A Handbook on Periglacial Field Methods

International Permafrost Association (IPA)
The Working Group on Periglacial Processes and Environments

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Contents

Introduction

The IPA Working Group (WG) on Periglacial Processes and Environments was back in 1993 at the Beijing 6th International Permafrost Conference mandated to produce a handbook on recommended methods to measure periglacial processes. The proposal received additional support at the Berlin meeting of the IPA Council in 1995 when a resolution was passed stating: "Considering the importance of documenting and understanding long-term change in permafrost terrain the IPA recommends: 1) the establishment of an international network for long-term monitoring of the thermal state of the permafrost and active layer in both hemispheres; and 2) the standardization of methods for measurement and site selection.."

At the 1998 Yellowknife 7th International Permafrost Conference the IPA Council decided that all IPA working groups should have two Co-chairs, instead of one Chair and one Secretary. At this conference the existing chair for the present WG, Dr. Toni Lewkowicz (University of Ottawa, Canada) and Secretary, Dr. Charles Harris (University of Wales, Cardiff, UK), decided to step down from their posts following several years of intense activities, leadership and administrative duties. As new Co-chairs of the WG were elected Professor Ole Humlum (The University Courses on Svalbard, Norway) and Dr. Norikazu Matsuoka (University of Tsukuba, Japan).

At the Yellowknife conference it was also decided that the single main objective during the next five years for the WG should be the production of a handbook on recommended methods to measure periglacial processes, and that this handbook should be available at the 8th International Permafrost Conference in Switzerland 2003.

The present publication represents the first version of such a handbook and will be followed by other, more comprehensive and updated versions. The present Working Group on Periglacial Processes and Environments will be terminated at the Zürich 8th International Permafrost Conference, but it is foreseen that the handbook will live on the Internet to be followed by other, more comprehensive and updated versions. The present version of the handbook is accessible on Internet on the address:

www.unis.no/research/geology/Geo_research/Ole/PeriglacialHandbook/HandbookMain.htm

In addition to this, a special issue of the journal Permafrost and Periglacial Processes (14/4) "*Monitoring periglacial processes: new methodology and technology*" will be published later this year (Vol.14, no 4), containing 13 papers on measurement techniques.

Rationale

The impetus to standardize techniques is drawn from the need to be able compare circumpolar and alpine studies, particularly in the context of global change research. Standardization of methodology has been followed in the International Tundra Experiment (ITEX) and in work on the Paleoclimates of Arctic Lakes (PALE), part of Past Global Changes (PAGES) that is a core project of the International Geosphere-Biosphere Program (IGBP).

Subsequent discussions between the two chairs of the WG have narrowed the proposed scope of the handbook. What is going to be produced is '*A handbook on field methods*' rather than '*A handbook* *on both field and laboratory methods*'. We believe that efforts should be concentrated toward this, as highly sophisticated laboratory techniques are continuously being developed and improved by a rather small number of laboratories and scientists. Therefore, a handbook of recommended laboratory techniques would presumably be of limited use for these institutions and individuals. Compared to this, a handbook of various field techniques would be of much more general use for students and scientists involved in periglacial research.

The handbook is designed to provide scientists and others conducting research on periglacial processes and landforms with an introduction to selected techniques which can provide useful information for these studies. This is based on the premise that some earth scientists may not have received formal training in such (partly geophysical) measurement techniques and so may not be familiar with the techniques and instrumentations that may be available to address the questions of their research. For this reason, the presentations here focus on first principles, and provide illustrations and examples from various studies that may be useful in assessing periglacial processes, landforms, and environmental change. Information is provided on how to conduct surveys using the techniques described, and how to interpret the results, including, in both cases the pitfalls to avoid. Most techniques is relatively easy to learn and inexpensive to apply; in most cases, each is suited to small field parties operating with limited logistical support.

By this, the handbook may assist in a certain standardization of various measurement techniques, so that studies undertaken at different locations in the northern and southern polar areas and at high altitude produce comparable results. The handbook also should provide solutions to a number of specific problems arising in the field. The aim of the handbook is not to stifle creativity, but to suggest useful methods available at the present. New methods that may be developed in the future can then be compared with the old so that the data will remain comparable.

The handbook is not going to represent a formal textbook on periglacial field techniques. It is intended as a field handbook to be used during both planning and conduct of periglacial field research. Its prime purpose is to contain useful information for efficient fieldwork and by this, act as an *aide memoire* and a source of inspiration. One fundamental assumption made while compiling the handbook is that the user should be familiar with at least the essentials of the techniques that she or he proposes to employ. For fuller discussions on the relative merits of a wide range of periglacial techniques and for further references on them, the user should consult appropriate textbooks or journals.

It is the aim to ensure a cheap publication of the manual, so that it can be published, sold for minimal cost or given away. Above all, latest version will always be available on the Internet (see address above), which ensures easy and efficient update.

Approach

Two extremes are possible in a handbook of this sort. The first provides a true cookbook approach, concentrating on the exact instructions for setting up equipment (e.g. the ITEX manual). At the other extreme, it is possible to simply refer to the literature and leave many of the details for the interested reader to look up (e.g. many of the PALE protocols).

Unfortunately, the latter method works only if the reader has easy access to the original literature, which may not always be the case. The approach proposed for the production of this publication combines the two methods. Within the body of the text concerning each process, reference is made to the literature and there is a discussion of the advantages and disadvantages of different methodologies and techniques. However, the actual procedures to be followed in order to initiate measurements are described line by line in an Appendix for some techniques. This should leave the text interesting to the general reader while those actually conducting research will have full protocols to follow. For the Internet version, the use of hyperlinks to other sources of relevant information is exploited.

The recommendations expressed in the manual by no means prevent ongoing advances in measurement techniques. They simply provide baseline standardized methods so that as newer, better techniques are developed, data obtained can be compared to the existing records. In addition, the manual can be readily updated for a given topic, or broadened as it becomes possible and desirable to include additional processes.

Acknowledgments

We want to acknowledge the willingness of all authors to contribute to this project. Each authors name and professional affiliation is stated at each contribution. In addition, we also want to acknowledge the support by a number of additional scientists, who has not been able to prepare contributions to the present version of the manual, but who have declared their willingness to contribute at a later stage. This has been a valuable support during the preparation of the handbook.

Ole Humlum and Norikazu Matsuoka; Editors.

A device for monitoring shallow ground temperatures

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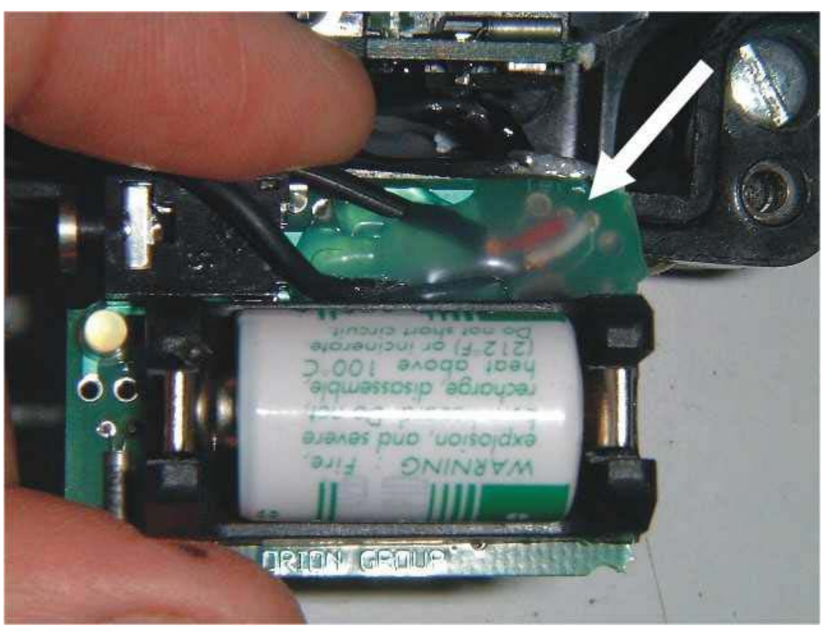
Introduction

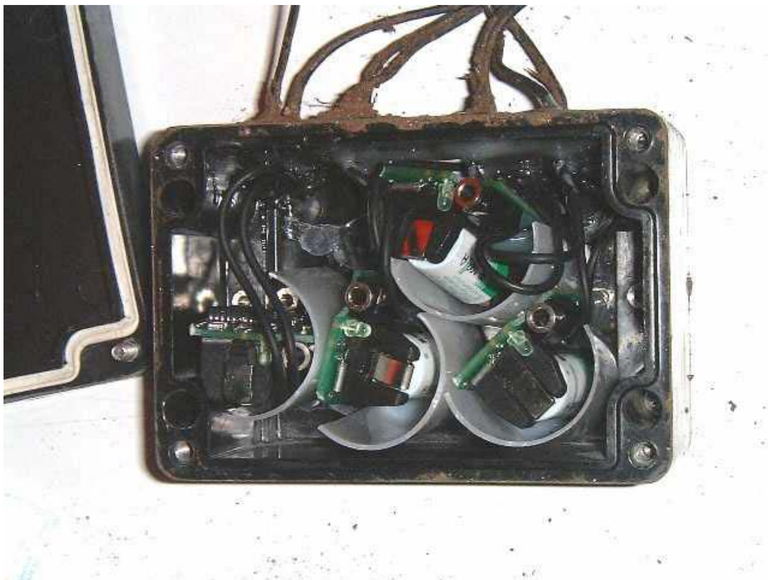
In marginal periglacial areas like the medium altitude Mediterranean mountains, the High altitude Tropical mountains or the Subantarctic Islands, a daily frost regime with shallow penetration of the freezing front in the ground controls most of the geocryological processes. Many geomorphological features are originated by shallow frost action in the ground, like miniature sorted nets and stripes, needle-ice raked ground, nubbins, shallow solifluction lobes, etc. Monitoring the ground temperatures at shallow depths contributes to characterize and better understand these marginal processes. In this note we describe the design and construction of a low-cost device used for that purpose in the Serra da Estrela range (Portugal).



View of the data logger after modification of the thermistor setting. The arrow indicates the original position of the thermistor. In the picture it is possible to see the wires and a mechanical protection made of "melted plastic glue".

Design and construction of the device

The device is based on miniature data loggers from Gemini. In order to minimize costs, Tiny Talk II® without protection cases were chosen. This model also has the advantage of a small size (34 mm of diameter and 52 mm of length). A detailed description of Gemini data loggers can be found elsewhere in this field book or at www.geminidataloggers.com. Other companies provide similar data loggers, which may probably be used following this approach.



Arrangement of the 4 data loggers inside the IP68 case.

a) Data logger setting

Tiny Talk II data loggers are compact electronic devices, with one built-in NTC100 thermistor. Our design is based on 4 data loggers recording independently at 4 depths. The data loggers are protected inside a standard IP68 case (water and dust protection), which will be totally buried in the ground. This proved to be a very efficient protection from people and animals.

In order to obtain an optimal contact with the ground, we extracted the thermistors from the data loggers and mounted them on external electrical wires. The sensor must be detached from the data logger with special care in order to do not cause damage to the circuits and to the thermistor itself. It is however a very simple procedure made using a good soldering iron.

View of the device with the 4 external sensors.

b) Protection case

The 8 wires (each thermistor has two) pass to the exterior of the case through 8 small holes, which are sealed using epoxy glue, both on the inside and outside parts of the case. It is important that the wires have a circular section and that there is not a cotton infill between the metal and the plastic protection of the wire. That kind of material could easily deform the wire section, making it easier for moisture to migrate into the case.

The case that we used opens from above and is sealed with 4 screws. It proved very efficient and we never had problems with moisture. It is especially important in this kind of approach to use an IP68 case.

Case opening for data download in the field.

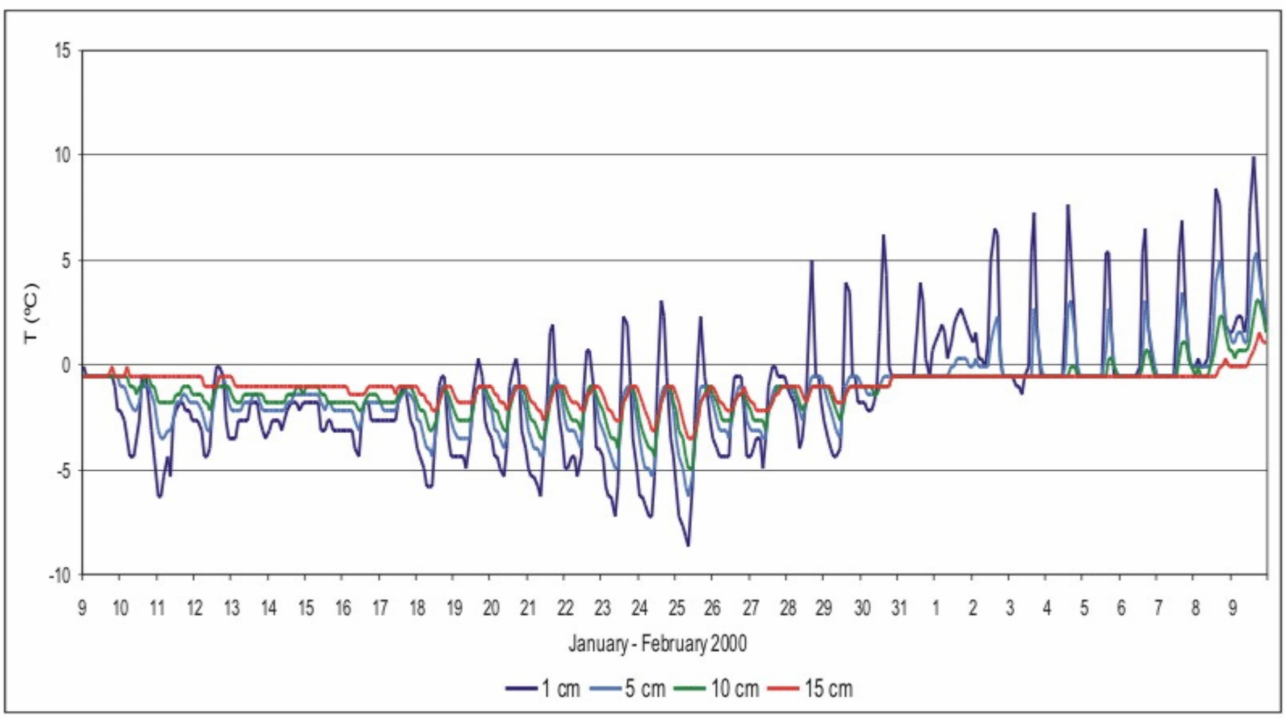
c) Sensors

For maximizing the contact with ground particles and to obtain an average value of the temperature at the same depth, the external thermistors were glued (epoxy) to high-diffusivity aluminium plates. In our study sites, near to the surface, the material is coarser and finer at depth. Therefore, the shallowest thermistor, which was buried 1 cm deep, was glued into a 15 x 15 x 0.5 cm aluminium plate, and the other three (5, 10 and 15 cm) were glued into very thin aluminium sheets with 2 x 2 cm.

d) Field setting

In the field, the case is buried together with the sensors. The case should stay at an intermediate level between the lower and the upper sensor, in order to minimize the possible effect of heat conduction through the sensors wires. Depending on the ground texture and climate regime, frost-heave may disturb the position of the sensors. Either their position needs to be checked frequently, or better, they can be fixed to some kind of anchoring device fixed deeper in the ground. In our experiment the sensors did not show detectable movement.

For the data transfer, the case must be opened (but not necessarily removed from the ground) to connect the RS232 cable from the computer to the data loggers. Our experience shows that it is difficult to clean the case properly before opening it, especially when the ground is moist. We therefore suggest covering the case with a plastic bag, before burying it, in such a way that it can be easily opened and kept clean, without the need to remove it from the ground.



Example of data collected at the Cântaro Gordo ridge (Serra da Estrela, Portugal).

Final note

Prices, capacity and models of data loggers available in the market are becoming more competitive as time passes, and simpler systems are for sure, becoming more frequently available at reasonable prices. Therefore, the intention of this note is only to contribute with some ideas for those who are interested in field monitoring of periglacial processes.

Acknowledgments

The data loggers were constructed and used in the framework of the Project "ESTRELA – Geomorphological and biophysical processes and landscape units in Mediterranean mountains. The case-study of Serra da Estrela" (PRAXIS/P/CTE/11153/98) – http://www.ceg.ul.pt/proj_estrela, funded by the Fundação para a Ciência e a Tecnologia.

Methods for Measuring Active-Layer Thickness

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General considerations

The term "active layer" refers to the relatively thin layer of ground between the surface and permafrost that undergoes seasonal freezing and thawing (Muller, 1947; Burn, 1998). Across this layer energy and water are exchanged between the atmosphere and underlying permafrost. Because most biological, physical, chemical, and pedogenic processes take place in the active layer, its dynamics are of interest in a wide variety of scientific and engineering problems.

The definition given above is based entirely on thermal criteria, without regard to material composition or properties. The volume and properties of the active layer are highly variable in time and over space. Idealized diagrams showing smooth trends of active-layer thickness (ALT) across latitudinal gradients (e.g., Brown, 1970, Figure 4, p. 8) can be misleading because variations in vegetation, substrate properties, and water content can result in very large differences in ALT, even over small distances (Nelson *et al.*, 1999; Hinkel and Nelson, 2003). Temporal changes, particularly surface temperature and moisture conditions, can also lead to substantial year-to-year differences in ALT, even at fixed locations. For these reasons, it is necessary to monitor ALT using well-defined measurement and sampling techniques. The Circumpolar Active Layer Monitoring (CALM) program was developed to provide standards of measurement and a comprehensive database describing the history and geography of ALT and other selected parameters at a large number of sites representative of permafrost terrain (Brown *et al.*, 2000).

This note discusses several common methods used to measure the thickness of the active layer, including mechanical probing, frost/thaw tubes, soil temperature profiles, and remote methods such as ground penetrating radar (GPR) and satellite measurements. Only nondestructive methods are discussed. Many of the methods and sampling designs described in this note were developed or refined by various investigators working in association with the CALM program.

The term "active-layer thickness" is used in reference to the maximum development of the thawed layer, reached at the end of the warm season (van Everdingen, 1998). This is distinct from the term "thaw depth," used here to refer to the thickness of the thawed layer at any time during its development in summer. Stated alternatively, thaw depth is an essentially instantaneous value that is always less than or equal to the thickness of the fully developed active layer. Active-layer thickness can vary substantially on an interannual basis. In general, it is greater in years with warmer summers and thinner in those with cooler temperatures (Brown *et al.*, 2000). Both thaw depth and active-layer thickness display large spatial variability over short lateral distances and, because rates of thaw vary in response to the properties of surface and subsurface materials, the spatial variability of thaw depth increases over the course of a single summer (Nelson *et al.*, 1997). The magnitude of active-layer variability can be quantified and used to characterize various types of permafrost terrain (Nelson *et al.*, 1998; Hinkel and Nelson, 2003).

Observation methods

Probing

Probing of the active layer is performed mechanically with a graduated rod. The typical probe is a 1 m long stainless-steel rod with a tapered point, is 1 cm in diameter, and has an attached handle (Figure 1). At sites where thaw depth is very large (e.g., 1-3 m), the diameter of the probe must be also be greater to withstand the bending stress generated by insertion. It is very difficult, however, to extract a probe in deeply thawed soils, and this problem is exacerbated if the probe's surface area is very large.

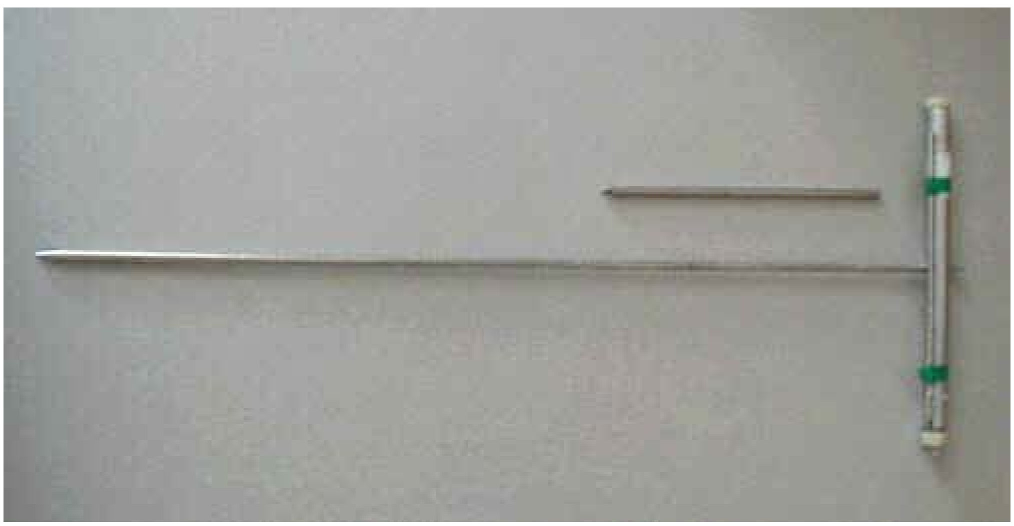

Figure 1: Steel 1-m probe, graduated in 1-cm increments. This model breaks down into three pieces for transport in handle, and has additional flights. This design was developed at the U.S. Army Cold Regions Research and Engineering Laboratory in the 1970s.

The probe rod is inserted into the ground to the point of resistance. A gentle pumping motion is used to gradually force the rod progressively deeper into the thawed ground without bending. A distinctive sound and feel is apparent when ice-rich frozen ground is encountered. The rod is grasped with the hand, and the hand is slowly slid down the rod to the top of the soil material; i.e., to the base of the vegetation. The rod is grasped firmly and removed, using the fingers to carefully mark the position on the rod. Thaw depth is then read from the graduations and recorded. All measurements are made relative to the surface; in standing water, both thaw depth and water depth are recorded.

Typically, two measurements are made at each location and the average reported. If a standard spacing is maintained between the two samples, the researcher has one metric of thaw variability. Identical probing methods can be used to measure the depth of the snow pack.

Advantages: Probes are relatively inexpensive and several models and sizes are available (see vendors at http://k2.gissa.uc.edu/~kenhinke/CALM/equipment.html). Measurements are relatively easy to make, and require little time. The primary advantages of probing are: (a) its suitability for collecting large numbers of measurements; (b) its ability to generate samples of data that are statistically representative of local areas; and (c) it can be used in conjunction with vegetation and soil information to estimate the volume of thawed soil over extensive regions (e.g., Nelson *et al.*, 1997; Klene *et al.*, 2001; Shiklomanov and Nelson, 2002).

Although single point measurements have utility, measurements along transects or on grids enable the researcher to plot or map annual thaw patterns, make volumetric estimates, and identify the factors responsible for active-layer variability (Nelson *et al.*, 1999; Gomersall and Hinkel, 2001). Because measurements can be made rapidly and with little effort, probing is well suited for implementing formal sampling designs (Nelson *et al.*, 1998, 1999; Gomersall and Hinkel, 2001). The length of transects or the dimensions of grids depend on scientific objectives and the scale of the active layer's local variability, and a program of exploratory sampling may be necessary to establish a grid of dimensions appropriate to the locale and the scientific goals (Nelson *et al.*, 1998, 1999). Grids are typically 10, 100 and 1000 m on a side, with grid nodes spaced evenly at 1, 10, or 100 m, respectively (Brown *et al.*, 2000). Node locations are identified using stakes or other semi-permanent markers, and replicate measurements are made at approximately the same location each year to facilitate interannual comparison.

Disadvantages: Timing is one of the primary limitations with probing. Ideally, measurements should be collected at the time of maximum thaw depth. Field measurements are, however, often constrained by logistical or weather-related considerations. Experience can help the researcher decide when to collect end-of-season measurements, but the date usually varies from year to year at each site. It is therefore unlikely that measurement of thaw depth coincides perfectly with the actual active-layer thickness. However, because thaw progression is usually proportional to the square root of the time elapsed since snowmelt, late-season thaw-depth measurements generally correspond closely with the maximum thickness of the active layer.

More intractable problems with probing arise when substrate properties prevent accurate determination of the frost table's position. In some cases, the top of the frozen (ice-bearing) zone does not coincide with the position of the frost table as defined by the 0°C criterion. The relation is dependent on soil salinity, particle size, and temperature. Well-drained sands and gravels may contain too little interstitial ice for adequate resistance to probing to develop. In saline or extremely fine-grained soils probing can yield inaccurate estimates owing to the presence of unfrozen water. Under such conditions it may be possible to calibrate mechanical probing using a thermal probe (Mackay, 1977; Brown *et al.*, 2000, p. 172). Readings may be very difficult to obtain in stony substrates such as glacial till (see paper by S. Hanson, this volume). Probing cannot ascertain if thaw subsidence has occurred.

Frost/thaw tubes

Thaw/frost tubes are devices extending from above the ground surface through the active layer into the underlying the permafrost. They are used extensively in Canada. Construction materials, design specifications, and installation instructions are available for several variants of the basic principle (Rickard and Brown, 1972; Mackay, 1973; Nixon, 2000). A schematic for a recent design is shown in Figure 2.

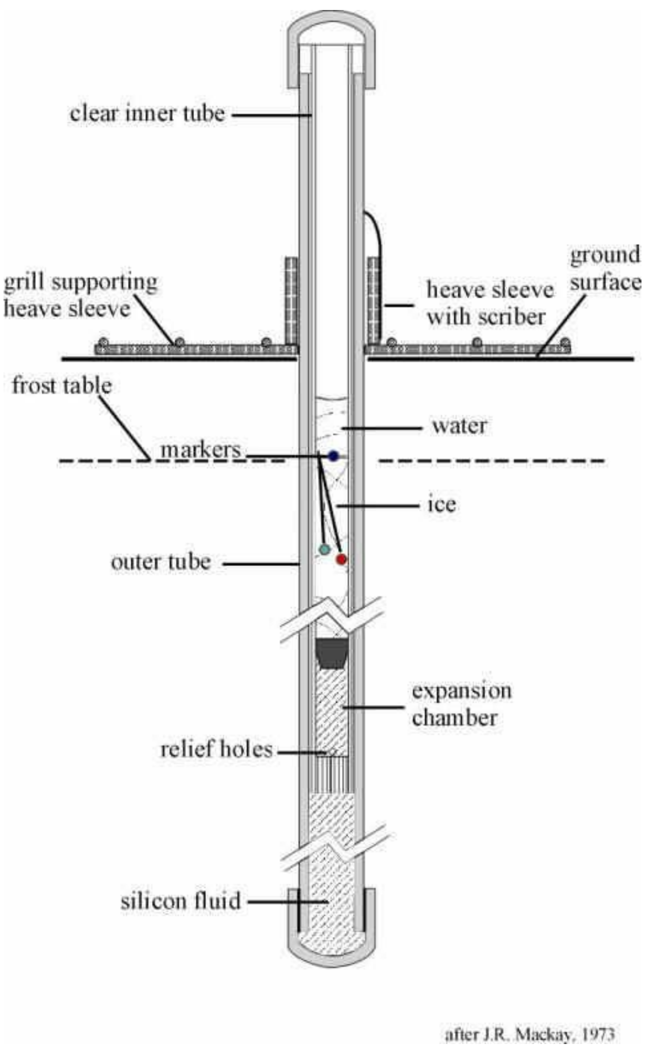

Figure 2. Schematic diagram of a recent frost/thaw tube design implemented by the Geological Survey of Canada. This design incorporates a scribing device to record thaw settlement induced by ablation of an ice-rich layer near the interface between the active layer and permafrost table. Diagram courtesy of F. M. Nixon, Geological Survey of Canada. From Nixon et al. (1995).

A rigid outer tube is anchored in permafrost, and serves as a vertically stable reference; an inner, flexible tube is filled with water or sand containing dye. The approximate position of the thawed active layer is indicated by the presence of ice in the tube, or by the boundary of the colorless sand. Each summer the thaw depth, surface level, and maximum heave or subsidence is measured relative to the immobile outer tube. These measurements are used to derive two values for the preceding summer: (1) the maximum thaw penetration, independent of the ground surface and corrected to a standard height above the ground established during installation; and (2) the active-layer thickness, assumed to coincide with maximum surface subsidence. With modifications, the accuracy of the measurements is about 2 cm.

Advantages: The primary advantage of frost/thaw tubes is that they provide an inexpensive annual record of both maximum thaw penetration and active-layer thickness, although it is not possible to determine the date. Because thaw tubes are durable, a multi-year record is available for comparison. Thaw tubes are especially useful in areas where thaw is too deep to monitor by probing, and in stony, fine-textured, or saline substrates in which probing is not feasible. Because the device is embedded in permafrost, the outer tube serves as a stable reference to determine if thaw subsidence or heave has occurred (Nixon, 2000).

Disadvantages: Thaw tubes have several limitations. First, each tube records only a single point measurement, which may or may not be representative of a larger area. Second, installation typically entails drilling, and the difficulty and time required may prohibit multiple tube installation at a site. Finally, there may be significant disruption of the surface and subsurface materials during installation, and the structure itself may influence local heat and moisture flow. It is likely that the optimal situation is to install a thaw tube at long-term sites, and collect additional measurements derived from spatially extensive sampling such as probing. Over time, a comparative record can be developed.

Soil temper ature profiles

Soil and air temperature are recorded as basic information at many CALM sites, especially with the increasing availability of inexpensive, reliable temperature data loggers. Temperature sensors (usually thermistors) are inserted into the active layer and upper permafrost as a vertical array. Several CALM installations currently use an array of thermistors embedded in a small-diameter acrylic cylinder (Figure 3) and connected to a high-capacity data logger.

Temperature records from a vertical array of sensors can be used to determine active-layer thickness at a point location. The thickness of the active layer is estimated using the warmest temperatures recorded at the uppermost thermistor in the permafrost and the lowermost thermistor in the active layer. The temperature records from the two sensors are interpolated to estimate maximum thaw depth during any given year. For this reason, the probe spacing, data collection interval, and interpolation method are crucial parameters in assessing the accuracy and precision of the estimate.

Figure 3. Thermal probe incorporating one external and 12 internal thermistor sensors in fixed positions within a rigid acrylic tube. The probe employs sophisticated electronics and is usually connected to a large-capacity data logger capable of making and recording high-frequency readings. The probe illustrated here was originally designed by the U.S. Army's Cold Regions Research and Engineering Laboratory, and is manufactured by MRC (Measurement Research Corporation), Gig Harbor, Washington USA.

Advantages: The advantages are similar to those for frost tubes. However, since temperature monitoring is already being preformed, there is no additional cost. Further, it is possible to estimate the date of maximum thaw with a reasonable degree of accuracy. Depending on whether probes are in a fixed or floating configuration, it may be possible to determine if thaw subsidence has occurred at the location. Numerical methods can be used with high-frequency thermal observations to estimate the thermal properties of the substrate, such as effective thermal diffusivity (e.g., Hinkel, 1997). Thermal records can also be used to identify the operation of non-conductive heat-transfer processes in the active layer, and can be related to meteorological events at the surface (Hinkel *et al.*, 1997, 2001; Kane *et al.*, 2001).

Disadvantages: Limitations are similar to those of frost tubes; thermistor strings effectively comprise only a single point measurement. They are relatively expensive. They are also subject to surface and installation disruptions, including vandalism and disturbance by animals. The accuracy of the active-layer thickness estimate is fundamentally limited by the vertical spacing of the probes and the data-collection interval. Many field investigators use a simple linear interpolation to estimate maximum seasonal thaw depth, although an exponential best-fit can be employed if there are several thermistors. Estimates of error should be calculated and reported.

Remote sensing methods

Ground penetrating radar (GPR) has been used with some success to map active-layer thickness along transects. Because water effectively absorbs electromagnetic pulses, profiling is most effective in winter, when the ground is frozen and covered with snow. The method relies on the principle that the active layer contains less ice than the permafrost immediately below, resulting in a reflection horizon at the interface. With careful local calibration, usually accomplished through coring, estimates of thaw depth along a continuous profile can be made. The accuracy of the estimates is incompletely known, but appears to be within ± 15% in fine grained soils. The expense, however, is often prohibitive. It is likely that GPR methodologies will continue to develop. Further details on the use of GPR in active-layer investigations are available in Doolittle *et al.* (1990) and Hinkel *et al.* (2001). Another ground-based approach was developed by McMichael *et al.* (1997), who used the Normalized Difference Vegetation Index (NDVI) to exploit known relations between vegetation units and ALT across a toposequence in northern Alaska.

Satellite imaging systems hold promise for monitoring thaw depth across large areas. In particular, synthetic aperture radar, carried at appropriate wavelengths, may have sufficient energy to penetrate the often-saturated active layer and return a signal to the satellite receiver (Kane *et al.*, 1996). Interpretive, convergence-of-evidence approaches have been used by Peddle and Franklin (1993) and Leverington and Duguay (1996) with some success, although the derived classes of ALT were very broad.

All aircraft- or satellite-based systems necessitate collection of training data on the ground for calibration and verification of the signal processing algorithms. The impetus for such a system may come from unmanned missions to Mars.

Other considerations

The issue of *thaw subsidence*, alluded to at several locations in the preceding text, is a critical issue and forms the focus of several field-based experiments in the CALM program. Thaw subsidence (thaw settlement) refers to downward displacement of the ground surface occurring when ice-rich permafrost thaws. Melting massive ground ice, typically veins and/or lenses, leaves a void; the weight of overlying material, combined with drainage of meltwater, can result in appreciable subsidence at the surface. This consolidation may not be apparent in ALT records obtained exclusively by mechanical probing.

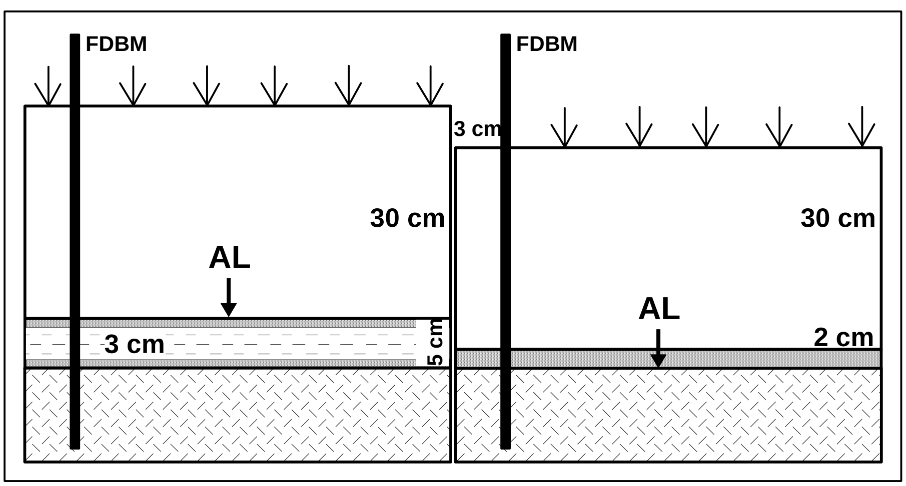

Figure 4: Thaw subsidence results from melting of 3 cm thick ice lens in the upper permafrost. Frost defended bench mark (FDBM) is used to monitor subsidence and heave as base of ALT changes.

Imagine, for example, that the typical active-layer thickness is 30 cm at a site. (Figure 4) Below this is a 5 cm thick layer containing a 3 cm thick ice lens. During one especially warm year, the thaw front penetrates to a depth of 35 cm, causing the ice lens to melt. The measured thaw depth would be only 32 cm, since the 3 cm of ice will have melted and the ground surface subsided by approximately this amount. Thus, the measured active-layer thickness will actually underestimate total thaw penetration. Conversely, the ground surface may heave upward on a seasonal or permanent basis with the growth of segregation ice. This is particularly problematic in medium-textured mineral soils.

Probing may not detect thaw subsidence or heave. For this reason, some recent investigations have employed *frost defended bench marks* or other methods of tracking changes in surface elevation (Nixon and Taylor, 1998; Little *et al.*, 2003). This may entail installing rigid poles or bars several decimeters into the upper permafrost to ensure that there is no vertical movement. The top of the bar or rod serves as a stable vertical reference point to monitor subsidence and heave. Rock outcrops can also be used for surveying purpose. Simple and inexpensive vertical displacement gauges have been developed to monitor seasonal heave and subsidence. These devices are anchored into the permafrost using a thin, flexible steel cable, and can also be used to monitor long term surface displacement. A description of one of gauge is available on the CALM web site (http://k2.gissa.uc.edu/~kenhinke/CALM/active_layer.html).

To an increasing degree, differential global positioning systems (DGPS) technology is being used to collect vertical control points to monitor and map surface movement (Little *et al.*, 2003). Mobile DGPS units can achieve vertical resolution of less than 1 cm under the proper operating conditions. In many applications, this precision may be sufficient for the user.

Conclusions

Many methods are currently being used to measure thaw depth in the active layer above permafrost. Each method is associated with distinct advantages and disadvantages. Each relies on a specific tool; in the words of Craftsman™ spokesperson Bob Vila, it is a question of "using the right tool for the job." The researcher must decide on the most useful and practical method given the scientific objectives, duration of the study, and availability of funds. It is likely, however, that a mixture of methods will be most suitable for long-term sites.

Acknowledgements

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Active Layer Temperature Monitoring in Blocky Material

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Introduction

The processes in the active layer and its connection to the atmosphere is of great importance for the state of the frozen ground below. These processes depend to a great extend on the actual material of the active layer (e.g. boulders, solid bedrock, gravel or soil) and the fieldwork should be designed with regards to what sub-surface is being measured. The here discussed procedures focus especially on active layer monitoring in areas of coarse boulders which usually covers considerable parts of the high alpine environment. Two main procedures are considered. One simple and quit cheap; the other more sophisticated and definitely more expensive and difficult to complete.

In bore hole palaeoclimatology, it is commonly assumed that a direct coupling exists between air and ground temperatures. This assumption is valid only if variables affecting ground-surface temperature exchange have remained constant through time. It should therefore be taken into awareness that ground temperatures can contain non-climatic noise due to changes in ground-surface variables, including vegetation cover, duration and thickness of snow cover, precipitation and melt water, wind speed and thereby wind pumping within the boulders, net radiation, phase change and boundary conditions. All this, as well as if one measure site or a network of sites is necessary should therefore be considered when designing the fieldwork in proportions to what is expected to be evaluated from the data.

Processes which influence the temperature regime within the active layer has been discussed in the literature (e.g. Williams and Smith, 1989; Humlum, 1997; Humlum, 1998; Harris and Pedersen, 1998; Kane et al., 2001; Hinkel et al., 2001; Schmidt et al., 2001)

Miniature temperature data loggers (mini loggers)

Mini loggers can be used as a simple and cheap approach when establishing a temperature profile above and within the active layer. The mini loggers are described in detail elsewhere in this publication. The mini loggers can normally be programmed to measure and store data at a variety of time spans and are simply placed with the desired spacing within the boulders. Mini loggers, though do not have endless memories and the more often temperatures have to be registered the shorter the time the mini loggers will be operating. Further disadvantages are that the batteries have to be replaced to not loose data and that the resolution of the data often is quite coarse.

Bore hole and thermistor chain

The system recording the data using this approach consists of the thermistor sensor chain, lowered in a bore hole, and connected to a data logger and a storage module normally driven by a battery or a solar panel. The data logger is the brain of a data acquisition system. They do the measurements at a specified scan rate and process the data. The data logger needs to be programmed to measure and download data at a certain time and form. The storage module is the device used to transport the data and programs between the field site and the office or transferring the data directly to a laptop. Furthermore, it also increases the data logger's storage capacity by storing data and programs in a solid state module or a memory card. The thermistor chain itself consists of the thermistor sensors which are placed with the desired space between them and wrapped up in a plastic coating.

The drilling

This part of the fieldwork is not to be underestimated, especially not if the drilling takes place in loose material or boulders. It is heavy work and do involve quit a lot of practice. If one has to do the drilling one-self several things have to be taken into consideration.

The type of drill needed is dependent on how deep the bore holes will be, the diameter of the hole and the material within the drilling takes place. The drilling requires electricity and water supply which can turn out to be a problem in remote areas. It is possible to drill dry but it is much to prefer drilling with water. This will cool the drilling head during the drilling, smoothen the drilling and is a good deal faster than dry-drilling.

For the design of the bore hole system, the first step is to decide the diameter of the bore hole. To reduce air circulation within the bore hole choose the diameter of the drilling tubes as small as possible. Otherwise the air circulation within the bore hole, once established, can disturb the natural temperature profile. The chain should be fastened to a weight at the end to be sure that there is weight enough to keep the chain straight and get it all the way to the bottom. This weight can have a larger diameter than the actually chain which is to keep in mind when deciding the diameter. Consider as well the option of wrapping neoprene tightly to one side of the chain. When the chain is lowered in the afterwards the sensors will be pressed against the wall of the bore hole. This will result in a more precise measurement of the material and also prevent air circulation in the hole.

Next step is to decide the length of the bore tubes. It is a good idea to divide the full length of the bore hole, and thereby the tube length, into a certain number of meters. Or said in another way: if the hole has to be 6m deep use 6 * 1m. tubes plus one 1/2m. tube. This is due to practical reasons during the drilling.

Third step is to decide for the drilling crowns. It is necessary to know the geology of the material where the drilling will take place. In loose or coarse material several different crowns that can be changed according to varying material during the drill are needed. This often implies at least one crown for loose material and one that fit the main hardness of the boulders. Let the company guide you according to the material, how deep the bore holes will be and how many holes needs to be drilled.

A final very important consideration is wherever the bore hole should be installed with an inner tube. An inner tube is a thin plastic tube which is installed during the drilling. The advantage of installing an inner tube is that a lot of problems will be avoided during the actual drilling as it prevent the hole from collapsing every time the tubes are pulled out of the hole to be emptied. The disadvantage is that it will also act as a thin barrier between the thermistor sensors and the material which temperature is to measure.

The sensor chain

The chain itself consists of the sensors and the bundle of their wires coated tightly with a plastic mantle. A temperature sensor consisting of a semiconductor that provides rapid and large changes in resistance for relatively small changes in temperature. Several configurations of the wires can be devised to minimize the risk of loosing data from all the sensors if some part of the chain is damaged. Again it has to be considered that the very mantle protecting the sensors also reduce the precision of the measurements just as it is the case with the coating of the bore hole.

It is possible to fabricate the chain oneself but it is definitely easier to let the company from where the sensors are bought construct it. The extra money can quickly turn out to be good value in the long run. Whatever the choice is the following issues has to be considered.

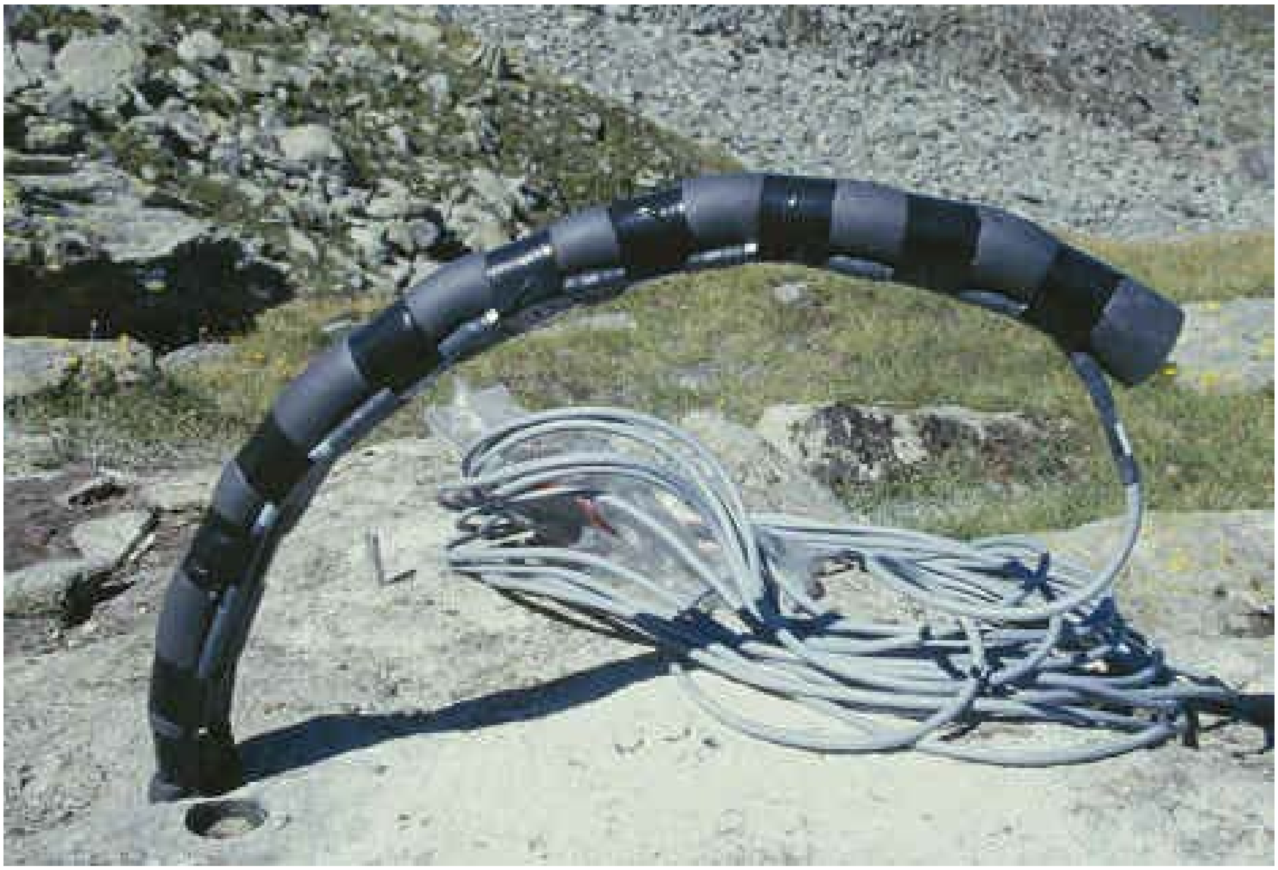
First the decision has to be made on how fine the spacing between the sensors on the chain should be. The temperature sensor spacing in the bore hole is usually dependent on the vertical resolution required and the stratification of the sub-surface. The top 50cm will experience the most rapid near-surface short-term temperature variation due to the diurnal changes of the atmosphere above. There is thus a certain logic in less spacing between the sensors in the upper 50cm to 1 m of the chain. The registration of the exact surface temperature is quite tricky as the actual boundary is infinitely thin. A mini logger or another thermistor sensor placed nearby as a reference is one approach.

The drill with drilling tubes, Corvatsch, 2002. Photo: P. Blétry.

The thermistor chain should be calibrated depending on the accuracy and temperature range of interest as well as the absolute accuracy of the whole system should be taken into account. If measuring over a wide range of temperatures calibration of each thermistor in several temperature ranges is needed. This will give a calibration curve for each sensor, for each temperature range. These are then applied individually for the conversion of the measured resistance in the corresponding range of temperature. In such a case it makes sense to log the data as measured resistance. If the actual temperature range is narrow the data logger can be programmed to calculate and store the data as temperatures.

The measured temperatures in the bore hole will for some time reflect the fact that drilling generates a lot friction heat which is transmitted into the surrounding material. It is hard to say how long time it takes before the system is back to its original state as it depends on the actual situation. Three months to half a year has been reported. The temperature profile has to be examined closely till it is evident that it is no longer cooling and first from then on the data can be used.

The durability of the sensors has to be judged as well. Over time the sensors should be calibrated again if possible. This is possible only if the chain can be pulled out e.g. the chain is lowered in a bore hole which is coated or drilled in firm bedrock. If the chain is lowered in a hole drilled in loose material the chances that the hole is collapsed at some point is high and it can not be recommended to pull the chain out as it will probably not be possible to lower it back in again.



Lowering the chain in one of the bore holes at Corvatsch, 2002. Neopren is attached to the chain to prevent circulation. Photo: S. Hanson

Setting up the system

Always inspect if the measuring site is also prone to avalanches or other natural hazards. When the system is established cover all exposed wires on the ground with rocks. That will to some extend protect the wires from e.g. animals which chews in the cables and from weathering of wind and stone fall. Do also remember to do a GPS point measurement to be able to locate the site under a thick snow cover. When the system is first established there is not much maintaining other than checking that the system is running and repair ongoing weathering.

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Geomorphological mapping with kinematic GPS

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Introduction

Detailed geomorphological mapping is a difficult or even impossible task in areas without topographic information or where the scale is too small for the precise location of the phenomena. Even in locations where good topographic maps are available, mapping of small or very irregular landforms or deposits can be difficult and not rigorous. The development of Global Positioning Systems (GPS) is a significant contribution for detailed geomorphological surveying and mapping. It is now possible to map with an accuracy only achieved with the traditional (and time-consuming) geodetically surveys, at much faster rates than before. This is especially true with a kinematic GPS system that (GPS-RTK) allows mapping continuously points or lines in the terrain with an error of a few centimeters.

General principles of the kinematic GPS system

The GPS was conceived to indicate positions in the Earth surface in any place independently of the meteorological conditions. For calculating the traveling time of a signal from a satellite to the receiver, specific codes are used. These codes allow the positioning with a precision of about 100 m.

Yet, if the GPS is located in a known position, its data can be used to correct most of the errors that are intrinsic to the system. The correction factors can be transmitted via radio to another GPS receiver in the area that uses them to achieve better accuracy (between 2 and 5 m). This technique is called differential GPS (DGPS) (LEICK, 1990; SEEBER, 1994).

If the carrier phase of the satellite signal is used in combination with the codes, better precision can be obtained. The calculation of the distance between the receiver and the satellite is much more accurate, but also more difficult to calculate, because of the ambiguity (number of full carrier phase cycles between the receiver and the satellite in the beginning of the observation). While ambiguity remains unknown this higher precision level cannot be achieved. The whole process lasts usually some minutes.

If a GPS in a known position is used in order to calculate the system errors it is possible to send the corrections via radio to other receivers with similar characteristics. These receivers are then able to calculate their positions in real-time with an error of approximately 2 to 5 cm in relation to the static receiver. The accuracy diminishes with increasing distance to the static receiver, and the corrections are useless after more than 10 km (GÁRATE, 1997).

Methodology

The example that we present is from a geomorphological survey in the area of the Spanish Antarctic Station "Juan Carlos I" (SAS) in Hurd Peninsula, Livingston Island (Antarctic). The GPS-RTK system was used to map the moraine ridges at the valley to the NE of the SAS. The survey was conducted by walking along the lines to map. It is a relatively fast procedure, but with the disadvantage that one must walk all the way along the mapable phenomena.

System setting

A steady GPS antenna was installed in a geodetic point with known coordinates. The antenna was connected to a GPS receiver with RTK and DGPS capability (in the laboratory of the Spanish Antarctic Station), which calculates its position, solves the ambiguities and transmits them via an UHF Radio Modem. For this purpose, both the antenna near the station or one in a nearby hill (Reina Sofia Hill, 270 m ASL) could be used.

GPS antenna

UHF antenna

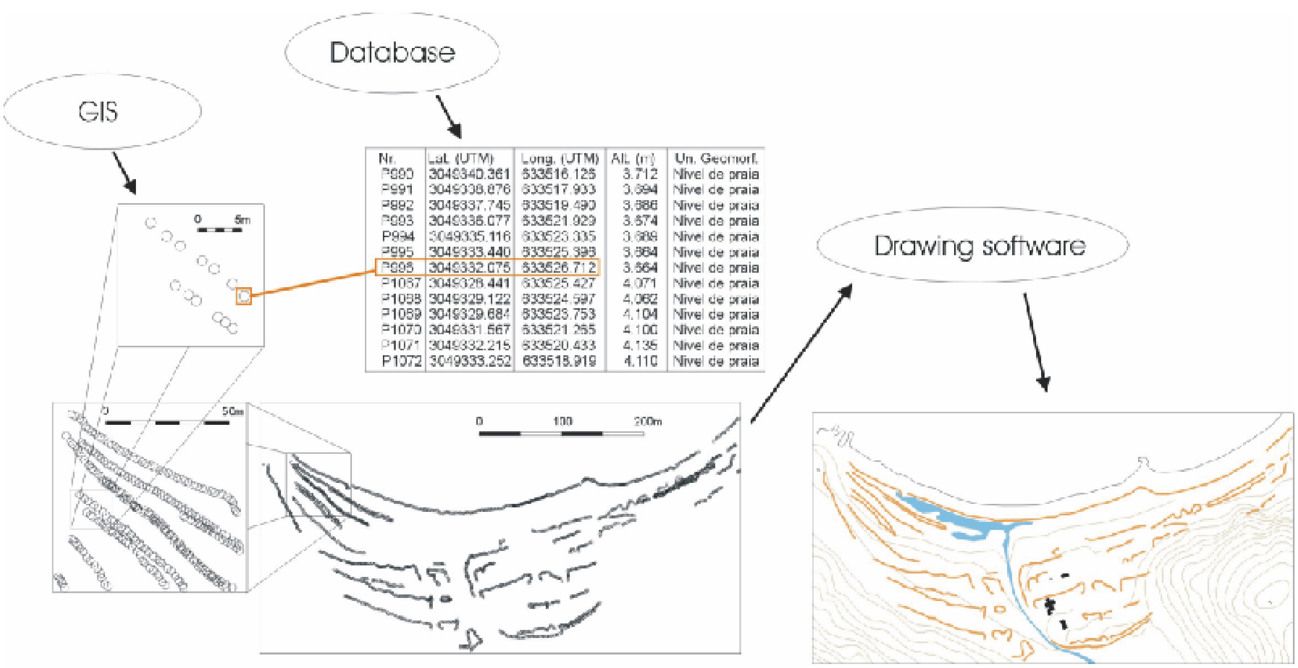
A small receptor in a backpack receives the GPS signal via a geodetic antenna and the corresponding corrections via an UHF antenna. That information allows a fast calculation of the ambiguities and it becomes possible to calculate the position of points with errors under 2 cm. The coordinates are displayed on the screen of a small hand-held computer and saved in the memory. In this way it is possible to reconstruct the track followed by the operator.

GPS backpack

Operator in the field

Field survey

For the detailed geomorphological survey the system was programmed for measuring continuously the coordinates at 1 m intervals as the operator was moving. The chosen paths were saved in memory as sets of individual points representing latitude, longitude and altitude.



General framework of the mapping procedure. Point coordinates are stored in a database and transferred into a GIS as points. Finally the points are exported into a mapping software for the final map. This example corresponds to the mapping of raised-beach scarps in the valley of the Spanish Antarctic Station..

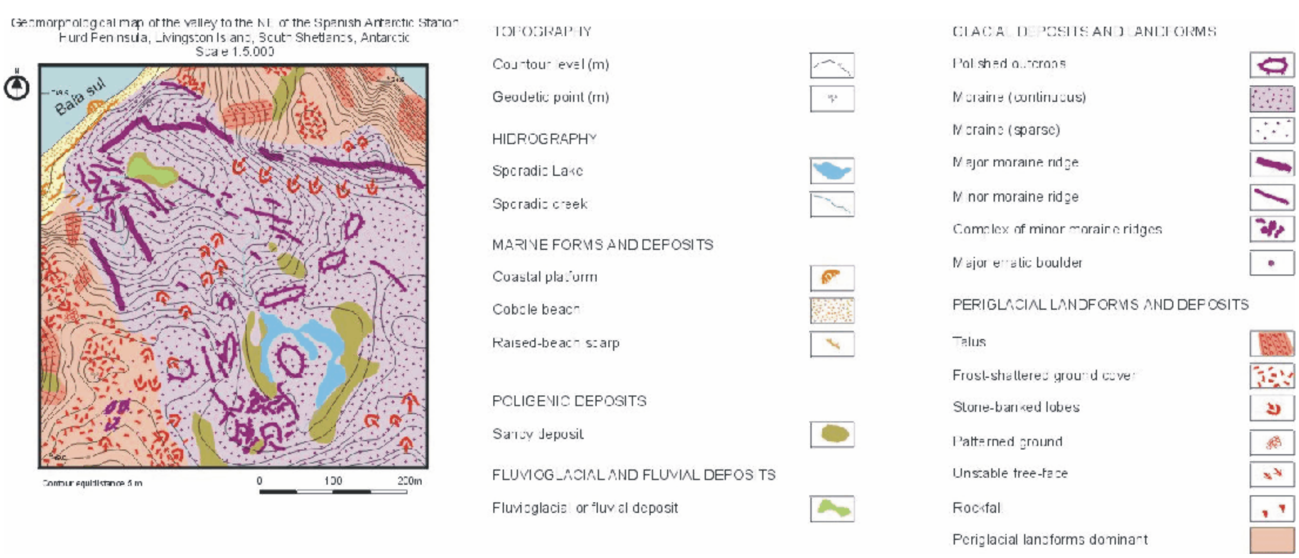
Map construction

The data collected in the field survey was exported into an ASCII table, with the identification of the measurement point number, latitude (UTM), longitude (UTM) and altitude (m ASL). This table was then imported into the Geographic Information System ILWIS 2.2. The coordinates were used to produce a point map that was exported in to a drawing package. The proximity between the points is large enough for drawing the lines that form the cartographic phenomena.

The final geomorphological map was constructed within the drawing package and includes both the information collected with the GPS-RTK system and the classical field survey. The latter is not commented in this note.

The area was mapped before by other authors at detailed scales (MARTÍNEZ DE PISÓN *et al.*, 1991; LÓPEZ-MARTÍNEZ *et al.*, 1992a and b; PALLÀS, 1996). The maps that we present benefit from the information of these works, but contain also new data, especially in what respects to periglacial forms and deposits. The reason why the maps are not completely GPS-RTK based was the scarce amount of time available for the use of the system and the experimental nature of this approach.

It is important to note that the kind of information generated during this survey is very accurate and can be used in much more detailed scales than the 1:5,000. The independent georeferenced data allows a high flexibility for its future use making its application possible in a variety of scales. Furthermore, the use of this kind of system allows a very accurate and fast mapping and a full integration with a GIS. These can be significant factors for its implementation, once despite its relatively high cost, the system has applications for a wide range of mapping purposes in the framework of earth, biological or social sciences. In areas without or with bad topographic maps the GPS-RTK can also be used to generate or to correct the topographic background.



Map example with legend

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Assessent of Chemical Denudation in Cold Environments

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Process

Rapp's (1960) paper on Kärkevagge in northern Swedish Lapland stands out as the study, which opened awareness of chemical denudation in cold regions and is today a classical paper on chemical denudation in periglacial regions. Following Rapp's studies investigations have been undertaken in other cold climate areas such as for example in Colorado (Caine, 1979; Caine and Thurman, 1990), the northern Cascade Mountains (Reynolds and Johnson, 1972), Alaska (Dixon et al., 1984) and Iceland (Beylich 1999, 2000) and besides, in later years investigations have been undertaken again in Swedish Lapland (e.g., Darmody et al., 2001; Thorn et al., 2001; Campbell et al., 2001, 2002; Beylich et al., 2003; 2004a; 2004b; submitted). Yet, even if investigations show that chemical denudation does take place in subpolar, polar and alpine areas to various extent, there is still only little information to reliably assess the general importance of chemical weathering in relation to specific environmental factors such as climate, topography, lithology, regolith thickness and ground frost. Therefore a quantitative investigation of denudation rates requires an integrated approach, combining different methods.

To improve upon the knowledge and understanding of how dilution processes, chemical denudation and water chemistry are related to individual environmental parameters, investigations are needed in a number of confined drainage basins with different but individually homogeneous lithology. In turn, these basins should differ internally with regard to aspect and radiation, slope angles, regolith thickness, ground frost conditions and other factors of importance.

This paper gives an outline of different methods that have been applied and integrated with assessment of chemical denudation in the Latnjajaure confined drainage basin, an arctic-oceanic periglacial test area in northernmost Swedish Lapland. The methods have been presented previously in different contexts together with the related results (Beylich et al., 2003; 2004a; 2004b; submitted) and further details as well as some of the figures and tables referred to can be found in those papers. The present outline focuses on a description of the methods and their combination.

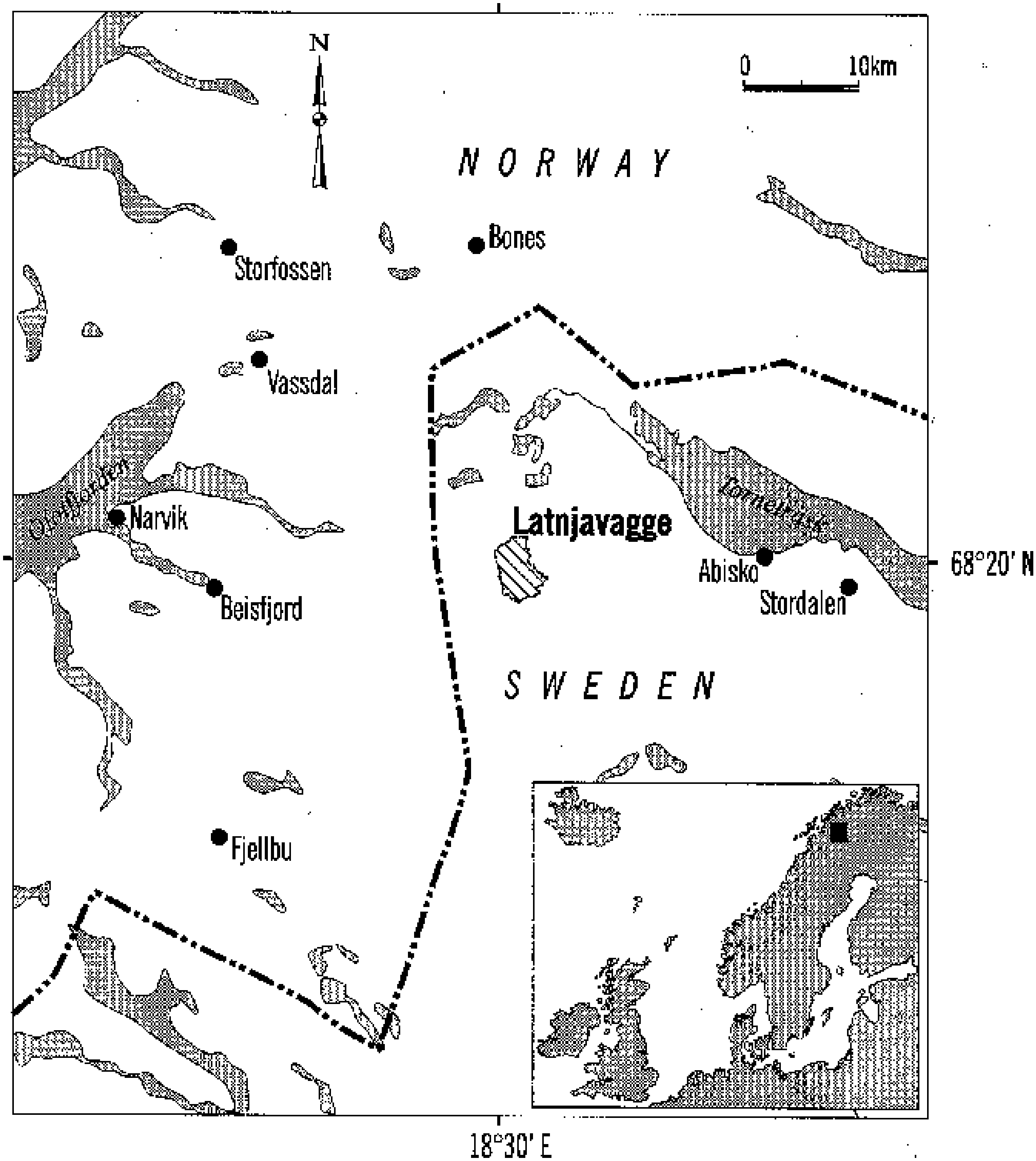

Figure 1. Location of the Latnjavagge drainage basin in northernmost Swedish Lapland.

The Latnjavagge drainage basin

The Latnjavagge drainage basin (Fig. 1) is ca 9 km2, its altitude is between 950 m and 1440 m a.s.l. and the location is 68o20’N, 18o30’E. The mean annual temperature in this arctic-oceanic periglacial environment is -2,3 oC (1993-2001), the mean annual precipitation is 818 mm (1990-2001) (Beylich, 2003). The basin has relatively homogeneous bedrock of mica schist and the regolith is predominantly of local origin. In addition to the small size of the area this makes it possible to regard lithological composition and climate as principally constant parameters over the area. Sub-catchments and sampling sites within the drainage basin (Fig. 2) were selected by means of aerial photographs and detailed field work so that different slope angles, aspects to radiation, regolith thickness, snow cover duration and ground frost conditions are represented.

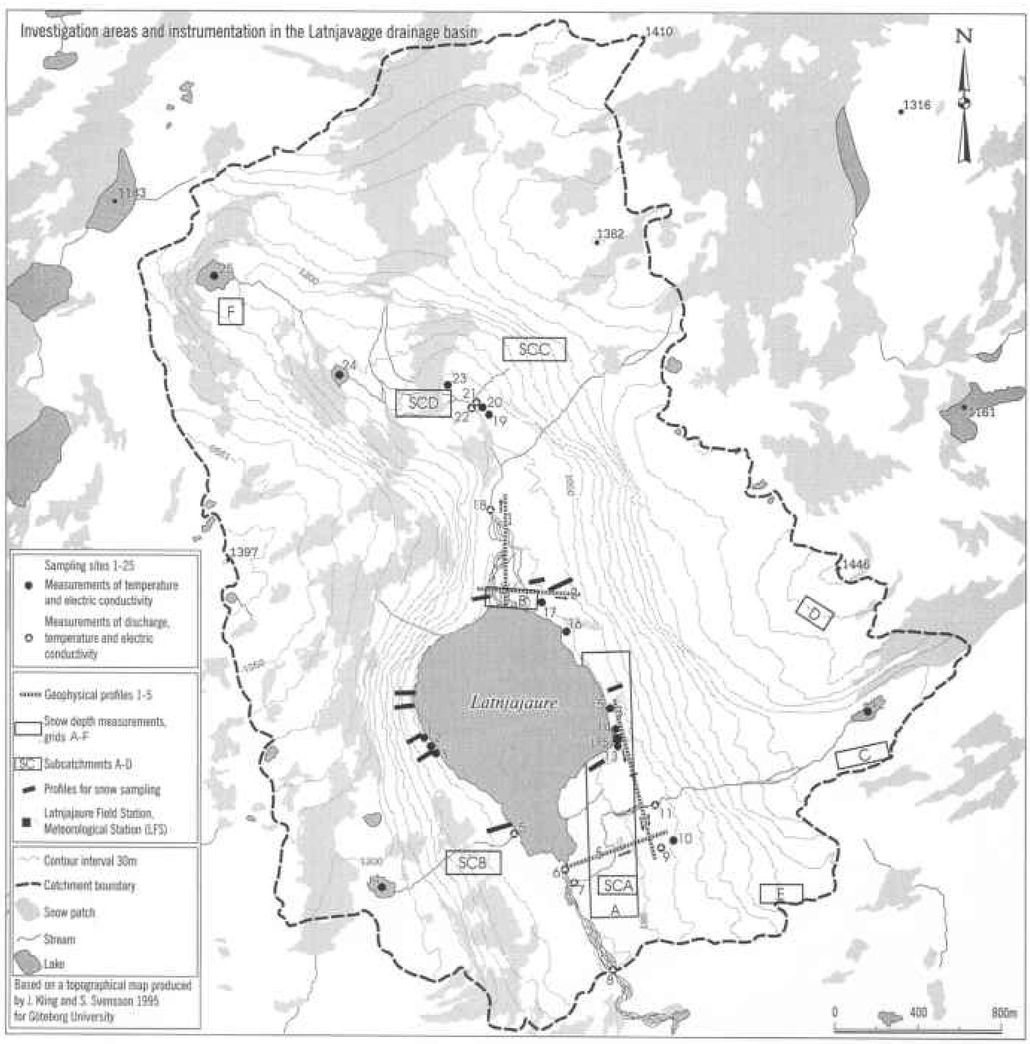

Figure 2. Location of investigation areas, sampling sites and geophysical profiles within the Latnjavagge drainage basin.

Techniques

Quantification of solute inputs

Calculation of net chemical denudation rates requires quantification of atmospheric solute inputs into the defined catchment area. The basis for a reliable quantification of solute inputs is measurement of total annual precipitation. Precipitation was measured with a Hellmann totalisator (surface area 200 cm2) installed 1 m above ground and with wind shelter (Molau, 2001; 2004). Snow cores from the annual snow pack were taken along defined profiles (Fig. 2) before the beginning of snow melt in spring (Beylich et al., submitted). The precipitation samples and snow core samples were filtered in the field laboratory with a portable pressure filter and Munktell quantitative filter papers (OOH).

A quick method to calculate total dissolved solids (TDS) in precipitation and melted snow samples is to measure the electric conductivity of the water. In Latnjavagge this was done by means of a portable conductivity meter (Cond 315i/SET, WTW Weilheim) corrected to 25 oC. The conductivity values (µS/cm) multiplied by a factor (in our area 0.7, see also Strömquist and Rehn, 1981; Darmody et al., 2000) can provide information on total dissolved solids (TDS) [mg/l] values. Atmospheric solute input rate (mean weighted TDS concentration in wet deposition [kg km-2 y-1]) can then be calculated from the annual precipitation for an area of known size (Barsch et al., 1994).

Atmospheric input of solutes (wet deposition) over four years in Latnjavagge is given in Table 1 (at end of this chapter).

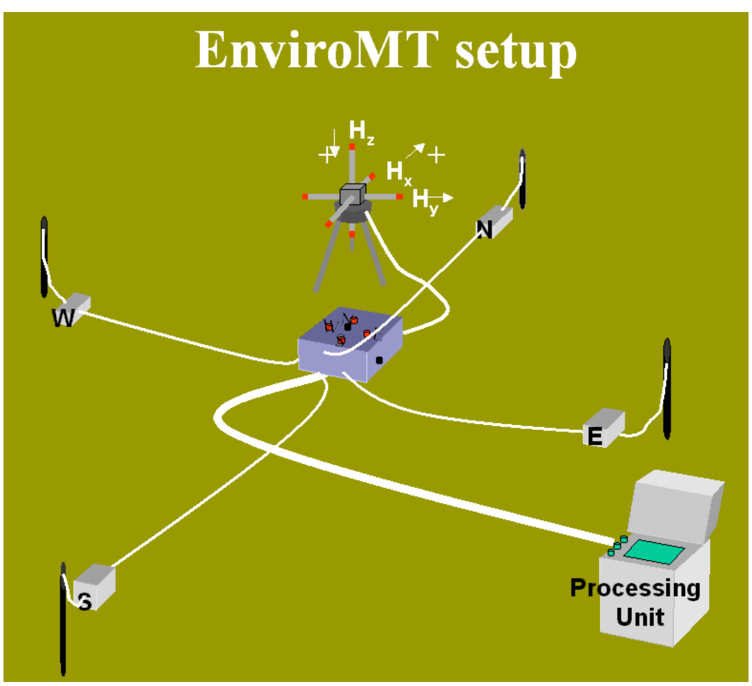

Figure 3. . Illustration of the geophysical equipment: Schematic of the field layout for RMT measurements.

Quantification of solute yields and annual net denudation rates

Calculation of net chemical denudation rates requires information on atmospheric solute inputs and quantification of solute concentrations in surface water and of runoff from the defined catchment area. This requires information on channel discharge and surface water chemistry.

Hydrological measurements and sampling for chemical analysis were conducted over the entire arctic summer from the beginning of snowmelt in late May until the beginning of September. The analyses for discharge and water chemistry presented below are simple and therefore applicable in the extreme climatic and topographical conditions of the remote test area. The methods allow a high spatial density of daily measurements but are work intensive. The techniques were used according to the general regulations given in, for example, Barsch et al. (1994).

Discharge from several channels and at sub-basin outlets was measured three times daily with an Ott-propeller C2 (Ott GmbH & Co. KG, Kempten) immediately prior to sampling of water. The stream velocity was measured at defined channel cross-sections at horizontal distances of 10 cm along each cross-section and at 60% depth of the total water depth at each measuring point. Velocity isolines over the entire channel cross-sections were calculated by interpolation. Discharge [m3 sec-1] was calculated by multiplying the velocity [m sec-1] by the corresponding cross-section area. Daily discharge [m3 d-1] for each channel was estimated by interpolating the three daily measurements. Daily specific runoff [mm d-1] was then calculated from the daily discharge data in relation to the contributing (sub-)catchment areas (see Beylich, 1999). Installation of fixed gauge stations was not possible because of the characteristics of the channels (bedrock and/or larger blocks, shifting channels during snowmelt, slush flows) and the remote locations of the measuring sites. At each of the sampling sites (Figure 2) surface water electric conductivity was measured by the portable conductivity meter mentioned above. Total dissolved solids of surface water was calculated in the same way as for the input water, and mean daily TDS values [mg/l] could then be found. Annual gross yields [kg km-2 yr-1] for confined sub-areas as well as for the entire catchment could then be calculated.

The resulting annual net yields for the basin (= chemical denudation rates [kg km-2 yr-1]) were found from the difference between total annual output and input values and a yearly mean was calculated for a measurement period of three years.

Water and rock chemistry

Following the conductivity measurements water chemistry analysis was done to detect the composition of ions for comparisons between precipitation and surface water (Beylich et al., 2004b).

A total of 205 samples from the different surface water sampling sites (sampling with 1000 ml, wide-necked polyethylene bottles), the precipitation (collected by the Hellmann-Totalisator) and from the snow packs were stored in 200 ml polyethylene bottles in a freezing box after the samples had been filtered (see above). The samples were kept frozen until they were analyzed in the laboratory for different ions. Na+ and K+ were determined with a "Flammenphotometer Eppendorf Elex 6361"; Ca2+, Mg2+, Fe2+, Mn2+ were determined with an AAS Perkin-Elmer 5000. SO42-, Cl- and NO3- contents were measured with an ion chromatograph (DX 100 Dionex) and PO43- with an autoanalyzer II Technicon.

Two fresh and two weathered representative rock samples (mica schist) were collected from, respectively, exposed bedrock and debris at the W- and E-facing valley slopes and were chemically analysed for various major and rare earths elements by SGAB Analytica, Luleå Technical University according to standard G-5. Densities (kg m-3) of the same samples were calculated according to the pycnometer method according to Swedish Standard SS 13 21 24 at the Swedish Geological Survey (SGU), Uppsala. The densities of the fresh samples were clearly higher than the weathered ones and also the chemical components of the two sets differed somewhat (Beylich et al., 2004b). These results were compared to the contents of the water samples for detection of rock mineral components that could have been lost to the water (e.g. CaO). The lanthanides and some other elements in the rocks show a clear loss from fresh to weathered samples, but these components can not be compared with the ion content results from the water analysis and are therefore not included here.

Radio magnetotelluric (RMT)-geophysical method

To assess chemical denudation rates for a defined area the regolith volume needs to be known because it largely determines the contact surface between water and mineral particles during drainage. At the start of the investigation there was no information on regolith thickness in Latnjavagge, but it was known that the regolith consists of poorly sorted material of all grain sizes. It was also uncertain in how far there was permafrost within the basin. Since coring in this stony soil would not have given reliable information, it was decided to make geophysical profiles along selected lines during the late part of the summer when the ground had thawed as much as possible before freezing set in again.

Radio magnetotelluric (RMT)-geophysical method

Geoelectrics are generally suitable in studies of permafrost as frozen ground has a high resistivity as compared to unfrozen sediments. Furthermore, the thickness of the regolith can be determined in case of resistivity contrast between regolith and basement. A comprehensive description of EM geophysics is found in Nabighian (1987, 1991).

A newly developed tensor radio magnetotelluric instrument, EnviroMT (Fig 3) (Bastani, 2001), was applied (see also appendix, photos 1-7) to obtain information on regolith thickness and frozen ground conditions across selected parts of the Latnjavagge drainage basin. The tensor radio magnetotelluric (RMT) method makes use of the electromagnetic fields from distant radio transmitters working in the frequency range 10-250 kHz. At all frequencies unique transfer functions exist (i.e. the impedance tensor) dependent only on the earth`s electrical properties. The impedance tensor enters into the linear relation between the horizontal electric field and the horizontal magnetic field. The transfer functions are immediately displayed in the field as apparent resistivities and phases for the two perpendicular measuring directions used. This allows a first impression of the resistivity structure and the data quality. The system allows 1-D inversion in the field, giving a more direct impression of the resistivity structure than the raw data. The data is later typically inverted using a 2-D inversion code such as REBOCC (Siripunvaraporn and Egbert, 2000) to get a final image of the resistivity structure in the ground as a function of depth and profile direction. Inversion is the process of finding a model that fits the data to a certain level under certain constraints (e.g. smoothness). Even though the earth is generally 3-D, 2-D or even 1-D interpretations are often used because of lack of data or negligible 3-D/2-D effects. A useful introductory text in inversion theory is Menke`s (1984) book.

In the most populated areas of Europe there are usually between 25 and 35 radio transmitters from which sufficiently strong signals in the band 14-2509 kHz can be received. In less populated areas such as parts of the Northern Hemisphere the number is considerably lower. For example, the signal power distributions from Latnjavagge and Central Greenland (68o44’N, 51o12’E) respectively, show that 10-15 and about 6 different transmitters, could be recieved more or less continuously (Figure 4). In spite of this, the number of VLF (Very Low Frequency Band: 3-30 kHz) and LF (30-300 kHz) transmitters is sufficient to make the results reliable for Northern Europe and Greenland.

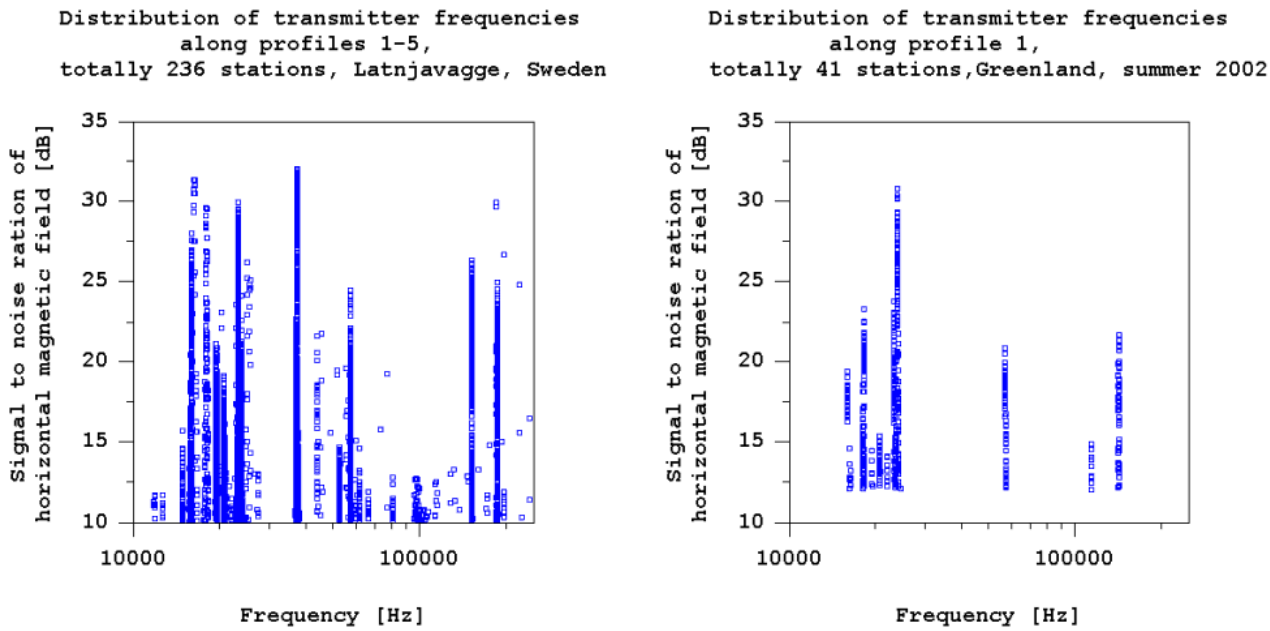

Figure 4: Signal to noise ratio of the horizontal magnetic field as a function of frequency at Latnjavagge, Northern Sweden, and Central Greenland during August 2001 and summer 2002 respectively. The signal to noise ratio is given in decibel units, i.e. 10 log10 ([Power of signal]/[Power of noise]) for a bandwidth of 125 Hz.

The station spacing in Latnjavagge was 10 m. A TSVD (Truncated Singular Value Decomposition) processing scheme (Bastani and Pedersen, 2001) was used to estimate reliable transfer functions based on the original data. Inversion was carried out using the determinant of the impedance tensor, because it is believed to be less affected by 3-D effects than other choices for inversion, using the REBOCC code (Siripunvaraporn and Egbert, 2000). The TSVD data, the predicted data from the model, and the residuals for one of the profiles are given in Beylich et al. (2003, plate 1) as an illustration. The resulting model is given in the same paper.

The RMT technique provides a good resolution of electrically conducting sediments and it is favourable for studying the geometry of the regolith and variations therein because it is fast and has low power consumption owing to the fact that existing radio-transmitters are used as a source, the latter being of particular importance in isolated and remote areas. The well conducting mica shists in Latnjavagge form ideal conditions for mapping the bottom of the regolith with EM methods. A more resistive basement (e.g. granite or gneiss) would make the transition between the regolith and the basement less well determined.

Refraction seismics with explosives at the groundwater level could have been an alternative methodology especially in case of a resistive basement. However, refraction seismics is invasive and trained staff must be employed to carry out the field measurements. DC Geoelectrics is often better in determining high resistivity features, such as permafrost or resistive basements. An inductive method is in this case superior as it would be difficult to get ground contact among the bare bedrock. GPR measurements would be much affected by scattering due to dominance of boulders in the upper part of the regolith. Furthermore, the depth to the basement would probably not be penetrated. In the absence of transmitters controlled source tensor magnetotellurics (CSTMT) is an alternative. CSTMT is comparatively slow, the equipment is heavy and more power is needed. The method would yield little extra information in this application. Other inductive methods are possible as reported by Hauck et al. (2001). Methods such as the VLF method or EM31 are faster than the EnviroMT method, but yield much less information as they only measure at one frequency, whereby the depth to the basement is only weakly constrained. However, such methods are extremely useful for recognisance studies and to assess qualitative changes in the resistivity structure.

EnviroMT works well in remote areas, data and preliminary models can be overviewed in the field, it is non-invasive and could be used to study occurrence of permafrost. However, the equipment is at the present stage relatively heavy and requires two to three persons for operation. It is also difficult to measure in very rough terrain, or where larger creeks and streams must be crossed. Finally, the system does not yet have a correction for changes in altitudes along profiles (Beylich et al., 2004a).

Integration of hydrological, chemical and geophysical data: Examples of results

As illustration of results Figure 5 presents daily precipitation, daily specific runoff, daily water temperatures, daily discharge weighted mean concentrations and daily gross yields of dissolved solids over the 2001 field season at the outlet of Latnjavagge. Table 2 in Beylich et al. (2003) provides water chemistry data from precipitation and snow pack samples together with chemistry data from surface water samples for selected sites within the basin.

The geophysical profiles (see Beylich et al., 2003, Plate 2; Beylich et al., 2004a, Fig. 3) are related to the hydrological measurement and sampling sites. For example, profile 2 which crosses the delta is related to site 18, and profile 3+4 along the west-facing slope of the basin relates to sites 13, 11, 9 and 7.

The solute concentrations and chemical denudation rates in Latnjavagge were generally found to be low but there were significant differences between sub-areas. The geophysical data show a clear distinction between the upper moderately resistive part of the profiles and the lower highly conductive part that represents the bedrock and it thus provides an estimate of regolith thickness along the profiles. The thickness seems to be only a few meters in many places, an impression confirming field observations there. Further, the resistivity of the regolith is too low to indicate presence of large bodies of frozen ground (compare e.g., Isaksen et al., 2000; see also Kling, 1996, 2004; Beylich et al., 2004a).

The combined information provided by the chemical and geophysical data can be used with data along the profiles but also, by extrapolation, to areas further upstream or upslope. For example, pure water with constantly low ion concentrations over the summer and a mean annual denudation rate of only 2333 kg km-2 yr-1 (Beylich et al., 2003; submitted) came from the subcatchment north of Latnjajauare (site 18, Table 2). Geophysical profile 2 (Plate 2 in Beylich et al., 2003) shows that across the delta there was no permafrost in August. Yet, the ground in most of the basin was frozen during the early part of the summer. As the water yield and TDS values of August do not differ much from those of previous months after snow melt it seems that (most of) the thin regolith of this upper region would have to be frozen during the whole field season in order to maintain such low values. This is in agreement with the shaded position and the longer duration of snow cover in part of this sub-catchment, which makes up the coldest part of the Latnjavagge catchment (Beylich et al., 2003; 2004b; submitted). The water chemistry data indicate that there must have been some chemical weathering in this upper catchment as the TDS values and the chemical composition of the drainage water deviate from those of the rain water (see also Beylich et al., 2004b).

From soil temperature measurements at Latnjajaure Field Station (Molau 2001; 2004) it was known that the lower slope segment along the eastern shore of Latnjajaure had ground temperatures above 0oC shortly after the melting of the snow in early June (Beylich et al., submitted). In the measurement sites (e.g., 9 and 13) on this slope the TDS values were comparatively high already from the early part of the season and further increased until late July after which they remained at about the same level, although fluctuating. The geophysical profile indicates that there was probably no frozen ground in August along the lower slope segment, and it is therefore likely that this radiation exposed area thawed comparatively early and remained unfrozen over the summer, and that even the upper parts of the slope had thawed by late July. This impression is confirmed by the chemical composition of the water from this slope: There are relatively higher values of ions that are not related to rain water, especially of Ca2+, and as a consequence, the chemical weathering in this part was comparatively intense.

In the southeastern part of the Latnjavagge drainage basin, in sub-catchment A (Fig. 2), the mean annual chemical denudation rate is 7894 kg km-2 yr-1. In the surface water at sampling site 7, which integrates values from the sub-catchment, the ion concentrations became gradually higher during the summer to reach relatively high concentrations during the late part of the season. The geophysical investigation suggests a relatively thick unfrozen regolith for August and from the combined data, including the increasing TDS values during the field season, it therefore seems that the ground had had time to gradually thaw during the summer and that water could percolate freely through the whole regolith during the late part of the season.

It is, however, also possible to distinguish differences within sub-catchments: Sampling site 9 compares well with site 13 in having high TDS and ion values over the summer. In contrast, a comparison between data at the inlet to Latnjajaure (site 18, geophysical profile 2) and the corresponding data at site 11 (within sub-catchment A) shows that even if there is thick unfrozen regolith in A as indicated by the geophysical profile, the chemical values at site 11 are more similar to site 18 than to site 9; i.e., site 11 is regarded as representative of the relatively inactive conditions further upstream where there was still snowmelt during August. The combined data sets can thus help to point out areas with comparably high chemical activity such as radiation-exposed and/or relatively gently sloping west-facing slopes with early snow melt and thick, unfrozen and possibly also rather warm vegetated regolith on the one hand and areas of thinner and colder regolith in areas of more shade and/or greater elevation on the other, even if such areas are not directly crossed by the geophysical profile.

A further potential of the combined methods could be to relate the regolith volume and the ground temperatures in defined sub-areas to the TDS values measured in outlets along the slope and/or from sub-catchments in order to arrive at more quantitative results on factors controlling chemical denudation rates. Yet, the variable regolith thickness along terraced slope systems and along differentially eroded slopes require a high number of geophysical and ground temperature measurements.

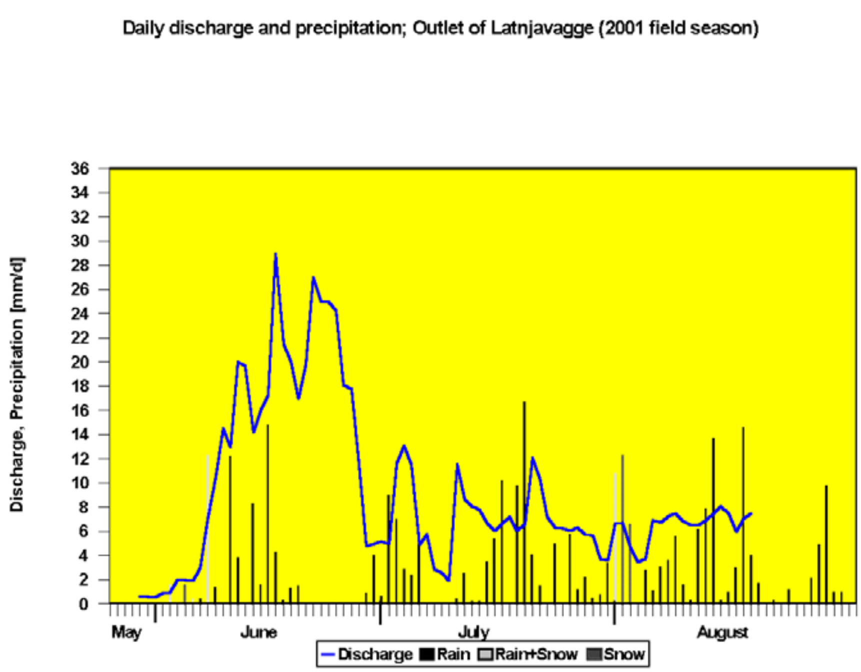

Figure 5.1

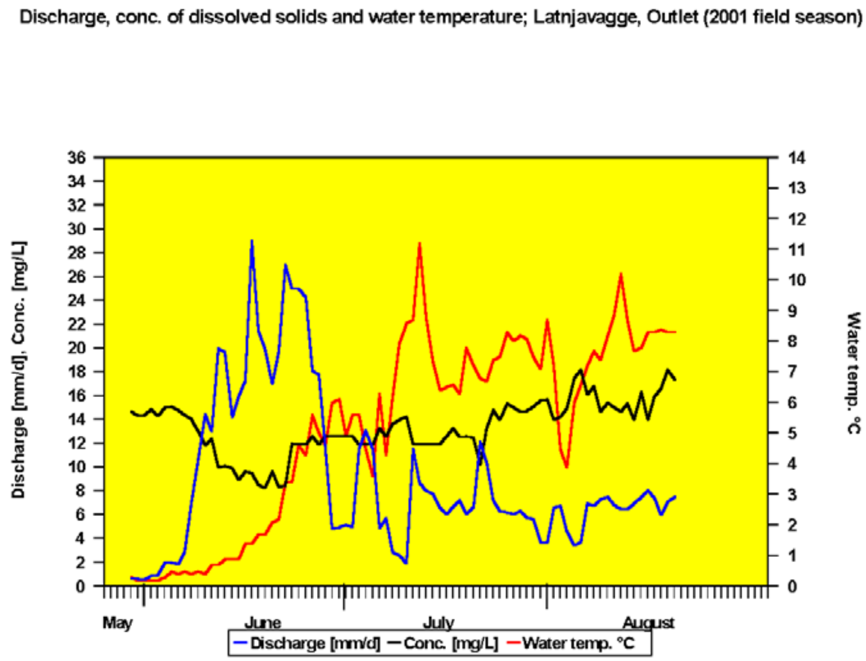

Figure 5.2

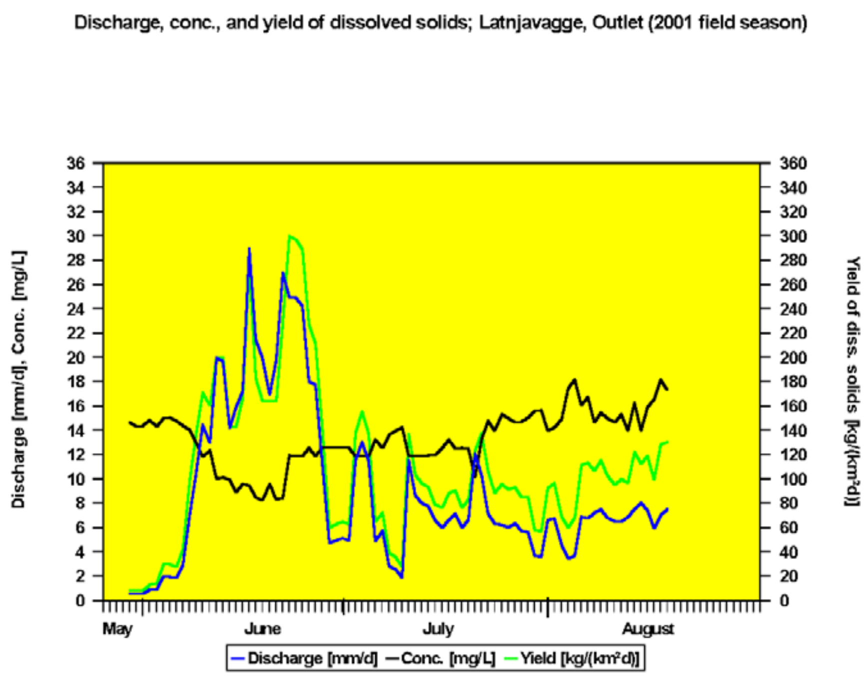

Figure 5.3

Figure 5. Daily precipitation, daily specific runoff, daily water temperatures, mean daily discharge weighted mean concentrations (TDS) and daily gross yields of dissolved solids over the 2001 field season at the outlet of the Latnjavagge drainage basin (sampling site 8 in Fig. 2).

Conclusions

The combination of hydrological, chemical and geophysical methods applied in Latnjavagge stresses the advantages of combining different investigation methods when studying temporal and spatial variability within even small catchments of homogeneous lithology. The combination can be used with assessment of regolith thickness in well-defined areas as well as of presence or absence of frozen ground conditions. Further, integration of the methods can provide a basis to assess surface water and subsurface discharge conditions within confined areas; and changes in the TDS values over the summer in combination with geophysical data representative of the late part of the season can also be used to detect how ground frost conditions have changed over the season not only along the location of the sampling sites and geophysical profiles, but also in upslope and upstream source areas.

Finally, comparisons between sub-areas of homogeneous lithology by means of the applied methods can help to assess the importance of individual environmental parameters such as for example the influence of slope aspect to radiation, ground frost or regolith thickness for the intensity of chemical weathering and the rate of chemical denudation in selected periglacial areas.

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Total period	Sub-period	Sampling	Number of samples	Concentration of diss. solids [mg l⁻¹]	Total precipitation [mm]	Atmospheric solute input [kg km⁻²]
01.10.1999 - 30.09.2000	01.10.1999 – 31.05.2000	Snow cores (taken in May/June)	60	Mean: *3.52* Max: 4.35 Min: 3.11	764.6	2691.4
	01.06.2000 – 30.09.2000	Precipitation (gauge at LFS)	66	Mean: *6.15* Max: 13.79 Min: 1.47	304.8	1874.5 Total: **4565.9**
01.10.2000 – 30.09.2001	01.10.2000 – 31.05.2001	Snow cores (taken in May/June)	65	Mean: *3.64* Max. 4.26 Min. 3.21	356.4	1297.3
	01.06.2001 – 30.09.2001	Precipitation (gauge at LFS)	58	Mean: *4.87* Max: 14.84 Min: 2.10	325.4	1584.7 Total: **2882.0**
01.10.2001 - 30.09.2002	01.10.2001 - 31.05.2002	Snow cores (taken in May/June)	25	Mean: 3.54 Max: 4.20 Min: 3.08	748.2	2648.6
	01.06.2002 - 30.09.2002	Precipitation (gauge at LFS)	-	Mean: *5.51* (mean of 2000 and 2001)	296.2	1632.1 Total: **4280.7**
01.10.2002 - 30.09.2003	01.10.2002 - 31.05.2003	Snow cores (taken in May/June)	52	Mean: 3.58 Max: 4.31 Min: 3.12	472.6	1691.9
	01.06.2003 - 30.09.2003	Precipitation (gauge at LFS)	32	Mean: 5.89 Max: 16.02 Min: 2.94	399.3	2351.9 Total: **4043.8**

Table 1. Atmospheric solute inputs in Latnjavagge (1999/2000 – 2002/2003).

Frost heave: monitoring with strain gauge transducers

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Automated monitoring of frost heave on sorted stripes in the Swiss Alps.

Background

Frost heave is a fundamental periglacial process dominating over soil surfaces in cold regions. On periglacial slopes, frost heave is followed by mass movements including frost creep, gelifluction, debris flow and active layer detachment slides. The repetition of frost heave and thaw consolidation also produces periglacial features such as solifluction lobes, sorted patterned ground and earth hummocks. Field monitoring of frost heave (see figure above) allows us to understand these geomorphological features and to estimate the potential frost creep (PFC), which is given by PFC = H tan θ, where H is the heave amount and θ is the slope angle.

A number of attempts have been undertaken on measuring frost heave. The remoteness of the research sites with periglacial features, however, have hindered long-term, continuous measurements with a highly instrumented monitoring system, because such locations are normally visited only once to several times per year and electricity is not available.

Field measurements during the 1960's addressed the annual heave amount of heaved targets (Washburn, 1967; Benedict, 1970), but the amount tended to underestimate the actual value because the targets may have failed to record partial settlement during thawing. Measurements during the 1970's-1980's used "the bedstead" as an anchored frame on which a mechanical recorder is fixed

(Fahey, 1973; Smith, 1987; Matsuoka and Moriwaki, 1992). A soil heave curve was drawn on a rotating sheet. This technique allowed continuous recording of heaving, but low resolution (at most 0.1 mm) and frequent mechanical troubles prevented acquisition of long-term, high-quality data.

Since 1990's, electrical sensors connected to data loggers have allowed high resolution, continuous recording of frost heave, and this system requires only annual maintenance (e.g. Matsuoka, 1996; Matsuoka et al., 1997; Hallet, 1998). This report introduces an example of such electric measurements used on high mountains.

Techniques

The figure below illustrates an instrumentation in the field. Soil heave with reference to a fixed point is recorded with a sensor attached to a bedstead anchored in subsurface permafrost or bedrock. An angle iron frame is commonly used as a bedstead. Upheaving of the angle iron legs is avoided by inserting the base of legs well into the bedrock or permafrost, with the aid of an anti-heaving material (e.g. timber or concrete) attached at the base. Where such a subsurface hard bed (bedrock or permafrost) is absent, the base of the bedstead has to be installed deeply in sediments, at least below the seasonal frost depth. Where a deep snow cover (> 2 m) is expected, the frame has to be reinforced to resist snow pressure, for instance, using a three-dimensional frame.

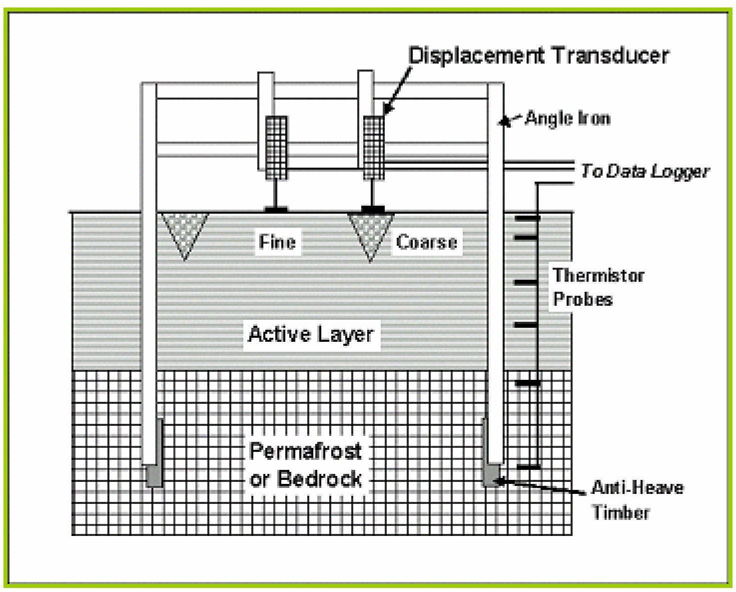

Fig. 2. Field monitoring of differential heave on sorted pattern ground.

A displacement transducer senses soil heave. The capacity of the transducer should exceed the expected maximum heave amount. The use of a single transducer allows recording of 1D (vertical) soil movement, while a combination of two intersecting transducers permits recording of 2D displacement (cf. laboratory techniques by Harris et al., 1997). Matsuoka (1996) and Matsuoka et al. (1997, 2003) use a commercial strain-gauge type transducer (DT-100A) manufactured by Kyowa Electronics, Japan. This sensor can record displacement up to 10 cm at a resolution of 0.04 mm. Since strain gauges show some temperature dependency (usually negligible compared with heave amounts), calibration may be required. A plate (a few cm in diameter) is attached at the base to sense planar heave. Subsurface heave can be measured by installing the base at a depth below the surface. A spring in the sensor enables elastic response to settlement of the heaved surface. However, the spring may in turn exert pressure to the soil. For example, the DT-100A sensor presses the ground with a 450 gf force, which often results in slight penetration of the basal plate into the soil softened during thawing (e.g. Matsuoka et al., 1997). Waterproofing is also necessary, where snow meltwater is significant.

The strain-gauge type sensor requires a date logger having strain inputs. The strain readings are translated to heave amounts using a correction factor. The detailed process of heave and settlement can be evaluated by a concurrent measurement of soil temperatures at various depths (Fig. 2). Diurnal frost heave cycles are detected by recording at 1 to 3-h intervals. Shorter intervals are required to detect detailed differential heave, for instance, between fine and coarse stripes of patterned ground.

Examples of field monitoring

1. Timing and amount of heave in the Japanese Alps (Matsuoka, 1996).

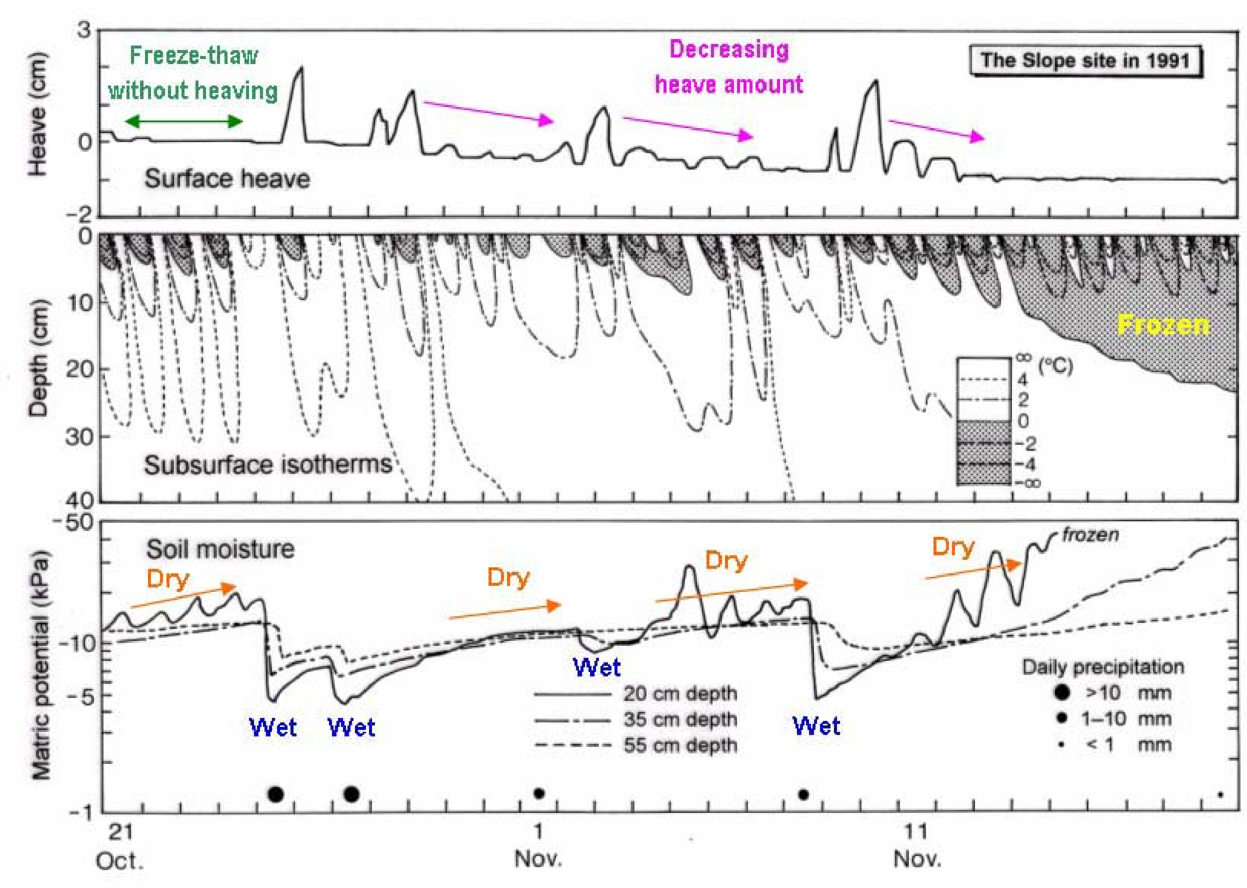

Fig. 3. Soil heave, temperature and moisture during the autumn freeze-thaw period of 1991 on a debris slope (2880 m ASL), southern Japanese Alps.

Diurnal frost heave activity was monitored on debris slopes subject to deep seasonal freezing (1-2 m) in the southern Japanese Alps. Figure 3 displays results on a 30° slope during an autumn freeze-thaw period. A comparison between data on the heave amount, frost depth and soil moisture shows frequent heaving up to 3 cm with shallow freezing (< 10 cm). Not all freezing events result in heaving. Moisture supply controls heave amounts more critically than the diurnal frost depth. Despite nocturnal sub-freezing temperatures soil desiccation does not allow heaving after continuous sunny days. In contrast, the heave amount reaches a maximum when soil freezing immediately follows precipitation (rain or snow) and then decreases with soil desiccation.

Frequent cycling of heave and settlement in the topsoil is responsible for shallow but rapid soil creep with a surface velocity in places exceeding 50 cm/a (Matsuoka, 1998). Such a movement eventually produces small-scale periglacial features including thin stone-banked lobes and small sorted stripes, which are widespread on low- to middle-latitude high mountains (e.g. Bertran et al., 1995; Matsuoka, 2001).

2. Differential heave on sorted stripes in the Swiss Alps (Matsuoka et al., 2003).

Small-scale sorted patterned ground (with a diameter or spacing less than 30 cm) in which sorting occurs within the top few centimeters of soil is considered to reflect diurnal frost heave cycles. Differential heave, rather than soil convection requiring a high moisture level, is likely to be responsible for such small stripes (e.g. Werner and Hallet, 1993). However, previous field studies have rarely linked differential heave to the formation of small patterns, with a notable exception of a field experiment by Ballantyne (1996).

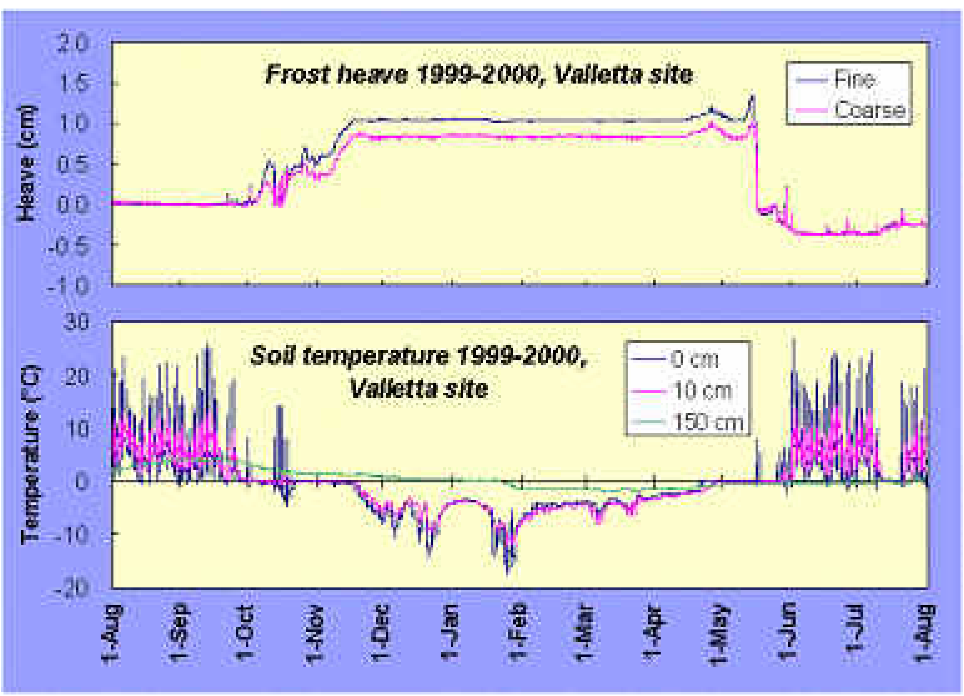

Fig. 4. Soil heave and temperatures in 1999-2000 on small-scale sorted stripes, Valletta site (2810 m ASL), the Swiss Alps.

An attempt has been done to monitor differential heaving between coarse and fine stripes on a limestone hill in the Swiss Alps (Fig. 1; Matsuoka et al., 2003). Here the ground undergoes both frequent diurnal heave cycles and an annual heave cycle (Fig. 4). The seasonal heave amount (ca. 1 cm) is similar for the coarse and fine stripes. Differential heave mainly accompanies diurnal freeze-thaw cycles. Figure 5 shows the amount and timing of diurnal heave sometimes differ between the two stripes. In particular, shallow freezing with needle ice formation seems to be most responsible for the differential heave amount, because needle ice occurs only on the fine stripe. In addition, the surficial coarse material delays heaving of the subsoil below the coarse stripe, causing a time lag in heaving between the two stripes. Such a time lag may enhance sorting, because the earlier heave on the fine domain favors transport of coarse debris on to the coarse border by toppling of needle ice.

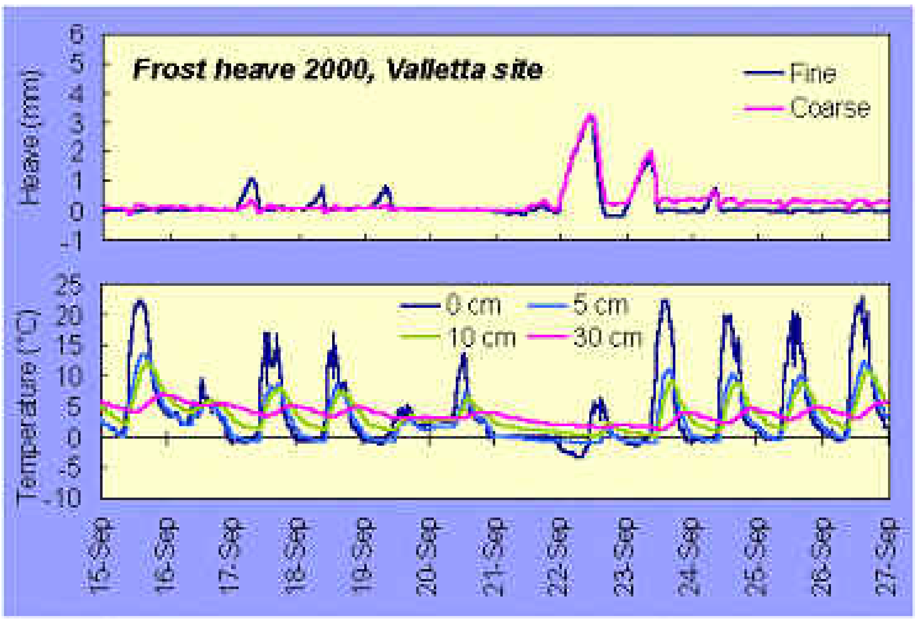

Fig. 5. Soil heave and temperatures during the autumn freeze-thaw period of 2000 at Valletta site.

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Cold Climate Weathering

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Processes

In cold regions, especially where lacking vegetation, physical weathering processes dominate fragmentation of rocks and characterize the periglacial landscape. Of these processes, frost weathering (rock breakdown by ice action) prevails where moisture is abundant, while salt or insolation weathering becomes more important where moisture is limited. The weathering products range from boulders to silt-clay size materials, depending on the types of fragmentation, such as wedging in pre-existing cracks, surface flaking and granular disintegration along mineral boundaries.

Cold climate weathering has been studied in both the field and laboratory. Early studies emphasized the predominance of frost weathering and production of angular blocks. The pioneering laboratory work by Tricart (1956) has been followed by a number of experiments exploring the contribution of environmental and geological factors to frost weathering (e.g. Lautridou and Ozouf, 1982). Whereas early researchers regarded the 9 % volumetric expansion upon phase change as the major cause of rock breakdown, recent theoretical and experimental studies have highlighted ice segregation in rocks, similar to frost heave in soils (e.g. Walder and Hallet, 1985; Akagawa and Fukuda, 1991). Long-term ice segregation may produce brecciated bedrock near the top of permafrost (Murton, 1996; Murton *et al.*, 2000). Laboratory results have often been used to analyze field data (e.g. Thorn, 1979). Field data on bedrock shattering, temperature, moisture and rock mass strength have been integrated to construct an empirical model of the rate of frost weathering (Matsuoka, 1991).

Whereas numerous field observations suggest that frost weathering prevails on humid rocks subjected to meltwater from nearby snowpatches (e.g. Berrisford, 1991) or located close to water table (e.g. Matthews *et al.*, 1986), recent studies demonstrate that other weathering processes dominate depending on the environmental and geological conditions. In the Antarctic cold desert, for instance, the primary weathering process varies with aspect (intensity of insolation or exposure to the prevailing wind), moisture availability and lithology (e.g. Hall, 1992; Matsuoka *et al.*, 1996). Hydration weathering is operative even far below 0 degree C preferably in argillaceous rocks, possibly controlled by the adsorptive clay composition (Dunn and Hudec, 1972). Water chemistry indicates that chemical weathering is also significant even in non-karstic cold regions (e.g. Caine, 1992; Darmody *et al.*, 2000).

Techniques

Review

Field measurements on cold climate weathering should target both process itself and controlling factors. Field data on the former have been only sporadic because weathering progresses so slowly that long-term monitoring is necessary. The most popular method for estimating the rate of weathering is to measure the volume of rockfalls from a rockwall using a trap (e.g. Rapp, 1960; Church *et al.*, 1979; Fahey and Lefebure, 1988). Another method is to investigate the fragmentation of a painted rock (Matsuoka, 1991; Mackay, 1999). Despite permitting direct determination of the rate of rockwall retreat, these manual methods require frequent field visits when seasonal variation in the rate is determined. Indirect measurements include the exposure of rock tablets to a variety of field situations (e.g. Matsuoka *et al.*, 1996). Removing the influence of lithological variation, this method highlights environmental controls on the rate of weathering.

Recent advances in data logging technology have enabled automated, continuous recording of weathering processes. A relevant contribution has been provided by monitoring of strain in alpine rockwalls, where significant damage of rocks and frequent rockfalls are actually observed. Recorded movements include widening of rock joints on a rock face (e.g. Matsuoka *et al.*, 1997) and dilatation in bedrock permafrost (e.g. Wegmann and Keusen, 1998), both indicating expansion of rock joints associated diurnal and/or seasonal freezing.

Parameters controlling cold climate weathering have often been measured separately. Rock temperature has most widely been measured by installing thermal probes (thermistor, thermocouple, etc.) in the bedrock (e.g. Thorn, 1979; Coutard and Francou, 1989; Gardner, 1992). The probes are connected to a data logger that can store 10^3-10^5 data. Sampling intervals are usually set at 1-3 hours when frost weathering is evaluated, while 1-minute intervals are preferred for the analysis of insolation weathering that is most effective when the rock surface is warmed or cooled at >2 degrees C min^{-1} (Hall, 1997). Monitoring of near-surface thermal profiles is essential to determine the depth reached by fracturing (e.g. Matsuoka, 1994; Anderson, 1998).

The second parameter is the moisture content of rocks. Where the rock surface is distant from the water table, water migration and resulting ice segregation are limited and a high initial saturation level (>80 %) is required for significant frost weathering to occur (e.g. Prick, 1997). Where moisture is restricted during the freeze-thaw period, other weathering processes would be more effective, although slow seasonal freezing may allow slow but long-lasting water migration that eventually produces ice lenses at a certain depth in the bedrock. The rock moisture has been determined manually by weighing a rock tablet placed at a field situation (e.g. Hall, 1988; Humlum, 1992). This technique requires an observer staying in the field over the expected weathering period. Other manual measurements include the collection of seepage water from rock joints (Fahey and Lefebure, 1988). Automated measurements (e.g. with TDR sensors) are preferable but under development (Schneebeli *et al.*, 1995).

Rock properties are another parameter governing cold climate weathering. As regards frost weathering, physical properties such as porosity, permeability and specific surface area contribute to the ice pressure, while tensile strength determines the resistance against the ice pressure (Matsuoka, 1990). In the field, a crucial rock property is the degree of fractures, because the most effective damage occurs in the pre-existing fractures in the bedrock (e.g. McGreevy and Whalley, 1982). The seismic measurement enables us to estimate the strength of fractured bedrock (Matsuoka, 1991). Point-load compressive strength and Schmidt Hammer rebound are indicative of the inter-joint strength of bedrock (e.g. Hall, 1987).

Combined measurements of several parameters provide data for understanding the timing and trigger of rock disintegration. For instance, monitoring of rock temperature, water seepage and rockfall volume highlighted the contribution of thermal and moisture regimes to the rockfall activity (Fahey and Lefebure, 1988).

Examples of Recommended Measurement Techniques

Since the rate and process of rock weathering vary seasonally, year-round automated measurements are recommended. In addition, detailed analysis of processes requires simultaneous measurements of rock disintegration and its variables. The crack extensometer (Figure 1a) is a useful tool for measuring frost wedging in a rock joint (see Appendix for details). Where winter snowcover exerts significant pressure, the sensor should be protected (Figure 1b). Thermal probes are installed in the joint or boreholes as well as attached to the sensor. The latter provides data for calibration against the thermal drift of the extensometer. Figure 2 displays data from an alpine rockwall, which demonstrate joint widening associated with cooling below 0 degree C in the joint (Matsuoka, 2001).

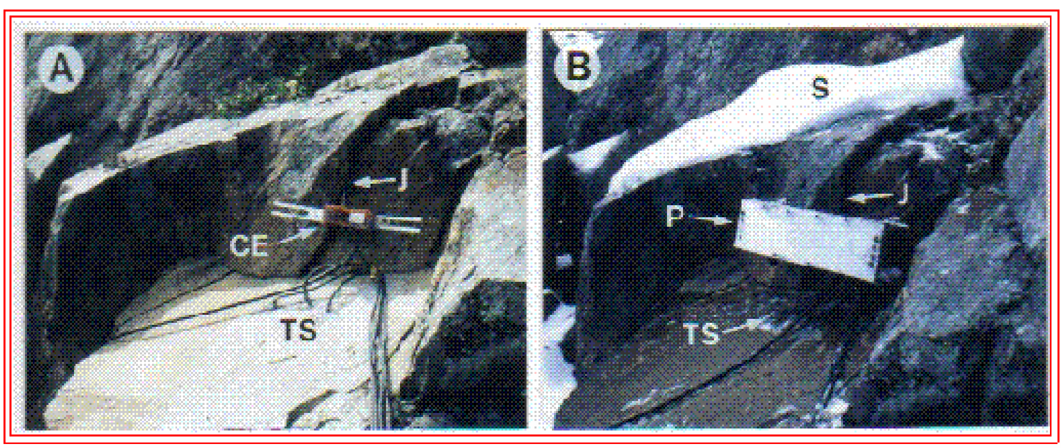

Figure 1 The crack extensometer (CE) for measuring widening of a rock joint (J). The protector (P) minimizes possible pressure from winter snowcover.

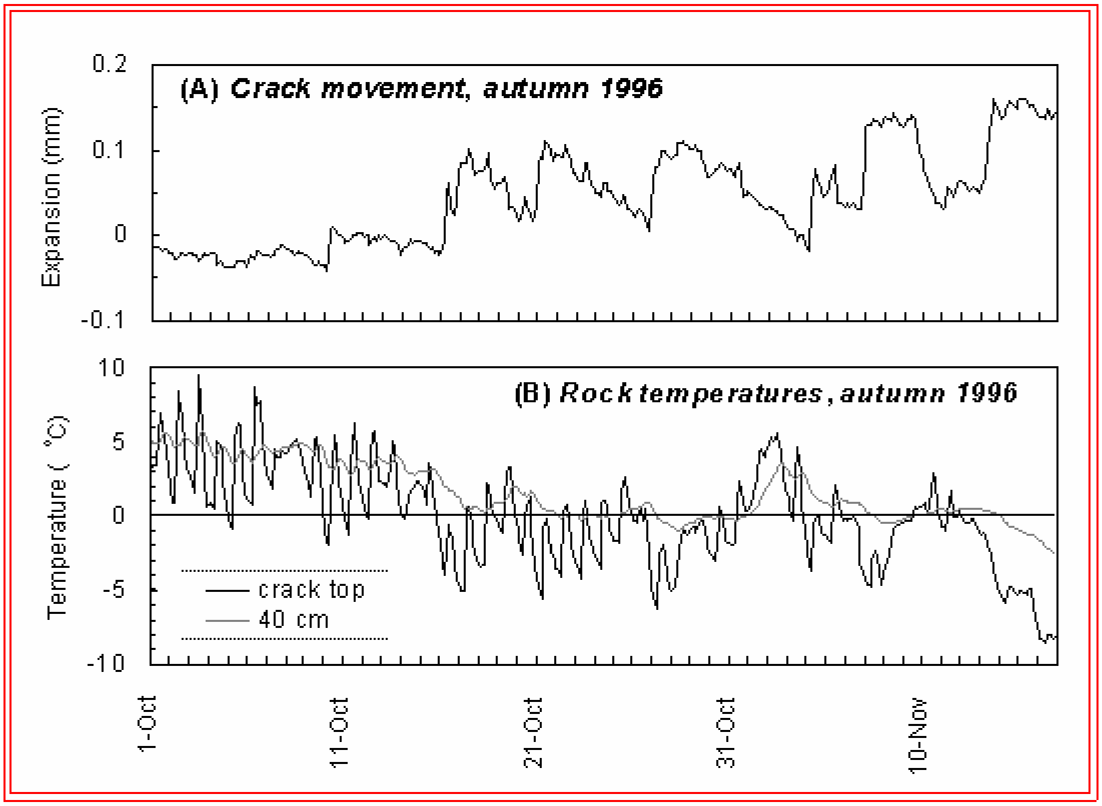

Figure 2 Joint widening (a) and associated change in rock temperatures (b) during a freeze-thaw period in autumn. The data were obtained from an alpine rockwall in Japan (the same site as in Figure 1).

Another useful method is to expose rock tablets to a variety of field situations. This method is useful for exploring environmental factors affecting small-scale disintegration. The tablets are prepared in the laboratory to have the same size and lithology. In order to obtain significant results within a few years, we should choose lithology sensitive to weathering (i.e. rapidly broken in the laboratory). In addition to periodical measurements of weight loss of the tablet, automated monitoring of dilatation using a strain gauge, with simultaneous recording of temperature, allows us to detect progressive rock deterioration and the thermal regime at which the tablet cracks. A global monitoring network using the same lithology will provide data source for establishing the quantitative relationship between climate and weathering rate.

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Appendix

The crack extensometer

The crack extensometer measures movement of a crack with strain gauges. A commercialized example is the crack extensometer BCD-5B (Figure 3) manufactured by Kyowa Instruments, Japan: cost ca. US$ 300. Similar sensors may be purchased from other companies dealing with strain gauges. The BCD-5B sensor consists of a curved steel strip connecting two steel bars. Widening of the crack reduces the curvature of the curved strip, which is recorded as a change in electric resistivity of two strain gauges attached to the strip. Two bolts anchored in boreholes at both sides of the crack allow us to fix the steel bars to the bedrock. This sensor detects widening of a crack of up to 10 mm with a resolution of 2.5×10^{-3} mm.

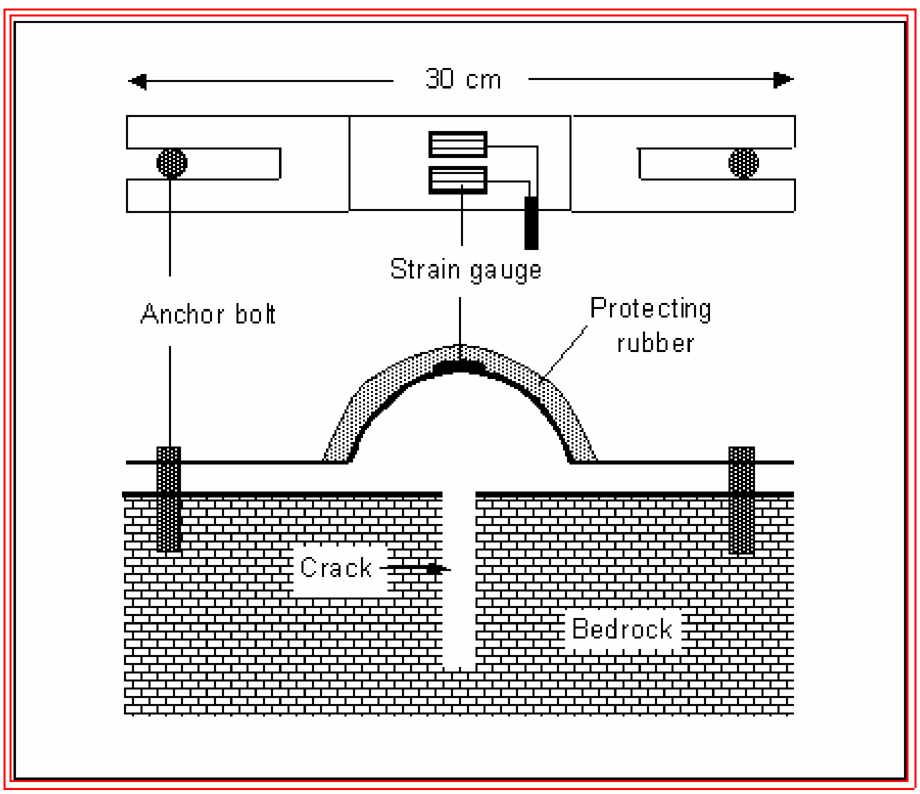

Figure 3 The crack extensometer BCD-5B.

The extraction of frost-induced strains from the extensometer readings requires the elimination of three kinds of thermally driven strains, which originate from the expansion/contraction of (1) the strain gauge itself, (2) the steel bar of the extensometer and (3) the bedrock. However, distinguishing the strain components is usually difficult. Alternatively, the field data can be used to estimate the total thermal strain arising from both the extensometer (including the gauge and steel) and inter-joint bedrock (see Matsuoka, 2001, for more details). When highlighting insolation weathering, the above strains (1) and (2) should be eliminated.

Correlating crack widening events with thermal regimes of the bedrock requires a multi-channel data logger that permits year-round, concurrent monitoring of strain and temperature. Examples of the commercialized loggers are the CR10X logger (Campbell Scientific Inc., USA) and the B5-Strain-8A logger (Log Electronics, Japan): cost from US$ 2500, changeable with options.

Handling samples for 18O-isotope analysis

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General

The link between long-term changes in the isotopic composition of precipitation and surface air temperature at a given location is probably the most important relationship as far as paleoclimatic applications are concerned. Today, a semi-empirical temperature/stable isotope relationship was established for coastal stations in the mid and high northern latitudes. Isotope analyses have been applied for several years within glaciology, but this technique is still relatively new in periglacial- and permafrost-related research.

As this technique is likely to see widespread use in periglacial/permafrost research in the years to come, a short description of how to handle ice or precipitation samples before delivery to a laboratory is given below.

Sample size

Normal is 20 ml, 5 ml is used as a minimum.

Bottle.
Use small plastic bottle than can tolerate freezing without rupture. Cap opening should not be smaller that 15 mm.

Storage
Stored non frozen for a maximum of 2 months. Maximum time depends on how clean the sample is. Store in darkness. For prolonged storage, freeze.

Sample treatment
During sample preparation, water and CO2 has to equilibrate. For this process to run, the pH should be lower than 5. For absolutely clean water (inland ice), the CO2 in itself will lower the pH sufficiently. For less clean samples, it may be required to add acid. If acid should be added, this must be done prior to delivering the samples to the laboratory. Use concentrated sulphuric acid. Dip a thin glass pin in the acid, and then in the sample. Avoid evaporation, and be sure that the pH don't get lower than 3,5.

Number of samples
Investigate how many samples the laboratory takes in one batch in order to make efficient use of their working time. Often a standard batch is 115. If less samples are delivered, the laboratory will usually fill up with dummy samples or duplicates.

Packing
Pack the samples, so that consecutive samples are nicely in order. Place a description of the numbering scheme in the box, so its possible to measure the samples in correct sequence.

Standards
Usually the laboratory would appreciate to know the approximate delta value in order to select the working standard. At many laboratories they will then use two different standards for the measurements, one that should be close to the mean value of the samples, and one that is somewhat (15 permille) off. Both sets will be used in the automatic correction of the measurements.

Automatic Digital Cameras

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General

Most cold-climate scientific field work is carried out during the summer season for obvious reasons. The winter season thereby is underrepresented when it comes to observations. This drawback is somewhat counteracted by the introduction of various dataloggers, but reliable visual information has proved more difficult to obtain throughout the autumn, winter and spring seasons.

A rugged automatic digital camera producing color images of good resolution is now being produced by MetSupport ApS and J.E.Teknik in Denmark. You will find more information on the camera on: www.metsupport.dk.

The camera is powered by a battery, charged by solar panels and can be programmed to obtain one or several pictures daily. Mounting in nature may be directly on the ground, on a large boulder or in a stone cairn. The camera is prepared for easy mounting on a tripod, as well.

Prototypes of these digital cameras have been tested in a number of harsh environments since 1998; e.g. Greenland, Iceland, Faroe Islands and in Svalbard. The camera type has proven itself able to operate satisfactorily during several months of winter darkness and prolonged, low temperatures, as well as in very humid environments.

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Temperature Measurements using Gemini Miniature Data Loggers

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General

Gemini data loggers comes in several varieties, precipitation, humidity, movement, shock and temperature. Only temperature data loggers with external sensor will be discussed at this place.

The logger unit

Presently, the 12-bit Gemini temperature data loggers (Tiny Tag Plus High Resolution) with external sensor probe measures over the range –40^{o}C to +125^{o}C. The logger itself may not work properly if operated outside a temperature range from –40^{o}C to +85^{o}C. They are waterproof to 15 m (50 ft), measures 34 x 59 x 80 mm and weights 110 g.

The resolution on the individual readings is 12 bit. The logging interval is user-controlled and may be set from 1 sec to 10 days. There are several start options: now, delayed (up to 45 days), event, magnetic impulse. Stop options: when full, after N readings, never (wrap around). Reading type: actual, min or max. The logger may be offloaded while running when logging in minute multiples.

All programming and offloading of the logger is done by means of easy-to-use Windows-based software.

Memory

The logger has an internal memory of 32k (EPROM; non-volatile), storing about 16,000 readings. If the logger is programmed to take hourly readings this corresponds to almost two years of service, or you may obtain 5 month data at 15 minute intervals.

Battery

The logger uses Saft 3.7V 1/2AA Lithium cells, having a battery life up to 5 years. However, battery replacement is recommended every 2 years. The logger should be stopped before replacement. A complete Tinytag Plus Service Kit including battery, seal and silica gel pack may be obtained from the firm.

External sensor probe

The external sensor probe (type: 10k NTC thermistor) is connected to the logger by a 3 m cable and measures 5 x 150 mm. The measuring range is –40°C to +125°C. The response time is 45 sec in air and 20 sec in water. The accuracy is about ±0.2°C.

Price

The current price (December 2000) is about US $ 200 for the logger unit and about US $ 22 for the probe. The Gemini Group are based in UK, but you may obtain the logger and probe from local distributors in several countries. Please check the Gemini homepage for further details.

Special notes

When using the logger at low temperatures, condensation may form inside the chase. Therefore, before opening the chase for any reason (e.g., battery replacement), allow the unit to reach the room temperature if the operation is carried out indoor. You need no open the chase for offloading of data.

When using the logger and sensor probe in a wet or humid environment (water or melting snow pack) you should take care to ensure that the connector cap (for offloading) and sensor probe are securely fitted. Silicone may with considerable success be applied at these points.

This type of data logger have been used with satisfactorily results for several years in Greenland, the Faroe Islands, Scotland, Denmark and on Svalbard. The EPROM memory ensures that you often will be able to recover data from a logger which accidentally has been water filled. After proper drying and battery replacement you may even succeed in reviving the logger after such an event!

Precipitation Measurements using Gemini Miniature Data Loggers

Ole Humlum, The University Courses on Svalbard (UNIS), Norway.

General

Gemini data loggers comes in several varieties, precipitation, humidity, movement, shock and temperature. Only the precipitation data logger with external rain gauge will be discussed at this place.

The logger unit

The 12-bit Gemini precipitation data logger (Tiny Tag Plus High Resolution) should not be operated outside a temperature range from –40°C to +85°C. The logger may not work properly outside this temperature range. The logger is waterproof to 15 m (50 ft), it measures 34 x 59 x 80 mm and weights 110 g.

The resolution on the individual readings is 12 bit. The logging interval is user-controlled and may be set from 1 sec to 10 days. There are several start options: now, delayed (up to 45 days), event, magnetic impulse. Stop options: when full, after N readings, never (wrap around). Reading type: actual, min or max. The logger may be offloaded while running when logging in minute multiples.

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The logger uses Saft 3.7V 1/2AA Lithium cells, having a battery life up to 5 years. However, battery replacement is recommended every 2 years. The logger should be stopped before replacement. A complete Tinytag Plus Service Kit including battery, seal and silica gel pack may be obtained from the firm.

External rain sensor

The external rain gauge is a drop-contact sensor with a diameter of 110 mm and a height of 90 mm. It is connected to the data logger by a 2 m cable (see illustration above). The measurement range is 0-25 mm per interval. The resolution is 0.2 mm, the accuracy is ±0.1 mm per interval. The maximum amount of precipitation which can be recorded is 25.5 mm per interval, or 0.03 mm per second. During very heavy rainfalls or during strong winds, additional errors may be encountered due to raindrops splashing over the side of the sensor.

Price

The current price (December 2000) is about US $ 290 for the complete unit (data logger and rain gauge). The Gemini Group are based in UK, but you may obtain the logger and probe from local distributors in several countries. Please check the Gemini homepage for further details.

Special notes

When using the logger at low temperatures, condensation may form inside the chase. Therefore, before opening the chase for any reason (e.g., battery replacement), allow the unit to reach the room temperature if the operation is carried out indoor. You need no open the chase for offloading of data.

When using the unit in very humid environments take take care to ensure that the connector cap (for offloading) is securely fitted. Silicone may with considerable success be applied at this location.

This type of data logger have been used with satisfactorily results for several years in Greenland, the Faroe Islands, Scotland, Denmark and on Svalbard. The EPROM memory ensures that you often will be able to recover data from a logger which accidentally has been water filled. After proper drying and battery replacement you may even succeed in reviving the logger after such an event !

As seen in the illustration below, the unit may easily be installed flush with the ground surface, which is of considerable relevance within a geomorphological context, compared to the standard 2 m measuring height used for many normal meteorological stations.

A drawback of installation at the ground surface is the risk of getting the rain gauge blocked by debris, especially if operated in a windy environment. Therefore the rain gauge should be inspected and cleaned whenever possible.

During installation, due to the drop-contact principle, care should be taken to ensure that the upper surface of the sensor is horizontal. If not, some drops may not make proper contact in the lower part of the device and will not be recorded.

The unit can be left in the field during winter as no liquid water is stored in the gauge and this has no moving parts. No freezing damage will therefore be induced. If the unit is left in the field during the winter season, no precipitation will of cause be registered as long as temperatures stay below freezing. However, if properly installed, the unit will record the subsequent melting of the snow cover present at the measuring site when melt commences. This is a very useful information in relation to cold-climate geomorphology.

Rain gauge (lower part of picture) installed flush with the ground surface.

Humidity Measurements using Gemini Miniature Data Loggers

Ole Humlum, The University Courses on Svalbard (UNIS), Norway.

General

Gemini data loggers comes in several varieties, precipitation, humidity, movement, shock and temperature. Only the humidity data logger will be discussed at this place.

The logger unit

The 8-bit Gemini temperature data logger (Tiny Tag Plus) measures over the range 0 to 100% relative humidity. The logger itself has an operational range from –20^{o}C to +85^{o}C. The logger measures 34 x 59 x 80 mm and weights 110 g. The logger is waterproof to 15 m (50ft).

The logging interval is user-controlled and may be set from 1 sec to 10 days. There are several start options: now, delayed (up to 45 days), event, magnetic impulse. Stop options: when full, after N readings, never (wrap around). Reading type: actual, min or max. The logger may be offloaded while running when logging in minute multiples.

All programming and offloading of the logger is done by means of easy-to-use Windows-based software.

Memory

The logger has an internal memory of 16k (EPROM; non-volatile) and will store about 16,000 readings. If the logger is programmed to take hourly readings this corresponds to almost two years of service. If running at 15 minute intervals about 5 months of data may be obtained.

Battery

The logger uses Saft 3.7V 1/2AA Lithium cells, having a battery life up to 5 years. However, battery replacement is recommended every 2 years. The logger should be stopped before replacement. A complete Tinytag Plus Service Kit including battery, seal and silica gel pack may be obtained from the firm.

Sensor

The sensor (capacitive) is mounted on the side of the logger, see photo above. The measurement range is from 0 to 100% RH, with an accuracy of ±3% at 25^{o}C. The resolution is better than 0.5% RH and the response time is about 10 seconds at 90%.

Price

The current price (December 2000) is about US $ 200 for the logger unit with sensor. The Gemini Group are based in UK, but you may obtain the logger and probe from local distributors in several countries. Please check the Gemini homepage for further details.

Special notes

When using the logger at low temperatures, condensation may form inside the chase. Therefore, before opening the chase for any reason (e.g., battery replacement), allow the unit to reach the room temperature if the operation is carried out indoor. You need no open the chase for offloading of data.

When using the logger in a very humid environment care should be taken to ensure that the connector cap (for offloading) is securely fitted. Silicone may with considerable success be applied at this point.

The sensor apparently has satisfactorily long-time performance. It can be wetted without damage, although the accuracy then will be impaired temporarily and it may need about 30 minutes to recover. In order to avoid direct wetting of the sensor when used in the field, the unit may be placed in a small, ventilated housing or otherwise protected towards direct wetting.

The unit should not be operated in a very salty environment, as salt solutions may cause permanent damage to the sensor. Salt crystals forming within the porous surface layer of the sensor will affect the moisture level there.

This type of data logger have been used with satisfactorily results for several years in Greenland, the Faroe Islands, Scotland, Denmark and on Svalbard. The EPROM memory ensures that you often will be able to recover data from a logger that accidentally has been water filled. After proper drying and battery replacement you may even succeed in reviving the logger after such an event!

Housing for Miniature Data Loggers in the Field

Ole Humlum, The University Courses on Svalbard (UNIS), Norway.

General

Several modern miniature data loggers are constructed for harsh environments and may, for that reason, be placed directly in nature without encountering difficulties. Quite often, however, a need for physical protection (animals) or camouflage (humans) will make it necessary to provide a kind of housing for loggers. A very simple solution, which has proved itself useful in many arctic areas, is constructing a small cairn around the logger(s), as shown on the photo above.

Temperature sensor installed inside small stone cairn, about 20 cm above the ground surface.

Temperature loggers with external sensor

Air temperature measurements usually require some kind of protection against direct solar radiation. In the case of measuring near ground surface air temperatures this protection may be provided by the logger cairn as shown in the photo above. The open structure of the cairn enables good ventilation but hinders direct radiation. In addition, turbulence created around the cairn often keep the thermistor free of snow burial during winter time. In this picture, a stone has been removed in order to show the position of of the temperature sensor inside the cairn. Top of cairn is rising about 20 cm over the general snow surface.

Precipitation loggers

Precipitation gauge (110 mm diameter; lower part of picture) installed flush with ground surface.

By tradition, standard precipitation gauges are positioned 2 m above the terrain surface. In cold-climate regions this often only applies during the summer, as the effective terrain surface moves up and down during the winter, in concert with the snow cover growth. In addition, in many geomorphic and botanical contexts, the precipitation at the terrain surface is of higher interest, relative to precipitation measured 2 m level above.

Due to their small size, the Gemini precipitation loggers are ideal for measuring precipitation at the terrain surface. Often, the gauge may be installed flush with the ground surface (see picture above, gauge visible in lower part of picture), while the connecting 2 m cable allows for logger location in protective cairn at some convenient place nearby, without interfering with airflow around the precipitation gauge itself.

A drawback of installation at the ground surface is the risk of getting the rain gauge blocked by debris or fragments of vegetation, especially if operated in a windy environment. Therefore the rain gauge should be inspected and cleaned whenever possible.

Measuring Net Snow Accumulation by Miniature Data Loggers

Ole Humlum, The University Courses on Svalbard (UNIS), Norway.

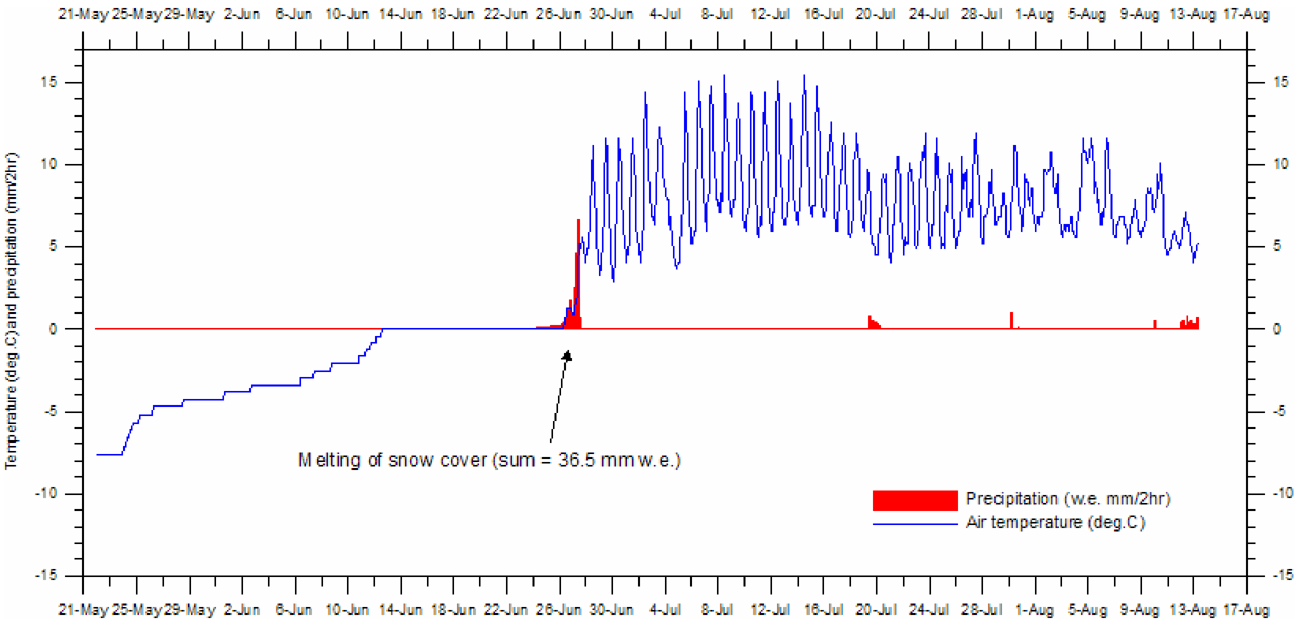
General

Automated measurements of solid precipitation is a difficult task and usually requires complicated instrumentation with internal heating and elaborate wind shielding. As snow moves readily around in the landscape during winter by wind action (picture above), a correct measured value of the amount of precipitation is often of limited use in a geomorphic and biological context. What really matters is the amount of snow accumulated on the ground surface when spring melting commences. The Gemini precipitation loggers offers a simple way of obtaining this information.

Installation of Precipitation Gauge

During installation, due to the drop-contact principle used by the instrument, great care should be taken to ensure that the upper surface of the gauge is horizontal, as satisfactory operation requires water drops to make proper contact in the lower part of the device.

The unit is then left at the measuring site for the winter. This will not damage the gauge by freezing as no liquid water is stored in the instrument and this has no moving parts. While being snow covered, no precipitation will of cause be registered as long as temperatures stay below freezing. However, if properly installed, the unit will record the subsequent melting of the overlying net snow cover present at the measuring site when melt commences. This is illustrated by the diagram below.



Ground surface temperatures and precipitation gauge readings spring 2001 at head of Qivitut rock glacier, Diskofjord, Disko Island, W. Greenland.

Measuring Snow Cover Thickness by Miniature Data Loggers

Ole Humlum, The University Courses on Svalbard (UNIS), Norway.

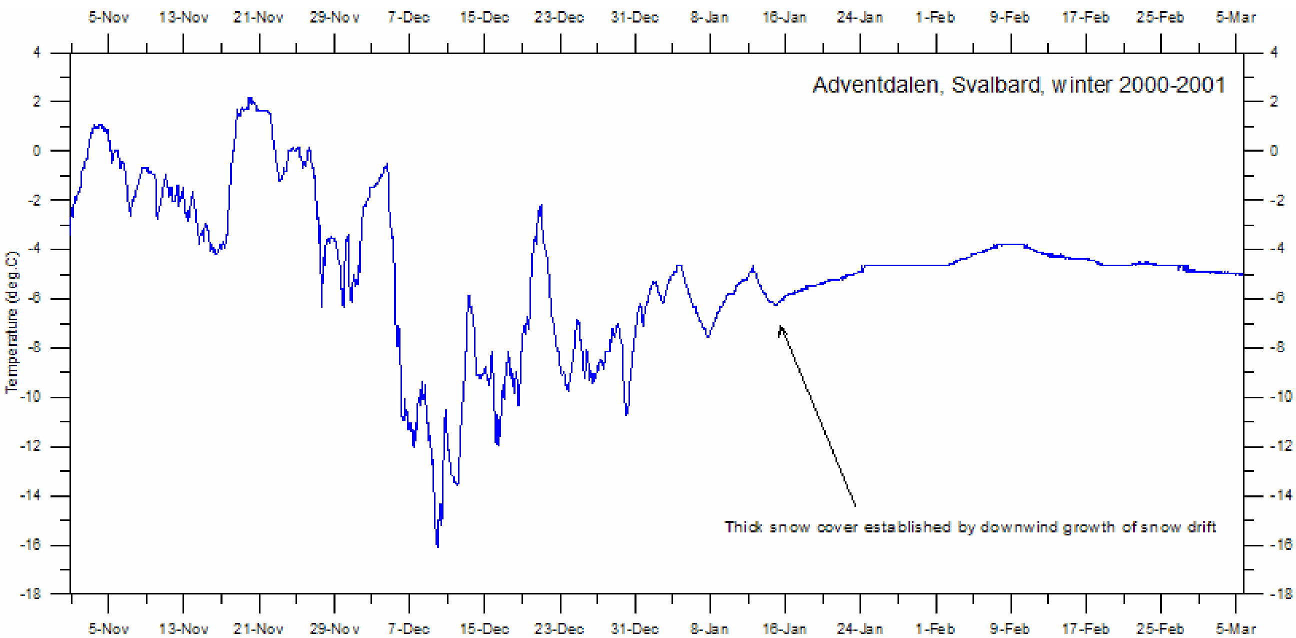
General

The thickness of the winter snow cover represents an important control on ground surface temperatures (see diagram below), and by this on ground temperatures below. In the late winter picture above, the ground below the scooter is covered by 5-10 cm snow only, while about 180 cm snow covers the ground below the person to the left. For this reason, the average winter ground surface temperature is 6-7 ^{o}C lower at the scooter than at the person.

One way of monitoring the snow cover thickness is by manual measurements throughout the winter; another is by means of automated digital photography. The first method requires manpower at hand at the study site throughout the winter, and the second method does not work satisfactory during periods of complete winter darkness. To circumvent this difficulty, a simple setup with miniature data loggers may be applied as described below.

Installation of Temperature Loggers

A number of temperature data loggers with external thermistor are mounted at intervals on a vertical structure, as shown in the photo below. Depending upon the vertical distance between individual thermistors, the temperature recordings will enable an estimate of the position of the snow cover surface, and from this, the snow cover thickness. In addition, information on the internal temperature in the snow pack is obtained by this setup.



Ground surface temperature at monitoring site in Adventdalen, Svalbard, showing the isolating effect of snow. The dampening effect is significant for even a shallow snow cover (3-5 cm).

The vertical structure should be able to withstand high winds during the winter, before burial by snow. The data loggers and thermistors should be mounted securely, in order no to be displaced during compaction and metamorphosis of the snow pack. During spring, considerable internal water pressure may be build up in the snow pack near the ground surface or above internal horizons with reduced permeability. For this reason data loggers and thermistors should preferentially be of watertight type.

In areas of complete winter darkness, the setup should be equipped with reflecting material (see photo below), in order to warn scooters and skiers. If possible, supporting wires should be avoided, in order not to represent a danger for animals, such as, e.g., reindeers. Stability without support wires may be obtained by burial of the lower part of the structure, if unconsolidated sediments are at hand. Later freezing will then provide the stability required. For this reason, the optimal time for installation is late autumn.

Setup for registering thickness and vertical temperature profile in snow pack, Adventdalen, Svalbard.