Could retrieval of snow layer formation by optical satellite remote sensing help avalanche forecasting? Presentation of first results

Rune Solberg[1], Regula Frauenfelder[2, 3], Hans Koren[1], Kalle Kronholm[3]
[1] Norwegian Computing Center, Oslo, Norway
[2] International Centre for Geohazards, c/o Norwegian Geotechnical Institute, Oslo, Norway
[3] Norwegian Geotechnical Institute, Oslo, Norway

ABSTRACT: Of special interest within the field of avalanche research and avalanche warning are properties related to snow grain type and snow grain size at the surface. In continental and intermountain avalanche climates weak layers or interfaces are the main cause of avalanches. Knowledge about such weak layers helps to increase the precision of avalanche forecasting. Some of these potential weak layers form on the snow surface and are preserved until burial.

Optical satellite sensors measure reflected sunlight at different wavelengths. The near-infrared region is sensitive to the optical grain size of the snow. Due to the distinct size and shape characteristics of potential weak layers such as, for example, surface hoar, their reflectance is quite different from new snow in general. If the weather permits optical observations it should, therefore, be possible to detect such layers by remote sensing.

We present the results of a pilot study where in situ measured surface snow grain characteristics are compared to snow grain characteristics as derived from multispectral data from the MODIS satellite sensor. The pilot study showed that parallel in situ snow measurements and snow analyses exploiting data from MODIS are possible for the selected test sites in Norway. The study aims at establishing a relationship between the satellite-observed snow grain size index (SGS) variable and the snow grain size and shape as measured in the field. Based on satellite and in situ data measured over several years, we intend to establish a snow grain evolution model. The model will be used as an input to the avalanche forecasting model.

KEYWORDS: Avalanche forecasting, remote sensing, snow grain size, snow temperature, snow wetness

1 INTRODUCTION

Snow properties related to snow grain type and snow grain size at the surface are of special interest within the field of avalanche research and avalanche warning. In continental and intermountain avalanche climates weak layers or interfaces of the snow pack are the main cause of avalanches (Fig. 1). Knowledge about such weak layers helps to increase the precision of avalanche forecasting. Some of these potential weak layers, such as surface hoar, form on the snow surface where they are preserved until burial.

Optical satellite sensors measure reflected sunlight at different wavelengths in the visible and infrared part of the electromagnetic spectrum. The near-infrared region is sensitive to the optical grain size of the snow. Due to the distinct size and shape characteristics of potential weak layers such as, for example, surface hoar, their reflectance is quite different from other types of snow, such as new snow or melting snow (e.g., Bühler et al., 2009; Fily et al., 1999; Nolin and Dozier, 2000). If the weather permits optical observations it should, therefore, be possible to detect such layers by remote sensing.

Figure 1. Fractured and collapsed (left) and unfractured, intact (right) part of a weak layer of buried surface hoar. Picture credit: ASARC (Applied Snow and Avalanche Research), University of Calgary Canada. By courtesy of Prof. B. Jamieson, ASARC.

We present the first results of a project aiming to utilise information retrieved from remote sensing data to improve avalanche risk forecasting. The focus of the pilot study is the simulta-

Corresponding author address: Rune Solberg, Norwegian Computing Center, Oslo, Norway; tel: +47 22 85 25 00; fax: +47 22 69 76 60

neous collection of in situ data and the acquisition of satellite data in order to establish a relationship between avalanche-relevant variables and variables retrieved from the remote sensing data. Specifically, in situ measured surface snow grain characteristics are compared to snow grain characteristics as derived from multispectral data from the MODIS satellite sensor.

2 STUDY REGION

Data from four test sites have been studied so far. Three sites are located in the Strynefjell mountain range, Western Norway (Fig. 2). On these sites it is possible to get satellite data without getting signals from vegetation, roads or other objects into the field of view of at least one MODIS pixel. However, due to the alpine terrain, topography will influence the signal measured by the satellite sensor. Two test sites (Fonnbu and Grasdalsvatnet are located in Grasdalen, close to the snow and avalanche research station Fonnbu of the Norwegian Geotechnical Institute. The third test site is situated at Breiddalsvatnet, a lake on the eastern side of the Strynefjell mountain. Here, the effects of the topography are eliminated.

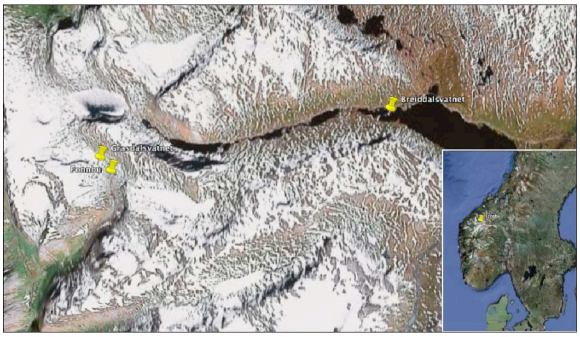

Figure 2. Location of the three test sites (Fonnbu, Grasdalsvatnet and Breiddalsvatnet) in the Strynefjell mountain range, Western Norway. Map source: GoogleEarth, 2009.

The test sites in the Strynefjell mountain range are quite far from the premises of the research institutes, which in practice limits the number of field measurements that can be taken during the snow season. Therefore, a fourth site in the Oslo region (close to Lillestrøm) was added in order to allow for quick response for fieldwork when the weather permits satellite data acquisition. The site is located in a flat agricultural area situated about 30 km north-east of Oslo, thus eliminating topographic effects.

3 METHODS

Field measurements of snow surface characteristics on an approximately two-weekly basis at the three different sites in the Strynefjell area started in January 2009 and continued until mid-April 2009. The Lillestrøm site was established later in the season and has been measured frequently between mid-March and the end of April.

The in situ measurements were principally restricted to the uppermost 5 to 10 cm of the snowpack, even though we also have several complete snow pit profiles at hand for interpretation. Yet, even for the snow pit profiles, only the uppermost layers are considered when comparing the in situ data to the remote-sensing-derived data. Measurements of the uppermost layer(s) consisted of standard snow measurements, i.e. the measurement of snow grain size, snow grain type, snow temperature and hardness of layer (Fig. 4). In addition, air temperature, coordinates, height and aspect of measurement location, cloud cover and wind speed were recorded. All data were stored and visualized using the SnowPilot programme (see www.snowpilot.org).

A number of field visits included measurements of spectral reflectance of the snow surface. The spectra were acquired with an 'Analytical Spectral Devices Fieldspec Pro spectroradiometer' (Fig. 3) measuring in the interval 350–2500 nm of the electromagnetic spectrum.

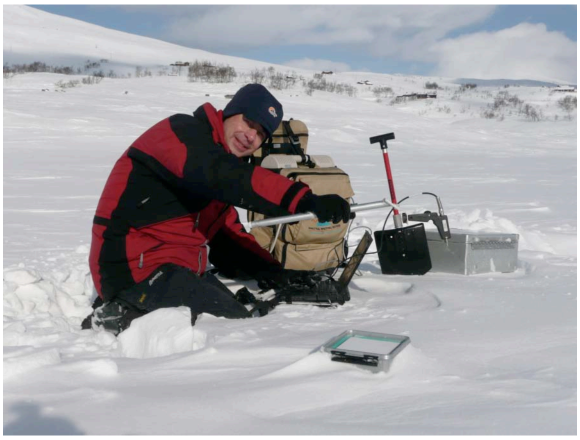

Figure 3. Measurements of spectral reflectance of the snow surface with the 'Analytical Spectral Devices Fieldspec Pro spectroradiometer' on Breiddalsvatnet, March 5th, 2009. Measurement results are presented in Figure 5.

The primary satellite instrument which has been used so far is the Terra MODIS optical sensor, which provides 36 spectral bands in the visible and infrared region. At the latitudes of our test sites, image acquisition takes place at least once a day. All images through the measurement period (January-April) have been checked with respect to cloud cover. Three variables have so far been retrieved from the cloud-free images: snow surface temperature (SST), snow grain size (SGS) and snow surface wetness

(SSW). SST and SSW have been retrieved at 1 km spatial resolution (given by the thermal bands used in the algorithms), while SGS has been retrieved at 500 m spatial resolution.

The STS algorithm is based on an approach proposed by Key et al. (1997). In a comparison study by Amlien and Solberg (2003) this algorithm was identified as one of the best single-view techniques for retrieval of STS for polar atmospheres, and it can be applied on MODIS as well as NOAA AVHRR data.

For SGS we have used a normalized grain size index based on work by Dozier (1989) and followed by experiments by Fily et al. (1997). MODIS bands 2 and 7 have been used as the resulting index has been shown to be less sensitive to snow impurities.

The approach used for retrieval of SSW is to infer wet snow from a combination of observations of STS and SGS in a time series. The temperature observations give a good indication of where wet snow could be present, but are in themselves not sufficient to provide full evidence of wet snow. However, if a rapid increase of the apparent grain size is observed simultaneously with a snow surface temperature of approximately 0°C, this is a strong indication of a wet snow surface. The algorithm is described in more detail in Solberg et al. 2004.

4 FIRST RESULTS

Simultaneous measurements of field data and acquisition of partly or fully cloud-free MODIS data was possible for six events during January to April 2009. On five additional events, usable MODIS data exists for a day prior or after field data collection.

Two examples of field measurement results are shown in Figure 4 (standard snow measurements) and Figure 5 (field spectrometer measurements). Examples of SSW maps retrieved from MODIS data are shown in Figure 6.

Figure 7 provides an overview over the achieved in situ snow measurements and the usable MODIS data for the corresponding period.

5 DISCUSSION

The pilot study showed that simultaneous in situ snow measurements and snow retrieval from MODIS data are possible for the selected test sites in Norway.

We have started the data analysis work aiming to establish a relationship between the satellite-observed apparent SGS variable and grain shape/size characteristics as measured in the field. Based on satellite and in situ data measured over several years, we intend to establish a snow grain evolution model. This model can then be used as an additional input variable to the avalanche forecasting model.

The study also showed, however, that establishing such an empirical relationship between satellite-measured SGS and field-measured grain shape/size characteristics requires frequent acquisition of satellite and field data. For this aim the test sites on Strynefjellet proofed, as already mentioned above, to be too remote. The additional test site outside Oslo, close to Lillestrøm, is important to improve the time resolution of our measurements, hopefully resulting in a better model.

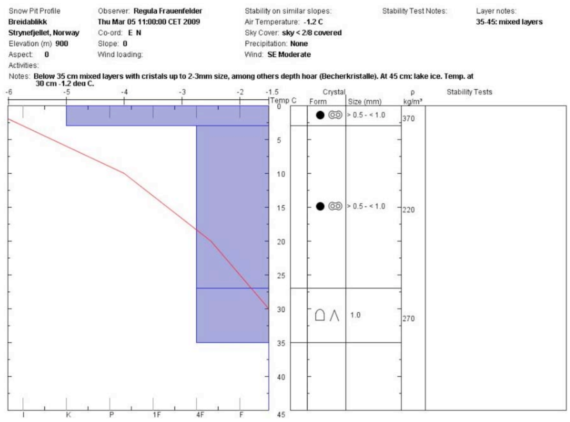

Figure 4. Traditional snow surface characterization at Breiddalsvatnet on March 5th, 2009.

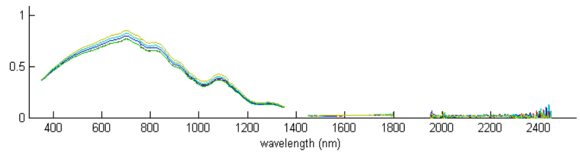

Figure 5. An example of snow reflectance spectra measured at Breiddalsvatnet on March 5th, 2009 with the FieldSpec Pro spectroradiometer. Six spectra acquired from the same snow surface sample are plotted in different colours.

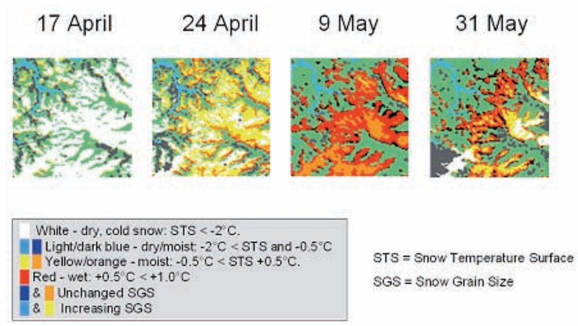

Figure 6. Inferred snow wetness categories based on STS and SGS retrieved from MODIS data for the Strynefjellet region in 2008.

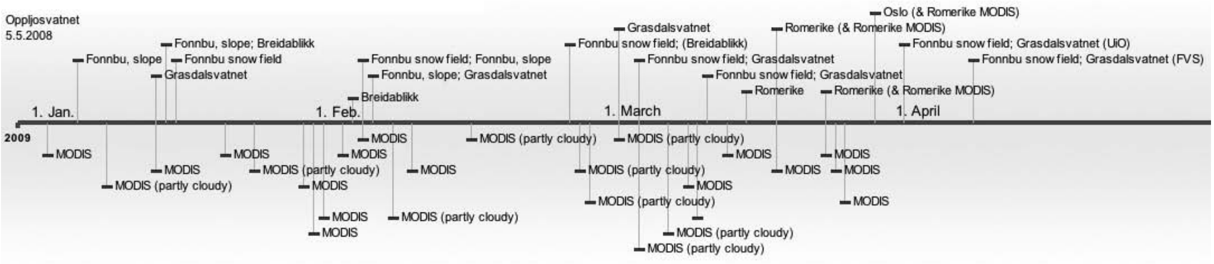

Figure 7. Timeline of in situ snow measurements and usable MODIS imagery. In situ measurements were taken at: Fonnbu snowfield, different slopes around Fonnbu (labelled ‘Fonnbu slope’ in the graph), at Grasdalsvatnet, at Breiddalsvatnet, and at additional sites near Oslo (Romerike area, among others at the mentioned site near Lillestrøm).

6 CONCLUSIONS AND OUTLOOK

Based on the first project results presented here, the work is going to be continued and will focus on (at least) one more season of field measurements with parallel MODIS image acquisitions. Measurement site selection will be spatially less restricted. The subsequent data set will hopefully enable the development of the abovementioned model, linking in situ measured snow grain shape/size characteristics with snow parameters retrieved from the analysis of MODIS data. Software will be developed in a way that inclusion of higher-resolution data will be possible, once such data are available on a quasi-daily basis from satellites like Sentinel 2.

Model testing and model application will be the subsequent steps after model establishment. Both for the development and the application phase, comparison of measurement results with results from snow cover models, such as, for example, the SNOWPACK model (Bartelt and Lehning, 2002; Lehning et al., 1999) will be crucial.

7 REFERENCES

Amlien, R. and Solberg, R., 2003. A comparison of temperature retrieval algorithms for snow covered surfaces. IGARSS 2003, Toulouse 21.-25. July 2003.

Bartelt, P. and Lehning, M., 2002. A physical SNOWPACK model for the Swiss avalanche warning. Part I: numerical model. Cold Reg. Sci. Technol., 35(3): 123-145.

Bühler, Y., Hüni, A., Christen, M., Meister, R. and Kellenberger, T., 2009. Automated detection and mapping of avalanche deposits using airborne optical remote sensing data. Cold Regions Science and Technology, 57(2-3): 99-106.

Dozier, J., 1989. Spectral signature of alpine snow cover from the Landsat Thematic Mapper. Remote Sensing of Environment, 28: 9-22.

Fily, M., Bourdelles, B., Dedieu, J.P. and Sergent, C., 1997. Comparison of In Situ and Landsat Thematic Mapper Derived Snow Grain Characteristics in the Alps. Remote Sensing of Environment, 59(3): 452-460.

Fily M., Dedieu J.P. and Durand Y., 1999. Comparison between the Results of a Snow Metamorphism Model and Remote Sensing Derived Snow Parameters in the Alps. Remote Sensing of Environment, 68(3): 254-263.

Key, J.R., Collins, J.B., Fowler, C. and Stone, R.S., 1997. High-latitude surface temperature estimates from thermal satellite data. Remote Sensing of Environment, 61(2): 302-309.

Lehning, M., Bartelt, P., Brown, R.L., Russi, T., Stöckli, U. and Zimmerli M., 1999. Snowpack model calculations for avalanche warning based upon a new network of weather and snow stations. Cold Reg. Sci. Technol., 30(1-3): 145-157.

Nolin, A.W. and Dozier, J., 2000. A hyperspectral method for remotely sensing the grain size of snow. Remote Sensing of Environment, 74: 207–216.

Solberg, R., Amlien, J., Koren, H., Eikvil, L. and Malnes, E., 2004. Multi-sensor and time-series approaches for monitoring of snow parameters. Proceedings of the Geoscience and Remote Sensing Symposium 2004, Anchorage, Alaska, USA (IGARSS 2004). IEEE International, 3: 1661-1666.