The role of snow cover in the warming of arctic permafrost

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[1] Air temperatures at high latitudes are expected to rise significantly as anthropogenic carbon builds up in the atmosphere. There is concern that warming of the ground in permafrost regions will result in additional release of carbon to the atmosphere. Recent emphasis has thus been on predicting the magnitude and spatial distribution of future warming at high latitudes. Modeling results show that changes in below ground temperatures can be influenced as much by temporal variations of snow cover as by changes in the near-surface air temperature. The recent (1983–1998) changes in permafrost temperatures on the North Slope of Alaska are consistent with decadal scale variability in snow cover. The implication of these results is that a better understanding of how winter precipitation patterns at high latitudes will change over the coming decades is needed to comprehend evolving permafrost temperatures. *INDEX TERMS:* 1863 Hydrology: Snow and ice (1827); 1823 Hydrology: Frozen ground; 4215 Oceanography: General: Climate and interannual variability (3309). **Citation:** Stieglitz, M., S. J. Déry, V. E. Romanovsky, and T. E. Osterkamp, The role of snow cover in the warming of arctic permafrost, *Geophys. Res. Lett.*, *30*(13), 1721, doi:10.1029/2003GL017337, 2003.

1. Introduction

[2] The magnitude and spatial extent of high latitude warming in the last century is well documented [*Chapman and Walsh*, 1993; *IPCC*, 2001; *Overpeck et al.*, 1997; *Serreze et al.*, 2000]. In many arctic regions this warming is associated with increased precipitation [*Dai et al.*, 1997; *Groisman and Easterling*, 1994; *Ye et al.*, 1998], increased river discharge [*Peterson et al.*, 2002], a longer growing season [*Foster*, 1989; *Foster et al.*, 1992; *Stone et al.*, 2002], and a change in the distribution of plant species [*Sturm et al.*, 2001]. Borehole temperature measurements also indicate strong subsurface warming [*Lachenbruch and Marshall*, 1986; *Oberman and Mazhitova*, 2001; *Osterkamp and Romanovsky*, 1999; *Pavlov*, 1994; *Romanovsky et al.*, 2002; *Romanovsky and Osterkamp*, 2001]. However, it is not clear the degree to which increases in near-surface air temperature (NSAT) alone cause the subsurface warming [*Zhang and Osterkamp*, 1993]. Most studies presume no direct causality and use inversion techniques to reconstruct the history of temperatures at the permafrost table or at the ground surface, not NSAT changes, from the borehole data [*Beltrami and Harris*, 2001; *Beltrami and Mareschal*, 1991; *Harris and Chapman*, 1997; *Huang et al.*, 2000; *Lachenbruch and Marshall*, 1986; *Smith and Riseborough*, 2002; *Sokratov and Barry*, 2002]. Still, there is often an implicit assumption that changes in ground temperatures, as evidenced by borehole measurements, do reflect decadal- to century-scale climate warming. In this work, the influence of temporal changes in snow cover on permafrost temperature dynamics at Barrow, Alaska, are investigated. It is demonstrated that this variability needs to be taken into account when borehole data inversion methods are used for climate reconstructions or predictions.

[3] Snow is a strong insulator and limits the otherwise efficient communication of heat between the atmosphere and the ground. Where there is significant snow cover in the winter, the mean annual ground surface temperature is warmer than the mean annual air temperature owing to the insulating effect of the snow. Changes in the rate of accumulation, duration, timing, density, and amount of snow cover during the winter season play an important role in determining how the air temperature signal propagates into the ground [*Goodrich*, 1982; *Osterkamp and Romanovsky*, 1996; 1999; *Zhang et al.*, 1996].

[4] One dramatic indicator of change on the North Slope of Alaska is borehole temperatures [*Lachenbruch and Marshall*, 1986; *Lachenbruch et al.*, 1982; *Osterkamp*, 2003]. Measurements made over the last two decades in shallow boreholes show that, at the 20 m depth, there is a recent warming that ranges from 0.6°C at inland sites (1987–1998) to 1.5°C at coastal sites (1988–1998) (Figure 1a and 1b) [*Osterkamp*, 1999]. This measured warming is consistent with repeated borehole temperature logs taken by United States Geological Survey throughout the North Slope of Alaska [*Clow and Urban*, 2002]. This paper investigates how observed changes in North Slope permafrost temperatures resulted from NSAT and snow depth changes by driving a one-dimensional thermodynamic snow and ground model with observed air temperature and snow depth data from Barrow, Alaska, which is the only active meteorological site on the North Slope with long term climate records. Barrow is situated at 71.3°N, 156.8°W, in northwestern Alaska on the coast of the Arctic Ocean. It is one degree of latitude further north than the Prudhoe Bay area (Deadhorse and West Dock) and lies approximately 340 km further west (Figure 1a). It has a cold, dry climate dominated by the long winter season with a mean annual air temperature of -12.2°C (1949–2003; *NOAA*, 2002), slightly cooler than that observed at Deadhorse and West Dock. Barrow experiences an annual snowfall of 74.5 cm w (water equivalent), an amount 10% less than observed in the vicinity of Deadhorse and West Dock [*NOAA*, available online http://www.wrcc.dri.edu/summary/climsmak.html, 2002; *Zhang et al.*, 1996]. A snowpack is maintained at Barrow on average for 270 days each year, a week longer than its eastern counterparts [*Zhang et al.*, 1996]. Air temperature measurements at Barrow show a 1°C warming

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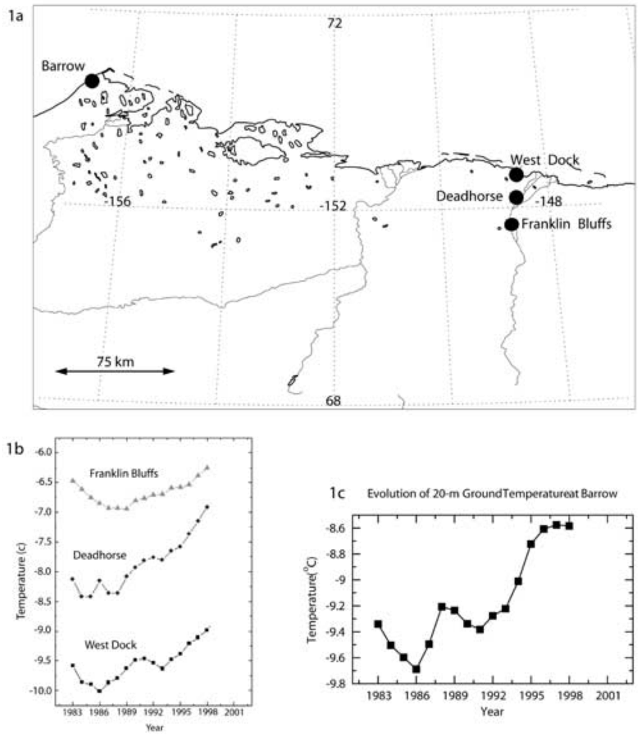

Figure 1. (a) Map of North Slope of Alaska depicting locations of interest. (b) Observed temperature at 20 m depth on a N-S transect on the North Slope of Alaska. Deadhorse and West Dock are located in the Prudhoe Bay area. Franklin Bluffs is located approximately 60 km south of Deadhorse. (c) Simulated evolution of the 20 m ground temperature at Barrow for the years 1983 through 1998.

over the last 60 years and approximately 3°C warming over the last 30 years (Figure 2a). The smaller warming trend for the 60-year period results from a cooling observed in the 1960s and 1970s at Barrow, as well as a notable reduction of snow depth in the second half of the record (Figure 2b). While there is concern about the urbanization effect at Barrow (the station is located near the village center), daily averaged winter air temperature measurements at Barrow are practically indistinguishable from those measured at the nearby (8 km east of Barrow) CMDL (Climate Monitoring and Diagnostics Laboratory; available since 1977) station. The reduction of snow depth after the early 1960s is also not an artifact of urbanization but a tendency that is observed throughout the Western Arctic [*Curtis et al.*, 1998; *Brown and Braaten*, 1998].

2. Methods

[5] NASA's Seasonal-to-Interannual Prediction Project (NSIPP) Catchment-based Land Surface Model (CLSM) [*Ducharne et al.*, 2000; *Koster et al.*, 2000] was used to simulate snow-ground thermodynamics. Previously, the model has been applied at high latitudes to accurately simulate the southern boundary of the North American permafrost as well as to explore snow cover heterogeneity issues [Dery, S. J., W. T. Crow, M. Stieglitz, and E. F. Wood, Modeling Snowcover Heterogeneity Over Complex Arctic Terrain for Regional and Global Climate Models, *J. Hydrometeorology*, submitted., 2003; *Stieglitz et al.*, 2001]. The version of the model used here employs three dynamic snow layers [*Lynch-Stieglitz*, 1994; *Stieglitz et al.*, 2001] and 200 ground layers. The ground is discretized in 25 cm intervals and extends to a depth of 50 m where a zero heat flux boundary is assumed [*Osterkamp and Romanovsky*, 1996]. Ground temperatures evolve in time through heat conduction. Input for the model consisted of Barrow NSATs and snow depths. It was assumed that the first ground layer, or the first snowpack layer, when snow is present, is equal to the NSAT.

[6] To explore the impact of snow depth changes independently of NSAT changes, several forcing data sets were constructed. Forcing input data for each day from 1940 to 1998 were generated using the observations of daily mean NSAT and snow depth (Figure 2a and 2b). Solid precipitation data were reconstructed such that the modeler snow depth matched the observed daily snow depth. Meteorological field measurements are linearly interpolated in time to provide forcing data at each model timestep of 20 minutes.

[7] Next, we constructed the annual mean cycle of NSAT and snow depth at Barrow by averaging measured data from all of the years for each day of the year. This provided a 365-day data set of forcing variables for Barrow based on 59 years (1940–1998) of observational data. While the precipitation data set was constructed using the measured snow depths, no snow is assumed for a given day if the mean depth is less than 2 cm. This yielded a mean 95-day snow free summer period, consistent with *Zhang et al.*

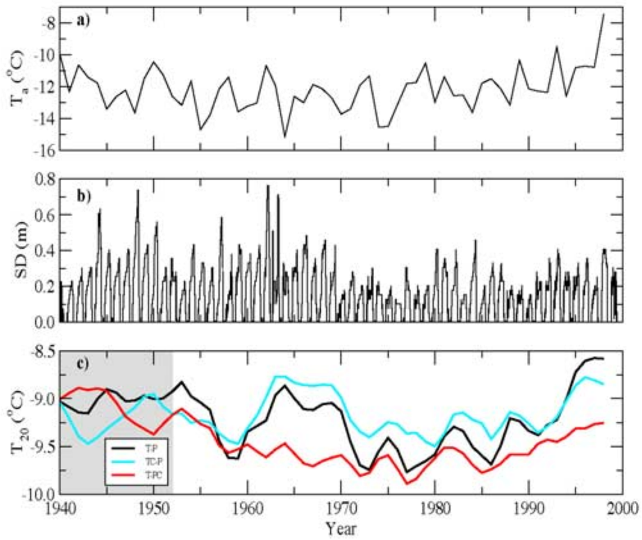

Figure 2. (a) The observed mean annual air temperature (T_a), (b) the observed daily snow depth (SD), and (c) the simulated 20-m ground temperature (T_{20}) at Barrow, Alaska for the period 1940–1998. Results from three simulations are illustrated in Figure 2c: one that employs the mean daily surface air temperature and the observational precipitation dataset (TC-P); another that employs the mean daily precipitation and the observational surface air temperature data set (T-PC); and finally, the observational surface air temperature and precipitation data sets (T-P). Model results in the grey area may be impacted by initial conditions.

[1996]. This data set (hereafter referred to as TC-PC) provides a complete year of forcing data that is used recursively to spin up the model to equilibrium, providing initial conditions for the subsequent simulations.

[8] Following this, three other combinations of NSAT and precipitation forcing data are used to simulate the 1940 to 1998 ground temperatures at Barrow: one that employs the daily mean NSAT data set and the observational precipitation data set (TC-P); another that employs the daily mean precipitation data set and the observational air temperature data set (T-PC); and finally, the observational NSAT and precipitation data sets (T-P). Independent use of these three data sets determines the effects of precipitation, temperature, and temperature and precipitation, respectively.

3. Discussion

[9] Except for small differences in magnitude and timing of the changes, the T-P simulation shows an evolution in the temperature at 20 m depth at Barrow similar to that which is observed in the Prudhoe Bay area (Deadhorse and West Dock) for the period 1983–1998 (Figure 1c). It should be noted that, for these simulations, the T-P 20 m temperature at Barrow in 1998 (−8.6°C) is only slightly warmer than that in the early 1960s (−9.0°C), which is consistent with *Romanovsky et al.* [2002]. As such, the recent rise in the 20 m permafrost temperature at Barrow might be interpreted as a recovery from a depression in ground temperatures in the early and mid 1970s, driven by both the preceding snow depth and air temperature history.

[10] The simulations shown in Figure 2c explicitly demonstrate the relative role that NSAT and snow cover changes play in determining the evolution of deep ground temperatures. To avoid the impact that the spin up (TC-PC) may have on the evolution of the simulated 20 m permafrost temperatures during the early years of the T-P, T-PC, and TC-P simulations, our analysis begins in 1952; for decadal forcing, the thermal damping depth is approximately 7 m and the surface-20 m depth signal offset is approximately 4 years. When only observed air temperatures are accounted for (T-PC), permafrost temperatures at 20 m roughly track a diminishing NSAT with a lag of approximately 4 years, ultimately cooling to −9.9°C in 1977. Thereafter, temperatures increase 0.64°C in response to the late century warming. Snow cover increases from the mid 1950s, remains high through 1970, falls off significantly in the early 1970s, and finally increases somewhat through the remainder of the century, albeit at lower levels than in the period 1940 to 1970. It should be noted that snow cover displays a near decadal modulation throughout the period of record. In response, the 20 m temperature in the TC-P simulation increases significantly through the early 1960s, remains high until 1970, and then falls to its trough in 1980. Temperatures thereafter recover 0.65°C, but in this case in response to the late century increase in snow cover. For comparison with the T-PC simulation, the TC-P 20 m permafrost temperature change from 1977 to 1998 is 0.51°C. From the T-P trough in 1977 to its peak in 1998 (an increase of 1.19°C in 20 m ground temperature), we can see that approximately half of the rise is due to increasing NSAT that began in the mid 1970s while the other half can be attributed to increasing snow cover in the latter part of the century.

4. Conclusions

[11] This study demonstrates that in snow dominated regions borehole data cannot simply be used to infer air temperature warming due to the ability of snow cover to impact ground temperatures independently of the NSAT. This is true when the temporal evolution of snow cover has significant variability that is not necessarily correlated with temperature variability. Using a state-of-the-art land surface model forced by a long-term record of snow depth and NSAT, the effects of air temperature changes can be separated from changes in snow depth and demonstrate that, while some of the subsurface temperature change observed over the last decade can be explained by climate warming, the observed borehole temperature records are influenced to a similar degree by snow cover variability.

[12] Future changes in the snow cover will have the potential to either amplify or dampen the expression of climate warming below the ground surface. The balance of these factors will control the fate of ground temperatures and the subsequent impact on carbon sequestration, and the evolution of the local landscape. For example, near-surface ground warming in permafrost regions can result in the loss of terrestrial carbon due to increased rates of near surface organic decomposition [*McKane et al.*, 1997; *Oechel et al.*, 1993; *Stieglitz et al.*, 2000]. Offsetting this, nitrogen mineralization increases and the higher nutrient availability may lead to increased biomass [*Shaver et al.*, 1998]. This study demonstrates the need to better understand how the associated changes in winter precipitation/snow at high latitudes will be altered in a warmer world.

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