POLISH POLAR RESEARCH
vol. 29, no. 1, pp. 73–91, 2008

Topoclimatic conditions in the Hornsund area (SW Spitsbergen) during the ablation season 2005

Krzysztof MIGAŁA, Tomasz NASIÓŁKOWSKI and Jerzy PEREYMA

Zakład Meteorologii i Klimatologii, Instytut Geografii i Rozwoju Regionalnego, Uniwersytet Wrocławski, Plac Uniwersytecki 1, 50-137 Wrocław, Poland
<migalak@meteo.uni.wroc.pl> <nasiolkowski@meteo.uni.wroc.pl>
<pereyma@meteo.uni.wroc.pl>

Abstract: The Hornsund region is characterised by a topoclimatic variation, which results principally from the local orography, the vicinity of open sea and the two contrasting environments: non-glaciated and glaciated. The specific types of atmospheric circulation determine the local thermal differences. The west coast is characterised by the most favourable thermal conditions, where air temperature is largely determined by foehn processes. The temperature at the Baranowski Station is 0.8°C higher on average than that of the Polish Polar Station on the northern shore of Hornsund. The temperature in the northern shore of the fjord happens to be higher than that on the west coast, which is attributed to the NW cyclonic inflow of cool Arctic air masses. During intermediate weather, when ground frost-thaw takes place, the northern shore of Hornsund is warmer by 0.5°C; whereas, during moderately frosty weather, it is warmer by 0.2°C than the west coast. The differences result from the effect of the warmer fjord waters on the surrounding air temperature. During moderately warm weather, more favourable conditions occur near the Baranowski Station, expressed by the mean temperature difference of 0.9°C. The greatest temperature difference of 1.5°C on average is normally recorded during warm weather.

Key words: Arctic, Spitsbergen, Hornsund, topoclimate, thermal gradient.

Introduction

Topoclimatic research of the specific environments in the Hornsund area (Fig. 1) has been one of the main objectives of the University of Wrocław expeditions to Spitsbergen, which were started in the 1970s. Extended studies were conducted in the Werenskiold Glacier Basin and in the Brattegg River, in the close vicinity of the Baranowski Station, established by University of Wrocław (Baranowski 1968, 1977; Głowicki and Baranowski 1974; Baranowski and Głowicki 1975a, b; Pereyma *et al.* 1975; Pereyma 1983; Pereyma and Piasecki 1983, 1988;

Brazdil *et al*. 1988). These authors identified a large thermal-humidity variation in particular summer seasons. Attempts have been also made at comparing selected meteorological elements in the region of the Werenskiold Glacier (on the west coast) and the northern shore of Hornsund, where the Polish Polar Station is located. Previous research has demonstrated that more favourable climatic conditions exist in the region of the Baranowski Station, when compared to the northern shore of Hornsund. Further research into polar night conditions indicates large thermal differences over the few kilometres distance between the west coast and the northern shore of the fjord. The cases of inverse thermal differences identified seem to reflect a strong influence of open water, sea ice, and orography (Migała *et al*. 2004). Both the records of air temperature in Hornsund area and the current intensive recession of the local glaciers probably reflect global warming effects (Jania and Hagen 1996; Przybylak 2007). It may be expected that expanding of the unglaciated areas has changed the local climate relationships. The weather conditions observed in 2005 reflect an increasing amount of heat transported to Arctic Ocean from lower latitudes in the summers 2000–2005 (Walczowski and Piechura 2006). Svalbard was particularly warm in that period, but in the opinion of some authors, these untypical Arctic-wide thermal conditions may be coming to end (*e.g.* Richter-Menge *et al.* 2006).

Study area

The research reported here, was carried out on Wedel Jarlsberg Land (SW Spitsbergen) and targeted two regions: the northern shore of Hornsund, where the Polish Polar Station is located and region of the Werenskiold Glacier and the non-glaciated Brattegg Valley, both situated on the west coast, about 12 km north of Hornsund (Fig. 1). Topoclimatological elements of the second region are recognized based on the data from the Baranowski Station located on the frontal moraine of the Werenskiold Glacier. The coastline of the area is very irregular, with several embayments representing the lower reaches of valleys, which recently have been occupied by retreating valley glaciers.

Mountain massifs with elevations of *c.* 500–600 m a.s.l. aligned longitudinally and coastal plains dominate in the landscape. Plains are mainly marine terraces, covered with very rich tundra vegetation. The mean annual air temperature is -4.4°C, varying between -11.3°C in January to +4.4°C in July (Marsz and Styszyńska 2007). The most notable features of the ablation season 2005 were: low solar radiation, a dense cloud cover, and an air temperature, which was slightly higher than the mean for other years. Cyclonic conditions predominated (>75%) of the observation period. The weather conditions and the topoclimatological differences were a consequence of Arctic Ocean warming and atmospheric circulation.

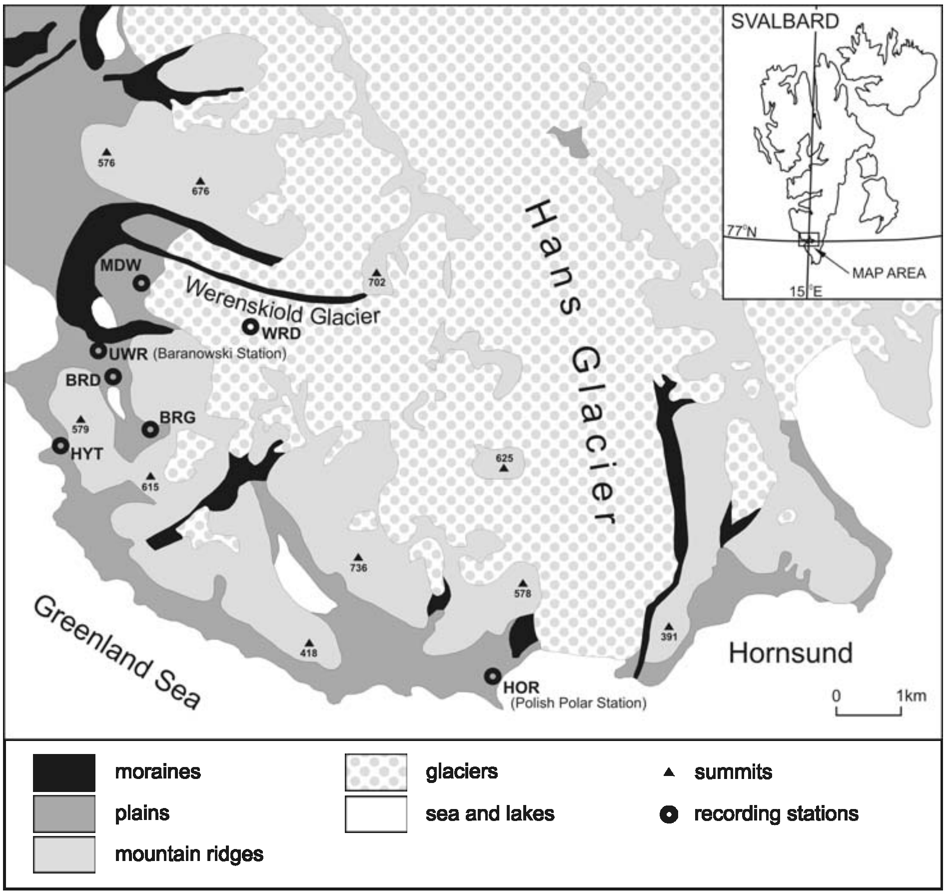

Fig.1. Map of study area showing position of the recording stations.

Material and methods

Data loggers HOBO PRO H8 (Onset Corp., USA) were used for air temperature measurements at selected stations. The loggers were installed on masts in radiation shields, 2 m above ground. Temperature was registered every 10 minutes, which made it possible to determine not only the local differences but also the dynamics of short-term changes. The records were analysed using standard climatological-statistical methods, giving topoclimatic characteristics, mean and extreme values. Based on meteorological data from the Polish Polar Station, weather charts and aerological sounding (Bjørnoya and Ny Ålesund), the ablation season 2005 was characterised against a background of long-term data with respect to circulation and principal meteorological elements. Selected synoptic situations were also characterised. Data from 1978–2005 were obtained from the Institute of Geophysics, Polish Academy of Sciences.

The studies included seven recording stations (Fig. 1, Table 1). The sites represented different environments, which occur in SW Spitsbergen. They varied with respect to their altitude, exposure, distance from the open sea and type of substratum.

Table 1

Characteristics of the recording stations.

Measurement point	GPS coordinates	Altitude [m a.s.l.]	Location
HOR	77°00.090' N 15°32.485' E	11	meteorological garden, Polish Polar Station at Hornsund, coastal terrace, 300 m from the fjord waters
UWR	77°04.259' N 15°10.712' E	26	meteorological garden on frontal moraine of Werenskiold Glacier at Baranowski Station
BRD	77°03.813' N 15°12.318' E	81	entrance to poorly glaciated Brattegg River valley, rock spur below Myrktjorna Lake
BRG	77°03.195' N 15°14.053' E	133	upper part of Brattegg River valley, near the middle lake, above the rock spur
MDW	77°04.700' N 15°13.252' E	20	terminal moraine of Werenskiold Glacier *c*. 300 m from its front, 2 km from sea coast
WRD	77°04.246' N 15°20.083' E	260	middle part of Werenskiold Glacier, 3 km above its front
HYT	77°2.600' N 15°9.001' E	10	coastal terrace in a narrow coastal strip at the foot of the Gullichsenfjellet Massif (Hyttevika)

Topoclimatic variations in the Werenskiold Glacier Basin

For the observation period (11 July – 30 September, 2005), the mean temperature on the frontal moraine (UWR) was 3.7°C, at the point in the glacier forefront (MDW) 3.6°C and, on the glacier (WRD), 1.5°C. The highest monthly mean temperature in July was recorded at the measurement site in the glacier forefront (MDW). In the remaining months, a higher temperature was observed at UWR. The correlation between temperatures at the different recording stations within the period of measurements was high, with the following values of correlation coefficients: UWR-MDW, R = 0.97; UWR-WRD, R = 0.96; MDW-WRD, R = 0.98. In July however, when cloudless weather prevailed, the values of correlation coefficients were lower. In September, with a new snow cover, the strength of the relationship was the highest of all the months.

During the polar summer, the air temperature varied little throughout the day. This is confirmed by the standard deviation values ranging from ±1.5°C to ±1.7°C.

Thermal differences between UWR and MDW were slight. During the whole ablation period, the temperature on the frontal moraine of the Werenskiold Glacier (UWR) was higher than that at the forefront point (MDW), on average by 0.1°C. However, until the start of August, nearly all the time, the temperature was higher at the MDW than at the UWR. It can be explained by the sheltered nature of the forefront and its concavity, shaped by the ridge of frontal moraine and front of the glacier. As a result, limited air exchange with the surroundings and, during sunny weather, heat accumulation took place inside the depression. The more favourable thermal conditions in the first half of summer in the forefront may result from higher insolation there and more frequent advection of maritime air masses, which limits the cooling effect of the glacier. However, there is no doubt that two strongly contrasting environments control the thermal conditions in the central part of the forefront of the Werenskiold Glacier: marine and glacial. The area has a variable local air circulation, which is manifest as alternating cool current from over the glacier and current of warmer air issuing from the ocean, which rise to the level of the glacier.

In 54.4% of the period, the mean daily temperature at the UWR was higher than at the MDW. During 38.5% of the time, the temperature at the UWR exceeded that recorded at the MDW by values within the range of 0–1°C. The greatest difference in favour of the UWR reached 4.7°C (18 July). A considerable increase in the temperature difference between the two points took place on days, when a strong easterly wind from the glacial interior prevailed, which had a cooling effect on the forefront. Such a situation occurred on 14–15 and 25–27 of August.

The situations, when air temperature at the glacier forefront (MDW) was higher than that at frontal moraine (UWR), were observed in 45.6% of the days, the difference being mostly within the range of 0–1°C. In July, such situations constituted as much as 78.9% of cases for the mean hourly temperature and were observed on all days in respect of mean daily temperature. The greatest differences in favour of the MDW were recorded most frequently on days, when there was strong insolation (20, 23 and 24 July) and reached maximum of 4.3°C (24 July). A higher temperature in the forefront was also recorded, when N-NW advections brought cold and heavy arctic-maritime air (*e.g.* 16–17 July).

As might be expected, more conditions that are favourable existed at the frontal moraine (UWR), compared to the central part of the glacier (WRD). The temperature at the UWR was higher, by 2.2°C on average. In 43.5% of cases, the temperature at the UWR was higher by 2°C to 3°C. Pereyma and Piasecki (1988) emphasised these differences, whereas Brazdil *et al.* (1988) reported a mean temperature difference between the moraine and the middle of the glacier, which could be as high as 4°C.

In respect of mean daily temperatures, the greatest differences reached 5.6°C (7 July), favouring the UWR point, with hourly temperatures exceeding 10.0°C. The vertical gradient of daily mean and daily maximum temperature reached 2.39°C/100 m and 4.27°C/100 m, respectively. On 7 July, Southern Spitsbergen laid at the edge of an anticyclone centred over the Barents Sea. The air pressure at the Polish Polar Station in Hornsund reached 1019 hPa, where a slight breeze (mean 3 m/s) from E direction prevailed. Slight cloudiness (1/8) with sporadic altocumulus and cirrus clouds and 19.1 hrs of sunshine resulted in warm weather. The daily mean air temperature in Hornsund (HOR) and in the Baranowski Station

(UWR) was 6.5°C and 12.2°C, whereas the maximum of air temperature was 13.5°C and 17.2°C, respectively. Intensive insolation favoured both melting on the glacier (WRD) and intensive heating of the unglaciated surface and the near ground air layer (UWR). This caused strong thermal contrasts.

There was not a single day when the mean daily temperature on the glacier (WRD) exceeded that at the frontal moraine (UWR). The smallest difference was 0.3°C (29 July). Considering mean hourly temperatures, in only 3.3% of cases the temperature was higher on the glacier. Inversion periods were irregular and short-lasting and occurred mainly in July (5, 6, 24, 25 and 29). Maximum differences in respect of the glacier were over 2°C (2.8°C on 24 July and 2.2°C on 31 August).

In terms of mean daily temperature, the glacier forefront (MDW) was also consistently warmer than the central part of the glacier (WRD). Air temperature at the MDW was, on average, 2.1°C higher. The differences between the temperatures at those stations were not as great as those observed for the pair UWR-WRD, and ranged from 1.0°C (15 September) to 2.7°C (19 and 24 August). In respect of hourly temperatures, the differences in favour of the forefront were most often within 2–3°C (51.8% cases), with a maximum over 4°C (4.2°C on 24 August and 4.8°C on 25 August). Only in 1.1% of cases in the study period, the temperature in the forefront was lower than that on the glacier. As in the case of the UWR-WRD profile, inversions were short-lasting. The maximum difference in favour of WRD was 1.3°C (15 September).

Thermal differences between frontal moraine (UWR) and glacier forefront (MDW) depend on several factors:

- type of substratum – substratum at the UWR is dry, whereas the MDW is subject to down flow of ablation water during summer and autumn. During the polar summer, the heat in the forefront is consumed for evaporation, whereas during the first frosts the latent heat of solidification is emitted,
- effect of different air masses – the forefront is more often subject to the effect of cold katabatic winds from the glacier.

The mean maximum temperatures were: 5.6°C at UWR, 5.6°C at MDW and 3.5°C at WRD (Table 2). The differences in maximum temperature between UWR and MDW are small. During the whole study season, the mean maximum temperature at the two points was 5.6°C. Slight differences were observed in August and September. In August, the higher maxima at UWR could be associated with more frequent inflow of air from the east, which had a cooling effect on the forefront. The converse situation occurred in September, when higher maximum temperatures were recorded at MDW. The difference could have resulted from the local orography because with prevailing N and NW advection during September, the rampart of the frontal moraine protects the forefront from the inflow of heavy arctic air masses. Differences in maximum temperatures between the points on the moraine and on the glacier were, on average, 2.1°C. The greatest differences occurred in August, and seem to relate to foehn phenomena.

Table 2

Mean five-day values of daily mean temperature (T), maximum temperature (T max) and minimum temperature (T min) at the recording stations, July – September 2005. Explanation of the station names abbreviations enclosed in Table 1.

Five-day period	T [°C]						T max [°C]						T min [°C]					
	HOR	UWR	BRD	BRG	MDW	WRD	HOR	UWR	BRD	BRG	MDW	WRD	HOR	UWR	BRD	BRG	MDW	WRD
1–5.07	4.8	–	–	–	–	–	6.5	–	–	–	–	–	2.8	–	–	–	–	–
6–10.07	5.7	8.2		–	–	5.5	8.3	12.0	–	–	–	8.8	3.2	5.7	–	–	–	2.9
11–15.07	3.9	4.8	4.6	–	5.3	3.1	5.9	6.2	6.1	–	6.9	5.5	2.3	3.5	2.9	–	3.7	1.3
16–20.07	4.4	4.1	3.7	–	4.6	2.4	6.1	7.2	5.7	–	6.5	4.5	2.5	2.6	2.1	–	2.7	0.7
21–25.07	4.7	5.5	5.6	–	6.3	4.1	7.2	9.8	9.3	–	9.3	7.5	2.8	3.7	3.1	–	3.6	1.5
26–31.07	4.0	4.7	4.8	–	5.3	3.5	5.4	7.3	6.9	–	7.6	6.1	2.5	2.9	2.6	–	2.7	1.3
1–5.08	4.1	5.2	5.1	4.8	5.3	3.0	5.3	7.3	6.9	6.5	7.3	5.0	3.0	4.2	3.8	3.5	3.7	1.7
6–10.08	4.5	5.4	5.3	4.8	5.3	2.9	5.6	7.1	7.2	6.4	5.0	3.3	4.3	4.0	3.5	3.6	1.5	–
11–15.08	4.6	5.8	5.7	5.2	5.2	3.0	6.0	7.4	7.7	7.0	6.9	4.4	3.6	4.4	4.0	3.5	3.7	1.6
16–20.08	3.9	5.0	4.9	4.4	4.8	2.4	5.5	6.4	6.7	6.0	6.5	4.2	1.9	3.0	2.7	2.4	3.1	0.9
21–25.08	4.9	6.8	6.7	6.3	6.4	4.0	6.9	8.5	8.4	7.9	8.6	5.9	3.2	4.9	4.7	4.6	4.3	2.0
26–31.08	5.9	7.5	7.4	7.0	6.5	4.4	7.6	9.1	9.5	8.7	8.4	6.3	4.2	5.8	5.3	4.9	4.8	2.8
1–5.09	4.8	5.9	5.6	5.1	5.3	3.2	6.2	7.4	7.0	6.5	7.2	4.7	3.4	4.3	4.1	3.8	3.5	1.7
6–10.09	1.9	2.5	2.2	1.7	2.5	0.5	2.6	3.6	3.5	3.0	3.8	2.3	0.6	0.9	0.2	0.0	0.9	-0.7
11–15.09	-1.2	-1.5	-2.0	-2.5	-1.7	-3.2	0.8	0.2	0.7	-0.5	1.2	-0.6	-3.5	-3.4	-4.4	-4.8	-4.3	-6.0
16–20.09	0.5	0.0	-0.4	-0.8	-0.1	-1.8	1.9	1.5	1.6	1.3	2.9	0.4	-1.4	-1.3	-2.2	-2.6	-2.4	-3.7
21–25.09	-1.2	-0.4	-0.9	-1.2	-0.8	-2.8	0.8	0.6	0.4	0.1	0.6	-1.5	-1.2	-2.1	-2.9	-3.1	-2.7	-4.5
26–30.09	-3.0	-3.0	-3.6	-4.1	-3.8	-5.8	-1.6	-1.6	-1.9	-2.4	-2.2	-4.2	-4.7	-4.9	-5.9	-6.2	-5.7	-8.0

A much greater variation was observed for minimum temperatures, especially between the stations located in the non-glaciated environment. The mean minimum temperature was: -1.1°C at UWR, -1.8°C at MDW and -3.5°C at WRD. As well as in July, more-pronounced minima were observed when MDW compared with UWR. Differences in August and September were 0.6°C and 0.7°C, respectively. By the comparison, in respect of the moraine and forefront stations, the differences were similar to those observed for the maximum temperatures.

The mean vertical temperature gradient between the UWR and WRD points was 0.94°C/100 m, varying between 1.78°C/100 m and 0.14°C/100 m. The mean gradient between the forefront (MDW) and the glacier (WRD) was somewhat smaller (0.87°C/100 m) and varied between 1.13°C/100 m and 0.42°C/100 m. The gradients, based on the daily maximum temperatures between the frontal moraine (UWR) and the glacier (WRD) and between the glacier forefront (MDW) and the glacier (WRD) were 0.86°C/100 m and 0.87°C/100 m on average. The rates varied respectively: between -1.11°C/100 m and 2.74°C/100 m and between -0.25°C/100 m and 1.58°C/100 m. The mean vertical gradient of daily minimum temperatures between the UWR and WRD were as high as 1.04°C/100 m, and 0.82°C/100 m between the MDW and WRD. The gradients varied between 0.03°C/100 m and 1.79°C/100 m and between -0.02°C/100 m and 1.38°C/100 m. The result is very similar to those of Pereyma and Piasecki (1988).

Thermal gradients between the moraine and glacier points increased when foehn conditions prevailed and on days of intensive insolation, when the moraine substratum heated considerably. The largest thermal gradients between the frontal moraine (UWR) and the glacier (WRD) occurred on sunny days (*e.g.* 7 July), when, during the day the gradient exceeded 3°C/100 m throughout a maximum of 4.3°C/100 m. Larger gradients between UWR and WRD (up to 1.6°C/100 m) were also recorded in the second half of August, when foehn winds were combined with an easterly circulation. Gradients for hourly temperatures during foehn conditions reached *c*. 2.3°C/100 m (25 August).

While the foehn increased, vertical thermal gradients for the pair UWR-WRD and for the profile MDW-WRD decreased to 0.8°C/100 m. The forefront was then affected by a cold wind from the glacier, which obliterated the thermal differences between the two points. It may be supposed that in average summer conditions, the forefront of the Werenskiold Glacier lies outside foehn influence, or that its influence is negligible.

Thermal relationships in the non-glaciated Brattegg Valley

Thermal relationships in the non-glaciated Brattegg Valley depend mainly on the altitude above sea level. The role of substratum is less important, since it is roughly the same throughout. Correlation coefficients between temperatures at particular stations (UWR, BRD and BRG) were higher than those for the moraine and the glacier, where the substratum has a considerable controlling influence. The correlation was the highest in September, when the substratum was already frozen and a permanent snow cover has already formed. The correlation was weaker in July when cloudless weather prevailed.

In the period of 31 June and 30 September, the mean temperature at the frontal moraine (UWR) was 3.3°C, in the lower part of the valley (BRD) 3.1°C and, in the upper part (BRG), 2.6°C. On 82.9% of this period, the temperature at the UWR was higher than that at the BRD, the difference being mostly within 0–1°C. The greatest difference was 0.9°C (29 September). On 17.1% of this period, the mean daily temperature was higher at the BRD that at the UWR, the maximum differences being 0.9°C (24 July) and 0.4°C (26 and 31 August). The greatest difference was 5.7°C (18 July). In 23.1% of the cases, higher temperatures were recorded at BRD (on 24 July, by 4°C). In average conditions of polar summer, the temperature differences between the BRD and BRG are limited, which results from their close location, similar properties of the substratum and similar hypsometry.

When the region of the frontal moraine (UWR) was characterised by more favourable thermal conditions compared to the station located in the upper part of the valley (BRG), the mean difference was 0.7°C. Only on one day (31 August), the mean daily temperature was higher by 0.2°C at the BRG. On all the other days, higher temperatures were recorded at UWR. The difference was mostly within 0–1°C. The maximum differences in favour of the UWR reached 1.6°C (29 September) and 1.4°C (13 September). Mean hourly temperatures in 91.9% of cases were higher at UWR. In less than 10% of cases, the temperature in the upper part of the valley was higher than at the UWR, the differences being mostly within 0–1°C. On 31 August, the difference was 2.5°C.

The mean maximum temperature for UWR and BRD during the whole measuring season was 4.9°C for each station. As in the case of the region of the Werenskiold Glacier, the recorded minimum temperatures were more variable. The difference in favour of UWR, when compared to BRD, was 0.6°C and 0.9°C compared to BRG.

The greatest vertical gradients of air temperature in the Brattegg Valley and their greatest variation occurred in July and August. Most often, the recorded vertical temperature gradients were within 0.5°C to 1°C/100 m. The mean temperature gradient for the period 31 July – 30 September between the frontal moraine (UWR) and the lower part of the valley (BRD) was 0.44°C/100 m. In July and August, the gradient was small, with the mean 0.2°C/100 m. A larger vertical temperature gradient was recorded in September (0.8°C/100 m). Maximum daily gradients were 1.53°C/100 m (30 September), 1.39°C/100 m (23 September) and 1.27°C/100 m (13 September). Situations with negative gradients (inversions) were frequent during the thermal summer. The greatest negative gradients were -0.76°C/100 m (31 August), -0.71°C/100 m (26 August) and -0.64°C/100 m (28 August).

The mean gradient between the frontal moraine (UWR) and the upper part of the valley (BRG) was 0.63°C/100 m. The greatest daily gradients were (as in the case of BRD) observed in September and reached 1.32°C/100 m (13 September). Only on one day, the mean daily gradient was negative and amounted to -0.18°C/100 m (31 August).

The mean gradient between BRD and BRG was 0.83°C/100 m. Maximum daily gradients between the lower and the upper parts of the valley were 2.10°C/100 m (30 September), 1.96°C/100 m (9 August) and 1.69°C/100 m (26 August). A negative gradient was recorded on 30 September (-0.93°C/100 m).

It should be noted that mean vertical temperature gradient between lower and the upper part of the unglaciated valley (the BRD and BRG points) was lower by 0.05°C in comparison with the mean gradient between the forefront (MDW) and the glacier (WRD), 0.87°C/100 m.

The gradient, based on the daily maximum temperatures recorded in the unglaciated valley reached 1.20°C/100 m and was higher than that in respect of the glacier. The mean vertical gradient of daily minimum temperatures between the BRD and BRG (valley) was 0.73°C/100 m and was lower in comparison with the gradient between the glacier forefront (MDW) and the glacier (WRD).

Comparison of thermal conditions in the Hornsund and Werenskiold Glacier regions

Undoubtedly, favourable thermal conditions exist in the region of Werenskiold Glacier than that in the Hornsund area as emphasised by Baranowski and Głowicki (1974), Głowicki and Baranowski (1975), Pereyma (1983) and Brazdil *et al.* (1988). The main reason for the variation is the local orography, which modifies the airflow, and the development of foehn processes. In respect of the prevailing circulation from the east, the UWR (frontal moraine of the Werenskiold Glacier) is located on the leeward side of the mountains. During the polar summer, when advection from southerly directions is frequent, the mountain massifs shelter the forefront of the glacier and produce local foehn effect. Hornsund is characterised by a very specific local climate, influenced mainly by the numerous glaciers, which are tributary to the fjord. Cool katabatic winds from the glaciers are frequent. They contribute to a decrease in the temperature of the adjacent coastal plains. Certainly, katabatic wind from the Hans Glacier located near HOR, have an obvious effect on the thermal conditions on the adjacent part of the coast.

During the polar summer, higher temperatures were recorded for all the points located in the non-glaciated environment near the Werenskiold Glacier (UWR, MDW, BRD, BRG) in comparison with the Polish Polar Station (HOR). Only in the second and third decade of September, the temperatures at HOR were higher. This resulted from a long-lasting advection of cool arctic air masses from N and NW. In these masses, the vertical thermal gradient is in consonant with the hypsometry. Additionally, such a direction of inflow creates a local orographic foehn originating on the mountain massifs located NW of the Polish Polar Station.

The occurrence of high temperatures at the forefront of Werenskiold Glacier (MDW) was rather surprising conclusion of this work. Significantly, high values were observed in July, when sunny weather prevailed, at a time of air inflow from the south. The temperature there was higher than at HOR, on average by 0.6°C. High temperatures were also recorded throughout the season in both lower and upper parts of the non-glaciated Brattegg Valley (BRD, BRG). The temperature in the lower part of the valley (BRD) was often as high as or higher than that in the neighbouring station on the frontal moraine (UWR).

The UWR was characterised by a significantly higher temperature than at HOR, on average by 0.8°C in the summer 2005. In July, the temperature difference was 0.9°C, in August 1.3°C and, in September 0.1°C. The mean daily temperatures for 75.1% of this period were higher at the UWR, the differences being mostly within 0–1°C. In respect of the daily temperatures, maximum differences reached 5.1°C (7 July) and for mean hourly temperatures, 8.5°C (7 July). During 24.9 % of this period, the mean daily temperature at HOR was higher than that at UWR, the difference never exceeded 1.6°C (17 July). For the mean hourly temperature, the difference was up to 3.9°C (23 July). A similar variation was displayed by maximum and

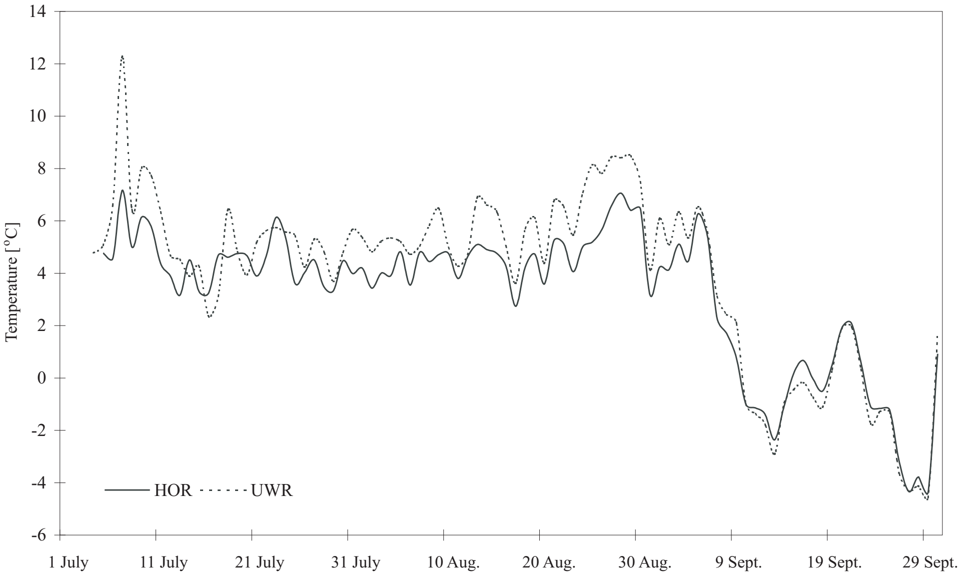

Fig.2. Plot of the mean daily air temperatures at the Polish Polar Station (HOR) and at the Baranowski Station (UWR) in the period of 6 July to 30 September 2005.

minimum temperatures. Higher maxima (70.8 % of the recorded days) and higher minima (71.9 % of cases) were observed at UWR, the differences being mostly within 1–2°C. The absolute maximum of air temperature in the ablation season 2005 occurred at UWR on 7 of July when the recorded value was 18.3°C, and 13.5°C at HOR. Absolute minima were -5.9°C at UWR (29 September) and -6.1°C at HOR (27 September). The greatest thermal differences in favour of the frontal moraine of the Werenskiold Glacier (UWR) were observed when a foehn developed during the easterly cyclonic circulation (the last five days of August) and during sunny and windless weather (the first part of July). During the inflow of arctic air masses from N and NW, higher temperatures were observed in Hornsund (HOR), in the second and third five-day periods of September and during short periods in July.

Variations in air temperature depending on atmospheric circulation

Topoclimatic variations have been characterised relating to atmospheric circulation classified by Niedźwiedź (1997, 2007) in respect of the Svalbard Archipelago (Table 3). In the ablation season 2005, cyclonic situations prevailed (75% of the entire period), which was 23% more than in the years 1951–1995 (Table 3). Their frequency was the highest in September (29 days), slightly lower in August (23 days) and in July (18 days). Anticyclonic situations occurred in 23.9% of cases, and thus their frequency was by nearly 20% lower than the multi-annual mean. They were the most numerous in July (13 days), less so in August (8 days) and, in September once only (7 September). On days classified as anticyclonic, the temperature at the Polish Polar Station (HOR) was 1°C lower on average than in the region of Werenskiold Glacier (UWR). During cyclonic days, the difference was smaller and amounted to 0.7°C. The circulation types Nc, NEc, Ec and NWc showed an increased frequency compared to the multi-annual period (Table 3). In the summer 2005, the types NEa, SEa, NWa, Ca and situations referred to as x, *i.e.* ambiguous and hard to assign to any type, were not apparent. The frequency of the remaining types of circulation remained at a level similar to the mean observed in 1951–1995.

The prevailing type of circulation in the ablation season 2005 was type Ec, which appeared on 13% of the time, *i.e.* over twice as often as in the years 1951–1995 (Table 3). Its frequency was the highest in the mid of August and, in the last decade of September. During this type of circulation, the temperature difference in favour of the UWR was 0.6°C on average.

The next most frequent type was type Nc, which occurred in 12% of the considered period, *i.e.* over twice as more frequently as in the multi-year period. This was most prevalent at the end of the first and in the second 10-day period of September, when the temperature at HOR was lower than that in the region of the Baranowski Station (UWR), by 0.4°C on average.

The NEc circulation type occurred on nearly 11% of the ablation season 2005 and, as in the case of the type Nc, was characterised by a frequency over twice as high as that observed in the 1951–1995 period and the same temperature difference relative to the region of the Werenskiold Glacier (0.4°C). This type prevailed in September.

In July and August, on days when the circulation types descended above were manifest, the temperature was usually lower in HOR than that in the region of the Werenskiold Glacier, whereas, in September, during the first frosts, the situation was reversed and higher temperatures were observed in HOR. This is probably related to the influence of the fjord waters, which warm the air at that time.

The NWc circulation type showed an 8.7% frequency. An uninterrupted period with this circulation type was observed in the period of 14–17 July and on single days in September. This is, however, the only more frequent synoptic situation, when a higher temperature was noted at HOR when compared to UWR, on average by 0.4°C. Similarly, when the Wa winds were circulating, the observed temperatures in HOR were higher by 0.7°C. However, there was only one such a day (20 July) and it would be unsound to generalise that with this type of circulation the difference is usually in favour of HOR. Smaller-than-usual, thermal differences between the places analysed also occurred during the circulation types Ea, Na, Nc and Cc.

The greatest temperature differences in favour of the region of the Werenskiold Glacier occurred during the circulation types Sa, Sc, SWc and SEc, *i.e.* those with a southerly component, which brought warm air masses from the Atlantic.

Table 3

Frequency of atmospheric circulation types above Spitsbergen in July, August and September (1951–1995) as well as during the ablation season 2005 and mean daily air temperature difference (T) between the Polish Polar Station (HOR) and the Baranowski Station (UWR) depending on circulation types (after Niedźwiedź 1997, 2007).

Circulation type	Frequency [%]		$T_{HOR-UWR}$ [°C]
	1951–1995	2005	
Na	2.9	2.2	-0.3
NEa	3.0	–	–
Ea	6.5	1.1	-0.1
SEa	4.5	–	–
Sa	2.5	3.3	-3.0
SWa	3.5	4.3	-1.0
Wa	2.9	3.3	0.7
NWa	2.2	–	–
Ca	1.7	–	–
Ka	13.2	9.8	-0.9
Nc	5.4	12.0	-0.4
NEc	4.9	10.9	-0.4
Ec	6.5	13.0	-0.6
SEc	5.9	7.6	-1.5
Sc	4.2	4.3	-1.7
SWc	5.6	3.3	-1.8
Wc	4.6	3.3	-1.0
NWc	3.8	8.7	0.4
Cc	4.2	6.5	-0.5
Bc	8.0	6.5	-1.1
x	3.9	–	–
total of:			
anticyclonic (a)	42.9	23.9	-1.0
cyclonic (c)	53.1	76.1	-0.7

Air temperatures related to atmospheric situation

NW advection. — Advection of air masses from N-NW takes place when a low-pressure centre is located northeast of Spitsbergen, or when a wedge of high pressure, or a high-pressure centre appears between Greenland and Spitsbergen. Such situations generate an inflow of humid, cool arctic-maritime air. During the summer 2005, they appeared rarely (*e.g.* 14–17 July). However, a higher frequency of N-NW advection occurred in the second and third 10-day periods of September. The recorded temperatures higher at HOR than those in the region of the Werenskiold Glacier were during these only synoptic situations. During this kind of advection, a local foehn occurs on the NW shore of Hornsund. The Polish Polar Station is sheltered from N and NW by non-glaciated mountain massifs, in which local dry-adiabatic process develop on the leeward slopes, resulting in an increased temperature and a slight decrease in humidity to 82% (87% mean for July).

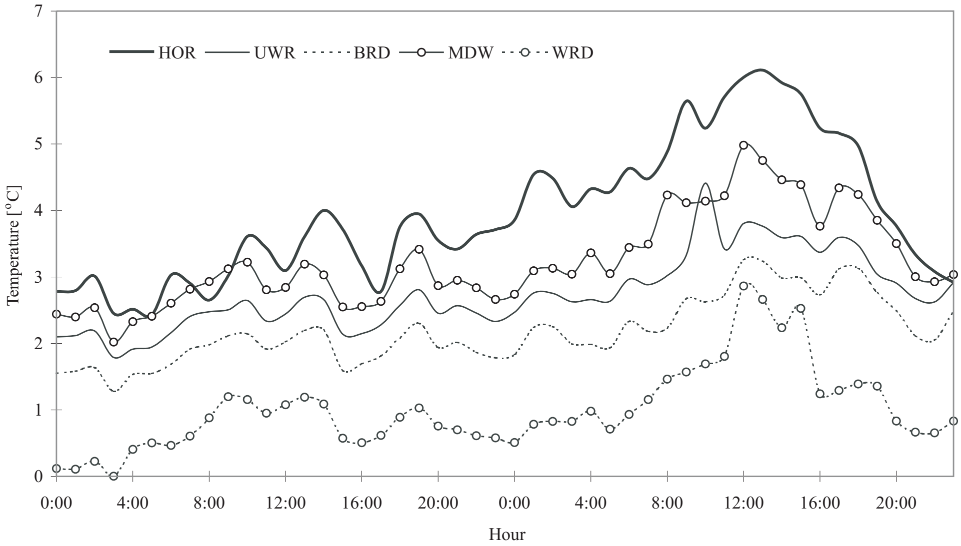

Fig.3. Plot of air temperature in the period of 16–17 July 2005 (Polish Polar Station – HOR, Baranowski Station – UWR, Brattegg Valley – BRD, glacier forefront – MDW, glacier – WRD).

The region of the Werenskiold Glacier is freely exposed to inflow of arctic air masses from NW. During this type of circulation, a distinctive temperature variation also occurs in the basin of the Werenskiold Glacier. The comparatively low rampart of the frontal moraine and the massifs of Tonefjellet and Jens Erikfjellet cause a partial orographic sheltering of the depressed forefront of the glacier, which results in a higher temperature at the station below the glacier front (MDW).

The temperature at the forefront (MDW) was *c*. 1°C on average, higher than that at the frontal moraine of the Werenskiold Glacier (UWR). Such a case is illustrated by the course of air temperature variation in the period of 16–17 July (Fig. 3). The inflow of cool arctic air resulted in a low-pressure centre, stationed NE of Spitsbergen. At that time, a rather strong wind was observed at HOR (up to 11m/s) from NW-NNW. The relative air humidity was also lower than usual (82.2%). The cloud cover was moderate to extensive. The daily mean temperature was higher at HOR than that on the frontal moraine of the Werenskiold Glacier (UWR) on these two days, by 0.9°C and 1.6°C respectively. In respect of hourly temperature variations, the maximum differences were up to 2.8°C. In addition, the station below the glacier front (MDW) was characterised by a temperature higher than that at the UWR by 0.5°C on average. The thermal differences at the other stations reflect an influence of altitude. The mean thermal gradient between UWR and BRD was 1°C/100 m.

Foehn days. — Foehn phenomena and associated effects are among the most characteristic weather phenomena in Spitsbergen. They have a significant effect on hydrological and glaciological processes (Pereyma *et al.* 1975; Pereyma and Piasecki 1988). The large scale foehn effects on the western coast of Spitsbergen occurs during the Ec or SEc circulation types (Table 3), when a low pressure centre is on the southern side of the island, and moves in the general direction from Iceland to Franz Josef Land. Air circulating in this way rises to a height of 700–800 m a.s.l. and moves from the E or SE above the mountainous glacial interior of Spitsbergen. On the western shore, it is largely devoid of humidity and is warmer. In some situations, such as anticyclone is located over Greenland Sea and air mass flow from W, foehn effects also develop on the eastern coast (Maciejowski and Michniewski 2007). Baranowski and Głowicki (1975) reported the situation on 20 July 1970 at the Baranowski Station (UWR), when a maximum temperature of 19.5°C was recorded, than the mean daily temperature in the Polish Polar Station (HOR) was 7.3°C, whereas on the forefront of the Werenskiold Glacier (MDW) it was 9.8°C.

A case of full foehn development included the region of Hornsund at the end of August 2005 (Fig. 4). Positive temperature changes were recorded at all the recording stations. The mean daily temperature at HOR on 28 August was 7.1°C, the second highest in the whole of 2005. The maximum temperature on 27 August at HOR was 9.7°C, which in turn, was the highest value of this month. In the region of the Werenskiold Glacier, a stronger development of foehn phenomena was observed than in the neighbouring Polish Polar Station (HOR), which contributed to a higher air temperature of 2–3°C on average. During foehn conditions, the region of the Baranowski Station was consistently warmer then the Polish Polar Station, by 2.1°C and maximally by 2.9°C, in respect of mean daily temperatures. In terms of the mean hourly temperature, the maximum difference, in favour of the Bara-

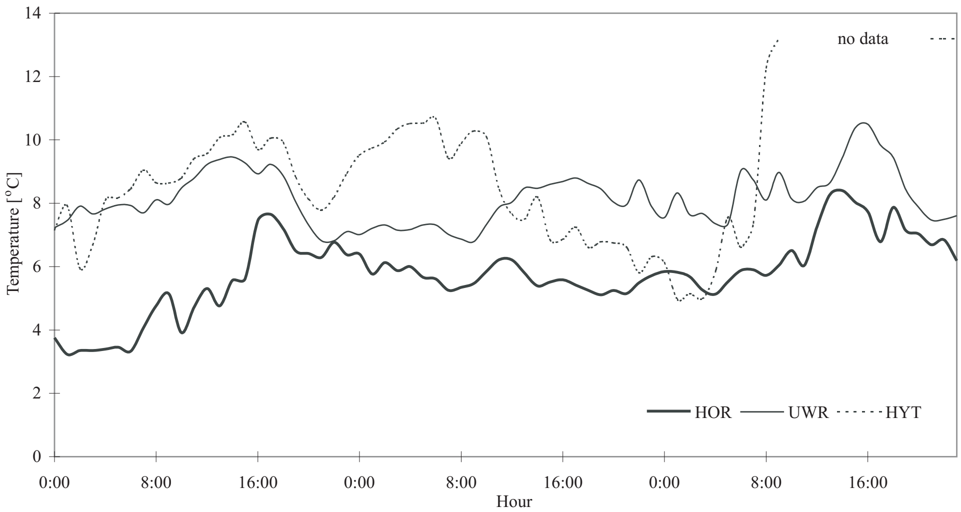

Fig. 4. Plot of air temperature in the period of 25–27 August 2005 (Polish Polar Station – HOR, Baranowski Station – UWR, Hyttevika – HYT).

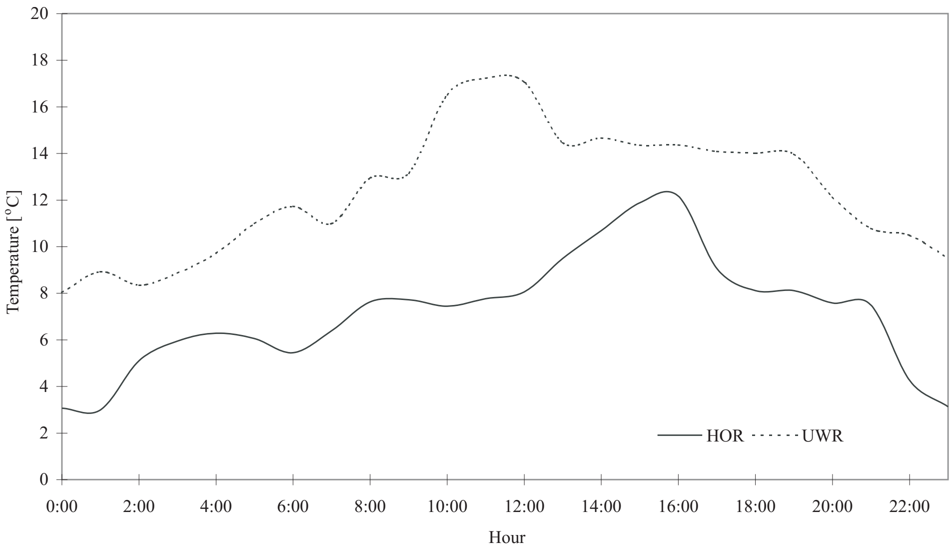

Fig. 5. Plot of air temperature on 7 July 2005 (Polish Polar Station – HOR, Baranowski Station – UWR).

nowski Station, was 4.6°C. The warmest place was Hyttevika (HYT), *i.e*. a coastal location, which is beyond the influence of the fjord. The HYT point is located on the leeward side of the Gullichsenfjellet Massif and the foehn effects are the most pronounced here. The maximum temperature difference compared to HOR was 7.1°C. It should be noted that HOR and HYT are separated by a distance of only 12 km, experience quite different weather conditions. The air flowing in from the poorly glaciated Angellfjellet Massif and from Brattegga mountain ridge favourably warms up the stations located along the axis of the Brattegg Valley during foehn weather. At that time, the UWR, BRD and BRG are warmer; whereas, the MDW and WRD remain under the cooling effect of the Werenskiold Glacier. During this kind of airflow, HOR experiences foehn winds, which originate in the Sofiekammen Massif, and then cool over the Hans Glacier.

Sunny days. — More sunny days were noted in July 2005 than in any other month. The maximum of sunshine duration at HOR was recorded on 7 and 23 July. In both cases, it was 19.1 hours, which is 80% of potential daily sunshine duration. These were the warmest days in the whole of 2005 at the studied area. On 7 July, the temperature reached 13.5°C, and 11.2°C on 23 July. On 7 July, the high-pressure centre laid SE of Spitsbergen, on the border of the Scandinavian Peninsula and the Barents Sea. It generated an inflow of warm and dry air from the Eurasian continent. At the Polish Polar Station, a weak wind (1–4 m/s) prevailed, from ESE, and most of the day was cloudless. The maximum temperature was recorded at the Baranowski Station at 11:10 (18.3°C). The next maximum was recorded on the Werenskiold Glacier at 12:20 (9.5°C). The daily maximum temperature at HOR reached 13.5°C at 15:50 and relative humidity dropped to only 39%.

Conclusions

The region of Hornsund is characterised by a very large topoclimatic variation, which results most by orography. Unquestionably, anemo-orographic systems cause local deformities of airflow and foehn effects.

The local thermal differences are largely caused by the effect of two strongly contrasting environments on the near ground air layer: non-glaciated and glaciated, between which they are the most striking. In addition, the thermal conditions are affected by the distance from the sea, altitude, exposure, and melting processes.

As well as local factors (topography, substratum, sea proximity), the intensified atmospheric circulation has a great effect on the climate of SW Spitsbergen. It causes an inflow of air of variable physical characteristics (temperature, humidity) from various directions, which contributes to the prominent variation in local conditions.

The west coast and foreland of the Werenskiold Glacier represented by the Baranowski Station is characterised by the most favourable thermal conditions; the air temperature there being largely determined by foehn processes.

In average conditions of the polar summer, the temperature at the Baranowski Station is 0.8°C higher than that at the Polish Polar Station in Hornsund. The higher temperature on the frontal moraine of the Werenskiold Glacier is almost irrespective of the direction of advection. A synoptic situation when the temperature at Polish Polar Station is higher than in the region of the Werenskiold Glacier attribute to the influence of the NW cyclonic circulation type, which permits an inflow of cool arctic masses. These masses have free access to the region of the Baranowski Station, which is fully exposed to this direction of advection; by contrast, the poorly glaciated mountain massifs shelter at the Polish Polar Station and foehn processes develop there. With respect to the other circulation types, a converse situation applies: higher temperatures occur in the region of the Baranowski Station. These temperatures are at a maximum during advections from southerly directions.

In the non-glaciated environment (Brattegg Valley), the temperature depends mainly on hypsometrical variations and, to a lesser extent, on the substratum. Thermal inversions rarely appeared in the profile up to *c*. 150 m a.s.l. They were short-lasting and occurred mainly during the phases of free atmosphere foehn, during sunny weather.

It should be noted that the mean vertical temperature gradient between lower and the upper part of the unglaciated valley (the BRD and BRG points) was lower by 0.05°C, when compared with the that of the glacier forefront (MDW) and the glacier (WRD), 0.87°C/100 m.

The gradient, based on the daily maximum temperatures recorded in the unglaciated valley reached 1.20°C/100 m and was higher by 0.33°C than on the glacier. The mean vertical gradient of daily minimum temperatures between the

BRD and BRG stations was 0.73°C/100 m and was lower by 0.09°C, when compared with that between the forefront (MDW) and the glacier (WRD).

During intermediate weather, when ground frost-thaw takes place, the mean temperature difference in favour of the Polish Polar Station is 0.5°C; whereas, during moderately frosty weather 0.2°C. The differences result from warming effect of the fjord waters during easterly airflow along the axis of the fjord. The same effect exists during polar night and winter, when the fjord is unfrozen. During moderately warm weather, more favourable climatic conditions occur near the Baranowski Station, with a mean temperature difference of 0.9°C, and the greatest temperature difference is observed during warm weather and is 1.5 °C on average.

Acknowledgements. — Field investigations were financed by the Polish Committee for Scientific Research (PBZ-KBN-108/P04/2004 *Structure, evolution and dynamics of lithosphere, cryosphere and biosphere in the European Arctic and Antarctic*). The members of the 27th and the 28th Polar Expedition of the Polish Academy of Sciences, leaded by Andrzej Kozik and Marek Grotta, supported logistic and field assistance fruitfully.

References

BARANOWSKI S. 1977. The subpolar glaciers of Spitsbergen seen against the climate of his region. *Acta Universitatis Wratislaviensis* 410: 1–157.

BARANOWSKI S. and GŁOWICKI B. 1975a. Meteorological and hydrological investigations in the Hornsund region made in 1970. *Acta Universitatis Wratislaviensis* 251: 35–39.

BARANOWSKI S. and GŁOWICKI B. 1975b. Przebieg wybranych elementów meteorologicznych w ciągu lata 1971 r. na Spitsbergenie. *Acta Universitatis Wratislaviensis* 287: 95–99.

GŁOWICKI B. and BARANOWSKI S. 1974. Glacjo-meteorologiczne badania w czasie wypraw 1970 i 1971 r. *Polskie Wyprawy na Spitsbergen 1970 i 1971 r. Materiały z Sympozjum spitsbergeńskiego, Wrocław 6–7 kwietnia 1972*. Wydawnictwo Uniwersytetu Wrocławskiego: 17–21.

JANIA J. and HAGEN J.O. (eds) 1996. Mass balance of Arctic glaciers. *IASC Report* 5: 1–62.

MARSZ A.A. and STYSZYŃSKA A. (eds) 2007. *Klimat rejonu Polskiej Stacji Polarnej w Hornsundzie – stan, zmiany i ich przyczyny*. Wydawnictwo Akademii Morskiej w Gdyni: 376 pp.

MACIEJOWSKI W. and MICHNIEWSKI A. 2007. Variations in weather on the East and West coasts of South Spitsbergen, Svalbard. *Polish Polar Research* 28 (2): 123–136.

MIGAŁA K., BUCHERT L. and PEREYMA J. 2004. Termika powietrza w rejonie fiordu Hornsund (SW Spitsbergen) w warunkach nocy polarnej. *XXX Międzynarodowe Sympozjum Polarne, Gdynia 23–25 września 2004, Streszczenia wystąpień*. Wydawnictwo Akademii Morskiej w Gdyni: 118–119.

NIEDŹWIEDŹ T. 1997. Częstość występowania typów cyrkulacji nad Spitsbergenem (1951–1995). *Problemy Klimatologii Polarnej* 11: 19–40.

NIEDŹWIEDŹ T. 2007. Warunki cyrkulacyjne na Spitsbergenie w latach 2005–2006. *In*: R. Przybylak, M. Kejna, A. Araźny and P. Głowacki (eds) *Abiotyczne środowisko Spitsbergenu w latach 2005–2006 w warunkach globalnego ocieplenia*. Wydawnictwo Uniwersytetu Mikołaja Kopernika: 17–32.

PEREYMA J. 1983. Climatological problems of the Hornsund area. *Acta Universitatis Wratislaviensis* 714: 1–131.

PEREYMA J. 1988. Climatology. *In*: R. Brazdil (ed.) Results of Investigations of the Geographical Research Expedition Spitsbergen 1985. *Folia Facultatis Scientiarum Naturalium Universitatis Purkynianae Brunensis* 24: 54–68.

PEREYMA J., BARANOWSKI S. and PIASECKI J. 1975. Warunki meteorologiczne i hydrologiczne lodowca Werenskiolda i jego przedpola w sezonach letnich 1972 i 1973 r. *Polskie Wyprawy na Spitsbergen 1972 i 1973 r. Materiały z Sympozjum Spitsbergeńskiego, Wrocław, 29–30 marca 1974*. Wydawnictwo Uniwersytetu Wrocławskiego: 35–39.

PEREYMA J. and PIASECKI J. 1988. Warunki topoklimatyczne i hydrologiczne w rejonie lodowca Werenskiolda na Spitsbergenie w sezonie letnio-jesiennym 1983 roku. *In*: Wyprawy Polarne Uniwersytetu Śląskiego 1980–1984. *Prace Naukowe Uniwersytetu Śląskiego* 910: 107–122.

PRZYBYLAK R. 2007. Recent air temperature changes in the Arctic. *Annals of Glaciology* 46: 316–324.

RICHTER-MENGE J., OVERLAND J., PROSHUTINSKY A., ROMANOVSKY V., BENGTSSON L., BRIGHAM L., DYURGEROV M., GASCARD J.C, GERLAND S., GRAVERSEN R., HAAS C., KARCHER M., KUHRY P., MASLANIK J., MELLING H., MASLOWSKI W., MORISON J., PEROVICH D., PRZYBYLAK R., RACHOLD V., RIGOR I., SHIKLOMANOV A., STROEVE J., WALKER D., and WALSH J. 2006. State of the Arctic Report. *NOAA OAR Special Report*. NOAA/OAR/PMEL, Seattle, WA: 36 pp.

WALCZOWSKI W. and PIECHURA J. 2006. New evidence of warming toward the Arctic Ocean, *Geophysical Research Letters* 33, L12601: 1–5.

Received 6 June 2007
Accepted 4 February 2008