06.aug.95	0.0	0.8	1.1	1.9		1.1	0.4	0.2	0.0	11
07.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	18
08.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	18
09.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	20
10.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	21
11.aug.95	0.2	0.4	0.8	0.2		0.5	0.6	0.2	0.0	16
12.aug.95	0.0	0.4	1.0	0.2		0.9	0.2	0.0	0.0	17
13.aug.95	2.1	3.1	2.1	1.0		3.4	2.4	1.4	0.0	5
14.aug.95	0.6	0.8	1.0	0.4		1.3	0.4	0.2	1.6	15
15.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	15

(Continuation)

Dates	A	B	C	D	E	F	G	999[illegible]	999[illegible]	CT
16.aug.95	0.8	2.1	1.5	1.4		1.8	0.0	0.3	0.1	14
17.aug.95	1.6	1.6	1.3	1.4		2.0	0.0	1.5	1.9	19
18.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	12
19.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	11
20.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	1
21.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	10
22.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	3
23.aug.95	0.2	0.0	0.0	0.0		0.0	0.0	0.3	0.3	3
24.aug.95	0.0	0.2	0.0	0.0		0.0	0.0	0.0	0.0	12
25.aug.95	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	12
26.aug.95	0.0	0.0	0.2	0.0		0.0	0.0	0.0	0.0	11
TOTAL (1995)	**34.5**	**50.6**	**50.1**	**38.6**		**61.3**	**49.9**	**28.2**	**31.9**	