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Boreal and subarctic soils under climatic change

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ABSTRACT

Changing climate and warming atmosphere are supposed to result in changing thermal regimes of soils with a spectrum of impacts for terrestrial heat-flow, ecological and biochemical processes including vegetation and carbon dynamics. Here, six sites within an area of significant recent climatic warming, between 70° and 60°N, provided data of air and soil temperatures and snow depth to analyze the spatiotemporal air–soil temperature associations during the period 1971–2010. The air temperatures exhibited significant trends of warming across the boreal and subarctic regions. The records of snow depth showed trends of snowpack thinning and the soil temperature trends of warming especially in the southern and middle boreal sites. The boreal and subarctic sites showed predominant influence of air temperature variability on soil thermal conditions, with modulating effects of thermoinsulation caused by the snowpack. The yearly variations in soil temperatures correlated highly with those of air temperatures and the positive trend in soil temperatures was sufficiently explained by air temperature warming in the majority of the sites. The results thus propose that the climate change could be directly causing alterations in the soil thermal regime and the warming of soils, with generally expected continuation, driven by air temperature warming as projected by model simulations. The thermoinsulation effects during the winter were strongest in the northern boreal zone where the temperature difference between the air and soil temperatures was largest and the correlations between snow depth and soil temperatures were highest during the winter months. Likewise, the rate of air temperature warming appeared strongest in our northern boreal site where the soil temperature warming showed non-significant trend only. The evidence for temporal air–soil temperature decouplings and spatial disparity between the air and soil temperature data both expressed the importance of studying the soil temperature change in situ. In the same context, the potential for temperature induced soil organic carbon decomposition coincided spatially with the highest quantities of available carbon as indicated for our boreal and subarctic soils.

1. Introduction

Physical, chemical and biological soil processes are under the influence of a changing climate (Blum, 2005). These impacts could have important role especially in the northern high-latitude areas expected and observed to warm increasingly in comparison to other regions (Gibbard et al., 2005; Serreze and Francis, 2006). Understanding these associations is especially important since the boreal and Arctic land surfaces and ecosystems provide multitude of feedback mechanisms essential to the climate system (Chapin et al., 2000, 2005). Albeit the variations in soil thermal regime influence many of these mechanisms, the soil temperature trends and changes are more poorly documented than the corresponding variations in the atmosphere. An actual reason for this discrepancy is the lack of long-term observations of soil temperatures and related climatic variables (Zhang et al., 2001). Nevertheless, the studies examining the existing long-term soil observational records indicate that the trends in soil temperatures do not necessarily correspond to the trends observed for air temperatures (Gilichinsky et al., 1998; Zhang et al., 2001). Conductive heat transfer models with phase change have been applied to resolve the soil temperatures for specific regions and over large areas of the northern Hemisphere (Venäläinen et al., 2001a, 2001b; Oelke et al., 2004; Oelke and Zhang, 2004; Ling and Zhang, 2007). While the modeling approach efficiently contributes to surmount the sparseness of the observational network, it could also be noted that conduction is not the only mode of heat transfer and that the relationships between the air and soil temperatures may not remain constant through time (Kane et al., 2001; Beltrami and Kellman, 2003).

High latitude air–soil temperature decouplings have shown to result from variation of the snow cover (Goodrich, 1982; Beltrami and Mareschal, 1991; Kubin and Kemppainen, 1991; Sutinen et al., 1999; Osokin et al., 2000; Zhang, 2005; Smerdon et al., 2006). In boreal and subarctic settings, the previous trend analyses have indicated decreasing springtime snow cover over the recent decades. However, the spatial variations in these trends appear evident showing less pronounced change toward the northern conditions (Tuomenvirta and Heino, 1996; Moberg et al., 2005). We hypothesize that these

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spatial differences in the snow cover trends may play a role in the development of the air–soil temperature decouplings. Consequently, the incorporation of snow depth data into the analyses of soil temperatures could be seen as a mandatory issue in attempts to better understand the influence of the changing climate on thermal regimes of soils at different spatial and temporal scales.

Our analyses operate in the uppermost soil (depth of 20 cm) and thus in root zone and may consequently provide climatological evidence specifically relevant for understanding of the soil-dependent processes in plant ecology (Sutinen et al., 1999, 2008, 2009a, 2009b; Vaganov et al., 1999; Solantie, 2000; Tuovinen et al., 2005; Repo et al., 2007, 2008). Moreover, this subsurface portion contains high soil carbon density (Liski and Westman, 1997a, 1997b). The substance of soil carbon lies in its capability of providing positive feedback to ongoing change in climate if warming accelerates its subsurface decomposition (Knorr et al., 2005). Despite empirical and modeling evidence (Davidson and Janssens, 2006; Fan et al., 2008; Vanhala et al., 2008; Karhu et al., 2010), uncertainties still remain in response of soil carbon dynamics to projected temperature change. Common to all decomposition model outcomes is that their meaningful applicability presupposes exact information about the temperature change not as much in the atmosphere but in the carbon storage in situ. In accordance with the aims of the present study, such information can be directly derived from the analysis of observational temperature records. In brief, our study contributes to the analyses needed to augment the understanding on the processes in soils and sediments induced by climate change (Blum, 2005) over the boreal and subarctic areas.

Here we employ the station network of the Finnish Meteorological Institute providing long-term continuous monthly air and soil temperature measurements accompanied with coexisting snow depth observations. The dataset covers the period of past 40 years and forms a latitudinal transect with contrasting temperature and snow conditions (Vehviläinen and Lohvansuu, 1991; Heino, 1994; Venäläinen et al., 2001a, 2001b) from subarctic environment to southern edge of the boreal zone, that is, between 70° and 60°N. Similarly, this is a geographical area known to have undergone markedly strong warming in the context of European continent as observed by annual air temperatures over much of the study period (Helama and Holopainen, 2010). The main aim of the study is to detail the influence of this air temperature warming on soil temperatures statistically, under the influence of presumable warming-induced variations on snow depths and conceivable differences in changing thermoinsulation effects through this transect.

2. Regional setting

Observations of meteorological variables originated from six stations in Northern (N1, N2), Central (C3, C4) and Southern (S5, S6) Finland (Fig. 1; Table 1). According to the Köppen–Geiger climate classification (Kottek et al., 2006; Peel et al., 2007), the most of the study region is governed by the continental subarctic climates (N1, N2, C3, C4) whereas the southernmost localities (S5, S6) are influenced by the warm summer continental climates. The two northernmost stations were situated in Lapland while the northernmost site actually represents clearly subarctic conditions. Biogeographically the six sites can be assigned to the northern, middle and southern boreal forest zones (Ahti et al., 1968) (Fig. 1). The distance between the northernmost and southernmost sites is slightly more than 1000 km.

3. Material and methods

3.1. Electronic database

The sites were those with stations with updated observations of air and soil temperatures in the electronic database of the Finnish Meteorological Institute for the interval 1971–2010. Similarly, the database enabled the usage of snow depth observations over the same interval. The air temperatures were measured at the height of 2 m and the mean monthly temperatures (T_{AIR}) calculated from the intra-daily observations (e.g. Tuomenvirta, 2004). Previous analyses have examined soil temperature records in the study region with a maximum length of few years (Lemmelä et al., 1981; Sutinen et al., 1999, 2008, 2009a, 2009b) and thus the long-term trends have remained unexplored. The soil temperatures have been recorded most regularly and continuously at the depth of 20 cm and this data served the observational framework for the analysis. Diurnal changes in air temperature propagated to a depth of about 20 cm (Goulden et al. 1998). Soil temperatures were measured in the 3rd, 8th, 13th, 18th, 23rd and 28th day of each month and the monthly mean soil temperatures (T_{SOIL}) were thus computed using these values. The observations of snow depth (D_{SNOW}) were made in the 15th day of each month. The yearly values were computed as the mean annual temperatures of T_{AIR} and T_{SOIL} and as the annual maximum thickness of D_{SNOW}.

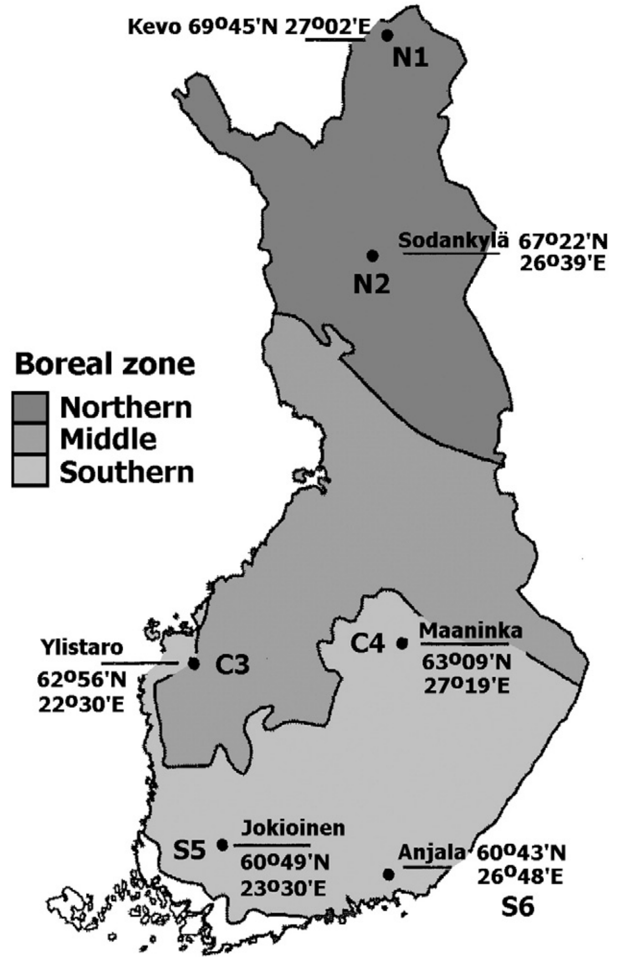

Fig. 1. A map of Finland showing the locations of the six stations, originating from Northern (N), Central (C) and Southern (S) parts of the country, referred to in the text accordingly with abbreviations N1, N2, C3, C4, S5 and S6. See Table 1 for more detailed information.

3.2. Statistics of temperature and snow observations

Comparisons were made using the monthly based time-series of T_{AIR}, T_{SOIL} and D_{SNOW}. Following Zhang (2005), the difference (ΔT) between the soil and air temperatures was determined throughout this study as

$$\Delta T = T_{SOIL} - T_{AIR}. \quad (1)$$