Climate change effects on high arctic mountain slope processes and their impact on traffic in Svalbard (CRYOSLOPE Svalbard)

1. RELEVANCE

Ground based transportation in the high arctic Svalbard landscape all takes place in mountainous terrain affected by various active slope processes. Traffic in the Svalbard landscape are increasing, especially near the settlements, and at the same time global climate models are projecting substantial increases in temperature and precipitation in northern high latitudes. This means that improved knowledge on the effect of climatic changes on slope processes in the high arctic landscape is timely and important.

The main scientific question we want to study is how cold mountain slopes in Svalbard will respond to future projected climatic changes. This we will study by combining investigations of past geological and geomorphological studies of slope process activity with monitoring of modern active slope processes and meteorology in the slope areas, to provide a process-climate based prediction of future slope process activity. By answering this main scientific question we also will address how potential changes in slope activity could affect the traffic on the roads in the Longyearbyen settlement and the surrounding highly used winter roads connecting the settlements and tourist attractions in Nordenskiöld Land. Winter roads on Svalbard are the only transportation routes for many local residents to and from their work (mainly coalminers travelling between Longyearbyen and Svea, the Red Cross Longyearbyen and the Governor of Svalbard police staff in avalanche accident protection and assistance and tourist guides) and for pleasure (recreational use by the Svalbard population mainly in Nordenskiöld Land), scientists and students field working in different parts of Nordenskiöld Land, and by tourists travelling on the main winter roads seen on Fig. 1.

The main output from the CRYOSLOPE Svalbard project will be projections of future slope process activity based on firm knowledge about past and modern slope landform activity and meteorology, and a database, including geomorphological maps of the study areas, with old and modern observations from the study areas of all types of slope landform activity in the project period, but also in the almost 100 year long period with meteorological observations from Svalbard. These direct outputs will be important in future infrastructure planning of possibilities, safety and costs of transport in the 40 km most used summer and winter roads in steep terrain in and around Longyearbyen, also for the Svalbard authorities responsible for safety such as the Governor of Svalbard and for the tourist business, with its important winter tourism.

2. SCIENCE PART

2.1 Background in climate change research and its impact on slope activity in Svalbard

Global climate models project substantial increases in temperature and precipitation in northern high latitudes as a response to increases in greenhouse gas concentrations (Houghton et al. 2001). In addition the high latitudes are to a large extent covered by sea-ice and a seasonal snow cover, which both plays key roles in potential albedo feedback mechanisms and hence may amplify the climatic response to a change in the external forcing (e.g., Benestad et al. 2002).

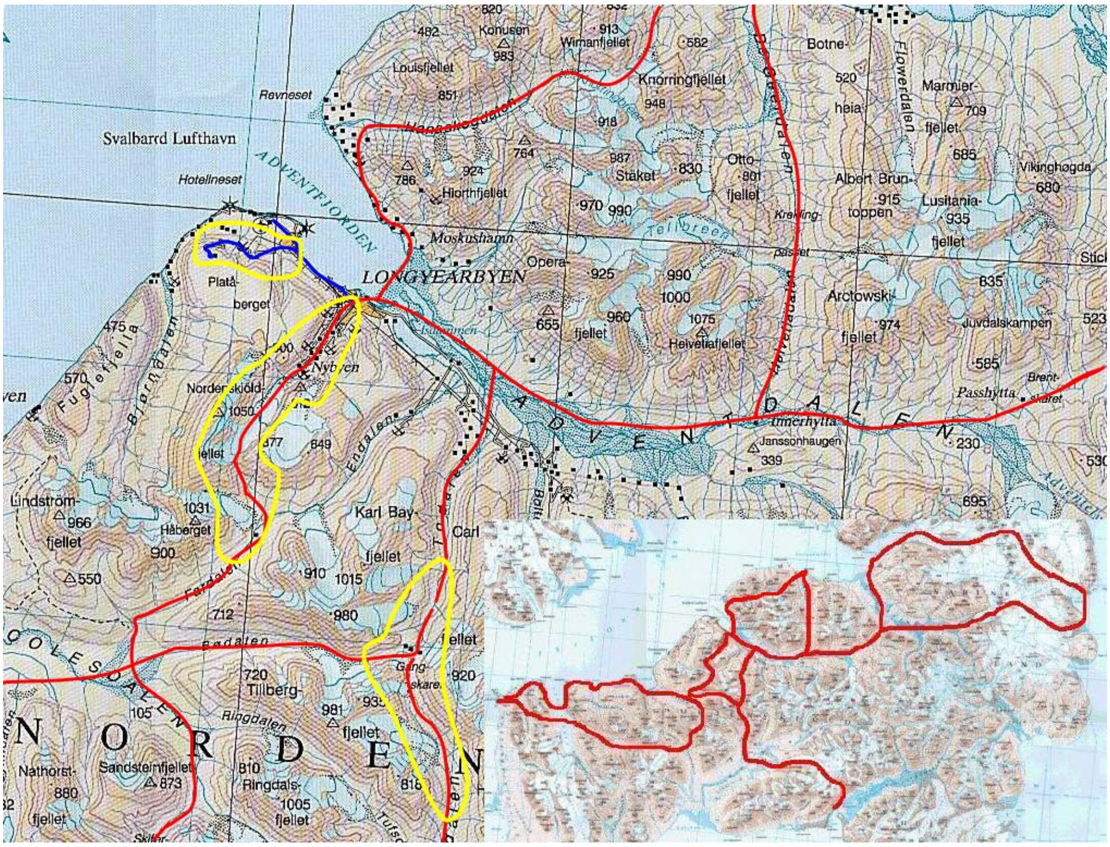

Figure 1. Red lines indicate winter roads. Blue line is the all-year road for cars. Yellow outlines show CRYOSLOPE Svalbard study sites. Insert showing the 400 km main winter roads in Svalbard that caterpillars, snowmobiles, skiers, dogsledsges and hikers use. Both maps from the Norwegian Polar Institute.

The most recent global coupled atmosphere-ocean general circulation models (AOGCMs) are believed to give realistic descriptions of large-scale features (Houghton et al. 2001). The model topography used in such models, however, has until now been crude and islands such as Svalbard and land areas such as the Norwegian mountain ranges are not represented realistically in these models. In fact, it has been suggested that the global climate models cannot give a good description of features smaller than sub-continental scales. It may nevertheless be possible to use AOGCMs to describe local climate characteristics if the local climate is highly affected by large-scale climate features, and if it is known how the large-scale features relate to local scale climate features. This transformation is generally known as downscaling and is based on either physical considerations or empirical relationships.

Downscaling experiments for Northern Europe (incl. Svalbard) 2000-2099 indicate strongest annual mean warming in the northeast, at higher altitudes, and in the interior (Benestad 2005). The strongest warming is estimated for Svalbard and the high mountains in southern Norway, and the interior of Finland, Sweden and Norway. Least warming, according to these results, is expected for the British Isles, east coast of Greenland and Iceland. As to precipitation, the analysis indicated positive future trends in general, about 0.5 mm/month per decade. Projected increase in precipitation is weaker over the British Isles and the Benelux countries and strongest in localized parts of Norway.

However, AOGCMs still have a large degree of uncertainty, especially for Arctic areas. One of the major problems is the representation of the atmospheric boundary layer (ABL). The ABL is to a very high degree controlled by local factors, such as topography and surface conditions and the physical processes in the Arctic ABL if often very different from the ABL on lower latitudes. How this difference should be represented in the climate models is far from understood and more studies are necessary to improve the understanding.

Most geomorphological processes and heat flow conditions at shallow depths below the terrain surface are highly influenced by air climate and should be expected also to be affected by future climatic changes. The coupling between climate and geomorphological process is, however, not simple and straightforward. In addition, there might well be significant regional differences, controlled by differences in seasonality, topography, bedrock type, snow cover characteristics and vegetation. Hence, in order to fully exploit the potential of climate projections to generate good projections of future geomorphic activity, it is essential first to conduct a detailed analysis of past geomorphological activity in a key regions in Svalbard, using available meteorological records and dated information on geomorphological slope activity, as well as to perform new detailed studies of the physical exchange processes between the atmosphere and the terrain surface.

The location of Svalbard in the North Atlantic Sea west of the warm North Atlantic sea current makes the meteorology unique, still arctic, but rather warm and shifting for these latitudes. Permanent human settlements have existed for only around 100 years, and both recreational and commercial land use have increased drastically, particularly over the last 10-15 years. Tourists travel around in the Svalbard landscape mainly during winter, whereas in summer they travel mainly on the sea by boats (Fig. 2). The frequency of potentially dangerous snow avalanche events, both destructive and non-destructive, has increased in the history of the Longyearbyen settlement. In 1953 (late winter), 2001 (mid winter) and 2004 (mid winter) the events were fatal, the latter two occurred under recreational activities close to the village, while the first occurred inside Longyearbyen killing 3 persons and with 12 persons wounded (Balstad, 1956).

Not much work has been published on avalanches in Svalbard. André (1990a; 1990b, 1995, 1996) focuses on the geomorphologic effect of avalanches and precipitation (Humlum, 2002), while others focus on safety aspects; Humlum et al. (2003; Humlum, 2005) uses wind and topography, Hestnes (2000) makes detailed investigations of confined areas, or (Hestnes, 1999) with a limited number of avalanche observations in the field.

No systematic registration of slope processes such as avalanches and other types has ever been carried out in Svalbard. Living and working on Svalbard, we will be able to perform such year-round observations intensively in the study areas. Also only large-scale geomorphological maps exist for some parts of Svalbard, such as the area around Longyearbyen (Tolgensbakk et al., 2000). But these are not showing individual landforms and cannot be used for infrastructure planning. In CRYOSLOPE Svalbard we want to establish such detailed geomorphological maps for the study areas.

2.2 Sediment and rock slope processes in the Svalbard landscape

<u>Talus slopes</u> are a widespread feature in periglacial mountainous areas, yet the influence of climate and other factors on the processes of weathering that lead to the rockfalls that feed them has remained the subject of considerable debate. It is, however, clear that the rate of rockfall supply to talus slopes is closely linked to variations in climate and that cooling usually led to significantly enhanced rate of <u>rockfall activity</u>. Rising temperatures or the complete thaw of permafrost in rock

walls can affect their stability. Present as well as projected future atmospheric warming results in permafrost degradation and, as a consequence, makes knowledge of the spatial distribution and the temporal evolution of rock temperatures important for estimating future rockfall and talus production rates.

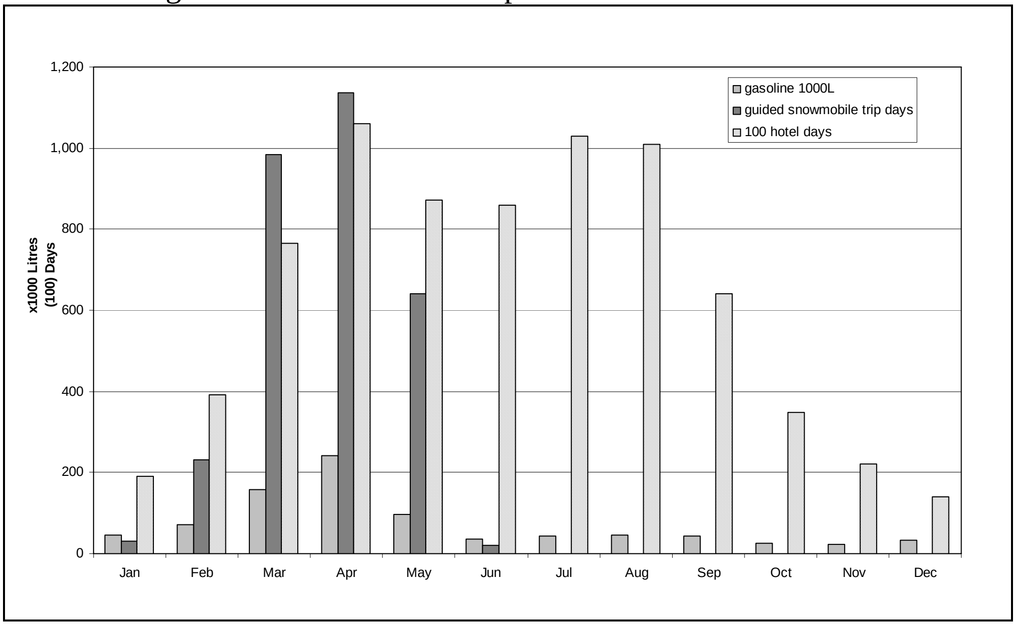

Figure 2. Tourist activity in the Longyearbyen area. 1995-2005 average monthly sale of 95 octane unleaded gasoline, data from Norwegian Polarinstitute; 2002-2004 average monthly number of guided snowmobile trips by days in Nordenskiöld Land; 2001-2005 average monthly hotel days, both data from Svalbard Reiseliv. The gasoline increase during winter reveals the increased traffic on the winter roads mainly with snowmobiles.

Active-layer detachment failures are translational landslides that occur in summer in thawing soil overlying permafrost (Lewkowicz and Harris 2005), and typically develop into mudflows in their lower reaches. They typically develop on very gentle to moderate slopes and are characterized by a shallow failure plane that runs parallel to the terrain surface. High pore pressures can be generated as the thaw plane penetrates the ice-rich base of the active layer and top of the permafrost, providing water is then released faster than it can drain, typically during periodic extreme thawing events. Downslope an active-layer detachment slide may develop into a debris flow. Such one developed during massive spring thaw in June 2003, and ran down slope into the kindergarten area in Longyearbyen (Svalbardposten, 2003), and as occurred more widespread affecting all the Longyearbyen roads during an intensive summer rainstorm 1972 (Larsson, 1982).

Solifluction, broadly defined as slow mass wasting resulting from freeze–thaw action in fine-textured soils (Matsuoka 2001), involves several components: needle ice creep and diurnal frost creep originating from diurnal freeze–thaw action; annual frost creep, gelifluction and plug-like flow originating from annual freeze–thaw action; and retrograde movement caused by soil cohesion. The depth and thickness of ice lenses and freeze–thaw frequency are the major controls on the spatial variation in solifluction processes, wherefore solifluction is controlled by climate. Slow deformation by solifluction may damage solid constructions such as buildings, bridges and roads, such as is occurring in the house ruins in the Gamle Longyearbyen areas (Jahn, 1976).

River action during the flood season induces the propagation of a thawing line within the frozen riverbank. Thermo-erosion refers to erosion by water combined with its thermal effect on frozen ground. Thawing of the ice within a porous medium reduces the strength of the thawed sediments and produces easily removable uncemented ground. This explains why thermal erosion is more effective than pure mechanical erosion, for cohesive sediments (Jahn, 1975).

2.3 Snow avalanches in the Svalbard landscape

Snow avalanches are active geomorphic agents of erosion and have been a source of natural disasters as long as man has lived in cold-climate high relief areas. A common feature of many mountainous regions, avalanches may fall wherever snow is deposited on slopes steeper than about 30 degrees. Small avalanches, or sluffs, run in high numbers each winter, while the larger avalanches, which may encompass slopes 200-1500 m wide and millions of tons of snow, fall less frequent but inflict most destruction. Such hazard has been familiar to inhabitants of the Alps and Scandinavia for many centuries, while it is a more recent experience in other parts of the world (see, e.g., Stethem et al. 2003).

A fundamental classification of avalanches is based on conditions prevailing at the point of origin, or the release zone, and is subdivided according to whether snow involved is dry, damp or wet, whether the slide originates in a surface layer or involves the whole snow cover (slides to the ground), and whether the motion is on the ground, in the air, or mixed.

Small loose snow avalanches. This type of avalanche generally occurs at the surface in new fallen, dry snow. This type of avalanche (sluff) often begins at a point and spreads out as it moves downslope. Loose snow avalanches seldom entrain enough snow to bury a person deeply and the chief danger from this type of avalanche is from being pushed over a cliff or rock band.

Big loose snow avalanches. Avalanches composed of dry snow usually generate a dust cloud as the sliding snow is whirled into the air by and is called powder snow avalanches. Their speed may exceed 200 km/hr. Such loose snow avalanches form in snow with little internal cohesion among individual snow crystals. When such snow lies in a state of unstable equilibrium on a slope steeper than its natural angle of repose, a slight disturbance sets progressively more and more snow in downhill motion. If enough momentum is generated, the sliding snow may run out onto level ground, or even ascend an opposite valley slope. Under certain circumstances, enough snow crystals are mixed with the air to form an aerosol, which behaves as a sharply bounded body of dense gas rushing down the slope ahead of the sliding snow. This windblast can inflict heavy destruction well beyond the normal bounds of the avalanche track.

Slab avalanches represent the most dangerous type of all snow avalanches, as the slab is difficult to see and avoid. It will often allow a person to travel well out onto it before rupture takes place. Slab avalanches originate in snow with sufficient internal cohesion to enable one or several snow layers to react mechanically as a single entity. A common source of weakness is depth hoar formed in the early winter snow cover, providing poor support for subsequent snowfalls. Even thin layers of depth hoar, surface hoar, or graupel can also provide a fragile bond when sandwiched between stronger layers. Another frequent cause of slab avalanching is an ice layer or crust, which provides a smooth sliding surface with low friction. Crusts formed by refreezing following rain are frequently formed during a typically Svalbard winter, and offer especially poor anchorage to subsequently deposited snow layers. A slab avalanche breaks free along a characteristic fracture line, a sharp division of sliding from stable snow whose face stands perpendicular to the slope. The entire surface of unstable snow is set in motion at the same time. Slab avalanches are often dangerous, unpredictable in behaviour and provide most of the winter avalanche hazard for people.

Cornice fall avalanches occur when cornices break loose from the lee side of ridges or mountain plateaus. Cornices form when prevailing winds remove snow from slopes or plateaus and deposit it in a leeside position. The snow that forms cornices is very dense and hard, yet can be extremely fragile. It is often difficult to determine from the mountaintop where the solid bedrock ends and the overhanging cornice is not supported from below.

Wet snow avalanches usually occur during spring, but may also occur during short spells of intense thaw in midwinter. Wet snow avalanches are generated by intrusion of percolating liquid water (rain or snow melt) in the snow cover. They move more slowly than dry snow avalanches and seldom are accompanied by dust clouds. However, their higher snow density can lend them enormous destructive force in spite of lower velocities.

2.4 Science goals and output

The main scientific goal of the CRYOSLOPE Svalbard project is to study the effects of modelled climate change in the high arctic Svalbard mountain landscape by using the existing landforms as archives of past activity, and by studying the ongoing slope process and meteorological activity to predict future slope activity and estimate its effect on traffic on both all-year and winter roads. Projected climate change scenarios will be based on regional climate models.

Sub goals:

- Analyse the meteorological data series 1912-recent with respect to extreme meteorological events, mainly with respect to intensive summer rain and winter wind activity.
- Make digital geomorphological maps of slope landforms in study areas, enabling potential future inclusion in the Norwegian national landslide database (www.skrednett.no).
- Establish a database with observations of all slope events in the project period including historical data.
- Date Holocene slope landforms in the study areas.
- Provide on-line updated information on status of slope activity in study areas, mainly snow avalanches.
- Provide on-line meteorological observations from different parts of study area.
- Establish scenarios of future slope activity in a changed climate.
- Obtain improved understanding of the importance of meteorological parameters on especially climatically sensitive slope landforms such as avalanches in high arctic Svalbard.
- Monitor physical exchange processes between the atmosphere and the surface in the study areas.
- Analyse the study areas with respect to typical physical phenomena in the arctic atmospheric boundary layer.

These different CRYOSLOPE Svalbard outputs will provide important baseline data for the establishment of potential future avalanche forecasting and warming models.

2.5 Study sites

We will study the 40 km most used summer and winter roads in three steep terrain areas in and around Longyearbyen (Fig. 1). In all these areas avalanches occur every winter causing problems for the traffic. Two persons were killed by driving into an avalanche on snowmobiles in one of the study areas in 2001. Our three study sites include the most used all-year and winter roads in the upper Fardalen valley and the entire Longyearbyen valley, as this is where people live and where most traffic occurs. We also include the mountain slopes above the Longyearbyen airport area with the all-year mountain road leading up to the Svalsat satellite receiving station on the plateau. Finally we include the narrow upper part of the valleys Todalen, Gangdalen and Bødalen, which is the main transport corridor from Longyearbyen to the coalmine settlement Svea, but also used heavily for touristic and recreational purposes.

2.6 Work modules

Meteorological monitoring and surface exchange processes, work module 1 (WM1)

Leader: Anna Sjöblom, UNIS. Participants: Coordinator at UNIS and UNIS students.
Detailed measurements of physical exchange processes between the atmosphere and the surface, using meteorological masts with measurements of temperature, wind and humidity in two levels. Net radiation will also be measured during intensive campaigns in order to determine the surface energy budget. Masts will be placed in the key areas on two places with different topographic and surface conditions in order to study the local effects on processes in the atmospheric boundary layer that are typical for Arctic conditions.

Meteorological observations from existing automatic weather stations in the study areas such as the UNIS meteorological stations on Gruvefjellet and in Adventdalen and from the Svalsat meteorological station on Platåberget will be made available on-line on the CRYOSLOPE Svalbard website, allowing differences in the local meteorological conditions to be available directly to the public for planning personal and public transport, and to the Svalbard authorities working with transport safety such as the Governor of Svalbard. During the intensive meteorological measuring campaigns also data from the moveable meteorological masts will be made available.

Geomorphological/geological mapping and monitoring, work module 2 (WM2)

Leader: Hanne H. Christiansen, UNIS. Participants: Ole Humlum, UiO, coordinator at UNIS, Knut Stalsberg, NGU, and UNIS students.
Observations of the different types of slope (snow, soil or rock) processes, including exact position, photos and size measurements of the extent of slope activity will be carried out on regular visits to the three study sites mainly in winter, but also in summer. Miniature shock loggers will be used for automatic registration of slope activity in combination with continuous photographical observations (Christiansen, 2001). Laser scanning to establish detailed terrain models of the slopes will be carried out in the first and last summers of the project for establishment of detailed digital terrain models. These can then be directly compared in a GIS to study any changes in landform sizes and thus activity. The digital terrain models will also be the basis for the geomorphological maps.

To reconstruct former slope activity we will produce digital geomorphological maps based on field and aerial photograph studies. These maps will classify the slope landforms, and estimate their recent level of activity. In order to evaluate the frequency of slope processes we will study the stratigraphy of landforms using natural exposures and/or geophysical investigation methods such as georadar or geoelectrical resistivity surveys. We will also date the slope landforms, expecting them to be mainly of Holocene age (Christiansen 1998). Dates will be obtained by the cosmogenic surface exposure, luminescence and carbon 14 methods.

Coordination and future projections, work module 3 (WM3)
Leader: Ole Humlum, UiO. Participants: all other project participants.
A main goal of WM3 will be the establishment of a slope process database in close cooperation with existing databases at NGU for other parts of Norway. Inclusion of slope process observations and data from automatic monitoring by the miniature dataloggers, the cameras and the geomorphological maps all from WM2 will go into the database. The meteorological monitoring data from WM1 will also be added into the database, allowing for future potential testing of avalanche models for Svalbard.

The different data in the database will allow for combined analyses of meteorological and slope landform activity data thus enabling the preparation of scenarios of future slope landform activity during changed climatic conditions in the study sites.

2.7 Project management and cooperation

Participating institutions will be the Department of Geology, The University Centre in Svalbard, UNIS with the Principal Investigator, PI: ***Associate Professor, Dr. Hanne H. Christiansen***, the Institute of Geosciences, University of Oslo, UiO, PI: ***Professor, Dr. Ole Humlum*** and the Norwegian Geological Survey, NGU, PI: ***Senior researcher Dr. Knut Stalsberg***. Additional participating scientist will be **Associate Professor Dr. Anna Sjöblom**, Department of Geophysics, UNIS. We will employ a full time project data coordinator for the three-year project period to perform large parts of the data collection and database establishment.

The project coordinator will be Hanne H. Christiansen. The work will be occurring in the WMs 1, 2 and 3. The project period will be three years from 1 January 2007 to 31 December 2009.

CRYOSLOPE Svalbard will develop new cooperation between the systematic meteorological and slope process observations that UNIS staff living and working in the field area in Svalbard can obtain with the established experience on slope landform mapping and geological database operation existing at the Norwegian Geological Survey. Additional to the CRYOSLOPE Svalbard planned activities, we expect to be able to cooperate with the Norwegian Geotechnical Institute on developing in the future avalanche forecasting and warning tools for Svalbard.

CRYOSLOPE Svalbard will be an important high arctic Norwegian part of the suggested European Science Foundation (ESF) network programme ‘Monitoring, dating and modelling cold-climate European mountain slope processes’, abbreviated CRYOSLOPE. The CRYOSLOPE Svalbard project manager is also the principal applicant and contact person for the applied CRYOSLOPE network programme, to run 2007-2010.

3. PERSPECTIVES AND STRATEGIES

3.1 Institutional and societal relevance

The project-managing partner, UNIS, who is located in the study area in Longyearbyen and equipped for year-round high arctic field operations, has as one its goals to contribute science output to the local society in Longyearbyen. This will be done through the proposed CRYOSLOPE Svalbard project by supplying several institutions in Longyearbyen with relevant data and projections for future slope activity affecting the local traffic, both on all-year roads but also along the most used parts of the winter roads. The Norwegian Geological Survey, NGU, has as it aim to provide geological data for use in society. The cooperation between UNIS and NGU on operation of a geological database and on production of digital geomorphological maps of the study areas will provide important tools for improved understanding of how future climatic changes will affect the sensitive high arctic landscape in and around Longyearbyen. The project will benefit from the fact that the work module 3 leader from UiO is also co-chair for the working group 'Periglacial Landforms, Processes and Climate' under the International Permafrost Association (IPA), allowing for international cooperation on cold-climatic slope landform processes.

Because of the importance of obtaining more information on avalanche activity in the Svalbard landscape, which also UNIS use intensively for research and educational activities all year round, a minor UNIS multi departmental avalanche observation project is funded to run during 2006. The UNIS departments of Technology, Geophysics, Geology and Technics all participate in this project. This project will provide some important initial data for the CRYOSLOPE Svalbard project, when this can start in early 2007, enabling data from a first year full winter season.

CRYOSLOPE Svalbard provides also several excellent possibilities for UNIS, UiB and UiO master student theses including important fieldwork both within meteorology, geology and physical geography.

Distribution of output to different user groups

See publication plan directly in the application form.

References

-) André, M.-F. (1990a) Frequency of debris flows and slush avalanches in Spitsbergen: a tentative evaluation from lichenometry. *Polish PolarResearch*, 11, 345-363.

-) André, M.-F. (1990b) Geomorphic impact of spring avalanches in northwest Spitsbergen (79°N). *Permafrost and Periglacial Processes*,1, 97-110.

-) André, M.-F. (1995) Holocene climate fluctuations and geomorphic impact of extreme events in Svalbard. *Geografiska Annaler Series A-Physical Geography*, 77A, 241-250.

-) André, M.-F. (1996) Geological control of slope processes in northwest Spitsbergen. *Norsk Geografisk Tidsskrift*, 50, 37-40.

-) Bakkehøi,S. Skredulykken under Håbergnuten, Svalbard. 2001. Unpublished Work.

-) Balstad, L. 1956. Kvinna på Svalbard. Forum, Stockholm, 264-266.

-) Benestad, R.E., Hanssen-Bauer, I., Skaugen, T.E. and Førland, E.J. 2002. *Associations between sea-ice and the local climate on Svalbard*. Norwegian Meteorological Institute Report No. 07/02, 1-7.

-) Benestad, R.E. 2005. Climate change scenarios for northern Europe from multimodel IPCC AR4 climate simulations. *Geophysical Research Letters* 32, L17704, doi:10.1029/2005GL023401.

-) Christiansen, H.H. 1998. Little Ice Age Nivation Activity in NE Greenland, *The Holocene*, 8, 6, 757-766.

-) Christiansen, H.H. 2001. Snow-cover depth, distribution and duration data from northeast Greenland obtained by continuous automatic digital photography. *Annals of Glaciology*, 32, 102-108.
-) McCarroll, D., Shakesby, R.A. and Matthews, J.A. 2001. Enhanced Rockfall Activity during the Little Ice Age: Further Lichenometric Evidence from a Norwegian Talus. *Permafrost and Periglacial processes* 12, 157–164.
-) Hestnes, E. (2000) Impact of rapid mass movement and drifting snow on the infrastructure and development of Longyearbyen, Svalbard. *International Workshop on Permafrost Engineering. Longyearbyen, Svalbard 2000.Proceedings.*, 259-282.
-) Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 881 pp.
-) Humlum, O. 2002. Modelling late 20th century precipitation in Nordenskiöld Land, central Spitsbergen, Svalbard, by geomorphic means. *Norwegian Geographical Journal* 56, 96-103.
-) Humlum, O., Instanes, A. and Sollid, J.L. 2003. Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. *Polar Research* 22(2), 191-215.
-) Humlum, O. 2005. Holocene permafrost aggradation in Svalbard. In Harris, C. & Murton, J.B. (eds). *Cryospheric Systems: Glaciers and Permafrost.* Geological Society, London, Special Publication, 242, 119-130.
-) Jahn, A. 1975. *Problems of the Periglacial Zone*. PWN Polish Scientific Publishers. Warsaw.
-) Jahn, A. 1976. Contemporaneous geomorphological processes in Longyeardalen, Vestspitsbergen (Svalbard). *Biuletyn Peryglacjalny*, 26, 253-268.
-) Larsson, S. 1982. Geomorphological effects on slopes of Longyear valley, Spitsbergen, after a heavy rainstorm in July 1972. *Geografiska Annaler*, 64A, 105-125.
-) Lewkowicz, A.G. & Harris, C., 2005. Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada. *Permafrost and Periglacial Processes*, 16, 115–130.
-) Matsuoka, N. 2001. Solifluction rates, processes and landforms: a global review. *Earth-Science Reviews* 55, 107–134.
-) Stethem, C., Jamieson, B., Schaerer, P., Liverman, D., Germain, D. and Walker, S. 2003. Snow avalanche hazard in Canada - a review. *Natural Hazards* 28 (2-3), 487-515.
-) Svalbardposten, 2003. Rassikrer barnehagen. Vol 23, 4.
-) Tolgensbakk J, Sørbel L, Høgvard K. 2000. Adventdalen, Geomorphological and Quaternary Geological map, Svalbard 1: 100,000, Spitsbergen sheet C9Q. Norsk Polarinstitutt Temakart nr. 32.