A projection of severe near-surface permafrost degradation during the 21st century

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Received 31 October 2005; revised 6 November 2005; accepted 15 November 2005; published 17 December 2005.

[1] The current distribution and future projections of permafrost are examined in a fully coupled global climate model, the Community Climate System Model, version 3 (CCSM3) with explicit treatment of frozen soil processes. The spatial extent of simulated present-day permafrost in CCSM3 agrees well with observational estimates – an area, excluding ice sheets, of 10.5 million km^2. By 2100, as little as 1.0 million km^2 of near-surface permafrost remains. Freshwater discharge to the Arctic Ocean rises by 28% over the same period, largely due to increases in precipitation that outpace increases in evaporation, with about 15% of the rise directly attributable to melting ground ice. Such large changes in permafrost may provoke feedbacks such as activation of the soil carbon pool and a northward expansion of shrubs and forests. **Citation:** Lawrence, D. M., and A. G. Slater (2005), A projection of severe near-surface permafrost degradation during the 21st century, *Geophys. Res. Lett.*, *32*, L24401, doi:10.1029/2005GL025080.

1. Introduction

[2] Recent observational studies suggest that permafrost extent is shrinking and that active layer thickness (ALT; the upper portion of soil that thaws each summer) is increasing [*Jorgenson et al.*, 2001; *Serreze et al.*, 2002; *Zhang et al.*, 2005]. Already, researchers have detected changes to the hydrologic cycle, vegetation composition, ecosystem functioning, as well as carbon dioxide and methane fluxes that appear linked to permafrost degradation [*McNamara et al.*, 1998; *Jorgenson et al.*, 2001; *Christensen et al.*, 2004; *Smith et al.*, 2005]. The damaging impacts of permafrost-degradation-induced subsidence on civil infrastructure are well known [*Nelson et al.*, 2002].

[3] Permafrost, which is defined as soil that remains at or below 0°C for two or more years, is estimated to occupy about 24% of the northern hemisphere land surface [*Zhang et al.*, 1999]. Permafrost influences hydrology by providing an impermeable barrier to the movement of liquid water. Where permafrost is deep, thawing can increase soil water storage via a greater ALT and thermokarst lake formation. Conversely, thawing that promotes talik formation or removes barriers to groundwater flow may decrease soil water storage [*Yoshikawa and Hinzman*, 2003; *Smith et al.*, 2005]. In a recent observational study of major Eurasian rivers, *Serreze et al.* [2002] show that current runoff ratios (runoff/precipitation) appear proportional to the extent of permafrost in the basins. A degradation of permafrost may, therefore, have a significant impact on freshwater discharge to the Arctic Ocean. Runoff to the Arctic Ocean is already changing, reportedly increasing by 7% over the last 70 years [*Peterson et al.*, 2002]. Change in the amount of freshwater reaching the Arctic Ocean affects sea-ice formation and may alter the oceanic thermohaline circulation [*Arnell*, 2005]. It is an open question how permafrost degradation will impact runoff to the Arctic Ocean. Observed increases in Yenessey river flow may be related to, among other factors, a degradation of permafrost [*Serreze et al.*, 2002].

[4] Prior studies of permafrost distribution under climate change have been conducted using a post-process method in which surface variables from a global climate model (GCM) are used to drive stand-alone permafrost models based on temperature indices [*Anisimov and Nelson*, 1997], analytic steady-state equations [*Sazonova et al.*, 2004], or heat conduction methods [*Zhang et al.*, 2003]. Permafrost has been evaluated in ECHAM4 [*Stendel and Christensen*, 2002], but that model did not include soil freeze-thaw processes. Hence, none of the aforementioned models can fully capture the thermal and hydrologic feedbacks to the climate system.

[5] Here, we conduct an examination of present-day and future permafrost in the Community Climate System Model (CCSM3), a fully coupled atmosphere-ocean-land-sea ice model with full soil freeze-thaw processes. The impact of projected permafrost degradation on Arctic hydrology is also evaluated.

2. Model

[6] The coupled GCM analyzed in this study is CCSM3 [*Collins et al.*, 2005]. Many GCM land surface schemes now include coupled hydro-thermo frozen soil processes [*Slater et al.*, 1998; *Luo et al.*, 2003] including the Community Land Model (CLM3 [*Oleson et al.*, 2004]), which is used in CCSM3. CLM3 includes a 5-layer snow model that sits atop a 10-layer, 3.43m-deep soil model. It explicitly treats thermal and hydrologic frozen soil processes as well as snow processes including accumulation, melt, compaction, and water transfer across layers. Sub-grid scale surface type heterogeneity is represented through satellite-derived fractional coverage of lakes, wetland, bare soil, glacier, and up to four plant functional types in each grid box. Fluxes of energy and moisture are modeled independently for each surface type and aggregated before being passed to the atmosphere model. Each grid box consists of a single soil column with soil moisture heterogeneity represented through differing runoff formulations for saturated and

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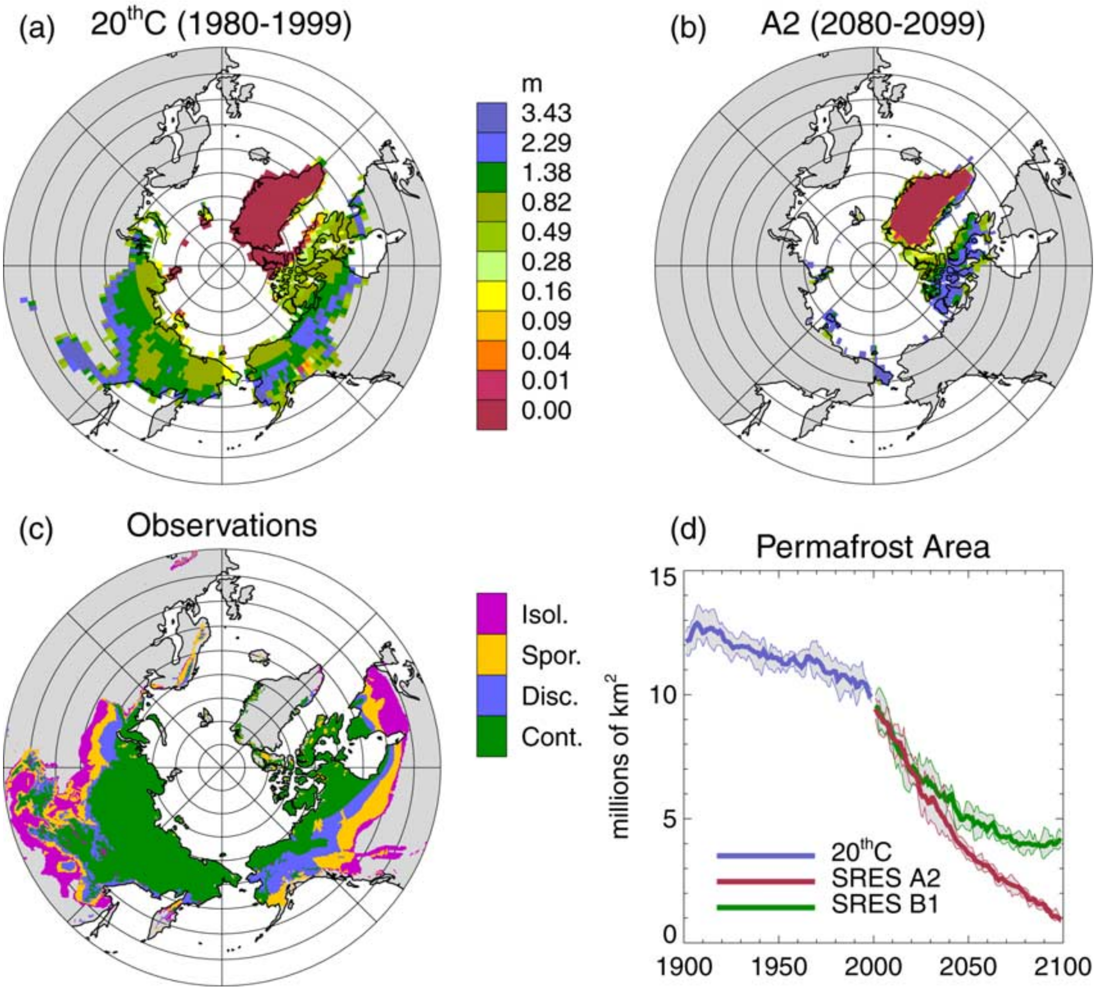

Figure 1. Ensemble mean permafrost area and active layer thickness as simulated in CCSM3 at the end of the (a) 20th and (b) 21st centuries. (c) Observational estimates of permafrost (continuous, discontinuous, sporadic, and isolated). (d) Time series of simulated global permafrost area (excluding glacial Greenland and Antarctica). The gray shaded area represents the ensemble spread.

unsaturated fractions of the grid box. Currently, there is no interactive representation of soil carbon in CCSM3. The atmosphere and land model resolution is T85 ($\sim$1.4° long. $\times$ 1.4° lat.). The CCSM3 runs analyzed here include five member ensembles of 20th century integrations as well as two sets of 21st century simulations, the SRES A2 (high) and B1 (low) greenhouse gas emission scenarios. More details on the suite of runs conducted with CCSM3 in support of the Integovernmental Panel on Climate Change Fourth Assessment Report are found in *Meehl et al.* [2005].

3. Permafrost in CCSM3

[7] Present-day (1980–1999 mean) permafrost extent and ALT, as simulated in CCSM3, are shown in Figure 1a. We use a simple definition of permafrost to identify where and when it exists; a model grid box is identified as containing permafrost if monthly mean soil temperature in at least one soil level remains below 0°C for 24 consecutive months. ALT is defined as the depth of the deepest soil level that thaws at some point during the 24-month period.

[8] Present-day CCSM3 permafrost extent is qualitatively compared to the International Permafrost Association (IPA) map [*Brown et al.*, 1998], which is reproduced in Figure 1c. Permafrost in the IPA map is depicted according to the following permafrost classifications: continuous (90–100% permafrost coverage), discontinuous (50–90%), sporadic (10–50%), isolated (<10%), and no permafrost. Due to the large size of its grid boxes, CCSM3 can only reasonably be expected to be able to simulate continuous permafrost. The CCSM3 permafrost distribution largely corresponds to that of IPA with CCSM3 replicating the extensive permafrost across northern Canada, Alaska, and Siberia and even capturing more isolated areas in northern China and Mongolia as well as in the Tibetan plateau (not shown). Permafrost in CCSM3 covers a total of 10.5 million km^2 (excluding glacial Greenland and Antarctica) which compares favorably to observed estimates of 10.69 million km^2 of continuous permafrost [*Zhang et al.*, 1999].

[9] The simulation of ALT in CCSM3 is compared to data from the Circumpolar Active Layer Monitoring (CALM) network which monitors ALT in the Alaskan Arctic. Measured ALTs in the Alaskan Arctic typically

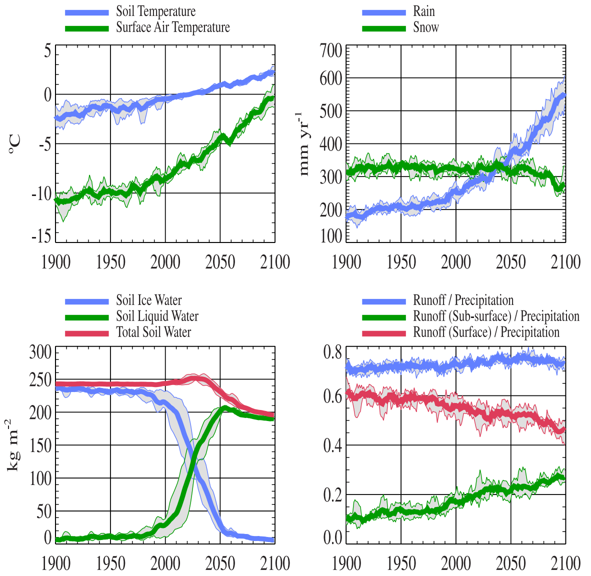

Figure 2. Area-mean time series averaged over the Alaskan Arctic (66.5°–72°N, 170°–140°W). Time series are filtered with a 7-yr running mean prior to plotting. Thick solid lines (gray shading) represent ensemble mean (spread). Soil temperature, ice water, and liquid water are obtained by integrating across all 10 soil levels.

range between 0.3 and 0.75m which compares reasonably with values around 0.5 to 0.8m seen in CCSM3.

4. Permafrost and Climate Change

[10] CCSM3 projections of permafrost extent under the A2 emission scenario are shown in Figures 1b and 1d. The area of near-surface permafrost decreases slowly from 1920 to 2000, but the degradation accelerates sharply during the first half of the 21st century. By 2100, only ~1 million km^2 (~4 million km^2) of near-surface permafrost remain under the A2 (B1) emission scenario. Permafrost degradation of this magnitude is likely to have significant adverse ecological and societal impacts.

[11] Time series of CCSM3 climate change projections for the Alaskan Arctic are shown in Figure 2. Surface air temperature rises slowly in the 20th century and soil ice content remains steady as annual mean soil temperature stays well below 0°C. When soil temperatures rise to near 0°C, soil ice begins to melt. Within 50 years, almost all frozen soil water is converted to liquid water. Without soil ice acting as a barrier, liquid water drains through the soil column more readily. Sub-surface runoff increases, at a faster rate than precipitation, while surface runoff decreases relative to precipitation as a larger fraction of incident water permeates the soil. Despite substantial increases in precipitation, enhanced drainage through the ice-free soil column contributes to a drying of the soil column from 2050 onwards.

[12] The ensemble mean annual cycle of freshwater discharge to the Arctic Ocean, as simulated by CLM3's River Transport Model [*Branstetter and Famiglietti*, 1999], is shown in Figure 3a. CCSM3 captures the observed June peak in freshwater discharge [*Dai and Trenberth*, 2002] and reasonably simulates total discharge. By the end of the 21st century, the discharge hydrograph is marked by an earlier initiation of the spring snowmelt discharge and by increased runoff throughout the winter.

[13] Over the past 70 years, runoff to the Arctic Ocean has increased by an estimated 7% [*Peterson et al.*, 2002]. CCSM3 shows a similar 7% increase, mostly due to heavier precipitation. Discharge grows by a further 28% by 2100. Figure 3b shows time series of the change in precipitation minus evaporation ($P - E$) and total runoff averaged over the Arctic Ocean discharge basin. The swell in total discharge is closely related to an increase in precipitation that is not fully offset by a weaker increase in evaporation. Note, however, that the increase in runoff is consistently higher than the change in $P - E$. Integrated over the 21st century, the extra discharge associated with melting soil ice contributes about 15% to the total increase in Arctic Ocean discharge. This permafrost-thaw related augmentation to the increase in discharge will presumably slow once the soil column adjusts to the absence of soil ice.

5. Discussion

[14] Of large concern is whether or not there are positive feedbacks associated with permafrost degradation that may accelerate climate change. The soil carbon pool in permafrost regions may be substantial since cold temperatures at high latitudes inhibit decomposition of dead vegetation. Estimates are uncertain, ranging from 60 to 190 Pg of carbon frozen in arctic tundra soils alone with 20–60% of global soil carbon stores thought to be in soils of boreal forests and northward [*Hobbie et al.*,

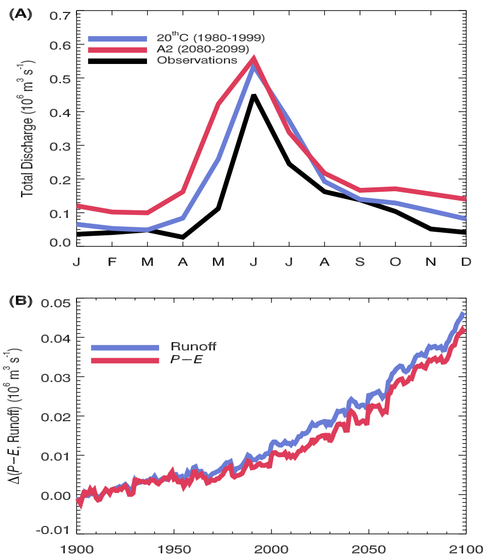

Figure 3. (a) Ensemble mean annual cycle of freshwater discharge to the Arctic Ocean. Observed discharge estimates are from *Dai and Trenberth* [2002]. (b) Time series of changes in ensemble mean $P - E$ and runoff averaged over Arctic Ocean drainage basin relative to the 1900–1919 baseline values.

2000]. As permafrost thaws, this soil carbon pool may become active leading to enhanced emission of greenhouse gases such as methane, if the melting forms new wetlands, or carbon dioxide, if the melting permits soils to dry out. A 22–66% increase in methane emission has been observed after permafrost thawed at Stordalen mire in Sweden [*Christensen et al.*, 2004]. Others report a 10-fold increase in carbon dioxide efflux upon soil thawing in a boreal forest [*Goulden et al.*, 1998]. Either way, greenhouse gas emissions associated with permafrost degradation of the extent seen in CCSM3 may be considerable and the feedback is likely to be positive and possibly large.

[15] Another potential feedback relates to changes in vegetation distribution. The CCSM3 predicted future climate above the Arctic Circle closely resembles that of present-day boreal forests in terms of air temperature and water availability (soil water availability, a diagnostic reflecting soil moisture stress on plant transpiration, increases substantially as conversion of ice to liquid makes more water available to plants even though the soils are slowly drying out), suggesting that hypothesized northward expansion of shrubs and boreal forests [*Rupp et al.*, 2000; *Chapin et al.*, 2005] may be a real possibility. Such an expansion may result in a further positive climate feedback if, as anticipated, the negative feedback associated with forest sequestration of carbon is compensated for by a stronger positive feedback related to lower albedos over snow-covered shrubs and forests compared to snow-covered tundra [*Betts*, 2000].

[16] A drawback of the representation of permafrost in CCSM3 is that the soil column is only 3.43m deep. Permafrost extends well below this depth in many areas, as do some current ALTs. This is of concern because thermal inertia related to deep frozen soils may mitigate the actual rate of ALT deepening. Additionally, some potentially critical hydrologic responses to permafrost degradation are not fully represented in CCSM3. Observations indicate that in some locations thawing permafrost creates thermokarst lakes, while in other situations, thawing promotes talik development and draining of lakes [*Smith et al.*, 2005]. The impact of deeper soils and improved hydrology on permafrost and related feedbacks is a topic of ongoing research.

6. Summary

[17] Permafrost is reasonably simulated in CCSM3 20th century climate simulations, with spatial extent of continuous permafrost closely matching IPA estimates both in terms of regionality and total area (10.7 million km^2 observed, 10.5 million km^2 in CCSM3). CCSM3 projections show dramatic permafrost degradation by 2100 under both high and low greenhouse gas emission scenarios. This degradation impacts Arctic hydrology and results in a slow drying of the soil and a redistribution of runoff into sub-surface runoff at the expense of surface runoff. Discharge into the Arctic Ocean increases by 28% by 2100, mostly due to increases in precipitation that exceed increases in evaporation, although 15% of the increase is attributed to contributions from thawing permafrost. Further analysis and model development is required to evaluate potential feedbacks of permafrost degradation on hydrologic and carbon cycles.

[18] **Acknowledgments.** Support provided by U.S. Department of Energy, Office of Biological and Environmental Research, cooperative agreement no. DE-FC03-97ER62402/A010 and NSF grants OPP-0229769 and OPP-0229651 and NASA NNG04GJ39G. We would like to thank T. Zhang for constructive comments.

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