Spitsbergen landscape transformations under the current global warming: case studies

Wieslaw Ziaja

Jagiellonian University, Institute of Geography and Spatial Management, Cracow, Poland

Abstract: The principal aim of this paper is to outline Spitsbergen landscape transformations under glacial recession driven by climate warming after the Little Ice Age, i.e. during the 20th and 21st century. Several very different areas were investigated in Sørkapp Land (the south Spisbergen peninsula, including both the eastern and western coasts) and Nordenskiold Land (central west Spitsbergen). Physical-geographical (landscape) mapping at a 1:25000 scale was the basic method of field investigations, complemented by the interpretation of air photos and analysis of satellite data.

The landscape transformation has recently been intensified by a positive feedback in the process (ongoing since the beginning of the 20th century) and a significant current warming (since the 1980s). The timing of this transformation has varied from west to east: the biggest alterations in the eastern coast occurred from the 1980s to the present, whereas in the western coast the rate of the landscape change was more consistent during the past century. In areas abandoned by Spitsbergen glaciers: (1) there is less dead ice in the east than in the west of the island, (2) solifluction plays a significantly weaker role in the east than elsewhere apart from nunataks, and (3) plant succession is also much slower in the east.

Key words: landscape transformation, global climate warming, Spitsbergen, Svalbard.

1. Introduction

The final cold phase of the Little Ice Age was achieved in Spitsbergen (the biggest island of the Svalbard archipelago) in the 1890s. A warm period began at the beginning of the 20th century. This period continues to the present day regardless of secondary cool phases during the 1940s and 1960s (e.g., Brazdil 1988, Forland and others 1997, Ziaja 2004a, Styszynska 2005).

Glaciers have reacted to the climate warming the most quickly (e.g., Jania 1988, Ziaja 2001). The summer season has lengthened due to the warming. This lengthening resulted in rising altitudes of the snow line and the equilibrium (of the mass balance) line of the glaciers. That is why the accumulative zones of the glaciers became smaller, thus delivering less ice to their ablation zones. As a result, areas abandoned by the glaciers have appeared, both in their lower marginal zones and on the edges of their upper parts, including the firn fields.

Differentiation of landscape transformation under the recession of glaciers depended on the degree and type of glaciation (which was determined earlier by climate and landforms). A landscape transformed by deglaciation on the eastern Spitsbergen coast is different from such a landscape on the south, north and west of the island, where significant areas were free of ice during the Little Ice Age. But the landscape of areas abandoned by small glaciers in the mountains of central west Spitsberegen, differs significantly from the abovementioned areas. Whether a glacier's bedrock is above or below sea level is crucial for a new post-glacial-recession landscape. The Spitsbergen areas investigated by the author during eleven summer expeditions in the period 1982-2006 are markedly varied on that score (Ziaja 1999, 2004a, 2004b, 2004c, 2005, Ziaja and others 2007, Ziaja and Ostafin 2007, Ziaja and Pipala 2007). By analyzing these areas it is possible to illustrate the principal ways in which glacial recession has been changing the Spitsbergn landscape, which is the aim of this paper.

Of course, the areas free of glaciers during the Little Ice Age were also transformed under the influence of the climate warming but later, by several dozen years.

2. Material and method

Physical-geographical field mapping at a 1:25000 scale was the basic method of distinguishing and characterizing almost 2500 small landscape units (geocomplexes). All the environmental components of each unit were described according to a special formula. Additional supporting methods were the interpretation of aerial photos of Norsk Polarinstitutt from the period 1936-1990, and analysis of satellite data (Landsat MSS, Terra ASTER) from the period 1985-2005.

3. Results and evaluation

3.1. Eastern Sorkapp Land

The landscape of the eastern coast of Sorkapp Land (the southern peninsula of Spitsbergen, *Figure 1*) is a typical representative for the entire eastern Spitsbergen coast. The cold East Spitsbergen sea current flows

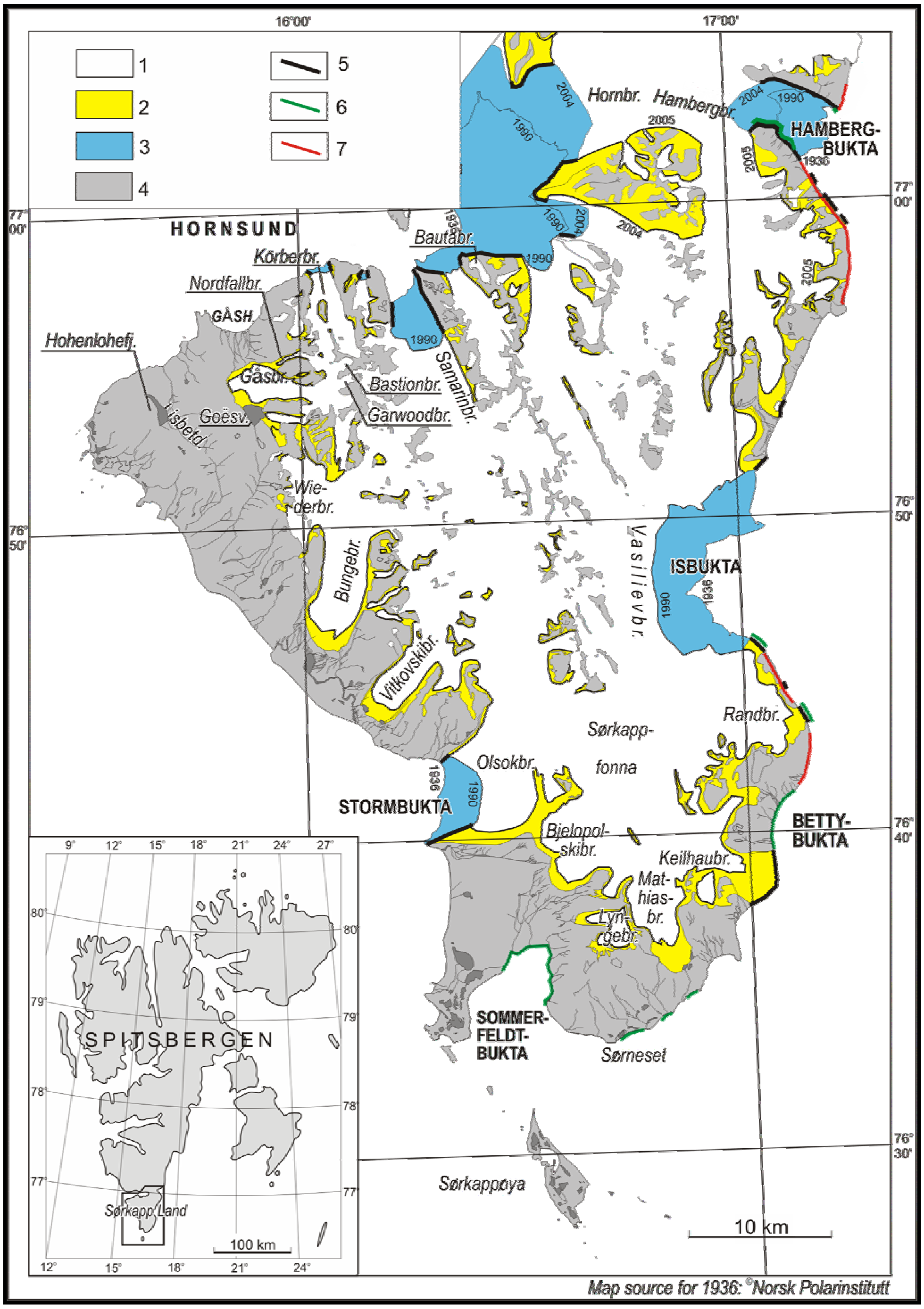

Figure 1. Map of Sorkapp Land, showing the extent of glaciation in 1990-1991 (1), land areas abandoned by glaciers after 1936 (2), deglaciated areas transgressed by the sea after 1936 (3), areas unglaciated in both 1936 and afterwards (4), new, nonglacial coast formed after 1936 (5), coastline undergoing intensive accumulation (6), and coastline undergoing intensive abrasion (7).

along this coast to the south, influencing climatic and glacial conditions there. The glaciers which now predominate on the land were much thicker and extensive during the Little Ice Age. Narrow sequences of unglaciated valleys and mountain slopes were much shorter during the Little Ice Age than today because many more glaciers had reached to the sea then. The biggest glaciers' tongues were fan-shaped, like Keilhaubreen in 1936, or lobe-shaped, like Hambergbreen in 1900 (Lefauconnier and Hagen 1991). A progressive recession of glaciers (Palli and others 2003) in the 20th and 21st centuries influenced the landscape of the eastern Spitsbergen mainly along the shoreline (*Figure 2*), first of all by delivering the following areas from glacial ice: (1) areas situated below the sea level, which had once been covered by the lowest parts of tide-water glaciers, (2) narrow coastal lowlands and coastal sea shallows, some of which began to transform into new coastal plains, and (3) valleys between the coastal mountains which had once been filled by glaciers and now are glaciated only in the upper parts.

Figure 2. New eastern Sorkapp Land coast in 2005, after abandonment by the Hambergbreen glacier and its tributary glaciers from the right side. Photo looking southeast.

Newly submerged areas that originated in the 20th and 21st centuries either have the impressive forms of fjords (like Hambergbukta) or buys, which are deeply incised in the land (like Isbukta and Stormbukta), or belong to a commonplace category of shallow coastal zone on the Barents Sea.

The coasts of the new fjords and buys show their relief just after deliverence from glaciers. Some of them are flat or slightly inclined, and others form more inclined slopes. The flatter ones prevail in the eastern Sørkapp Land coast, undergoing a further transformation into coastal plains. Succeessive storm ridges adhere to them on the shallows where marine accumulation prevails, e.g., on the new Hambergbukta fjord, formed in the 1990s, and on the Bettybukta buy. Some coastal plains have been worn down by marine abrasion in other places (Ziaja 2004a, Ziaja and others 2007).

The Hambergbreen lobe had functioned as a huge wave-breaker protecting the coast situated south of the glacier in the late 19th century and the early 20th century (Vasiliev and others 1907 *vide* Lefauconnier and Hagen 1991). A decline of this lobe eventually eliminated the coastal plain that contained the lake Davislaguna. The sea transgressed there due to the movement of the gravel bar between the lake and the sea (by c. 400 m from 1936 to 2005) to the foot of the coastal mountains' steep slopes.

Stable sequences occupy less than half of the eastern Sorkapp Land coastline.

Landscape changes are minimal at a distance further than 1 km from the sea, in spite of a clear decrease in the glaciers' thickness, e.g., by 50 m in the lower part of the Sykorabreen glacier from 1936 to 2005. This decrease can easily be observed at the edges of the valley glaciers that extend to lower altitudes than they once did, and on the slopes of enlarged nunataks.

Most of moraine material (which remained after a retreat or decline of the glaciers on the eastern coast) does not cover dead ice (do not have ice cores) due to a slight thickness (generally less than 1 m) and discontinuity. A large lateral ice-cored moraine of the Hambergbreen glacier (being a trace of the glacier's extent at the beginning of the 20th century) undergoes a quick degradation from both the land side and the sea side.

There is a lack of typical solifluction microforms in extensive areas on the slopes, valley bottoms and coastal plains of the eastern Sorkapp Land coast. Classical solifluction (congelifluction) is rare there due to the common presence of the other processes (gravitational falling and creeping, sheet wash, fluvial processes), steep slopes, lack of a continuous vegetation, a great permeability and slight thickness of the discontinuous Quaternary deposits.

It is possible to observe a plant succession both in the areas abandoned by glaciers and in the areas which were not glaciated but were devoid of plants because of more severe climatic conditions in the past. However, the plants are very sparse and low, growing in small patches or clumps. There are only a few sites with continuous or dense vegetation in the eastern Sorkapp Land coast, e.g., the Daudbjornpynten promontory with a patch 0,06 ha in the north (Ziaja 2004a, Ziaja and others 2007).

3.2. Western Sorkapp Land

The landscape of the western coast of Sorkapp Land is very typical for the entire southwestern Spitsbergen coast. This coast has been significantly less glaciated than the eastern coast both during the Little Ice Age and at present. However, the western Sorkapp Land coast is much more glaciated than the Nordenskiold Land in central-west Spitsbergen. The warm West Spitsbergen sea current which flows from the south influences climatic conditions there. Hence, the terraced coastal plains of the western Sorkapp Land (wide up to 5 km) were predominantly covered by a low tundra, even during the Little Ice Age.

The northwestern part of Sorkapp Land (containing the Struvefjella and Wurmbrandegga-Gavrilovjellet mountain ridges with the Lisbetdalen valley between them, apart from coastal plains) is completely devoid of glaciers. The lone small glacier from the Little Ice Age disappeared from the eastern slopes of Garvrilovfjellet before 1982. The peninsula's interior, with numerous glaciers, begins further to the east. The recession of these glaciers has been intensified since the beginning of the 20th century. The largest of them, Gasbreen, has been surveyed since 1899 (De Geer 1923). The front of the Gasbreen leaned against the Wurmbrandegga-Gavrilovjellet mountain ridge, creating a dam for the lake Goesvatnet. The dam decreased in height due to a decrease of the glacier's thickness during the 20th century. This lake disappeared after a significant shortening of the glacier at the beginning of the 21st century (*Figure 3*, Ziaja and Ostafin 2007). At a short distance to the south, a few small glaciers have been transformed into rock glaciers on the eastern slopes of the Slaklidalen valley during the 20th century.

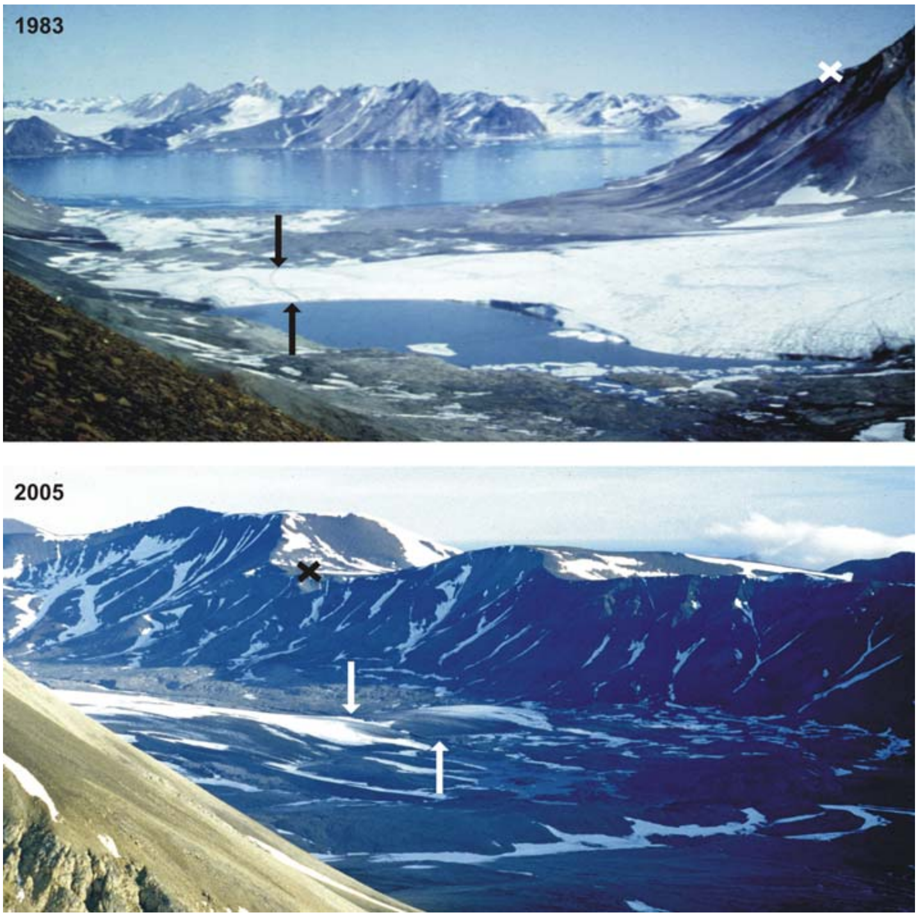

Figure 3. The lower part and marginal zone of Gasbreen glacier in 1983 (the upper photo) and 2005 (the lower photo). The inlet and outlet of the subglacial tunnel (1983) and narrow river valley between the glacier's front and dead ice patch (2005) are shown by arrows. The sites where the photographs were taken are indicated with crosses.

South of Struvefjella, the mountain slopes facing the Greenland See are unglaciated (the lone small glacier disappeared from the western slopes of Wiederfjellet before 1982) whereas from the land side the mountain slopes are partly covered by glaciers. These glaciers – and also the big glaciers which flow along wide valleys to coastal plains, Bungebreen and Vitkovskibreen – have significantly regressed (thinned and retreated) since the Little Ice Age. A retreat of the front of Olsokbreen (the only tide-water glacier in the western Sorkapp Land) lengthened the Stormbukta buy in an inland direction. New marginal zones have been formed as a result of the glacial recession south of Stormbukta, a large marginal zone at the front of Bjelopolskibreen and a few smaller ones (Ziaja 1999, 2002, 2004a).

The marginal zones surrounding the lower parts of the western Sorkapp Land glaciers are built of dead ice covered by continuous layer of moraine material, mostly 1 m thick. These zones are undergoing permanent widening due to glacial recession. Their transformation is driven by the ablation of dead ice (which remained unfinished everywhere) and the influence of proglacial rivers (e.g., the area of ice-cored moraines decreases and the area of intramarginal sandurs increases).

The steep slopes have been abandoned by glaciers due to a decrease of ice thickness in their upper parts, including firn fields. These slopes are not covered by moraine material and undergo weathering and gravitational processes. The surface of some glaciers located at the foot of the high rock walls, e.g., Gasbreen (Ziaja and Ostafin 2007) and Nigerbreen, lowered so much that they are now below the snow line. However, the glaciers do not decline because they are supplied by snow avalanches.

Plant succession in areas abandoned by glaciers, and unglaciated areas, is intensified by the proximity of the comparatively dense tundra in the coastal plains and the mountainous valleys of the northeast.

Solifluction is a very common process, that results from high humidity and the varied granulation of the continuous Quaternary deposits.

3.3. Northern Sorkapp Land

This mountainous part of the peninsula is very glaciated due its northern exposure and high altitudes (*Figure 4*). The mountains plunge into the Hornsund fjord and, in the east, to the isthmus between Sorkapp Land and Torell Land. There are numerous steep rock walls in the Hornsundtind mountain group, which are free of ice during the summer season. New buys have originated at the fronts of the large tide-water glaciers flowing to Hornsund on the northern Sorkapp Land coast. These buys are lengthening to the south (Jania 1988, Ziaja 1999, 2004a). The longest of them, Samarinvogen, became a fjord with very steep, high slopes. The isthmus is completely glaciated and has undergone narrowing (from more than 30 to c. 7 km) and lowering (from above 300 to 180 m a.s.l. in the pass from Hornsund to Hambergbukta) since the beginning of the 20th century due to the recession of tributary glaciers (Palli and others 2003, Ziaja, Ostafin, 2005, Ziaja and others 2007). The glaciers which flow to the isthmus from the northern slopes of the Ostrogradskifjella mountain group underwent a particularly heavy recession.

Figure 4. The upper part of the Korberbreen glacier at the food of Hornsundtind (1431 m a.s.l.). Photo looking south, taken in 2005.

3.4. Southernmost Sorkapp Land

The southernmost point of Sorkapp Land is the end of a huge Spitsbergen land wedge between the Barents and Greenland seas and because of that, takes up a relatively small area (30-40 km^2). Mathiasbreen is the only large glacier which flows from the Sorkappfonna glacial plateau to a local coastal plain. This glaciers recedes in the same way that the glaciers of the western Sorkapp Land do. A few small glaciers in small valleys on the Kistefjellet mountain's slopes declined during the 20th century. The southernmost end of Sorkapp Land is covered by a relatively mall number of species of tundra vegetation, more or less continuous (*Figure 5*) up to the local culmination of Kistefjellet (676 m a.s.l.), due to optimum exposures and lack of shadowing. The plant succession to areas abandoned by the glaciers is much easier thanks to this presence of continuous tundra and growing conditions.

Figure 5. Part of the southernmost Sorkapp Land: the terraced coastal plain Sorflya (up to 20 m a.s.l.), with the raised marine cliffs and the mountain slopes of Kistefjellet in the background. Photo looking north.

3.5. Nordenskiold Land mountains

Nordenskiold Land – the peninsula between Isfjorden and Van Mijenfjorden – is the centralmost and warmest part of Spitsbergen. It was predominantly free of glaciers even during the Little Ice Age. Firn fields of local glaciers are usually situated in the highest parts (c. 1000 m a.s.l.) of the characteristic table mountains and the glaciers usually do not reach down to the main valleys. Their quick recession (Sorbel and others 2001), which is intensifying over the course of time, was driven by the climate warming after the Little Ice Age.

The study area – the Lindstromfjellet-Habergnuten mountain ridge – is located in the proximity of Isfjorden (*Figure 6*, Ziaja 2004c), whose glaciation is particularly slight (less than 10% of the land surface in the present). Even during the Little Ice Age, glaciers there covered only the northern slopes and deep valleys. Investigations of the extents of the glaciers and landscape structure of the deglaciated areas in 1936, 1995, 2001, 2006 – proved that more than 50% of the area covered by the glaciers in 1936 was released from them during the next 70 years (the Norwegian topographic map 1:100000 actual for 1936, Ziaja 2001, 2002, 2004b, 2004c, 2005, Ziaja and Pipala 2007). The recession of the upper and/or more steep parts of the glaciers exposed the rocky slopes without any moraine cover. The recession of the lower parts of the glaciers' tongues (decrease of their thickness, narrowing, frontal retreat) results in widening marginal zones built of dead ice covered by a continuous moraine layer (*Figure 7*). This ice is undergoing more and more intensive ablation, which is causing the high dynamics in the valley landscape. High humidity, varied granulation of the Quaternary deposits, and quick plant succession on them are conducive to sulifluction (also on ice-cored moraines).

Glaciers which were situated below the equilibrium line altitude (following a rise of this line due to the warming) undergo an intensive summer ablation which leads to their quick decline, e.g., the Habergbreen glacier (Ziaja 2005, *Figure 7*). Glaciers which have at least a small part above this line persist, but change their type from valley glaciers into cirque or slope glaciers.

The regularities described above were evidenced by other authors (Sorbel and others 2001, Lonne and Lysa 2005) in other parts of the Nordenskiold Land. However, some glaciers on this land – outside of the author's study area – are covered by debris which is thawing from them or falling from the slopes above (Humlum 2007).

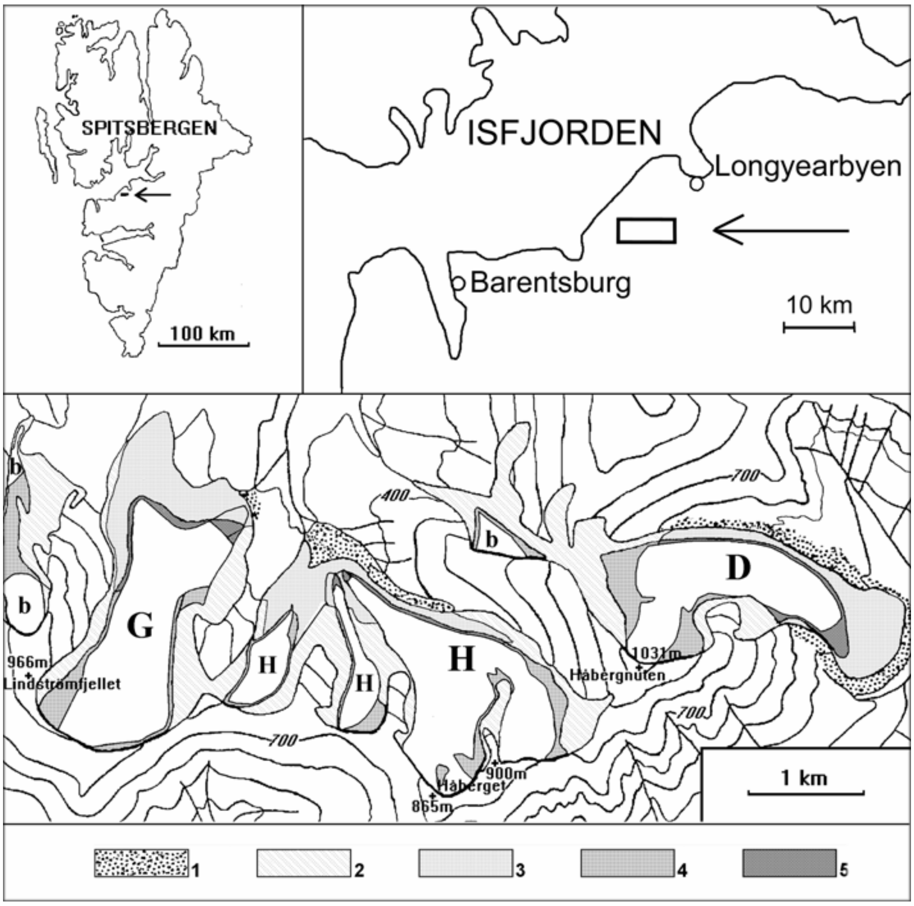

Figure 6. Lindstromfjellet-Habergnuten mountain ridge – location, topography and glacial recession: 1 – ice-cored moraines formed before 1936, 2 – slopes abandoned by glaciers between 1936 and 1995, without moraine cover, 3 – ice-cored marginal zones formed between 1936 and 1995, 4 – slopes abandoned by glaciers between 1995 and 2001, without moraine cover, and 5 – extensions of the marginal zones from 1995 to 2001. White color – the glaciers in 2001: Dryadbreen (D), Grumantbreen (G), and Habergbreen (H).

Figure 7. Central part of the northern slope of the Lindstromfjellet-Habergnuten mountain ridge with the highest top of Habergnuten in 2006. Photo looking east shows fragmentation of the former Habergbreen glacier and formation of the extensive marginal zone which consists mainly of ice-cored moraines, a result of glacial recession since the Little Ice Age.

4. Conclusions

The Spitsbergen landscape transformation has recently been intensified by a positive feedback in the process (continuous since the beginning of the 20th century) and a significant current warming (since the 1980s), evidenced among others by Styszynska (2005).

The timing of this transformation has varied from west to east: the greatest changes on the eastern coast occurred from 1980s to the present, whereas on the western coast, the rate of the landscape alteration was more consistent during the past century.

In areas abandoned by Spitsbergen glaciers: (1) there is less dead ice in the east than in the west of the island, (2) solifluction plays a significantly weaker role in the east than elsewhere apart from nunataks, and (3) plant succession is also much slower in the east.

Acknowledgements: Thanks to Elizabeth M. Giles for her native translation revision.

References

Brazdil, R. (1988) Variation of air temperature and atmospheric precipitation in the region of Svalbard, *Folia Facultatis Scientiarum Naturalium Universistatis Purkynianae Brunensis. Geographia*, 24, pp. 285-323.

De Geer, G., (1923) Pl. F. Environs de la Station Russe D'Hivernage. 1:50000 (map), in *Mesure D'un Arc de Meridien au Spitzberg, Entr. en 1899-1902, Mission Suedoise, Description Topographique de la Region Exploree, Geologie*, Aktiebolaget Centraltryckeriet, Stockholm.

Humlum, O. (2007) Comment on Lonne and Lysa (2005), *Geomorphology*, 84, pp. 145-149.

Forland, E.J., Hanssen-Bauer, I. and Nordli, P.R. (1997) Climate statistics and longterm series of temperature and precipitation at Svalbard and Jan Mayen, *DNMI – Rapport*, 21.

Jania, J. (1988) Dynamiczne procesy glacjalne na poludniowym Spitsbergenie w swietle badan fotointerpretacyjnych i fotogrametrycznych, *Prace Naukowe Uniwersytetu Slaskiego w Katowicach*, 955.

Lefauconnier, B. and Hagen, J.O. (1991) *S*urging and calving glaciers in eastern Svalbard, *Norsk Polarinstitutt Meddelelser*, 116.

Lonne, I. and Lysa, A. (2005) Deglaciation dynamics following the Little Ice Age on Svalbard: Implications for shaping of landscapes at high latitudes, *Geomorphology*, 72, pp. 300-319.

Palli, A., Moore, J.C., Jania, J. and Głowacki P. (2003) Glacier changes in southern Spitsbergen, Svalbard 1901–2000, *Annals of Glaciology*, 37, pp. 219-225.

Styszyńska, A. (2005) *Przyczyny i mechanizmy wspolczesnego (1982-2002) ocieplenia atlantyckiej Arktyki*, Akademia Morska w Gdyni.

Sorbel, L., Tolgensbakk, J., Hagen, J.O. and Hogvard K. (2001) Geomorphological and Quaternary Geological Map of Svalbard, 1:100,000. Sheet C9G Adventdalen, *Norsk Polarinstitutt Temakart*, 31/32, pp. 57-78.

Ziaja, W. (1999) Rozwój geosystemu Sorkapplandu, Svalbard, *Rozprawy Habilitacyjne UJ*, 343, Wydawnictwo UJ, Krakow.

Ziaja, W. (2001) Glacial Recession in Sørkappland and Central Nordenskioldland, Spitsbergen, Svalbard, during the 20th century, *Arctic, Antarctic, and Alpine Research*, 33(1), pp. 36-41.

Ziaja, W. (2002) Changes of the landscape structure of Sorkappland, in Ziaja, W. and Skiba, S. (eds.), *Sorkappland landscape structure and functioning (Spitsbergen, Svalbard)*, Wydawnictwo UJ, Krakow, pp. 18-50.

Ziaja, W. (2004a) Spitsbergen Landscape under 20th Century Climate Change: Sorkapp Land, *Ambio*, 33(6), pp. 295-299.

Ziaja, W. (2004b) Mountain landscape structure and dynamics under the 20th century climate warming in central Nordenskioldland, Spitsbergen, *Ekologia*, 23 (Suppl. 1), pp. 374-383.

Ziaja, W. (2004c) Zroznicowanie krajobrazowe obszarow uwolnionych spod lodowcow po Malej Epoce Lodowej w pasmie gorskim Lindstromfjellet-Habergnuten (Nordenskioldland, Spitsbergen), *Polish Polar Studies*, pp. 439-447.

Ziaja, W. (2005) Response of the Nordenskiold Land (Spitsbergen) glaciers Grumantbreen, Habergbreen and Dryadbreen to the climate warming after the Little Ice Age, *Annals of Glaciology*, 42, pp. 189-194.

Ziaja, W., Maciejowski, W. and Ostafin, K. (2007) *Northeastern Sorkappland landscape dynamics (Spitsbergen, Svalbard)*, Wydawnictwo UJ, Krakow.

Ziaja W. and Ostafin K. (2005) Dynamika krajobrazu przesmyku ladowego miedzy Sorkapplandem a reszta Spitsbergenu, *Polish Polar Studies*, pp. 218-225.

Ziaja, W. and Ostafin, K. (2007) Wspolczesna przemiana krajobrazu Lodowca Gas i okolicy, in Przybylak, R., Kejna, M., Arazny, A. and Glowacki, P. (eds.), *Abiotyczne środowisko Spitsbergenu w latach 2005-2006 w warunkach globalnego ocieplenia*, Uniwersytet M. Kopernika, Instytut Geofizyki PAN, Torun, pp. 235-245.

Ziaja, W. and Pipala, R., 2007, Glacial recession 2001-2006 and its landscape effects in the Lindstromfjellet-Habergnuten mountain ridge, Nordenskiold Land, Spitsbergen, *Polish Polar Research*, 28(4), s. 237-247.