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Using dynamical downscaling to close the gap between global change scenarios and local permafrost dynamics

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Abstract

Even though we can estimate the zonation of present-day permafrost from deep-soil temperatures obtained from global coupled atmosphere-ocean general circulation models (GCMs) by accounting for heat conduction in the frozen soil, it is impossible to explicitly resolve soil properties, vegetation cover and ice contents in great details. On the local scale, descriptions of the heterogeneous soil structure in the Arctic exist only for limited areas. Semi-empirical approaches, e.g. based on the Stefan [Stefan, J., 1891. Über die Theorie der Eisbildung, insbesondere über Eisbildung im Polarmeere. Ann. Phys. 42, 269–286] formula, give a more realistic depiction of permafrost temperatures and active layer thicknesses while at the same time avoiding problems inevitably associated with the explicit treatment of soil freezing and thawing. The coarse resolution of contemporary GCMs models that prevents a realistic description of soil characteristics, vegetation, and topography within a model grid box is the major limitation for use in permafrost modelling.

We propose to narrow the gap between typical GCMs on one hand and local permafrost models on the other by introducing as an intermediate step a high resolution regional climate model (RCM) to downscale surface climate characteristics to a scale comparable to that of a detailed permafrost model. Forcing the permafrost model with RCM output results in a more realistic depiction of present-day mean annual ground temperature and active layer depth, in particular in mountainous regions. By using global climate change scenarios as driving fields, one can obtain permafrost dynamics in high temporal resolution on the order of years. For the 21st century under the IPCC SRES scenarios A2 and B2, we find an increase of mean annual ground temperature by up to 6 K and of active layer depth by up to 2 m within the East Siberian transect. According to these simulations, a significant part of the transect will suffer from permafrost degradation by the end of the century.

Keywords: permafrost; climate change; active layer; snow cover; ground temperature; climate model

1. Introduction

There is observational evidence for recent high latitude warming (Hansen et al., 1998; Serreze et al., 2000). Changes have been observed for air temperature (Moritz et al., 2002), vegetation cover (Sturm et al., 2001), sea ice (Bjorgo et al., 1997), glacier mass balance (Arendt et al., 2002), ice sheets (British Antarctic

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Survey, 2002) and soil temperature (Majorowicz and Skinner, 1997; Osterkamp and Romanovsky, 1999; Romanovsky et al., 2002; Osterkamp, 2003). Many of these changes affect the permafrost body (perennially frozen ground) and the seasonally thawed layer between it and the surface, the active layer. Furthermore, climate change scenarios indicate that warming due to anthropogenic activities will be largest in the polar regions (see e.g. ACIA, 2004). Changes involving permafrost (which presently underlies nearly a quarter of the Northern Hemisphere land area; Zhang et al., 2003) may potentially be quite severe. This includes impacts on infrastructure and regional ecosystems due to thawing of the ground and development of thermokarst depressions (Romanovskii et al., 2000) as well as the release of large amounts of greenhouse gases to the atmosphere.

Several model studies with comprehensive coupled ocean-atmosphere general circulation models (AOGCMs) have been conducted which show that the area of the Northern Hemisphere underlain by permafrost could be reduced substantially in a warmer climate (Smith and Burgess, 1999; Anisimov et al., 2001; Nelson et al., 2001; Stendel and Christensen, 2002). However, thawing of permafrost, in particular if it is ice-rich, is subject to a time lag due to the large latent heat of fusion of ice. In deep layers, permafrost can therefore persist in relict form for centuries or even millennia, as in western Siberia (Stendel and Christensen, 2002). With state-of-the-art AOGCMs, it is not possible to adequately model these processes, since even the most advanced subsurface schemes rarely treat depths below 5 m explicitly. Therefore, permafrost properties cannot be obtained directly from model output. The same argument holds for a direct modelling approach to changes in active layer thickness. Soil thawing and freezing processes cannot be dealt with directly because present-day AOGCMs, operating at scales on the order of 300 by 300 km, cannot resolve realistically the fine scale heterogeneous soil structures in the Arctic, as already pointed out by Burn (1994). Estimates from such simulations would therefore offer little advance over more simple models (Anisimov and Nelson, 1997).

Based on these considerations, Anisimov and Nelson (1997) used a simple permafrost model based on the concept of a ‘surface frost index’ F, defined as $F=\sqrt{\mathrm{DDT}}/(\sqrt{\mathrm{DDT}}+\sqrt{\mathrm{DDF}})$, where DDF (DDT) stands for the annual degree-days of freezing (thawing), i.e. the sum of daily mean temperatures below (above) 0 °C. Note that although surface temperatures are not directly related to permafrost properties, they usually serve as a basis for such indices due to the lack of deep soil temperature observations. The concept was further elaborated by Stendel and Christensen (2002) who applied the Stefan (1891) solution for the heat transfer problem in a solid medium to GCM simulations of climate change based on the IPCC scenarios. The authors estimated the future evolution of permafrost by calculating a ‘deep soil frost index’ based on simulated temperatures from the lowest model soil level (5.7 m below ground) rather than air temperatures. Such an approach relates the frost index directly to quantities significant for permafrost, while at the same time it circumvents complications associated with the explicit parameterisation of snow cover as in Anisimov and Nelson (1997) and overcomes the inherent problem in many GCMs (including the ECHAM4 model used in this study) related to the lack of a specific description of freezing and thawing processes. However, all these approaches need information about soil properties, vegetation and snow cover. While soil and vegetation information hardly is realistic on a typical GCM grid, simulated precipitation on the GCM scale often lacks realism, in particular in mountainous regions. The coarse resolution leads to a general underestimation of orography in steep terrain so that precipitation is underestimated and the proportion of rain and snow is incorrect (e.g. Christensen and Kuhry, 2000).

One possibility to overcome resolution-related problems is by means of downscaling to use a regional climate model (RCM). The RCM HIRHAM (Christensen et al., 1996) has so far been the only one used for the entire circumpolar domain (ACIA, 2004), and it has also been used in this study. Since no specific treatment of soil freezing and thawing is done in HIRHAM, the same arguments as for the GCM apply, and so far only studies based on frost indices as outlined above have been conducted. Christensen and Kuhry (2000) applied the frost index to a high-resolution simulation over parts of the Arctic and found it well suited to diagnose general present-day permafrost zonation on a spatial scale of 15 km. However, these simulations also lack sufficient information about soil properties.

Instead of calculating a frost index from RCM data, we here use the RCM to create boundary conditions for a sophisticated permafrost model. Our approach is novel in that the spatial resolution of the RCM and the permafrost model is comparable (0.5°), so that output from the RCM can be directly used to force the permafrost model. Furthermore, the above mentioned problems can be overcome, as we can either pass information about soil properties etc. to the permafrost model from RCM output, or information from digitised Geographic Information Systems (GIS), where available, can be used to create enhanced forcing fields for the permafrost model. Also the inclusion of observed data is possible.