Wireless Sensor Networks in Permafrost Research: Concept, Requirements, Implementation, and Challenges

Andreas Hasler
Glaciology, Geomorphodynamics, Geochronology; Geography Department, University of Zurich, Switzerland
Igor Talzi
Computer Science Department, University of Basel, Switzerland
Jan Beutel
Computer Engineering and Networks Laboratory, ETH Zurich, Switzerland
Christian Tschudin
Computer Science Department, University of Basel, Switzerland
Stephan Gruber
Glaciology, Geomorphodynamics, Geochronology; Geography Department, University of Zurich, Switzerland

Abstract

In a joint project of computer- and geo-scientists, wireless sensor networks (WSNs) are customized for permafrost monitoring in alpine areas. In this paper, we discuss requirements for a rugged setup of such a network that is adapted to operation in a difficult environment. The experiences with a first deployment at Jungfraujoch (Switzerland) show that, beside hardware modifications of existing WSN platforms, special emphasis should be given to the development of robust synchronization and low-power data routing algorithms. This results from the fact that standard software tools are not capable in dealing with the high-temperature fluctuations found in high-mountains without compromising the power consumption and the network topology. Enhancements resulted in a second deployment at Matterhorn (Switzerland), from where we expect results in the near future. Once the technology of WSNs is a science-grade instrument, it will be a powerful tool to gather spatial permafrost data in near real-time.

Keywords: measurement; permafrost; PermaSense project; wireless sensor networks.

Introduction

Spatially distributed measurements of permafrost parameters over long periods are time consuming in deployment and maintenance, vulnerable to environmental impacts, and create inhomogeneous data sets, as no standard and easy applicable measurement devices exist. The project *PermaSense* addresses the development of a new generation of monitoring equipment for remote and harsh environments (Fig. 1). In this paper, we present the design and implementation of a wireless sensor network (WSN) to measure temperatures, dilatation, and diverse hydrological parameters in rock faces of alpine permafrost.

A WSN generally consists of distributed *network nodes* with attached sensors that communicate by local UHF radio within each other and that are up-linked by one (or several) *base stations* via mobile communication (e.g., UMTS, GPRS), internet, or other data transfer systems to a *data sink server* (Fig. 2). Each node contains a microprocessor, a radio transceiver, a sensor interface, some local memory, and an independent power supply. The network topology depends on the radio connectivity between the nodes. If data is transmitted via intermediate network nodes to the base station, this is called *multi-hop,* while a pure star-topology around the base station is called a *single-hop* network. Compared to existing logging systems using single radio-connected measurement devices, WSNs are designed to adapt their network topology dynamically according to the connectivity constraints, allowing observation of a larger area with multi-hop connection. While the dataflow is generally out of the network through the base station into the data sink, commands, network parameters or even executable programs can potentially be pushed into the network.

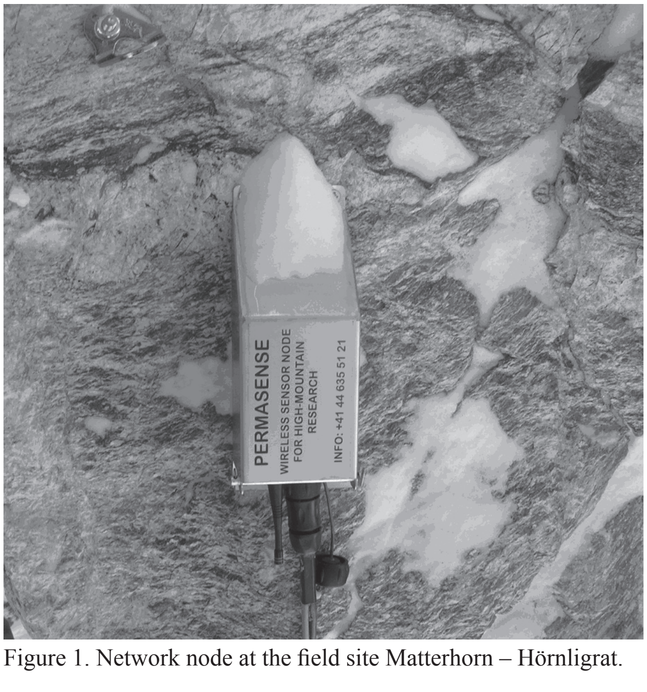

Figure 1. Network node at the field site Matterhorn – Hörnligrat.

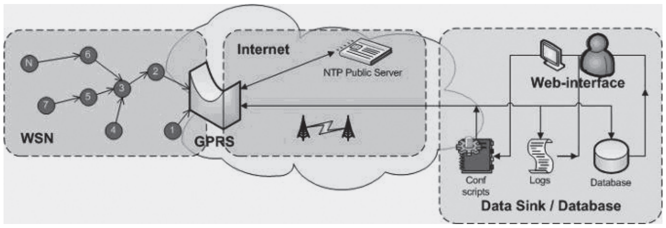

Figure 2. Framework of a WSN as used in our field deployments and test bed.

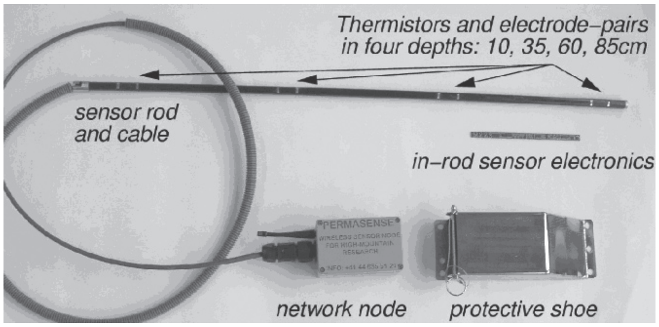

Figure 3. First-generation network node and customized sensor rod that measures temperatures and DC-resistivity as an indicator of liquid pore water at four different depths; the electronics and battery (lithium-thionyl) of the network node are mounted in a waterproof aluminum housing (125x80x57 mm) and protected from icefall and rockfall with a steel protective shoe. Measurement electronics are in the tip of the sensor rod to minimize temperature fluctuation errors.

Based on experiences with our first deployment on Jungfraujoch (3500 m a.s.l., Swiss Alps) during winter and spring 2006/2007, we specify requirements for yearlong stand-alone monitoring. WSN concepts and requirements for environmental use, and challenges for the implementation as well as the experiences from a second deployment generation are presented and discussed in this article.

Application of WSNs for Permafrost Research

Environmental WSNs

Environmental applications of WSNs have emerged in the past years following the general developments in mobile communication (Hart & Martinez 2006). Depending on the monitored variables and processes, the sensor networks differ in node size (e.g., from weather station to the futuristic "smart dust") as well as in spatial and functional extent of the network. In permafrost process research we are mainly interested in so-called localized multifunctional sensor networks. These systems are able to measure multiple parameters within an area of special interest. Despite the fast progress in the field of WSNs, only a limited number of application projects exists so far. The Projects *Glacsweb* (Martinez et al. 2004), *SensorScope* (http://sensorscope.epfl.ch/index.php), or the *Volcano monitoring project* (Werner-Allen et al. 2006) are such examples. A larger overview of existing environmental sensor network projects is given by Hart & Martinez (2006).

Potential of WSNs

For permafrost research and other remote environmental applications of WSNs, we identify the following potential:

- Once installed, maintenance and data acquisition is less time-consuming with WSNs than with standard logging systems, particularly at difficult accessible locations. The nodes inform the operator about battery level and functioning.
- Data is available all year-round at near real-time on a user interface. This is not only relevant for research, but can be very valuable for hazard monitoring.
- The data can be stored with redundancy, and not only locally on the logger. In case of destruction or loss of a sensor node, the data measured until this event is saved.
- Measurements are synchronous and arrive at one central database. No extensive manual post-processing and homogenization of the data is needed.
- Interval and mode of measurements do not require being statically predefined. They can be controlled by remote commands from the user interface or can be context-sensitive to other measurements of the network.

The project PermaSense

Wireless sensor networks have not yet been established for reliable, yearlong operation under cold climate and high alpine conditions. In PermaSense, computer- and geo-scientists upgrade in close cooperation the WSN platform *TinyNode* for permafrost research. Software for power-efficient operation of an adaptive multi-hop network topology is currently under development and being tested. Robust and reliable deployment hardware was designed, sensor interface hardware was developed, and software integration of sensors is being implemented. Customized sensors were manufactured, and compatible commercial sensors were evaluated and connected (Fig. 3). A detailed description of the network software of our first deployment, based on TinyOS, is given by Talzi et al. (2007).

Requirements for a permafrost WSN

Similar to standard logging systems for permafrost purposes, a WSN requires the following main features: Stable operation over a wide temperature range from -40°C to 40°C during at least one year or season, respectively (battery capacity). For analog measurements, a 12-bit analog-digital conversion (ADC) is generally sufficient, as the resulting resolution for temperature measurements over the indicated range is 0.02°C (a corresponding measurement accuracy can be reached with a zero-point calibration around 0°C). If pressure sensors are applied, a vibration wire (VW) compatible ADC, or frequency counter is of use. One or several digital interfaces (RS 232, RS 485, or SDI-12) for commercial sensors, allows the integration of diverse sensor types into the network. For power-intensive measurements (e.g., ERT), an incoming power supply line or solar panel control should be considered. All incoming and outgoing lines of this sensor interface should be lightning protected if the system operates at exposed locations.

As permafrost parameters typically change with slow rates, a temporal resolution of the measurements of some minutes to hours is required. Rarely, continuous measurements are needed (e.g., acceleration sensors), which is not further considered in this article. The mechanical setup should correspond to the operating conditions (e.g., Fig. 3).

WSN-specific requirements:

- The scale of the spatial extent ranges from decameters up to several hundred meters (depending on WSN limitations). To provide connectivity in complex alpine topography, a *multi-hop* system is preferable.
- Network topology is established automatically. A predefined topology is not applicable in practice and cannot adapt itself to a temporal lack of connection caused by snow cover, for example, of the devices.
- Connectivity through snow and ice is better with lower radio frequencies (<1GHz).
- Ultra low-power operation is supported. Sleeping cycles of the radio receiver, and consequently synchronization of the wake periods, are required.
- The measurements of different nodes are taken synchronically (in most cases, an accuracy of seconds is sufficient) and time-stamped.
- Nodes with no connectivity to neighbors store measured data locally on the node (capacity: 6 months).
- Data transmission capacity considers payload of the measured data with some margins to catch up data transmission from temporally invisible nodes. Generally, measured data does not exceed 2 kB per day.
- A *deployment mode* allows checking radio interconnectivity within the network during installation.
- A small form factor of the network node and a pluggable sensor interface ease the logistic effort for system maintenance.
- System health parameters (battery level, node temperature) inform the operator about network conditions and optimize the time of battery change.
- Command propagation into the network or context sensitivity allows to monitor periods of special interest in high resolution and to save power during less interesting periods.
- Data is stored in a database that provides metadata and has a safe backup strategy.
- A user interface supports the network maintenance (see above) and the database management.

Field Deployments

Energy balance models to estimate permafrost distribution and condition have recently been applied successfully to high-mountain topography (Gruber et al. 2004). Especially for steep and compact rock faces with little snow cover, modeling results correspond well with surface temperature measurements. Also mean annual subsurface temperature distribution and permafrost bodies are simulated satisfyingly with a 3D heat-conduction model (Noetzli et al. 2008). However, in such models processes of nonconductive heat transport are not considered despite their relevance for thawing depth and rate along fractures in the bedrock. The aim of our measurement site at Jungfraujoch is to quantify the spatial variability of thawing processes and heat transport in the near-surface layer.

First deployment: Jungfraujoch, winter 2006/2007

The influence of surface characteristics, fracturing, and meltwater availability is measured by eight of the above described sensor rods in gently steep (40°–70°) and fractured rock faces (general case in high alpine areas) around the Sphinx observatory at Jungfraujoch (ca. 3500 m a.s.l., Figs. 4, 5). Additionally, two thermistor chains are installed into the bordering ice faces.

The monitoring site consists of north and south faces of a ridge, which divide the network into two clusters with limited connectivity between them and differing thermal regimes (Fig. 4). Resulting from this topology, the thermal clock drift requires synchronization algorithms that let the node times converge even with such temperature deviations.

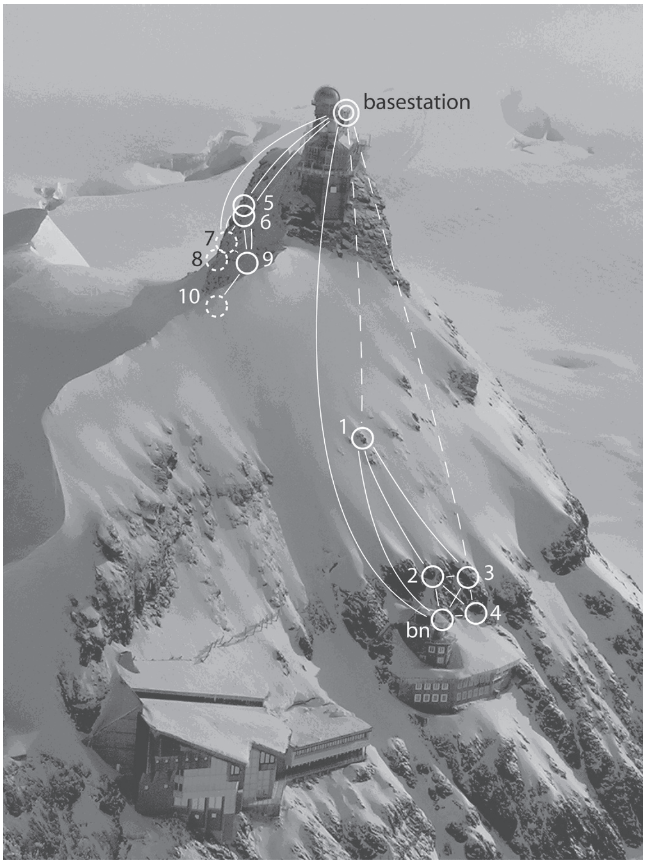

Figure 4. Deployment on Jungfraujoch (3500 m a.s.l., Swiss Alps) consisting of 10 sensor nodes with network topology; the base station is mounted on the Sphinx observatory. Each circle depicts a network node with its corresponding number. Lines indicate good radio connectivity between nodes; dashed lines indicate unstable connectivity; dashed circles are hidden nodes; and *bn* is a bridge node introduced to provide stable connection to the base station. The network is divided into to two clusters on the north-facing (left) and the south-facing (right) slopes of the ridge.

The initial installation of the sensors took place in fall 2006 after four months of system design and hardware production. We set up the first network at the same time, which, however, has not been successful due to the short development time and insufficient testing of the network software and hardware. In addition, a stability problem of the measurement values appeared under field conditions. After a debugging and testing phase over the winter of 2006/2007, first valid data could be gathered in April 2007 (Fig. 6). Yet no data transmission could be maintained over a period of more than two weeks. At this point, an extension of the project with the integration of network into a test bed prior to deployment was already planned for the second deployment in fall 2007. We decided to momentarily leave the network in a mode where data is stored locally to the node memory, and enhance and test the system for the second deployment.

Figure 5. Network node #4 and cable to the sensor rod, which is drilled one meter into the rock perpendicular to the surface. The network nodes can be easily exchanged and attached to the sensor by a waterproof plug.

Second deployment: Matterhorn "Hörnligrat" (3400 m a.s.l., Swiss Alps) in October 2007

Although public and research interests increased significantly following the hot summer of 2003, frost dynamics and natural hazards research in alpine permafrost areas has been discussed already a decade ago (e.g., Haeberli et al. 1997, Wegmann 1998). Frost weathering and rockfall activity is subject to yearlong field observations and measurements (e.g., Matsuoka & Sakai 1999, Matsuoka 2001) and lab experiments (Murton et al. 2006). These lab experiments have shown that ice segregation takes place also in solid (but porous) rock. Field data gave clear evidence for the contribution of temperature fluctuation and water to near-surface weathering and pebble fall. However, a direct physical linkage between temperature and rockfall disposition has not yet been demonstrated in the field. Different concepts of this linkage are discussed in Gruber & Haeberli (2007). The second deployment of PermaSense addresses this issue, to gather data of cleft ice and rock stability interaction.

The installation containing 13 sensor nodes with 6 sensor types, 2 bridge nodes, and 1 base station was made on the

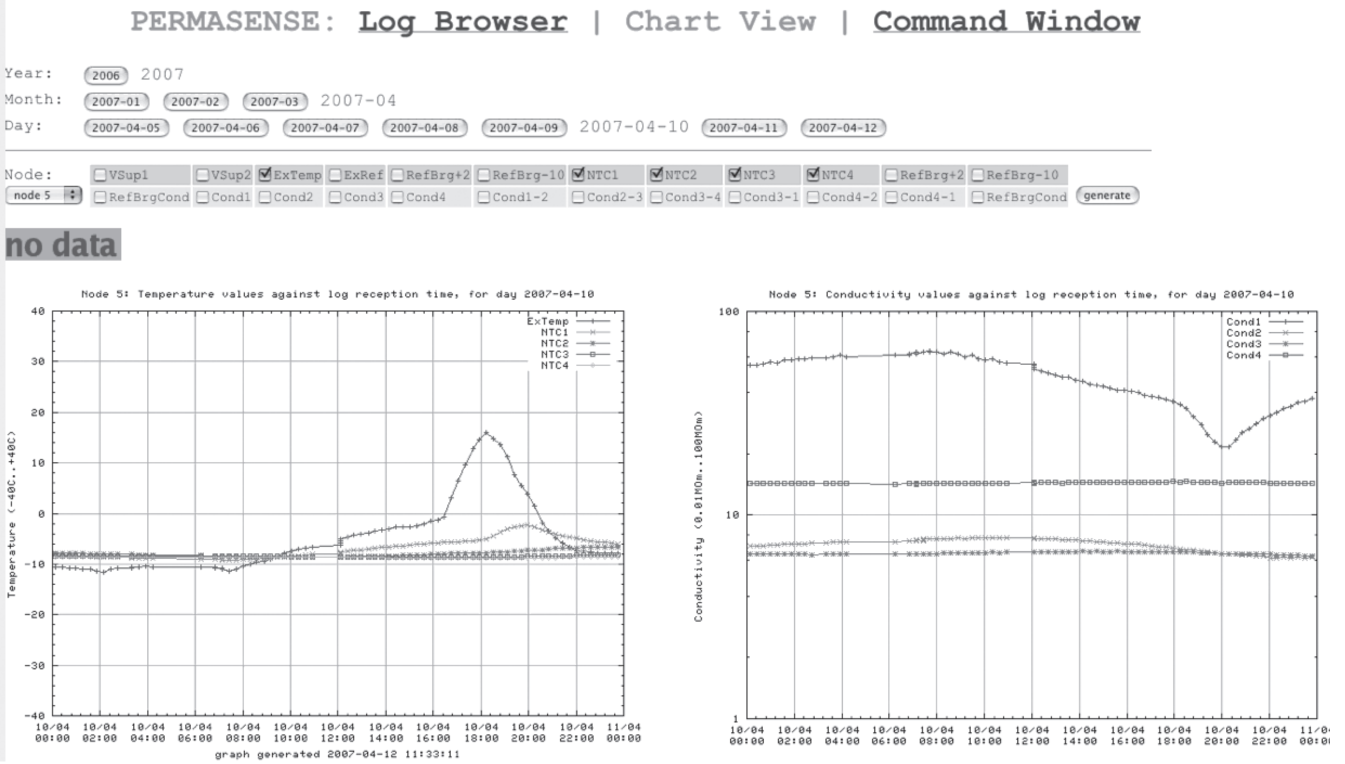

Figure 6. Screenshot of the user interface; direct visualization of one day of measurements from sensor rod #5 in the north-facing slope of the Sphinx. On the left, temperatures of the sensor rod thermistors (NTC1–NTC4) and the node temperature are plotted; the right diagram shows the corresponding rock resistivities. At the near-surface level (NTC/Cond 1), the temperature signal is clearly visible in the resistivity values.

northeast ridge of the Matterhorn at Hörnligrat in October 2007 (Fig. 7). At this site, a rockfall of some 1000 m^3 occurred in July 2003. Massive ice was observed at the surface of the detachment zone (Fig. 7) just after the event. This indicates the presence of stability-relevant ice-filled clefts in this area.

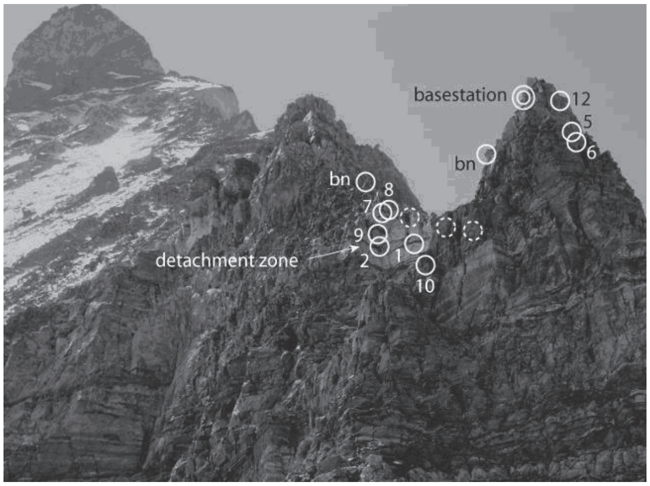

Figure 7. Deployment at Hörnligrat of the Matterhorn. Circles with numbers mark sensor nodes; dashed circles are sensors on the back (northwestern) side of the ridge; *bn* indicates bridge nodes.

Figure 8. Installation site with multiple sensors: At the bottom, two crack meters measure dilatation. Within the cleft, potential water pressure and ice stress, as well as temperatures at different depths, are measured. The tube between the two nodes is the reference air pressure measurement.

In addition to the sensors used on Jungfraujoch, we integrated commercial sensors with a newly designed *sensor interface board* (SIB) into our network. With these sensors we measure crack dilatation, water pressure, ice pressure, and water movements in the clefts. Thermistor chains are mounted into clefts to measure temperature profiles together with the mentioned parameters. One node and SIB has a combination of this sensors attached resulting in a multiple sensor network node. The installation of more than one network node at one spot allows a flexible combination of sensors adapted to the situation in the field (Fig. 8).

Discussion of Experiences and Challenges of PermaSense

In the initial phase of PermaSense until April 2007, diverse problems were critical for the function of the WSN and the subject of debugging. The quality of the measurements and the instable operation of the base station are two examples of early-stage and hardware-related problems. Other system parts, such as the mechanical setup or the battery type, appeared well adapted to the conditions met in the field over the winter and spring 2006/2007.

The network setup at Jungfraujoch at the end of April 2007 and the subsequent test runs at the test bed in Zurich showed two main topics remaining critical for stable, long-term operation:

1. Time synchronization of the nodes.
2. Stability and power efficiency of the data routing.

As described above, the conditions in the field make time synchronization challenging due to large temperature fluctuations and deviations between installation spots. Short radio receiving slots compared to the sleeping intervals due to power limitations require a high quality of synchronization. The fact that the clock quartz are generally optimized for 25°C and have high drifts at negative temperatures makes a precise synchronization of a permafrost WSN even more challenging. Software-based temperature-drift compensation could be a possible solution, but needs extensive testing before application.

The currently used statically predefined data transmission slots, the radio communication as a power intense component, are used in a rather inefficient way. To optimize power consumption and consequently increase battery life-time, a dynamic organization of the data transmission slots is promising. This could also increase the data transmission capacity in areas of the network where it is required and, as a consequence, support more stable data routing as well.

Conclusions

Based on the experience gained from technology development and two high-mountain deployments, we can draw the following main conclusions for the application of WSNs in mountain permafrost research:

For a successful application of WSNs in permafrost research and in other environmentally challenging situations, an adapted software design and extensive testing of the network under realistic but well-monitored conditions are essential.

Due to large temperature fluctuations and large lateral temperature gradients, in combination with complex network topologies and power limitations, synchronization of the nodes is a very challenging task. Major algorithmic work, as well as specific testing, is needed here.

The power efficiency and the duration of operation without battery exchange in the field can be increased significantly with further software development.

Once we succeed in overcoming the current major problems, WSNs have the potential to become a powerful technology to gather spatially distributed field data in near-real time for permafrost research.

Acknowledgments

We would like to thank Sandro Schönborn, Roman Lim, and Mustafa Yücel for their contribution to PermaSense. The project is partly financed by the Swiss Federal Office for the Environment (FOEN) and the National Competence Center for Research – Mobile Information and Communication Systems (NCCR-MICS). We also acknowledge the helpful technical advice of Hansueli Gubler, ALPUG, in the initial phase of PermaSense.

References

Gruber, S. & Haeberli, W. 2007. Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research* 112. doi:10.1029/2006-JF000547.

Gruber, S., Hoelzle, M. & Haeberli, W. 2004. Rock wall temperatures in the Alps: Modelling their topographic distribution and regional differences. *Permafrost Periglacial Processes* 15(3): 299–307.

Haeberli, W., Wegmann, M. & Vonder Muehll D. 1997. Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps. *Eclogae Geologicae Helvetiae* 90: 407–414.

Hart, J.K. & Martinez, K. 2006. Environmental sensor networks: A revolution in the earth system science? *Earth-Science Reviews* 78: 177–191.

Martinez, K., Hart, J.K. & Ong, R. 2004. Environmental sensor networks. *Computer* 37 (8): 50–56.

Matsuoka, N. 2001. Direct observation of frost wedging in alpine bedrock. *Earth Surface Processes and Landforms* 26: 601–614.

Matsuoka, N. & Sakai, A. 1999. Rockfall activity from an alpine cliff during thawing periods. *Geomorphology* 28: 309-328.

Murton, J.B., Peterson, R. & Ozouf, J-C. 2006. Bedrock fracture by ice segregation in cold regions. *Science* 314: 1127–1129.

Noetzli, J., Hilbich, C., Hauck, C., Hoelzle, M. & Gruber, S. 2008. Comparison of transient 2D temperature profiles with time-lapse electrical resistivity data at the Schilthorn Crest, Switzerland. *Proceedings.of the Ninth International Conference on Permafrost.*

Talzi, I., Hasler, A., Gruber, S. & Tschudin, C. 2007. PermaSense: Investigating permafrost with a WSN in the Swiss Alps. *In Proceedings for EmNets-07*: 8–12.

Wegmann, M. 1998. Frostdynamik in hochalpinen Feswänden am Beispiel der Region Jungfrau - Aletsch. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie an der ETH Zürich 161.

Werner-Allen, G., Lorincz, J., Johnson, J., Lees, J. & Welsh, M. 2006. Fidelity and yield in a volcano monitoring sensor network. *Proceedings of the 7th conference on USENIX Symposium on Operating Systems Design and Implementation* 7: 381–396.