Investigations into the Spatial Pattern of Annual and Interannual Snow Coverage of Brøgger Peninsula, Svalbard, 2000 – 2007

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Abstract

Two expeditions of the late cartographer and glaciologist Wolfgang Pillewizer from the Institute for Cartography (IfC) in Dresden in the 1960s gave motivation for nivological investigations in Pillewizer's former study area, the Brøgger Peninsula on Spitsbergen - Svalbard. Following the definitions of Carl Troll 1955 and Carl Rathjens 1982 the archipelago of Spitsbergen represents, despite its comparatively low altitudes, a terrain of highalpine nature. There, like in all artic areas, the importance of snow is all encompassing. The evolution of regional biota is closely correlated with the variations of snow coverage, distribution and depth. Furthermore, snow is a major indicator of the impact of global warming on the vulnerability of the arctic environment. As (amongst others) stated in the "Fourth Assessment Report (AR4)" of the Intergovernmental Panel on Climate Change (IPCC) from February 2nd 2007, especially the polar areas show dramatic changes in their snow and ice cover under the influence of the global climatic change. This gave rise for an investigation of the snow cover on the well-studied Brøgger Peninsula on Svalbard. Snow-depth data based on both point measurements and terrestrial radar profiles have been made by the Norwegian Polar Institute (NPI) in Tromsø since the year 2000. NPI and IfC jointly carried out a correlation study concerning the correlation between point probings, ground-radar, and QuikSCAT and MODIS Albedo remote sensing data. Taking into account the particular climatological and geomorphological conditions, the results presented in this paper are meant to serve as a basis for further investigations into remote sensing-based monitoring of snow patterns and snow depth. Difficulties in setting up formalisable relationships are pointed out.

1. Motivation and Objectives

It is no longer an issue of the scientific community, politicians and NGOs to discuss global warming, its origins and consequences – it is resounded in every stratum throughout the world these days. Since February 2007, the Intergovernmental Panel on Climate Change (IPCC) published several contributions to the "Fourth Assessment Report (AR4)", which pointed out the serious condition our planet is situated in. Polar areas play a major role in the context of global warming due to their vulnerability and influence on the global climate. In the Arctic three major mechanisms occur which influence our planet's climate and may amplify the process of global warming. The cumulative melting of ice and snow results in changes of surface reflectivity and the oceans' circulation by adding more and more freshwater. Beside these two mechanisms the proceeding warming leads to an increased quantity of greenhouse gas emissions. High concentrations of carbon dioxide, methane and nitrous in the global atmosphere result in warming and in a dramatic change of the snow and ice coverage of the Arctic and Antarctica. This phenomenon shows retroactive effects on the worldwide temperature distribution and evaporation. The situation in arctic areas implicates an intensified research of its underlying processes and consequences. Further, the snow cover in arctic areas shows a declination of 10 % over the last 30 years with respect to the springtime maxima. This implies a reduction of the snow season in correlation with an earlier pulse of river runoff. In combination with a decreasing snow quality like thin ice layers, the animals access to food and nesting sites is restrained. The additional variations of snow distribution, depth and coverage represent a dramatic intervention in the regional biotas' evolution (ACIA Group 2004; IPCC 2007).

The work presented here was meant to contribute to the ongoing work of the Norwegian Polar Institute (NPI) to investigate the effect of global warming on polar areas. Further, it is representing a revival of the cooperation between IfC and NPI since the Spitsbergen expeditions of Wolfgang Pillewizer in 1962 and 1964/65. In the sense of the approaches made by the group around Rune Solberg (Oslo; Solberg et. al 2005 cum lit.) this study should constitute a contribution towards a more operational snowpack monitoring

2. Data

For the analysis of the spatial pattern of the annual and inter-annual snow coverage on Brøgger Peninsula, in-situ measurements, remote sensing imagery, as well as meteorological data were used.

In-situ snow-depth measurements were provided by the Norwegian Polar Institute (NPI) in the form of snow probing and ground-penetrating radar (GPR) data. Annual snow probing measurements were carried out in the lowlands and on the two glaciers Austre Brøggerbreen and Midre Lovénbreen in the years 2000 till 2007. Using GPR, in the years 2000 and 2007 auxiliary snow depth measurements were conducted along several snow probing routes (Kohler 2007; Fig. 1).

Beside the in-situ measurements, imagery from the NASA Moderate Resolution Spectroradiometer (MODIS) was used. MODIS is mounted on the multi-instrument Earth Observing System satellites Terra and Aqua, which were launched in February 2000 and May 2002 respectively. MODIS provides a continuous, comprehensive and global

Fig. 1: GPR Equipment

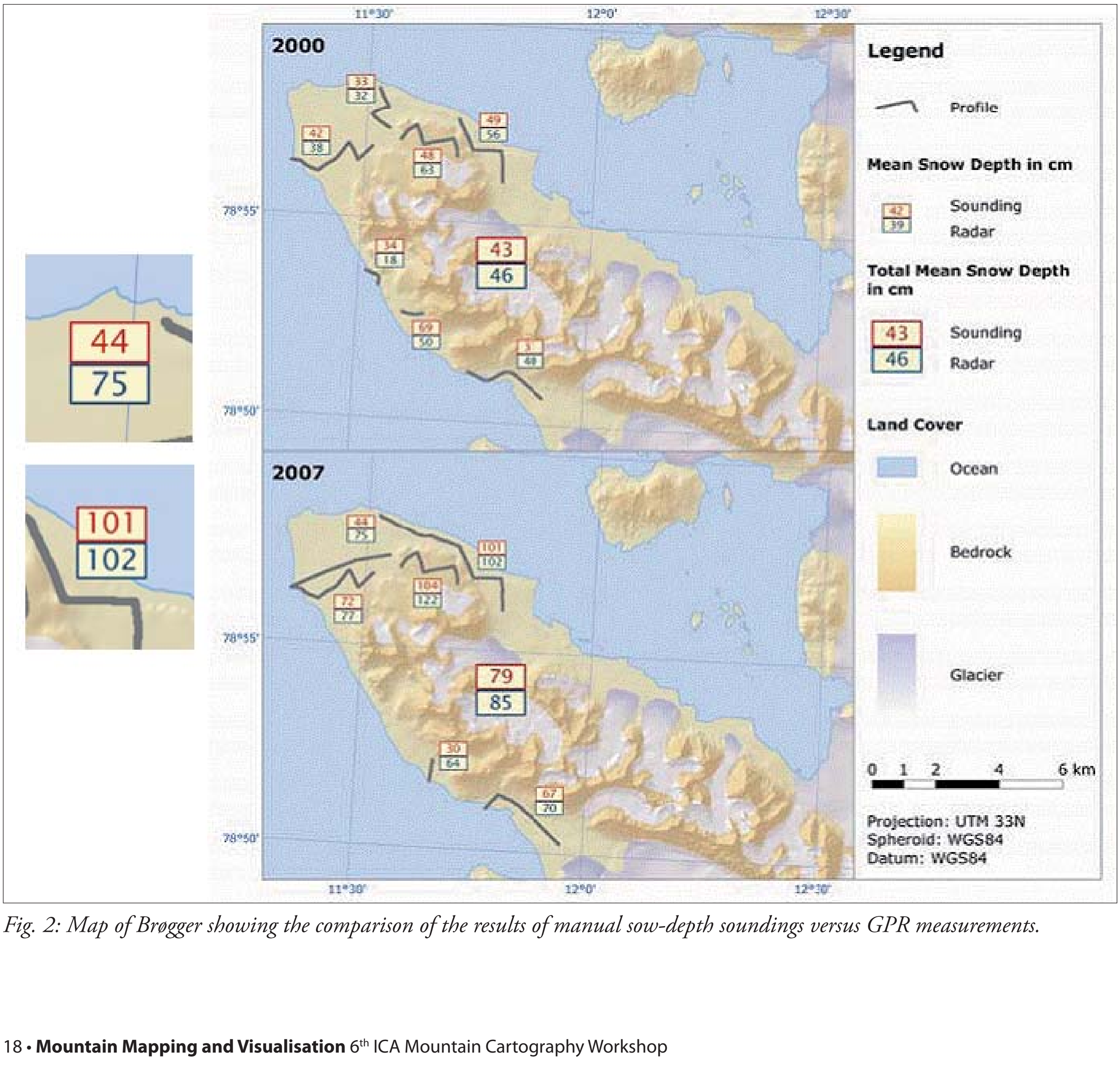

Fig. 2: Map of Brøgger showing the comparison of the results of manual sow-depth soundings versus GPR measurements.

coverage of biological and meteorological characteristics. From the wide variety of products, for the project the MODIS Albedo Product was chosen. This data provides black-sky and white-sky albedo for the spectral MODIS bands 1 to 7 and three broadbands (VIS, NIR, SW), wherefrom the white-sky SW was taken for the analysis (cf. Schaaf et al. 2002).

Other remote sensing data source used stem from the QuikSCAT/SeaWinds Scatterometer of NASA. A scatterometer is a radar system that determines the backscatter of the Earth's surface in function of the incidence angle. QuikSCAT was launched in July 1999 as the follow-up of the successful NASA Scatterometer (NSCAT) mission which was aborted in June 1997. QuikSCAT is providing different products as well, wherefrom the Normalized Radar Cross Section σ^0 was chosen.

The σ^0-signal indicates the amount of the reflected energy per specified resolution cell and is derived from the radar equation referred to a unit area on the horizontal ground plane. QuikSCAT provides σ^0-values for horizontal and vertical polarization at 46° and 54.1° nominal incidence angle, which correspond to the inner and outer beam of the system. For the analysis, the vertical polarization (VV) was chosen (cf. Long 2000).

In addition to the in-situ measurements and remote sensing products, meteorological data from the local weather station in Ny-Ålesund was used for the analysis. Temperature and precipitation data covering the period from August 1999 until July 2007 were provided by the Norwegian Meteorological Institute. From these data, a snow model was used for the modelling of snow accumulation on Brøgger Peninsula. Thereby, the input parameters were optimized for the in-situ snow observations, regarding the location in the lowlands or on the glaciers (Kohler & Aanes 2004).

3. Methods

The snow depth measurements in the lowlands and on glaciers from the years 2000 till 2007 were statistically correlated with the relief parameters: elevation, aspect, and slope. Therefore, box-and-whisker plots were used, which represent one dimensional graphics of numerical data in five dimensions: the lower and upper quartile define a rectangular box which is divided by a central dot or line representing the value of the median. The so-called whiskers at each end of the box regard potential outliers by the limitation of the whisker length on the basis of a fixed multiple of the interquartile. For the statistical analysis of the correlation between snow depth and relief parameters, the data was differentiated by year and location, i.e. lowlands and glaciers. Moreover, the three variables were divided into typical intervals each in order to ensure the significance of the conclusion.

Further, the quality of the sparse sounding observations was compared to the radar measurements in the years 2000 and 2007 (cf. Fig. 2). For this purpose, the (arithmetic) mean snow depths of the particular profiles were analyzed.

Regional and local variability were assessed using the standard deviation of the mean, grouped into individual elevation intervals for the lowlands and the glaciers due to the relation between altitude and measured snow depth. The standard deviation of the means of each year shows the measurement dispersion on the basis of the standard deviation divided by the square root of the number of measurements (cf. Fig. 3).

The analysis of the annual and inter-annual albedo changes is based on the albedo mean values of each image covering the period of April until September for the years 2000 to 2007. The same procedure was used for the evaluation of the σ^0-signal (VV-polarization) in comparison to the meteorological data covering the years 2000 through 2006.

The correlation of remote sensing data with the in-situ snow depth did not lead to any reasonable relation. Therefore only a short insight in the applied method is given, although this was the most time-consuming process during the study. The

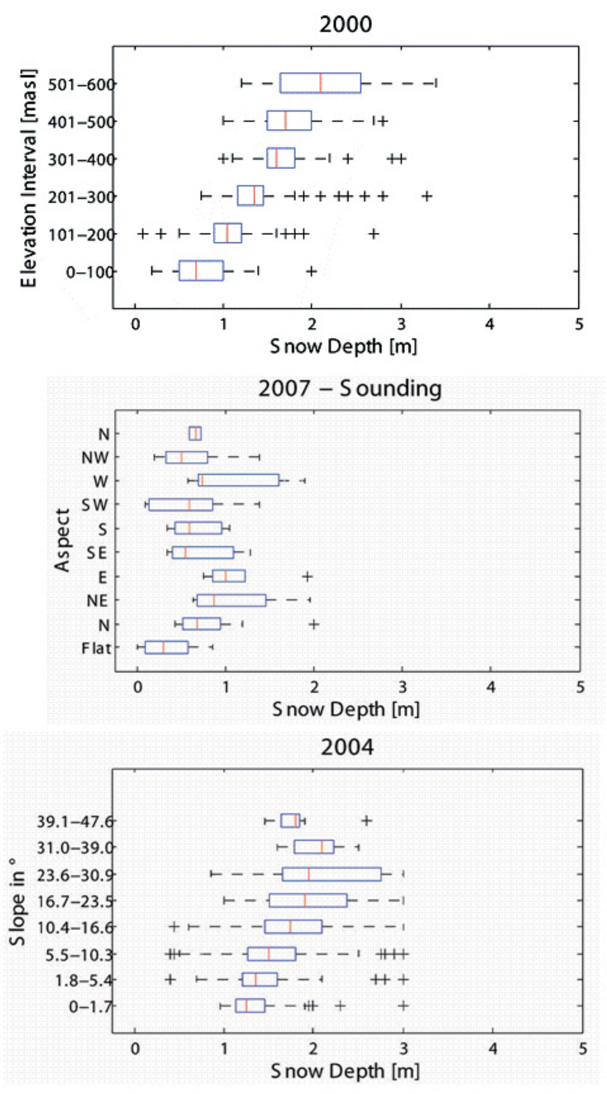

Fig. 3: Box-and-whisker plots showing the correlation between glacier snow depth, elevation, slope and aspect of the year 2000.

first step was the interpolation of the used MODIS data because of sporadically occurring data gaps. Further, the in-situ snow depth data was scaled in three steps, resulting in three matrices for the correlation with MODIS and QuikSCAT.

4. Results and Conclusions

The analyses of relief parameters and in-situ observations showed a high correlation between elevation and snow depth for both the lowlands and the glaciers (e.g. Fig. 3). Further, regional variations in snow accumulation related to the aspect could be determined. Thereby, a relation between greater snow heights and a North-Northeast-East trend for the lowlands as well as a South-Southeast tendency for glacier regions respectively was identified. On gentle slopes, a proportional increase of snow depth was found which is reversing for steeper slopes. A combination of these relief parameters with prevailing wind directions could lead to the generation of snow avalanche hazard maps (cf. Buchroithner & Kostka 1990, Kinberger and Kriz 2007cum lit.) for more remote areas.

The analysis of GPR versus manual sounding measurements led to a good accordance between the arithmetic means of radar and sounding for almost all profiles. Outliers could be excluded by determining median and trimmed values as well as circumjacent values which show continuous increases and/or decreases. Deviations in individual profiles could be assigned only to snow redistributions caused by e.g. aeolian processes which were, however, only detectable by dense GPR measurements.

Regarding the regional and local variability of the in-situ snow depths, a greater variation in altitudes above 201 masl for the lowlands and 501 masl for the glaciers was determined. For the inter-annual variability of glacier and lowland snow depths a high correlation was recognizable (Fig. 4). Glacier measurements showed a low annual variation. MODIS and QuikSCAT data hold almost parallel show-height profiles for the inter-annual variability of the two regions, the lowlands listing lower values for both data sets.

Due to the polar night MODIS albedo data from 2000 to 2007 only cover the periods from April to September. Maximum and minimum values tend to a decrease over the years, even though minor deviations are observable. Annual trends show a strong decrease around the end of April or beginning of May implying snowmelt. Individual summer peaks indicate snowfalls which could be verified by meteorological data.

Melting periods were also analyzed using the QuikSCAT signal in combination with weather data. Hereby, warmer periods during the snow accumulation as well as refreezing during the snowmelt could be identified. Further, an always occurring pattern was found in the QuikSCAT signal indicating the start of the annual melting period in May or June, while two years additionally revealed a pre-melting phase in March or April. Based on the modelled snow accumulation a delayed melting in comparison to the QuikSCAT data was determined, showing, however, the same behaviour for refreezing periods (cf. Fig. 5).

The correlations between in-situ snow-depth measurements and remote sensing data led to a restricted suitability. Due to multiple influencing factors which, for various reasons, could not be regarded in the analysis, the results show no good correlation between in-situ observations and satellite imagery. MODIS albedo (cf. Fig. 6) is, however, slightly better correlated than QuikSCAT backscatter because of the complex composition of snow conditions influencing QuikSCAT signal. For a good evaluation of the snow accumulation with QuikSCAT, areas with continuous snowpacks

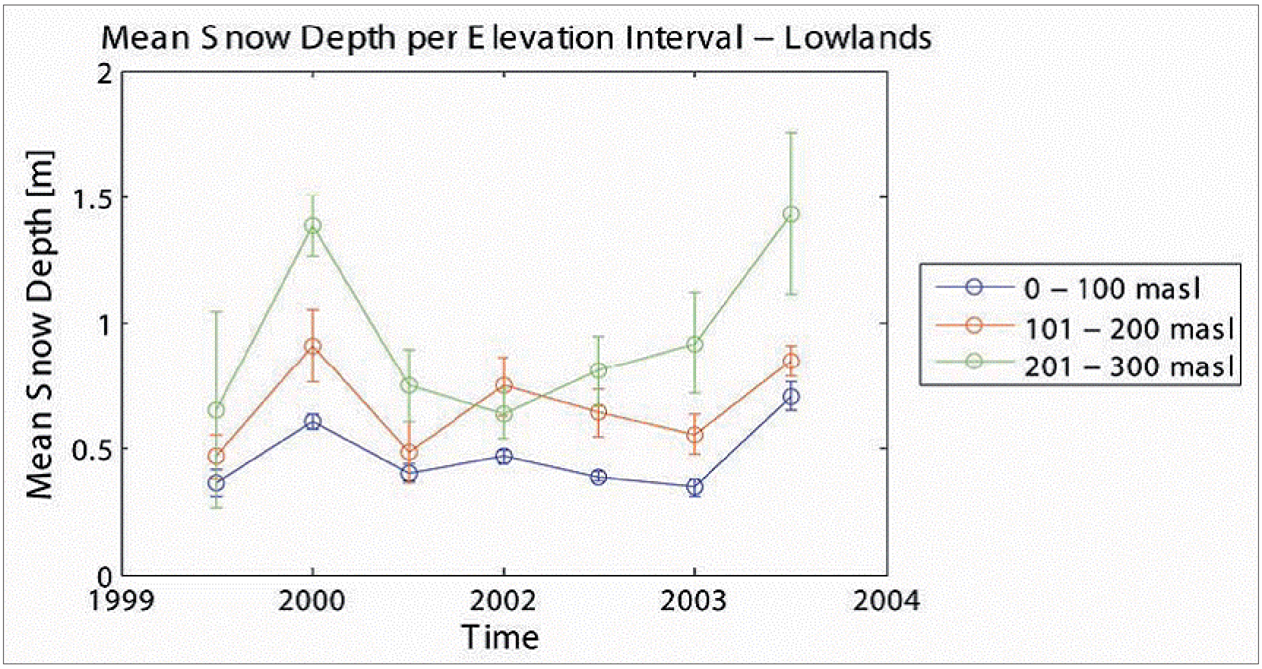

Fig. 4: Change of mean snow depth in the low lands (per elevation interval) from 2001 to 2007.

and information about the underlying layers are required (Drinkwater et al. 2001).

The inclusion of factors like snow density, grain size, liquid water content, microclimatic conditions, etc. can certainly enhance the suitability of the used remote sensing data sets. Additional measurements of in-situ albedo would provide a reference for the MODIS Albedo Product as assessed by Stroeve et al. (2005), in order to determine a better relation between snow depth and albedo.

All in all, an extension of the in-situ soundings on a regular grid covering the entire area instead of sparse profiles may provide a better basis for spatial and temporal variability studies of the snow patterns. Furthermore, it would be an advantage to gather in-situ observations three times a snow period.

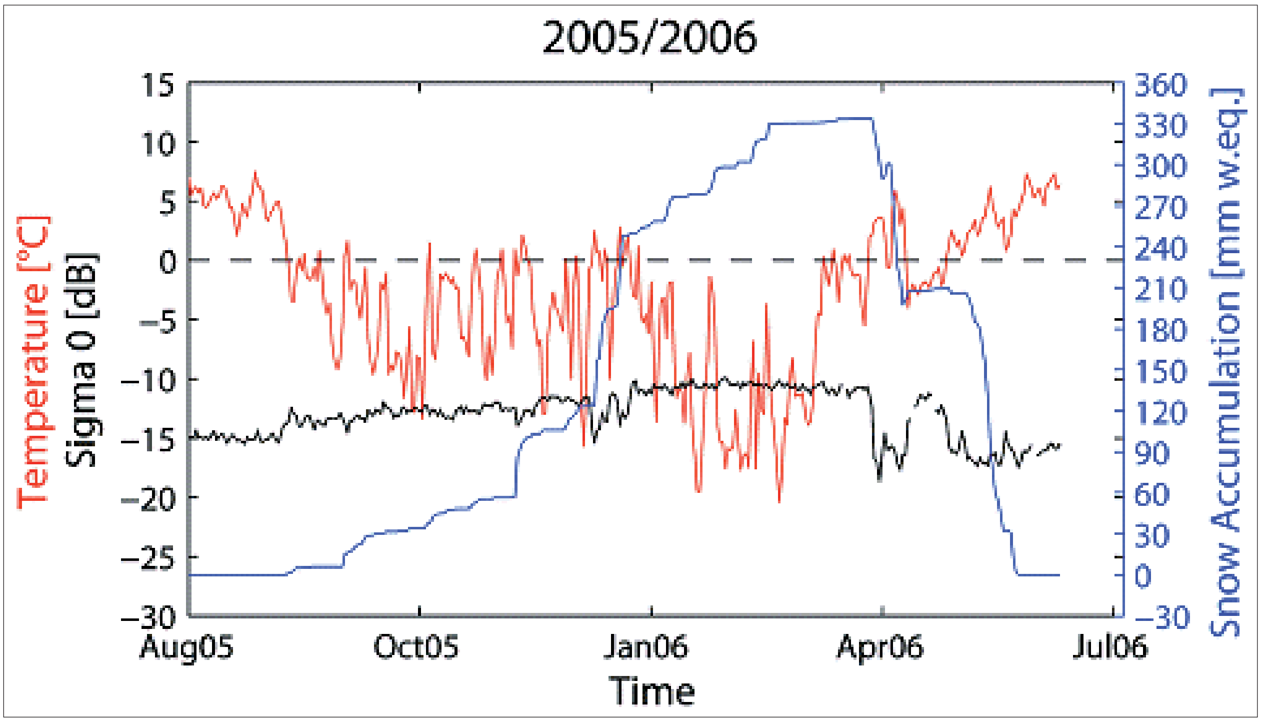

Fig. 5: QuickSCAT σ0-signal, temperature and modelled snow accumulation of the winter period 2005/2006.

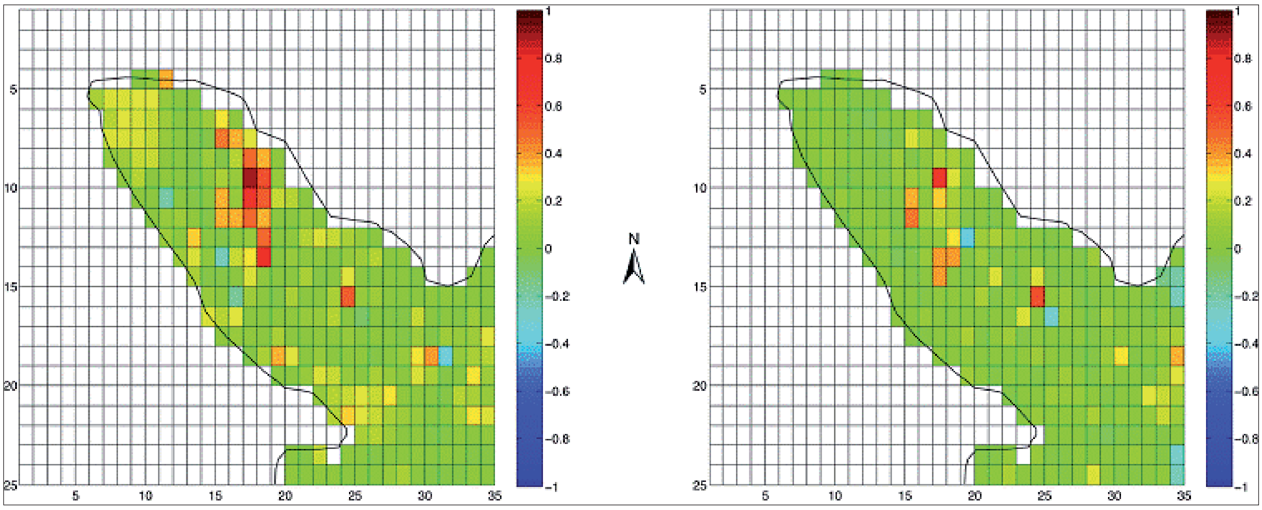

Fig. 6: R² of correlation for MODIS data. Shown are snow depth means per elevation interval (left) and overall (right).

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