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## The impact of snow depth and snowmelt on the vegetation variability over central Siberia

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[1] We report the results of a joint analysis of NDVI data derived from NOAA-AVHRR and snow parameters (snow depth and snowmelt timing) derived from satellite passive microwave measurements over Central Siberia. We investigate the influence of interannual variability in snowmelt and snow depth on vegetation activity from 1989 to 2000. In addition to the effects of temperature and precipitation, we observe significant correlations between the snow parameters and the NDVI. Later snowmelt dates and thicker winter snowpacks are related to higher NDVI values over a large latitudinal band at about 65°N. This may be explained by either increased water availability for plants after snowmelt or thermal insulation of soil by snow. These results reflect the importance of snow-related winter processes on the vegetation development and on the carbon cycle in boreal regions. **Citation:** Grippa, M., L. Kergoat, T. Le Toan, N. M. Mognard, N. Delbart, J. L'Hermitte, and S. M. Vicente-Serrano (2005), The impact of snow depth and snowmelt on the vegetation variability over central Siberia, *Geophys. Res. Lett.*, 32, L21412, doi:10.1029/2005GL024286.

### 1. Introduction

[2] Boreal regions play an important role in the global climate system because they are involved in strong feedbacks due to contrasted snow and vegetation energy budgets, the potential release of large carbon stocks and the impact of river discharge on the ocean-atmospheric circulation. These feedbacks urge for improved understanding of the processes involved in the snow and vegetation cycles.

[3] A marked increase in the vegetation production was demonstrated by *Myneni et al.* [1997] using the Normalized Difference Vegetation Index (NDVI), a combination of red and near-infrared reflectances enhancing the sensitivity to vegetation greenness. In spring, *Zhou et al.* [2003] related the NDVI increase to the warmer temperatures. A parallel evolution of snowmelt toward earlier dates was reported by *Dye and Tucker* [2003], but this does not seem to be the main factor affecting the increase in spring NDVI [Delbart et al., 2005]. Spring greenness variability and trends correlate with the positive phase of

the arctic oscillation in winter [Buermann et al., 2003], as well as the summertime drawdown of atmospheric CO<sub>2</sub> [Russell and Wallace, 2004].

[4] Little is known about changes in summer greenness at high latitude, except for its link to summer temperatures. Kaufmann et al. [2004] showed that tree rings variability correlates to summer NDVI, suggesting a major role of summer compared to spring climate forcing. A recent loss of correlation between tree rings and temperature [Briffa et al., 1998] was ascribed to increasing water stress or to later snowmelt [Vaganov et al., 1999; Jarvis and Linder, 2000]. Still, the relative role of spring and summer forcing and the possible lagged effects involved in the variability of vegetation activity are unclear.

[5] Several experimental studies underlined the importance of snow melt and winter snow depth for high latitudes ecosystems. Later snowmelt reduces subsequent summer CO<sub>2</sub> capture [Llody and Fastie, 2002], and tree ring density [Vaganov et al., 1999] but is shown to increase forest growth [Groffman et al., 2001], tundra and cold steppes productivity [Schimel et al., 2004; Shinoda, 2001] due to thermal insulation effects and summer water availability. However, the influence of the winter snowpack and of the timing of snowmelt on the vegetation development is still poorly known at a regional and global scale. Due to the shortage of ground measurements at high latitudes, remote sensing is in many cases the only means to monitor these areas.

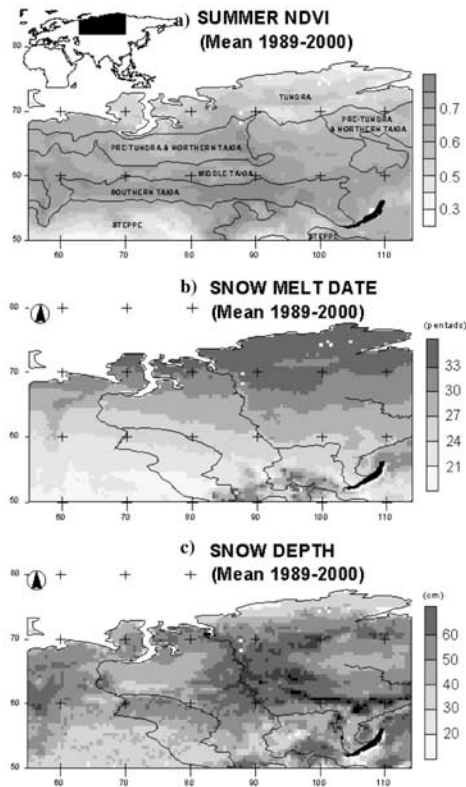
[6] The aim of this work is to investigate the relationship between the interannual variability of NDVI and snow estimates (snow depth and snowmelt) derived from satellite measurements to better understand the response of ecosystems to different forcing elements.

[7] The study area is the Siberia region above 50°N that extends in longitude between 55°E (west of the Ural Mountains) to 115°E (east of lake Baikal) and includes the Ob and the Yenisei river basins. The main vegetation zones consist of tundra in the north, Southern taiga (mixed broad-leaf/coniferous forest) and middle taiga (spruce and larch forest) and steppe and agricultural areas in the south-west (Figure 1a).

[8] We analyse the period 1989–2000 using data from NOAA-AVHRR to derive the NDVI and from the Special Sensor Microwave/Imager (SSM/I) to estimate snow depth and snowmelt dates. To understand the NDVI behaviour we also consider its dependence on temperature and precipitation, obtained from the CRU TS 2.0 dataset at 0.5° resolution. Mean values of temperature and precipitation over summer were calcu-

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**Figure 1.** (a) Summer NDVI, (b) snowmelt date and (c) snow depth: mean values for the study area over the period 1989–2000.

lated by averaging the monthly data between June and July. All data were reprojected into a  $0.5^\circ \times 0.5^\circ$  lat-lon grid.

## 2. Satellite Derived Parameters

### 2.1. NDVI

[9] We used the PAL-NDVI data set at  $1^\circ$  of spatial resolution and at ten days temporal resolution. We considered two measures of vegetation activity: 1- Growing season NDVI important in ecological for its relation to the annual Net Primary Production; 2- Summer NDVI, recorded during the mid-summer period only, linked to the vegetation physiological status near peak activity [Kaufmann *et al.*, 2004].

[10] Growing season NDVI was calculated by fitting two logistic functions to the PAL-NDVI annual time series for each pixel and taking the sum of these functions between the dates of maximum slope [Vicente-Serrano *et al.*, 2005]. Summer NDVI (Figure 1a) was calculated averaging the four decadal mean values between the 1st of July and the 10th of August. The lowest among these four values was eliminated from the mean to further minimise the effects of clouds. The summer vegetation activity indicator derived in this way was not influenced by the effects of snowmelt on the NDVI signal, except for the tundra area where snowmelt can occur after the 1st of July.

[11] Artifacts in the AVHRR archives were analyzed to quantify effects of orbital drift, calibration, and errors in solar angle computation [i.e., Kaufmann *et al.*, 2000; Slayback *et al.*, 2003]. Such effects are less important at

high latitudes. The results reported here did not seem influenced by such problems: excluding 1994 (highest zenithal angle year) or 1992 (high optical depth related to Pinatubo) did not significantly change our results.

### 2.2. Snow

[12] The snow parameters were calculated using SSM/I data at a spatial resolution of  $25 \text{ km}^2$ . To minimise the spatial gaps resulting from the swath width the daily data were averaged over pentads (5-days).

[13] When snow is absent the mean value of the spectral gradient (i.e. the difference between the brightness temperatures at 19 GHz and 37 GHz, horizontally polarized) is of about 3 K. The timing of snowmelt was therefore calculated as the date at which the spectral gradient was less than 3 K for at least 3 consecutive pentads [Grippa *et al.*, 2005, Figure 1b].

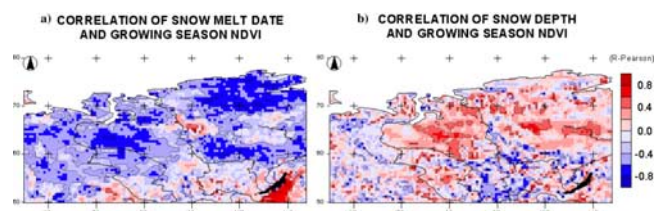
[14] A new dynamic algorithm has been recently developed to estimate snow depth over Western Siberia from SSM/I data [Grippa *et al.*, 2004]. This algorithm, based on the spectral gradient, takes into account the dependence of the microwave scattering on the snow grain size, by considering the snow metamorphosis originated by the temperature gradient within the snowpack. Applying this method, improved snow depth estimates were obtained over those achieved by applying classical algorithms. In this paper we used the snow depth derived for the month of February as representative of the winter snowpack (Figure 1c).

[15] Scattering by trees attenuates the microwave signal. Different empirical formulations were proposed to take this into account by including the forest fractional cover into snow retrieval algorithms [Pulliainen and Hallikainen, 2001; Kelly and Chang, 2003]. In this study we did not apply any corrections for this effect. This may have introduced a bias in the absolute values of the derived snow estimates over densely forested areas but did not affect sensibly their interannual variability and it had no impact on our analysis. Moreover, the interannual variability of the snow depth and snowmelt estimates were validated through the comparison with river discharge measurements in the Ob river basin [Grippa *et al.*, 2005].

## 3. Analysis

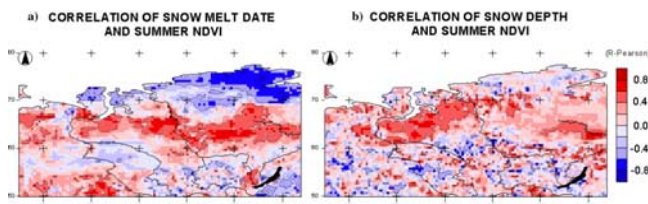
### 3.1. Correlation Between NDVI and Snowmelt Dates

[16] For the growing season NDVI (Figure 2a), negative correlation with the snowmelt date is generally found, i.e. a later snowmelt corresponds to a lower growing season



**Figure 2.** Correlation (R-values) between the growing season NDVI and (a) snowmelt date, (b) snow depth. Absolute correlation values higher than 0.4 are significant above 90% ( $p < 0.1$ ), those higher than 0.6 are significant above 98% ( $p < 0.02$ ).





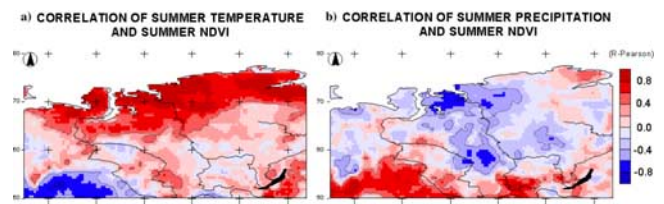
**Figure 3.** Correlation (R-values) between the summer NDVI and (a) snowmelt date, (b) snow depth (see Figure 2 caption).

NDVI. This can be explained by the shorter time period for vegetation to develop when snow melts later and by the correspondence between snowmelt date and the onset of positive temperatures that start up the vegetation greening. Moreover, snowmelt affects the optical reflectance by which the growing season NDVI is calculated producing a signature similar to the vegetation greening [Dye and Tucker, 2003; Delbart et al., 2005].

[17] When we consider the summer NDVI (Figure 3a and Table 1), only in the northern region of tundra is the correlation still negative. This can still be explained by the factors listed above since in this area snowmelt and green up can occur in July and it is not possible to separate the beginning of the growing season from the summer period.

[18] Significant positive correlation values are instead found in the latitudinal band about 65°N in the northern taiga and in the southern steppe region. Later snowmelt dates are expected to delay the depletion of soil moisture occurring in summer, therefore delaying and reducing plant water stress. This is very likely to occur in the steppe, characterized by both water and temperature stress in summer: in this area the interannual variations of NDVI are significantly correlated to precipitation and anti-correlated to temperature (Figure 4). Similarly, it has been established that most of the continental boreal forests are prone to drought, often on a regular basis [Briffa et al., 1998]. A later snowmelt may delay and reduce summer droughts in the Northern Taiga, because the water from the snowpack is released later in the season and also because later snowmelt coincides with cold springs with low evaporation.

[19] In-situ observations suggest another mechanism that may play a role in the positive correlation between snowmelt and summer NDVI. Earlier snowmelt exposes the soil to freeze events that enhance fine root mortality decreasing subsequent vegetation productivity. Such a mechanism has been observed in long-term in-situ data from a forest



**Figure 4.** Correlation (R-values) between the summer NDVI and (a) average temperature in June–July, (b) average precipitation in June–July (see Figure 2 caption).

catchment [Groffman et al., 2001] but it is not known whether it occurs at a larger scale.

### 3.2. Correlation Between NDVI and Winter Snow Depth

[20] Winter snow depth is positively correlated to NDVI over large areas between 60° and 70°, more significantly to the summer NDVI (Figures 2b and 3b and Table 1). The correlation between snow depth and NDVI is generally lower the correlation between summer NDVI and summer temperature (Figure 4a and Table 1) and it disappears in the northernmost areas where the temperature effect is the strongest.

[21] Ground-based observations and water budget considerations point towards the same two lines of explanation as for the snowmelt - NDVI positive correlation: enhanced water availability reducing water stress on one hand, snowpack insulation properties impacting vegetation productivity on the other hand. The first mechanism implies that snow depth is related to snow water equivalent, which drives the severity of summer water stress. However, the NDVI variability in the areas individuated by positive correlation coefficients with snow depth is not correlated to the precipitation variability (Figure 4b and Table 1). (Figure 4b and Table 1 indicate that summer NDVI and precipitation are negatively correlated over some areas. This may be due to a lower vegetation activity during summers with poor weather conditions (higher precipitation and lower temperatures). However, especially for the southern areas, we cannot exclude the possible effects of residual cloudiness on the NDVI composites.)

[22] The second explanation for the observed positive correlation is the insulating effects of a deeper snowpack on the soil during the cold Siberian winters. This has been suggested by several in-situ studies showing that the insulation by a deeper winter snowpack increased summer vegetation productivity, summer leaf nitrogen content, and soil nitrogen mineralization due to enhanced winter microbial activity [Schimel et al., 2004; Dorrepaal et al., 2004; Grogan and Jonasson, 2003]. Higher values of snow depth have been related to a 6-month lagged increase in the carbon uptake by vegetation [Welker et al., 2000]. Given the lack of snow depth estimates so far, the importance of these mechanisms at a large scale is not known. Our results suggest that 6 months-lag effects exist and are possibly caused by winter soil processes translating into summer vegetation processes.

## 4. Conclusion

[23] We have shown that snow variability has a significant impact on the NDVI interannual variability over large

**Table 1.** Correlations (R-Values) Between the Summer NDVI Spatially Averaged Over Different Latitude Bands and Snowmelt Date, Snow Depth, Summer Temperature and Precipitation Averaged Over the Same Latitude Bands<sup>a</sup>

Latitude Bands	Snowmelt Date	Snow Depth	Summer Temp.	Summer Precip.
58°–62°N	-	0.47	-	-
63°–67°N	0.57	0.41	0.70	-0.44
68°–72°N	-	0.54	0.84	-0.56
>72°N	-0.72	-	0.84	-

<sup>a</sup>Only significant values ( $p < 0.1$ ) are reported.

areas in central Siberia. In particular, we have found correlations between the summer vegetation activity and both snowmelt and snow depth in a latitudinal band at about 65°. This can be explained by either the water contained in the snowpack made available to plants after snowmelt or the thermal insulation of the soil provided by snow against the cold winter temperatures.

[24] Snow is recognized as a very important factor in the tundra ecosystem since it plays an important role on the melting of permafrost and in thermal insulation of the soil. Our results suggest that these effects are not only important for the northern regions of tundra but for a large portion of the boreal belt. The relationship between NDVI and snow depth underline the importance of winter processes on the vegetation physiology during summer.

[25] In the context of climate change it is necessary to better understand the interplay of snowpack, water cycle, nutrient cycle and fine roots at process level. Snow has to be considered as a key variable not only for the albedo feedback on the spring temperature, but also for its effect on the winter soil temperature and its impact on the ecosystem functioning. The relations among increased vegetation production over the Northern latitudes [Myneni *et al.*, 1997], shift of snowmelt toward earlier dates [Dye and Tucker, 2003] and increase in air temperature will also depend on the trend toward thicker snowpacks due to increased winter precipitation [Vaganov *et al.*, 1999].

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