Modeled current and future soil thermal regime for northeast Canada

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[1] Deepening of the active layer (i.e., the seasonally thawed layer overlying permafrost) was noted since the beginning of the 1990s in northern Canada, which has already caused substantial environmental and socioeconomic consequences. There is a strong consensus among projections of climate models used to study anticipated climate changes on the rise of the global average temperatures over the next century, with maximal changes being projected for high-latitude cold regions such as the permafrost regions. Given these projections, an evaluation of changes in the soil thermal regime becomes desirable for a number of reasons including assessments of possible ecosystem responses and impacts on man-made infrastructures. Such an evaluation of changes in the soil thermal regime for northeastern Canada is presented in this paper using a one-dimensional heat conduction model. Projected changes are estimated as the difference between two simulations of the soil model corresponding to the IPCC IS92a future scenario (2041–2070), which has effective CO_2 concentration increasing at 1% per year (2041–2070), and current (1961–1990) climates. The surface temperature and snow cover from time series of transient climate simulations with the Canadian Regional Climate Model (CRCM) are used to drive the soil model. Results suggest significant warming trends in the annual mean, maximal and minimal near-surface soil temperatures, with the mean annual soil surface temperature increasing by 3°–6°C for the continuous permafrost zone and by 2°–4°C for the rest of the permafrost zones in northeastern Canada. Results also suggest significant deepening of the active layer for the period 2041–2070, with its thickness increasing by more than 50% for most of the continuous permafrost region.

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1. Introduction

[2] Soil temperature is a valuable parameter for monitoring climate change as it integrates in time, over long periods, the interaction of several processes occurring at and above the ground surface, such as air temperature, precipitation, snowfall, seasonal snow cover, vegetation and surface microrelief, as well as effects of soil type, soil moisture, and freezing and thawing processes [*Oelke and Zhang*, 2004]. Recent observations of soil temperature profiles at high latitudes indicate a deepening of the active layer (i.e., the seasonally thawed layer overlying permafrost). This increase in the active layer thickness (ALT) and associated permafrost degradation can have adverse effects on infrastructures [*Nelson*, 2003] and on the socioeconomic and ecoenvironmental systems. However, permafrost cooling in the Ungava Peninsula of eastern Canada in recent decades has been widely cited as an exception to the dominant warming trend [*Nelson*, 2003]. Climate-change projections by General Circulation Models (GCMs) and Regional Climate Models (RCMs) for the period 2041–2070, under various Intergovernmental Panel on Climate Change (IPCC) Special Reports on Emission Scenarios (SRES) suggest an increase in winter surface air temperature by 2° to more than 7°C in the high-latitude regions of the Northern Hemisphere, and smaller changes, by 1° to more than 4°C, in the summer surface air temperature [e.g., *Plummer et al.*, 2005; *Arctic Climate Impact Assessment* (*ACIA*), 2005]. These changes in surface air temperature will lead to changes in the soil thermal regime in permafrost regions.

[3] Previous studies have investigated changes in the distribution of permafrost using indices such as the surface frost index derived from climate model simulation archives. *Anisimov and Nelson* [1997] used such an index, applied to three transient climate change simulations of general circulation models, to develop the first GCM-based assessment of permafrost dynamics over Northern Hemisphere. Their results indicate that a large, nearly circumpolar zone of relict permafrost would develop by the 21st century. In a similar study, *Stendel and Christensen* [2002] calculated ALT using the modified Stefan's equation with the climate change projection experiment conducted with the coupled atmosphere-ocean general circulation model ECHAM4/OPY3. They show a 30–40% increase in the ALT for most of the

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permafrost area in the Northern Hemisphere by the end of the 21st century, with largest relative increases concentrated in the northernmost locations. That is to say that, regions that currently have the shallowest active layer will experience the largest relative changes in a warmer world. It is worth mentioning that the above two studies had a spatial resolution of about 2.5–5° of latitude/longitude.

[4] The most viable approach to date has been the use of climate model outputs or analyzed data in combination with an off-line soil model [e.g., *Oelke and Zhang*, 2004; *Sazonova et al.*, 2004; *Zhang et al.*, 2005]. *Oelke and Zhang* [2004] applied a heat conduction model with phase change to the entire Arctic terrestrial drainage area for the period 1980–2001. Trend analysis revealed positive trends in the soil temperature at different depths for all permafrost regions in response to positive trends in the surface air temperature, with the strongest warming trend in regions of continuous permafrost. *Sazonova et al.* [2004] simulated the dynamics of the ALT and ground temperature along the East Siberian N-S transect with a quasi-two-dimensional, quasi-transitional, spatially distributed, physically based analytical model, both retrospectively and prognostically, using climate forcing from six GCMs. Their results suggest an increase in the ALT by 0.5–2 m, with significant increases projected to occur in the southwestern part of the transect in areas with coarse-grained sediments, characterized by low water content and high thermal conductivity. Recently, *Zhang et al.* [2005] studied the 20th century variations in the ALT over the major drainage basins of the Eurasian Arctic using three methods (historical soil temperature measurements, annual thawing index based on surface air temperature data and a numerical model) and showed an upward trend in ALT. *Lawrence and Slater* [2005] examined the near-surface permafrost distribution in a fully coupled global climate model, the Community Climate System Model, and report a reduction in the near-surface permafrost from 10.5 million km^2 to 1.0 million km^2 by 2100.

[5] Although the results of the above mentioned studies used a diversity of modeling approaches, there is a general consensus among the results that ALT are likely to increase by more than 50% in the permafrost regions, including much of Siberia, northeast Asia, the north slope of Alaska, and northern Canada [*ACIA*, 2005]. Most of the off-line soil model studies conducted so far to assess climate change effects on permafrost used GCM outputs as input to the soil model.

[6] In this paper, we study climate change induced shifts in the soil thermal regime over a domain covering northeastern Canada, using a 1-D heat conduction model [*Goodrich*, 1982] driven by the surface temperature (i.e., the temperature at the soil surface or snow surface if snow is present) and snow cover from the transient climate change simulations with the Canadian Regional Climate Model (CRCM [*Caya and Laprise*, 1999; *Laprise et al.*, 2003]). To our knowledge, this is the first study to look at changes to the soil thermal regime with a soil model using a regional model's data as inputs. Regional climate models offer higher spatial resolution than GCMs, allowing for greater topographic complexity and finer-scale atmospheric dynamics to be simulated and thereby representing a possibly more adequate tool for generating information for impact studies.

[7] The paper is organized as follows: section 2 outlines the soil model description, data and methods used. Verification of the driving data and the simulated soil temperature profiles for the current climate are addressed in section 3. The effects of climate change on the soil thermal regime of various permafrost zones are presented in section 4. In particular, we study the time trends in the simulated mean annual, minimal and maximal soil temperature profiles, for both current and future climates. The paper ends with conclusions in section 5.

2. Models, Data, and Methods

2.1. Configuration of the Soil Model

[8] The one-dimensional heat conduction model developed by *Goodrich* [1982] is used in this study. The model simulates soil temperature by solving the heat conduction equation with a finite element method subject to prescribed upper and lower boundary conditions. Nonlinear material properties and solid-liquid phase change are considered. Snow cover acts as an insulator and can raise mean annual ground temperatures, often by several degrees. The model includes the thermal effect of snow cover but it does not include capillary moisture transport or convective flows in the ground. In the soil model, latent heat release or absorption accompanying soil freezing and thawing is included, with the assumption that phase change takes place over a small temperature range and uses an effective heat capacity for the nodal volume that undergoes phase change. A detailed validation of the model is presented by *Goodrich* [1982], where it is shown that the model correctly simulates the influence of snow cover and the influence of soil type on the ground thermal regime. Several other previous studies used the same model [e.g., *Oelke and Zhang*, 2004; *Oelke et al.*, 2004; *Zhang et al.*, 2005; *Zhang and Stamnes*, 1998] and showed that the model succeeds in simulating active layer depth and soil temperatures when driven with suitable boundary conditions.

[9] The soil thermal model is applied over a horizontal grid that is uniform in polar stereographic projection and simulations are performed with a 45-km (true at 60°N) horizontal grid point spacing, with daily time steps, over a domain covering northeast Canada (Figure 1). The projection and resolution were so chosen to match those of the CRCM climate data used in this study, which is discussed in detail in the subsection to follow. Also shown in Figure 1 are the different permafrost regions from the International Permafrost Association (IPA) map [*Brown et al.*, 2001]. The different zones correspond to continuous, extensive discontinuous, sporadic and isolated permafrost zones, respectively from north to south. The IPA map defines these permafrost zones explicitly in terms of spatial extent and accordingly continuous, extensive discontinuous, sporadic discontinuous and isolated patches have >90%, 50–90%, 10–50% and <10% of the area with permafrost [*Heginbottom and Dubreuil*, 1993; *Brown et al.*, 2001].

[10] It should be noted that the model is 1-D and there is no lateral transfer of heat among grid cells, which is fully justifiable at this resolution. The soil properties such as type of soil, depth to bedrock are specified using the land-surface data sets developed by *Wilson and Henderson-Sellers*

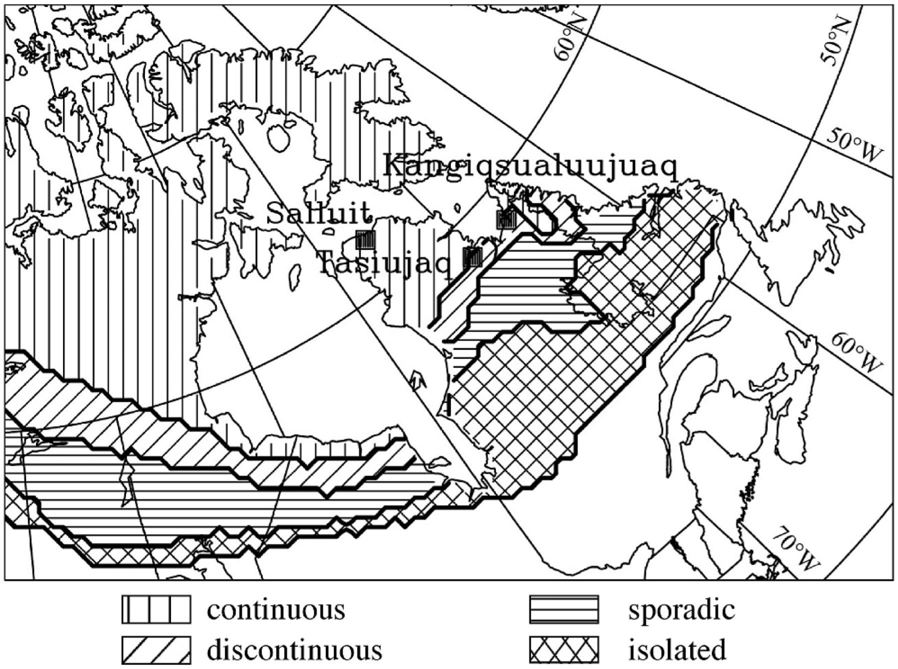

Figure 1. Geographic extent of the computational domain. The contour lines show the delineation of the continuous, discontinuous, sporadic and isolated permafrost zones from north to south, taken from the IPA map [*Brown et al.*, 2001].

[1985]. These data are global in extent and contain information on soil and vegetation types at a resolution of 1° lat × 1° long. In this study, seasonal changes in the soil moisture are not considered. However, soil moisture varies in space and is based on the average annual soil moisture values for 30-year runs with the CRCM, which is close to saturation for the northern parts of the continuous permafrost region falling within the study domain. Following the above assumption, no attempt was made to account for variations in soil thermal properties accompanying seasonal changes in moisture content at shallow depths. The values of frozen and thawed thermal properties approximate the empirical results of *Kersten* [1949]. Inclusion of moisture redistribution can cause changes to the mean annual ground temperature profiles. However, these changes many not be very significant for the continuous permafrost zone within our study domain since about 80% of the continuous permafrost zone has granitic bedrock generally at less than 0.6 m below ground surface.

[11] Daily surface temperature is used as upper boundary condition while lower boundary condition (at 45 m) is defined as a constant geothermal flux of 0.063W/m^2. Extensive geothermal heat flux database is not available over the study domain. Some borehole measurements are available from the borehole temperatures and climate reconstruction database [*Huang et al.*, 2000]. However, the borehole measurements available are mostly concentrated in the southern part of our study domain. According to this database, the fluxes at 45 km depth vary in magnitude between 0 and 0.1 W/m^2. Therefore the choice of 0.063W/m^2 is reasonable compared with the borehole data. Further, sensitivity studies performed for flux values in the range 0–0.1 W/m^2 at 45 m depth show that this depth is adequate to ensure no significant effect (<0.05°C) on temperatures in the first 35 m below surface [*Popadic*, 2006]. Calculations are performed for 85 soil layers; the layers in the upper 10 m are 0.2 m thick, providing 50 calculation nodes, and the layers in the remaining 35 m have 1 m thickness. The layer spacing in snow is 0.2 m.

2.2. Experiments and Climate Data

[12] The main forcing variables of the soil model are daily surface temperature and daily snow depth. Two simulations, corresponding to current (1961–1990) and future (2041–2070) climates, are performed and analyzed in this paper; these simulations will be referred to as SM_CRCM1 and SM_CRCM2 (here SM stands for soil model). The surface temperature and snow cover data from the 30-year current (1961–1990) and projected future (2041–2070) climate simulations with the third generation of the CRCM [*Caya and Laprise*, 1999; *Laprise et al.*, 2003], are used to drive the SM_CRCM1 and SM_CRCM2 simulations, respectively. It should be noted that the CRCM snow water equivalent was converted into snow depth assuming a constant snow density of 300 kg/m^3. The CRCM's horizontal grid is uniform in polar stereographic projection and its vertical resolution is variable with a Gal-Chen scaled-height terrain following coordinate. All CRCM simulations were performed with a 45 km (true at 60°N) horizontal grid point spacing and 29 unevenly spaced vertical levels over a domain covering the whole of North America and adjoining oceans, which is one of the largest domain ever used for a regional climate change simulation. The CRCM performs dynamical downscaling of the second generation Canadian Coupled General Circulation Model (CGCM2) simulated data to produce climate projections at

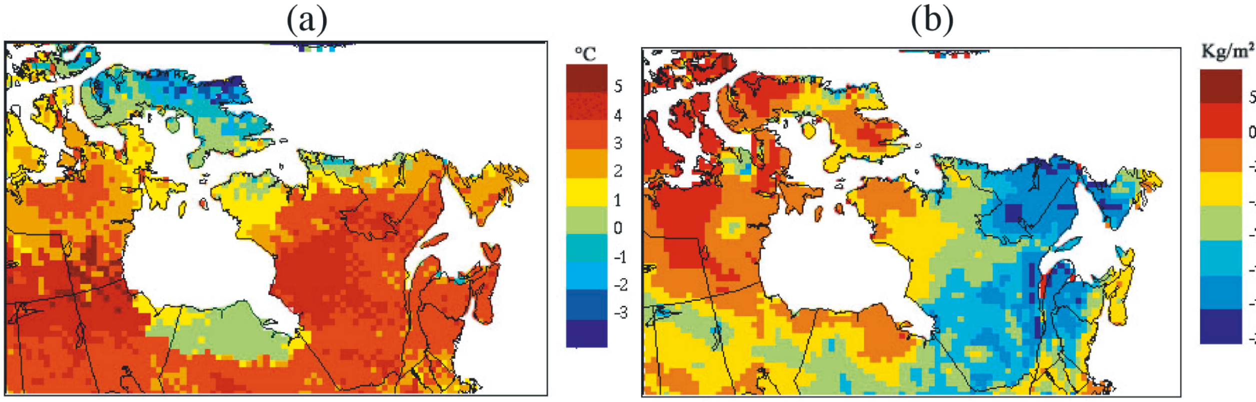

Figure 2. Biases in the CRCM (a) mean annual screen temperature (°C) when compared with CRU analysis of surface observations for the period 1961–1990 and (b) mean winter (DJF) snow water equivalent (kg/m^2) when compared with that analyzed by *Brown et al.* [2003] for the period 1979–1990. The CRCM simulation was driven by CGCM2 at its lateral boundaries.

the regional scale. The future climate corresponds to IS92a IPCC scenario, which specifies effective CO_2 concentration increasing at 1% per year [*Leggett et al.*, 1992]. The SM_CRCM1 run is the reference to which the future soil thermal regime projection, SM_CRCM2, will be compared.

2.3. Initialization of the Soil Model

[13] The initial profile of soil temperature for the current climate soil model simulation SM_CRCM1 is determined by iteratively running the soil model from chosen conditions, taken as a vertically uniform profile set to the mean annual surface temperature value for the study period (1961–1990). Climatological daily values of surface temperature and snow depth for the studied current period are used as boundary conditions. The model is run until equilibrium soil temperature conditions are achieved, i.e., the difference in annual mean soil temperature at all levels, is less than 0.001°C.

[14] Since the CRCM transient climate change simulations (and hence the daily driving data for the soil model) are available only for current and future 30-year time slices (i.e., for the periods 1961–1990 and 2041–2070), to obtain reasonable initial soil temperature profiles for the SM_CRCM2 simulation that would reflect the influence of the ongoing warming in the intervening 1991–2040 period, the soil model is run for the 1991–2040 period, forced by daily surface temperature and snow obtained through linear interpolation between the CRCM current (1961–1990) and future (2041–2070) daily climatologic values of respective fields, with the simulated soil temperature profiles at the end of the SM_CRCM1 period as the initial profiles. The simulated soil temperature profiles at the end if this 1991–2040 period are used as the initial profiles for the SM_CRCM2 simulations, and are believed to be reasonable, particularly for deeper soil layers since they capture only annual fluctuations in the surface temperature. As a result of using interpolated daily climatologic values for the 1991–2040 period, it is possible that the near surface initial values of soil temperatures for the SM_CRCM2 simulation are not as accurate as the deeper layers. However, this should not corrupt the SM_CRCM2 simulated near-surface temperatures since the response time for these layers is very small.

3. Verification of Input Data and Simulated Temperature Profiles

[15] The ability to project the soil thermal regime in future climate depends in part on the ability of the model to reproduce current conditions. Investigation of biases in the current climate simulations and corresponding soil thermal regime provides insight to interpreting projections of soil thermal conditions for future climate. Therefore, in this section, verification of the SM_CRCM1 simulations are performed, by comparing the simulated soil temperature at various depths with some locally measured temperature profiles. As the soil model simulations are directly influenced by the boundary conditions, it is useful to verify the input data used for SM_CRCM1 simulation; this is presented before the verification of the simulated soil temperatures.

[16] In Figure 2a, CRCM-simulated mean annual screen temperatures, for the period 1961–1990, are compared with the monthly mean gridded analysis from the Climatic Research Unit (CRU) data set [*Mitchell and Jones*, 2005] produced from station data. The CRU 0.5° gridded data includes six climate elements, including temperature and precipitation, and extends over the global land surface (excluding Antarctica) for the period 1901–2002. Comparing CRCM-simulated mean annual screen temperatures with that from CRU, one could notice a warm bias in the southern part of the domain, with values up to 6°C between 50 and 60°N latitudes; for the winter season (figure not shown), the warm bias reaches 6°C over some parts of central and eastern Canada. North of 60°N latitude the warm bias is found to decrease rapidly and across the Canadian Arctic Archipelago the model is found to be too cold by 2°–3°C.

[17] The CRCM-simulated mean winter snow water equivalent (SWE) is compared with analyzed winter mean snow cover [*Brown et al.*, 2003] in Figure 2b. The gridded North American snow depth database by Brown et al. was produced by applying the snow depth analysis scheme

developed by *Brasnett* [1999] to generate a 0.3° latitude/longitude grid of daily and monthly mean snow depth and corresponding estimated water equivalent for North America. This snow data is available only for the period 1979–1999 and hence for validation, the common period 1979–1999 is used in Figure 2b. Compared with analyzed data, in general CRCM underestimates snow cover over most of the domain, with maximal underestimation in the eastern part of the study domain (i.e., over southern Quebec, Newfoundland and Labrador). Like other climate models, CRCM has difficulties in representing the spatial and temporal variability of snow and this was also noted in previous studies such as that of *Frigon et al.* [2002] with a CRCM simulation performed over the Quebec/Labrador territory. The soil moisture regime in CRCM is represented through a single-layer scheme with a water holding capacity that varies over each grid point according to vegetation and soil characteristics. During fall, the single ground layer must freeze throughout before cooling the surface below 0°C, and therefore it is usually warm near the ground. Because of this warm bias in the fall air temperature, CRCM produces liquid precipitation rather than snow in this season and thus produces thinner annual snow cover. This negative bias in the snow cover can cause errors in the soil model simulated mean annual temperatures, more in permafrost regions than for seasonal frost conditions. However, in permafrost regions, the summer thaw depths and therefore the ALT, are only slightly affected by snow cover and the reliability of prediction depends primarily on the treatment of the summer temperature regime [*Goodrich*, 1982]. The above verification suggests presence of significant biases in the CRCM fields, which are due primarily to the internal dynamics and physics of the model and to the errors in the driving data at the boundaries of the regional model.

[18] The SM_CRCM1 soil temperature profiles are next compared with in situ ground thermal data from three localities, Salluit (62.197°N, 75.646°W), Kangiqsualuujuaq (58.709°N, 65.92°W) and Tasiujaq (58.67°N, 69.95°W), in northern Quebec (see Figure 1). The choice of these sites was based on data availability and most importantly their location. Salluit lies in the continuous permafrost zone, Kangiqsualuujuaq in the discontinuous permafrost zone and Tasiujaq at the boundary between continuous and discontinuous permafrost zones. For each site, the measurements are available from more than one thermistor cable. Cables are located in the natural environment in the vicinity of airstrips, but remote enough so as not to be affected by man made infrastructures. The measured soil temperatures from different cables in the same locality vary because of the heterogeneous nature of soil properties, topography and snow cover.

[19] Comparing SM_CRCM1 temperature profiles with observations for any particular day in a year does not represent a valid comparison since SM_CRCM1 is driven by a GCM (CGCM2) at its boundaries. GCMs can be judged only by the quality of the climate statistics and the same is true for RCMs driven by GCMs. For these above-mentioned reasons, the SM_CRCM1 climatological profiles for a chosen summer and winter day are compared to those observed in Figure 3. It should be noted that the comparisons are not done for the same day for all three locations as data is not available for the same dates. In addition, not all thermistor cables register soil temperatures within the first meter near surface and for this reason, the profiles presented in Figure 3 start at 1 m below soil surface. The diurnal fluctuations in the surface temperature are captured by the near-surface soil layers, while the deeper layers capture annual fluctuations in the surface temperature. For deeper layers, the SM_CRCM1 profiles agree reasonably well with the observations. Comparing CRCM climatological screen temperatures for the three sites with that of CRU (figure not shown), for the period 1961–1990, suggest that the CRCM temperatures have a cold bias in winter and spring, while the summer and fall seasons have a warm bias. As a result, the CRCM mean annual screen temperatures are closer to that of CRU and hence the closeness of SM_CRCM1 profiles to that observed at deeper layers. The SM_CRCM1 soil temperature near the surface for the summer day is warmer than observed for all three locations and is due to the warm bias in the driving CRCM surface summer temperature. Simulated near surface temperatures for winter for Salluit are very close to the temperatures registered by one of the thermistor cables (SAL 161). As discussed earlier, CRCM snow onset is delayed for all three locations with CRCM underestimating the winter snow cover for most part of winter. In spite of the reduced snow cover and the cold bias in the winter driving data, the simulated near surface temperatures for Kangiqsualuujuaq and Tasiujaq are warmer than observed. It is not easy to explain these differences in winter because of the complex response of soil temperatures at the surface to snow cover that insulates the soil from the cold atmosphere. This likely reflects the difficulty of the analyzed/modeled snow depth to take into account the wind drifting effect that redistributes snow cover over the undulating terrain.

[20] The soil model simulates the thermal offset, i.e., the difference between the mean annual temperature at the bottom of the active layer and that at the ground surface, reasonably well. Thermal offset is dependent on the difference between thawed and frozen soil conductivities. Most of the continuous permafrost region covered by the study domain has bedrock very near the surface and therefore the magnitude of thermal offset is very much reduced. For example the thermal offset of all the three stations Salluit, Kangiqsualuujuaq and Tasiujaq vary between 0.1–0.3°.

[21] In general, the SM_CRCM1 simulation captures most of the permafrost regions based on ground temperature, except for some parts of the sporadic discontinuous and isolated patches of permafrost zones, i.e., regions with permafrost extent less than 50% in area. This is no surprise, given the 45 km × 45 km resolution of the model and the fact that CRCM simulated temperatures are average values for such tiles. Had the model resolution been finer, and with suitable fields of soil properties, it may have been possible to capture better the sporadic and isolated permafrost zones. We therefore analyze the distribution of SM_CRCM1 simulated average ALT for the continuous and discontinuous permafrost regions and the results are shown in Figures 4a–4b. A general decrease in ALT with latitude is noted, especially for the eastern part of the domain. However, for the western part of the domain, the ALT increases in depth from north to south up till the southern boundary of the continuous permafrost zone, after which a decrease in the ALT is noted and is due to low-lying bedrock as

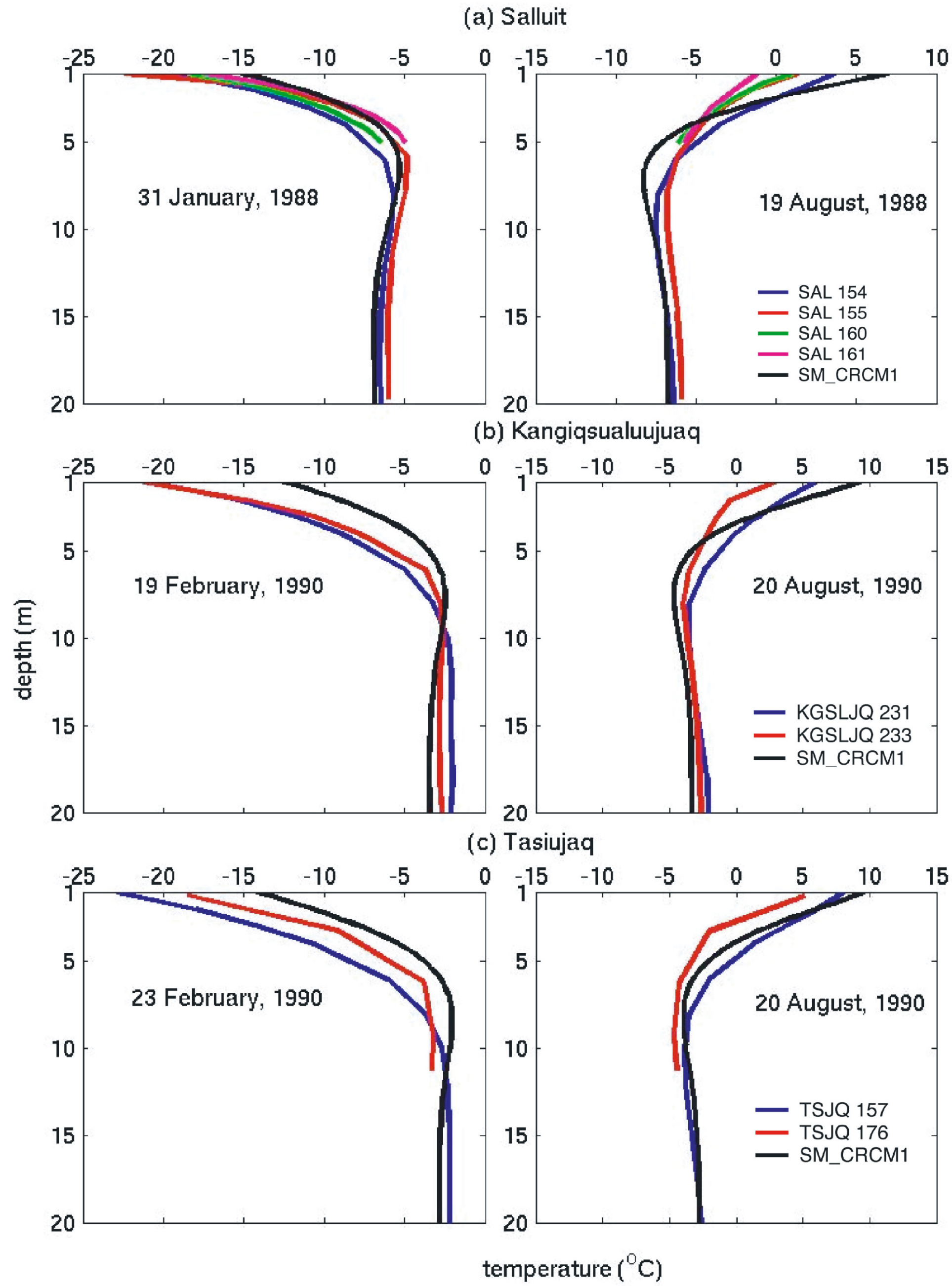

Figure 3. Simulated SM_CRCM1 and observed temperature profiles for a (left) winter and (right) summer day for (a) Salluit, (b) Kangiqsualuujuaq and (c) Tasiujaq. The days correspond to 31 January and 19 August 1988 for Salluit, 19 February and 20 August 1990 for Kangiqsualuujuaq and 23 February and 20 August 1990 for Tasiujaq. Four thermistor cable measurements were available for Salluit (SAL 154, SAL 155, SAL 160 and SAL 161) and two each for Kangiqsualuujuaq (KGSLJQ 231 and KGSLJQ 233) and Tasiujaq (TSJQ 157 and TSJQ 176).

opposed to high lying bedrocks common for most of the continuous permafrost region covered by the study domain. According to the simulated SM_CRCM1 ALT, almost 35% of the continuous permafrost zone has ALT less than 2 m. For the permafrost regions covered in the study domain, there are not that many observations for ALT, making verification difficult. *Oelke et al.* [2003] simulated the freezing and thawing of the active layer of soil in the Arctic terrestrial drainage basin, for the period 1998–2000, using the same heat conduction model used in this study, driven by topography-corrected NCEP reanalysis surface air temperature and snow height compiled from SSM/I satellite data and observed climatological snow density. Comparison of simulated ALTs with the results of Oelke et al. suggests that the SM_CRCM1 ALTs, particularly for the discontinuous permafrost regions, are overestimated. This overestimation of ALTs is believed to be due to the warm biases in the driving CRCM summer surface temperature, which is

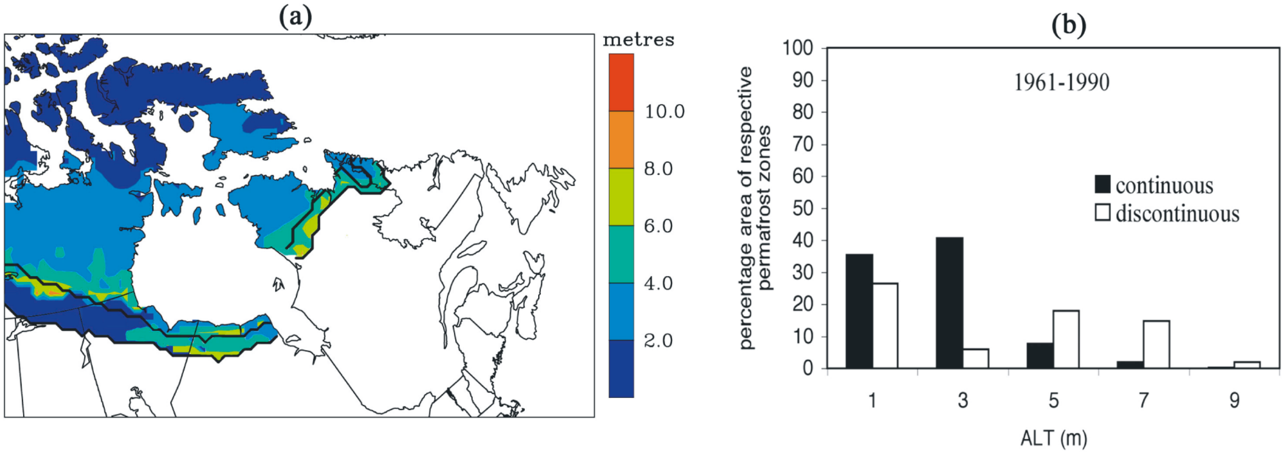

Figure 4. (a) Simulated SM_CRCM1 (1961–1990) average ALT (m) for the continuous and discontinuous permafrost zones and (b) their distributions. The average ALT is binned at an interval of 2 m.

the principal control on ALT. However, the SM_CRCM1 ALT for the town Salluit (figure not shown), agree with measured values; simulated ALT for Salluit is seen to vary between 2–3.1 m for the 1961–1990 period, with the maximal value occurring in 1983–1986 period, associated with a cooling trend in the winter temperatures.

[22] The above comparison of the simulated daily soil temperature profiles with those observed suggests biases in the near surface layers, and are mostly due to the biases in the driving CRCM data. Results also suggest positive biases in the SM_CRCM1 simulated ALTs for some regions, while the ALTs for other regions such as northern Quebec appear more realistic.

4. Climate Change

[23] In the previous section we looked at the ability of the SM_CRCM1 to simulate current conditions, particularly soil temperature profiles and ALT distribution. In this section, simulated changes in the ground thermal regime are evaluated as differences between the two soil model runs driven by CRCM scenario and control climates (i.e., difference between SM_CRCM2 and SM_CRCM1). This is a common method for evaluating simulated climate change, and is based on the assumption that systematic biases may partially cancel between the two model runs. Using a similar approach, projected changes in the driving data are also analyzed.

4.1. Driving Data

[24] Projected changes (increase/decrease) in the mean annual forcing fields (i.e., surface temperature and snow water equivalent), for the period 2041–2070 with respect to 1961–1990, are shown in Figure 5. All over the domain, an increase in the mean annual surface temperature can be noted (Figure 5a), with the average annual surface temperature increasing by 5°C and above for the northwestern part of the domain. The increase in winter temperature is more than that for summer (figure not shown). Several other studies also have shown similar trends, with higher increase in winter temperatures than for the summer ones [e.g., *Plummer et al.*, 2005]. A decrease in the average December–January snow water equivalent (0–10 kg/m^2 for the permafrost zones) can be noted all over the domain (Figure 5b), except for northern Quebec and some regions of Baffin Island, where the snow water equivalent increases slightly

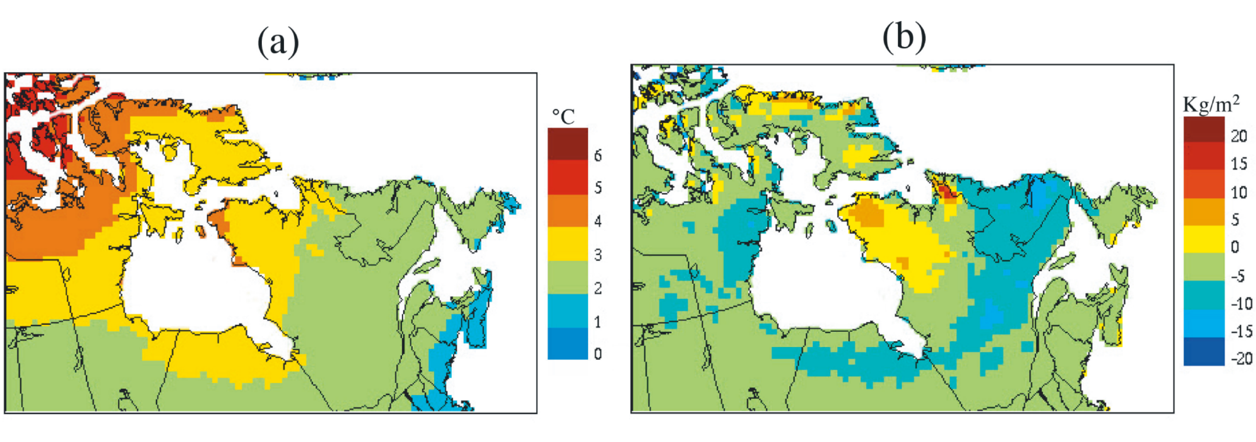

Figure 5. Projected changes in the CRCM climatologic (a) annual average surface temperatures (in °C) and (b) winter (DJF) snow water equivalent (in kg/m^2) used to drive the soil model.

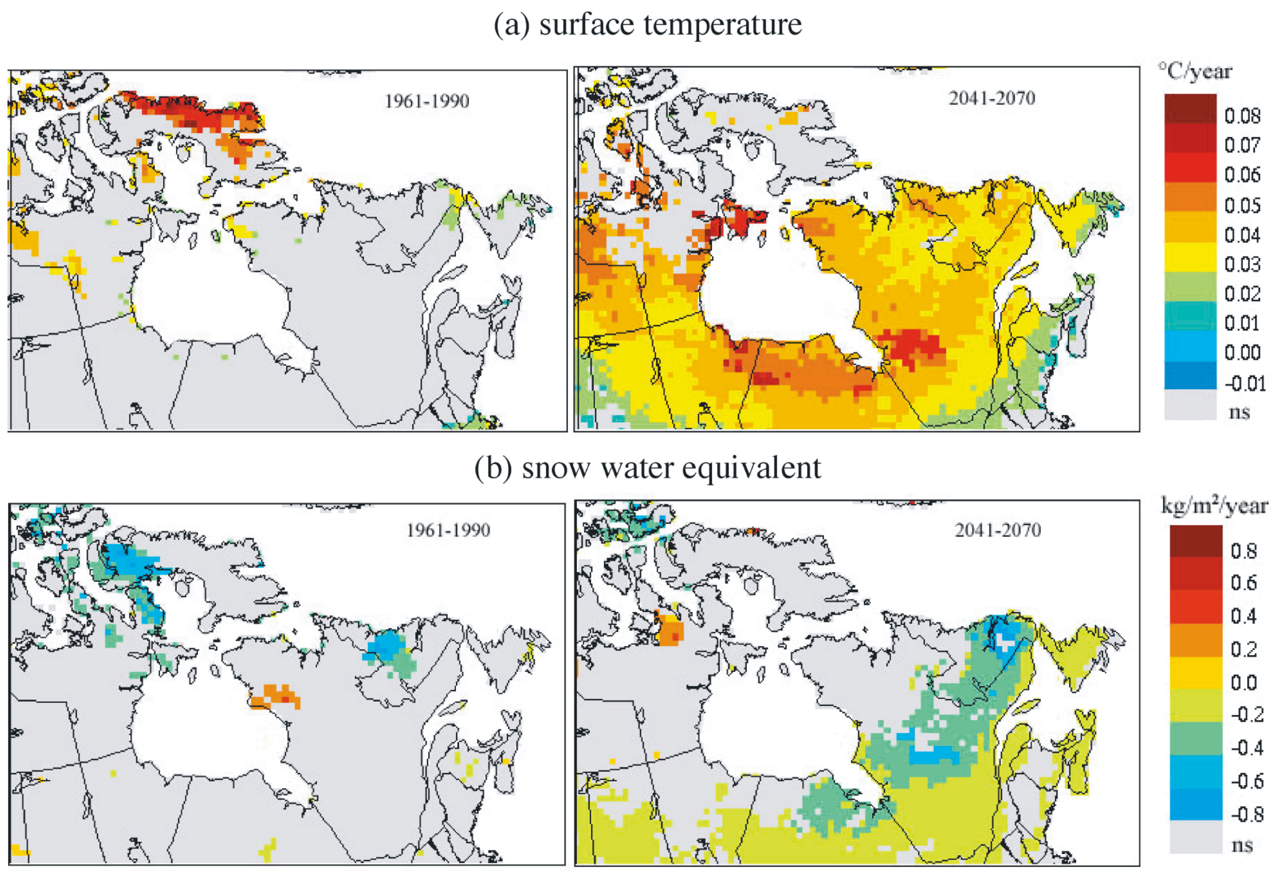

Figure 6. Estimated trends in the CRCM (a) mean annual surface temperature (°C/year) and (b) winter (DJF) snow water equivalent (kg/m^2/year) for (left) current and (right) future climates. Regions with statistically significant trends (positive or negative) at 90% confidence level are shown in color, while regions with no significant trend are shown in grey ("ns" stands for nonsignificant).

(0–10 kg/m^2). Thus compared with temperature, the projected changes in SWE are small as expected. Increased air temperature leads to shorter snowing periods and hence smaller SWE. At the same time increased air temperature, circulation changes, warmer ocean currents, etc. can lead to more precipitation. The combined effect of the above two would therefore result in only slight changes in the SWE.

[25] Nonparametric statistical methods are employed here to investigate temporal changes in the driving data. These methods are generally considered to be more robust as compared to parametric ones and are less affected by the presence of outliers and/or issues of nonnormality [*Lanzante*, 1996]. Mann-Kendall's test [*Kendall*, 1975] is used to examine statistical significance of time trend and Sen's method [*Sen*, 1968] to obtain estimates of the magnitude of trend. Since the presence of serial correlation can complicate the identification of true trends, the data is decorrelated [see *Zhang et al.*, 2000] before applying both Sen's and Mann Kendall's methods. We assume 90% confidence level to assess the significance of time trend throughout the study.

[26] Figure 6 shows estimates of the magnitude of monotonic time trend (positive or negative) in the CRCM current (1961–1990 (Figure 6, left)) and future (2041–2070 (Figure 6, right)) mean annual surface temperature (Figure 6a) and winter (DJF) snow water equivalent (Figure 6b). In these figures, trend values are shown only for regions with significant trend (positive or negative) at 90% confidence level. Trend estimates of mean annual surface temperature for current climate suggest significant positive trends for small regions in the continuous permafrost zone. However, for future climate, significant positive trend in the mean annual surface temperature is observed over most part of the domain, particularly for the discontinuous, sporadic and isolated permafrost zones, where the trends lie in the 0.03°–0.07°C/year range.

[27] In general, the estimated trends in the December–February snow water equivalent for the northern permafrost regions of the domain are nonsignificant, for both current and future climates (Figure 6b). However, for future climate, significant negative trends in the snow water equivalent are projected for the seasonally frozen southern part of the domain. For the permafrost regions, therefore, of the two driving fields, significant trends are noticed only in the surface temperature for future climate.

4.2. Soil Thermal Regime

[28] Freezing and thawing indices, defined here as the absolute annual accumulated departures of the surface temperatures below and above 0°C, are important controls on the soil thermal regime. Figures 7a and 7b show

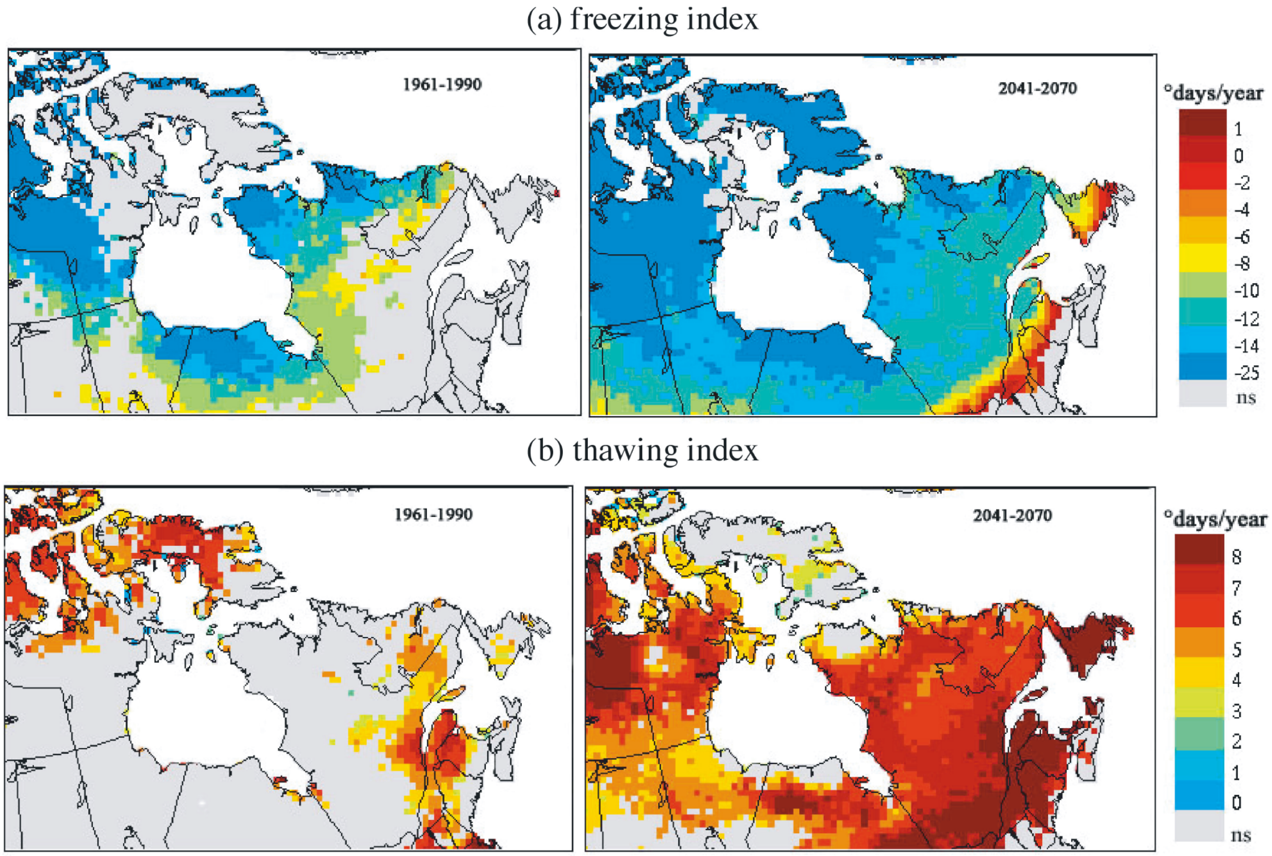

Figure 7. Estimated trends in the (a) freezing and (b) thawing indices (degree-days/year) based on the CRCM surface temperature, for (left) current and (right) future climates. Regions with statistically significant trends (positive or negative) at 90% confidence level are shown in color, while regions with no significant trend are shown in grey ("ns" stands for nonsignificant).

estimated time trends in these indices, for both current (Figure 7, left) and future (Figure 7, right) climates. The same nonparametric methods (Mann Kendall's and Sen's methods) described in the previous section are used here. Figure 7a shows estimated trends in the freezing index for current climate and significant trends can be noticed for some regions in the various permafrost zones. Like most climate models, CRCM project some summer warming, but larger changes are projected for winter, spring and autumn. This is reflected in the large significant negative trends in the freezing index (i.e., large significant warming of winter temperatures), over most part of the domain, for future climate (Figure 7a, right). For the permafrost regions they vary between −25 and −12 degree-days/year. Like for the freezing index, the thawing index shows significant positive trend (Figure 7b, right) over most part of the domain for future climate. However, the estimated time trends for the thawing index are smaller than that for the freezing index.

[29] The simulated changes in the 30-year average annual soil surface temperature are shown in Figure 8a. In the northern continuous permafrost regions, the mean annual soil surface temperature is seen to increase by a maximum of 5°C, while for the southern part of the domain soil temperature increases in the 0°–2°C range. Figure 8b suggests significant positive trend in the mean annual soil surface temperature, almost all over the domain, for future climate, compared with the trends for current climate. Interestingly, the spatial patterns in Figures 7b (left) and 8b (left) corresponding to trends in the thawing index and the soil surface temperature, respectively, for current climate resemble closely the trend patterns in the ALT presented by *Oelke et al.* [2004], despite the different driving data used in their study. Changes in the maximal summer temperature at the soil surface range from 1°–4°C, while changes in the minimal winter temperature are much bigger, ranging from 2° to 8°C in the continuous permafrost zone. These changes are primarily in response to changes in the surface temperature and also due to snow cover changes for the case of winter temperatures. However, maximal change in the mean monthly soil surface temperature is obtained for June and July (figure not shown), and differs from the trends noted with the surface temperature; maximal change in the surface temperature occurs during winter months. This is believed to be primarily associated with the projected maximal changes in snow cover for the months of June and July (figure not shown). These changes are due to the accelerated snowmelt caused by increased temperatures in future climate, which reduce the snow cover insulation of soil temperatures, allowing for more warming.

[30] We next analyze the time trends (°C/year) in the current (1961–1990) and future (2041–2070) annual mean, minimal and maximal soil temperature values, from surface

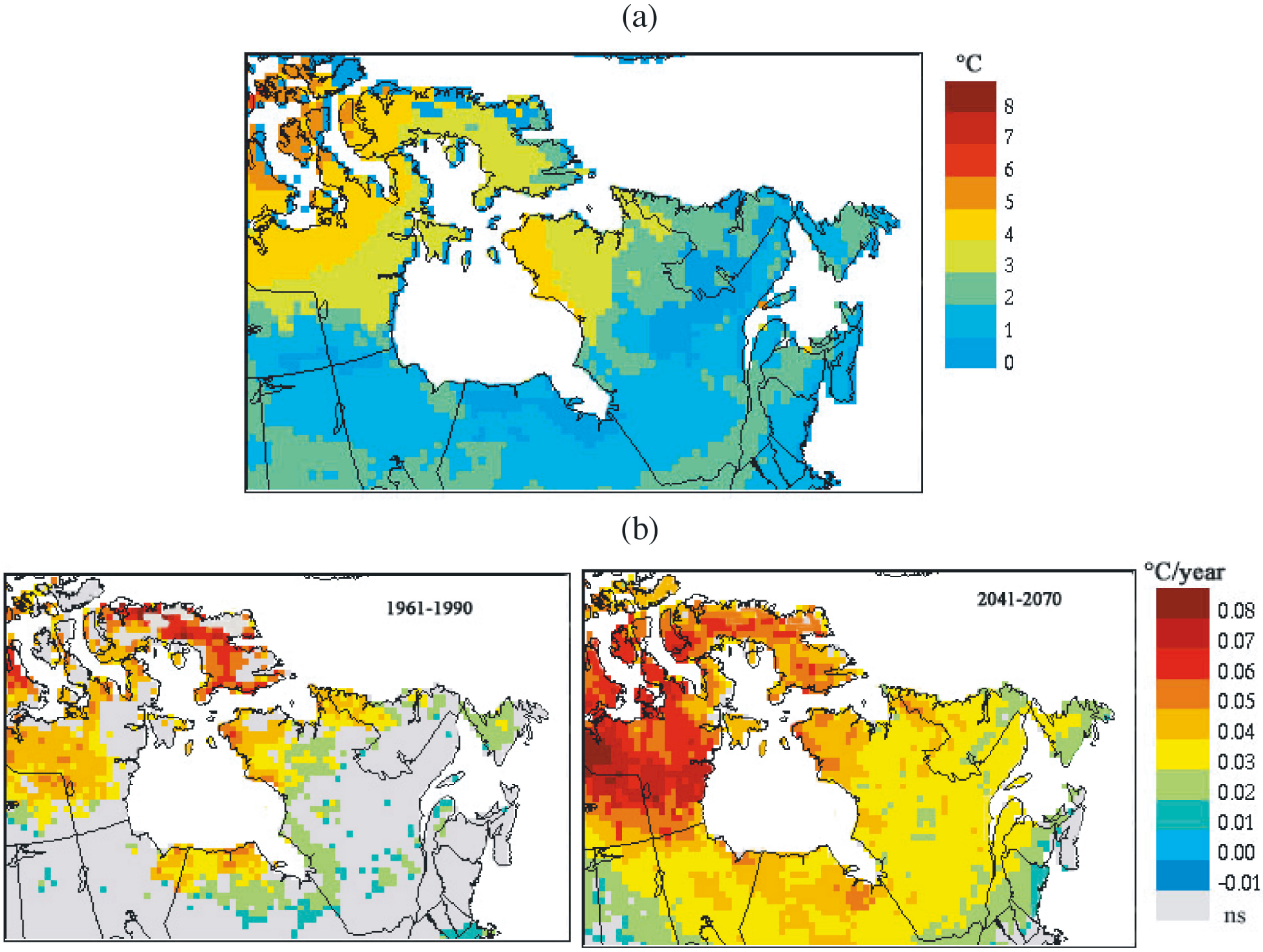

Figure 8. (a) Projected changes (i.e., the difference between future SM_CRCM2 (2041–2070) and current SM_CRCM1 (1961–1990) soil model simulations) in the climatological mean annual soil surface temperatures (°C) and (b) the estimated trends in the simulated mean annual soil surface temperature (in °C/year) for (left) current and (right) future climates. Regions with statistically significant trends (positive or negative) at 90% confidence level are shown in color, while regions with no significant trend are shown in grey ("ns" stands for nonsignificant).

up to 20 m depth, for the four zones of permafrost (Figure 1) and results are presented in Figure 9. Trends significant at the 90% confidence level are shown with filled circles and include lag effects. The differences between the future and current trends in the mean annual, minimal and maximal temperatures decrease with depth for all four zones. The strongest warming in the mean annual temperatures occur in the upper layers for all four zones, with values in the range of 0.03°–0.04°C/year for future climate. The estimated trends in the current climate mean annual temperatures at the soil surface agree in general to those given by *Oelke et al.* [2004]. For current climate the trends in the mean annual temperatures are mostly nonsignificant for the sporadic and isolated permafrost zones. The trends in the mean annual temperature at 20 m depth are much smaller compared to the near-surface trends for current and future climates, but significant for all zones for future climate. At the near-surface layers, for future climate, the trends associated with the minimal temperatures (Figure 9b) are higher than that of the maximal temperatures (Figure 9c), i.e., 0.05°–0.12°C/year versus 0.015°–0.025°C/year. In general, the trends in the minimal and maximal temperatures for future climate are larger than the trends for current climate.

[31] Figure 10 shows distribution of SM_CRCM2 simulated ALT for continuous and discontinuous permafrost regions. The principal control on ALT is summer air temperature and though the projected changes in the driving CRCM summer temperatures are small compared to that for winter, the study suggests significant increase in the ALT; for the continuous permafrost region ALT will increase by more than 50% during the 2041–2070 period (Figure 10a). As discussed earlier most of the continuous permafrost region falling within the study domain has bedrock at 0.1–0.6 m below surface. The projections also suggest disappearance of a small patch of continuous permafrost to the south of the Hudson's Bay. In simulated SM_CRCM1 current climate, about 35% area of the continuous permafrost zone has ALT less than 2 m, while in future SM_CRCM2 climate, less than 15% area will have ALT less than 2 m (Figure 10b). For the discontinuous permafrost regions, most of the current permafrost underlain

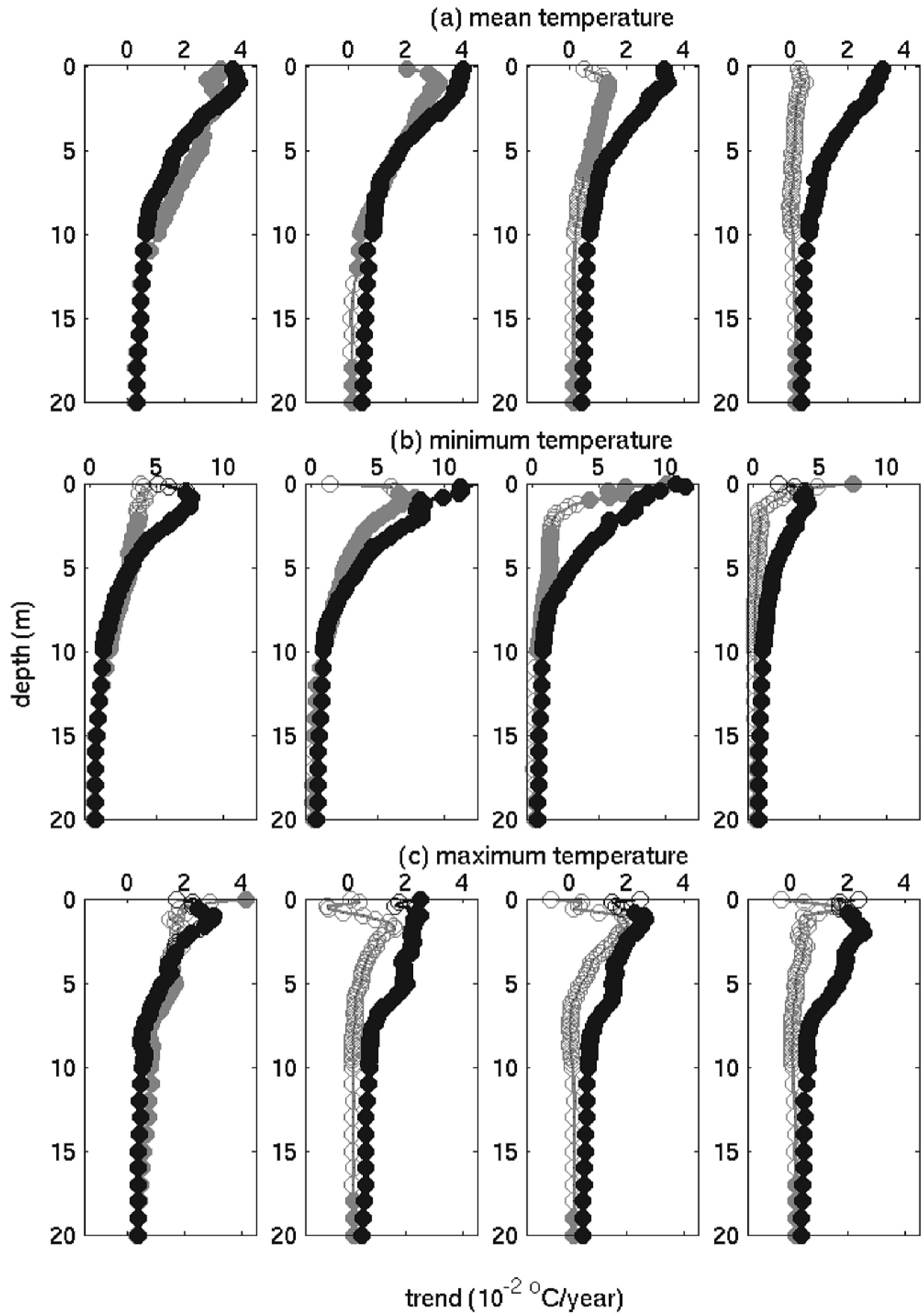

Figure 9. Estimated trends (10^{-2} °C/year) in the annual (a) mean (b) minimum and (c) maximum temperature profiles for current (shaded lines with open and solid circles) and future (solid lines with open and solid circles) climates for continuous (first column), discontinuous (second column), sporadic (third column) and isolated (fourth column) permafrost regions defined by the IPA map. Solid (open) circles suggest significant (nonsignificant) trends at 90% confidence level.

regions within the study domain will disappear by the end of 2070 according to the SM_CRCM2 projections.

5. Conclusions

[32] The soil thermal regime for northeastern Canada for current (1961–1990) and future (2041–2070) climates was simulated at 45 km × 45 km resolution using a one-dimensional heat conduction model [*Goodrich*, 1982] driven by the surface temperature and snow depth from the CRCM transient climate change simulations. Comparison of simulated soil temperature profiles with observed data suggests that the soil model simulations are possibly affected by the biases of the CRCM, particularly for near-surface layers. Projected changes in the soil thermal regime are

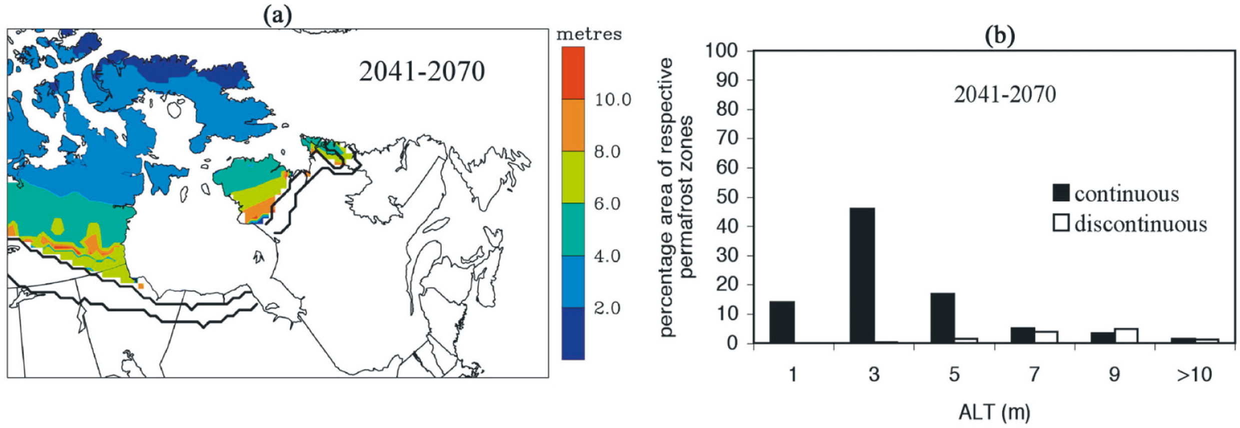

Figure 10. (a) Simulated SM_CRCM2 (2041–2070) average ALT (m) for the continuous and discontinuous permafrost zones and (b) their distributions. The average ALT is binned at an interval of 2 m.

evaluated as differences between the future and current soil model runs driven by CRCM scenario and control climates, respectively. Results suggest significant positive trends in the annual mean, maximal and minimal near-surface soil temperatures, with the mean annual soil surface temperature increasing by 3°–6°C for the continuous permafrost zone and by 2°–4°C for the rest of the permafrost zones in northeastern Canada. Trend analysis shows strongest warming in the annual mean temperatures occurring in the upper layers, with values in the range of 0.03°–0.04°C/year for future climate. The future trends in the mean annual temperature for deeper layers are much smaller compared with surface layers, but significant, for all permafrost regions. At the near-surface layers, the trends associated with the minimal temperatures are higher than that of the maximal temperatures (0.05°–0.12°C/year versus 0.015°–0.025°C/year) for future climate. This is in response to the CRCM projected larger temperature changes for winter than for summer periods. The projections suggest a significant increase in the ALT for the period 2041–2070, with ALT increasing nonuniformly by more than 50% over most of the continuous permafrost region. Results also suggest disappearance of most of the discontinuous permafrost region falling within the study domain, by the end of 2070.

[33] Despite the simplicity of the soil model used here and the biases in the driving data, the study does provide an important insight into the effect of warming on the soil thermal regime for northeastern Canada. It would be interesting to perform the experiments with a more physically based model that would include water movement and lateral transport of heat. As discussed earlier, the quality of the soil model simulation depends to a great extent on the driving data and it is necessary to have good driving data at the boundaries. The data used in this study came from the third generation of the CRCM, which had biases in the surface temperature and snow cover primarily caused by the radiation scheme and the simple land surface scheme used in this version of the model. A new version with a more physically based land surface scheme and better radiation scheme is being implemented at the moment and we expect to repeat the analysis when this new data becomes available. There is also a need for more ensemble members of current and future climate simulations output to drive the soil model in order to help reduce the uncertainties associated with the climate change projections. Also equally important are the soil properties. High resolution soil maps and better data set of soil properties can certainly improve the simulation results.

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