An RCM projection of soil thermal and moisture regimes for North American permafrost zones

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[1] The fourth-generation Canadian Regional Climate Model (CRCM4) projected changes to the soil thermal and moisture regimes for the continuous, discontinuous, sporadic and isolated permafrost regions in North America, for the 2041–2070 period with respect to the 1961–1990 base period, for the SRES (Special Report on Emissions Scenarios) A2 scenario are presented. The projections indicate significant increase in the near-surface soil temperatures for all permafrost zones, with maximum warming for the continuous permafrost zone. No significant changes in the timing of minimum and maximum near-surface soil temperatures are projected by the CRCM4. However, the distributions of both minimum and maximum temperatures, at the surface and for the various near-surface soil layers, for the future climate, are significantly different from those for current climate. Intensification of the hydrologic cycle in future climate for the various permafrost zones is projected with important changes to the soil moisture regime, which are reflected in the reduction of the frozen soil moisture content, which in turn increases the deep drainage for all permafrost zones.
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1. Introduction

[2] Many previous studies have looked at the impacts of climate change on the soil thermal regime for high-latitude permafrost regions. The most viable modelling approach to date has been the use of climate model outputs or analysed data in combination with an off-line soil model [e.g., *Oelke and Zhang*, 2004; *Sushama et al.*, 2006]. These offline simulations have the limitation that they cannot capture the feedbacks to the climate system [*Lawrence and Slater*, 2005]. Interactions between the atmosphere and the underlying surface are important, and determine the quality of many simulated near-surface variables. The fourth-generation Canadian Regional Climate Model (CRCM4) has a sophisticated land-surface scheme and represents land-atmosphere interactions as coupled processes, rather than as boundary conditions as was the case with earlier climate models. In this paper we study the CRCM4 projected changes to the near-surface soil thermal and moisture regimes for the North American high-latitude permafrost regions. It should also be noted that the higher spatial resolution of the CRCM4 compared to that of the global climate models, allows for greater topographic realism and finer-scale atmospheric dynamics to be simulated and thereby represent a possibly more adequate tool for generating information for impact studies. The different North American permafrost zones considered in this study correspond to continuous, extensive discontinuous, sporadic and isolated permafrost zones (Figure 1a), and is taken from the International Permafrost Association (IPA) map [*Brown et al.*, 2001].

2. Model and Experimental Configuration

[3] A detailed description of the earlier versions of the CRCM is given by *Caya and Laprise* [1999]. The version of CRCM used in this study, CRCM4, includes the physically based three-layer Canadian Land Surface Scheme (CLASS), version 2.7 [*Verseghy*, 1991; *Verseghy et al.*, 1993]. The soil layers in CLASS, from top to bottom, are 0.1 m, 0.25 m and 3.75 m thick, and they will be referred to as layer 1, layer 2 and layer 3 hereafter. The vertical flux of water in the soil column is governed by Darcy's law and deep drainage to the water table can occur if an impermeable soil layer has not been reached. Lateral heat flow is neglected in the model and one-dimensional heat conservation equation is applied to each layer to compute the change in layer-average temperatures. The soil properties are specified using the land-surface datasets developed by *Wilson and Henderson-Sellers* [1985].

[4] Several studies, including B. Music and D. Caya, Investigation of sensitivity of the CRCM hydrological cycle to the land surface parameterization, lateral boundary and initial conditions, submitted to *Journal of Hydrometeorology*, 2007, and references therein, present validation of CRCM4 over North America, and therefore, we only briefly discuss the performance and errors associated with those variables that are important for the soil thermal and moisture regimes. The thawing and freezing indices, defined here as the absolute annual accumulated departures of the surface temperatures above and below 0°C, along with snow cover, are important controls on the soil thermal regime. CRCM4 has a cold bias and therefore underestimates (overestimates) the thawing (freezing) index; in general the biases in the freezing and thawing indices are less than 30% over most of the permafrost zones, except for the western parts of the domain where the biases are larger than 30%. CRCM4 overestimates snow cover over most part of the domain and, the errors are larger for the western part of the domain.

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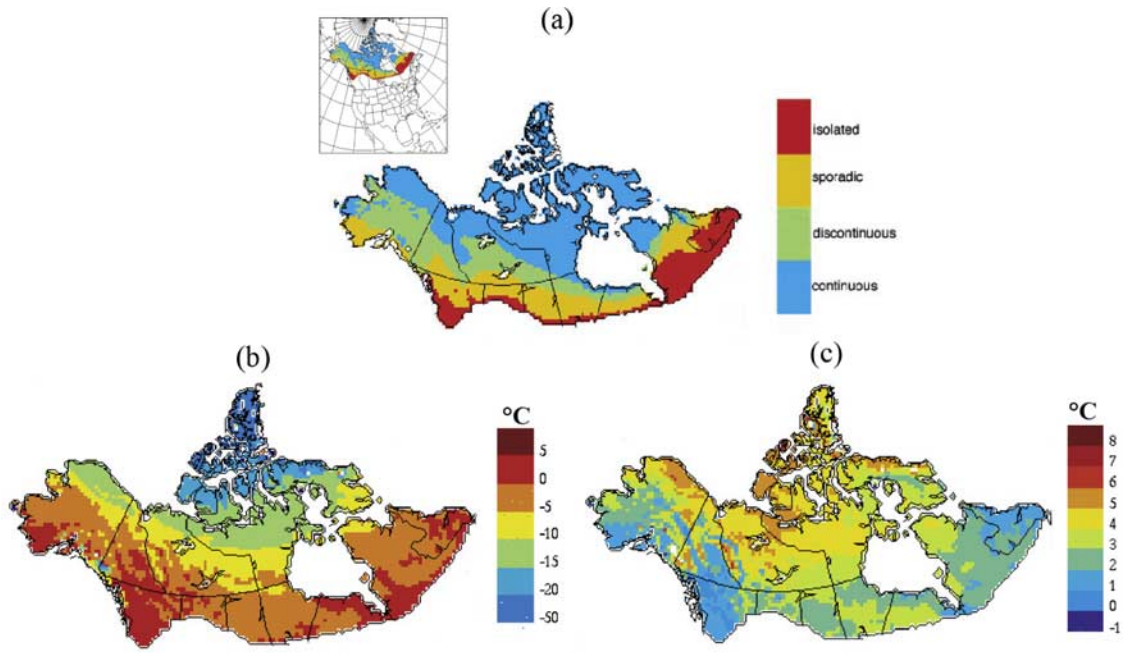

Figure 1. (a) North American permafrost regions from the IPA map [*Brown et al.*, 2001] that fall within the CRCM domain shown in the inset. (b) The CRCM-simulated average annual temperature (in °C) for the 1961–1990 period and (c) the CRCM projected changes (in °C) in the mean annual temperature for the 2041–2070 period, for soil layer 1.

Validation based on comparing model-simulated near-surface soil temperatures with in situ ground thermal data for locations with soil/geophysical properties very similar to those of the corresponding model grid (e.g. Kangiqsualuujuaq: 58.709°N, 65.92°W and Tasiujaq: 58.67°N, 69.95°W), suggest reasonable model performance with errors generally within the ±1.5°C range in northern Quebec. However, comparison of model-simulated ground surface temperatures with those from the ground temperature database for Northern Canada [*Smith and Burgess*, 2000], suggests significant cold biases, as large as −5 to −7° C, over western permafrost zones.

[5] The two CRCM4 simulations used in this study correspond to (1) current 1961–1990 period and (2) future 2041–2070 SRES (Special Report on Emissions Scenarios) A2 scenario [*Intergovernmental Panel on Climate Change*, 2001]; CRCM4 future simulations for other scenarios are not available at the moment and therefore only the A2 scenario is used here. The CRCM4 simulations were computed on a 200 × 192 points grid (see inset of Figure 1a), covering whole of North America and adjoining oceans, with a horizontal grid-point spacing of 45 km and 29 vertical levels, ranging from the surface to the model top near 29 km. The CRCM4 performs dynamical downscaling of the Canadian General Circulation Model III (CGCM3) simulated data to produce climate projections at the regional scale.

3. Soil Thermal Regime

[6] In CLASS, the one-dimensional heat conservation equation is applied to all three soil layers to calculate the layer-average temperatures. In the reference run for current climate, the model-simulated average annual temperatures for soil layer 1, for various permafrost zones, are shown in Figure 1b. The simulated temperatures for the continuous permafrost zone vary between −35 to −5°C, for soil layer 1. The CRCM4 projected changes in the average annual temperature for the same layer for the 2041–2070 period with respect to the 1961–1990 period are shown in Figure 1c, indicating a 4 to 6°C increase for the continuous permafrost zone. The southern permafrost zones experience smaller (0 to 3°C) changes compared with the continuous permafrost zone. Similar changes in the average annual temperatures are projected for soil layers 2 and 3.

[7] The phase-space plots of climatologic surface versus soil temperatures for layers 1 and 3 for the various permafrost zones for both current (1961–1990) and future (2041–2070) climates are presented in Figure 2a. The surface temperature is defined here as the temperature at the soil surface or at the snow surface if snow is present. The phase-space plots for soil layer 2 are very similar to those for layer 1 and are therefore not shown. Major features of the current climate surface/soil thermal orbits are discussed first followed by the projected changes to the orbits in future climate. For current climate, the interception figures (i.e., phase-space plots) have very distinct summer and winter parts for layer 1, particularly for the discontinuous, sporadic and isolated permafrost zones. As discussed by *Beltrami* [1996], the shape of the interception ellipse changes from summer to winter owing to the increased phase lag induced by snow cover.

[8] For the continuous permafrost zone, due to shorter summers, with the average surface temperature below 0°C for most of the year, the summer part of the orbit is relatively small compared with the winter part. Analysis of the yearly interception figures for layers 1 and 2 (not shown) suggest significant variations in winter due to the

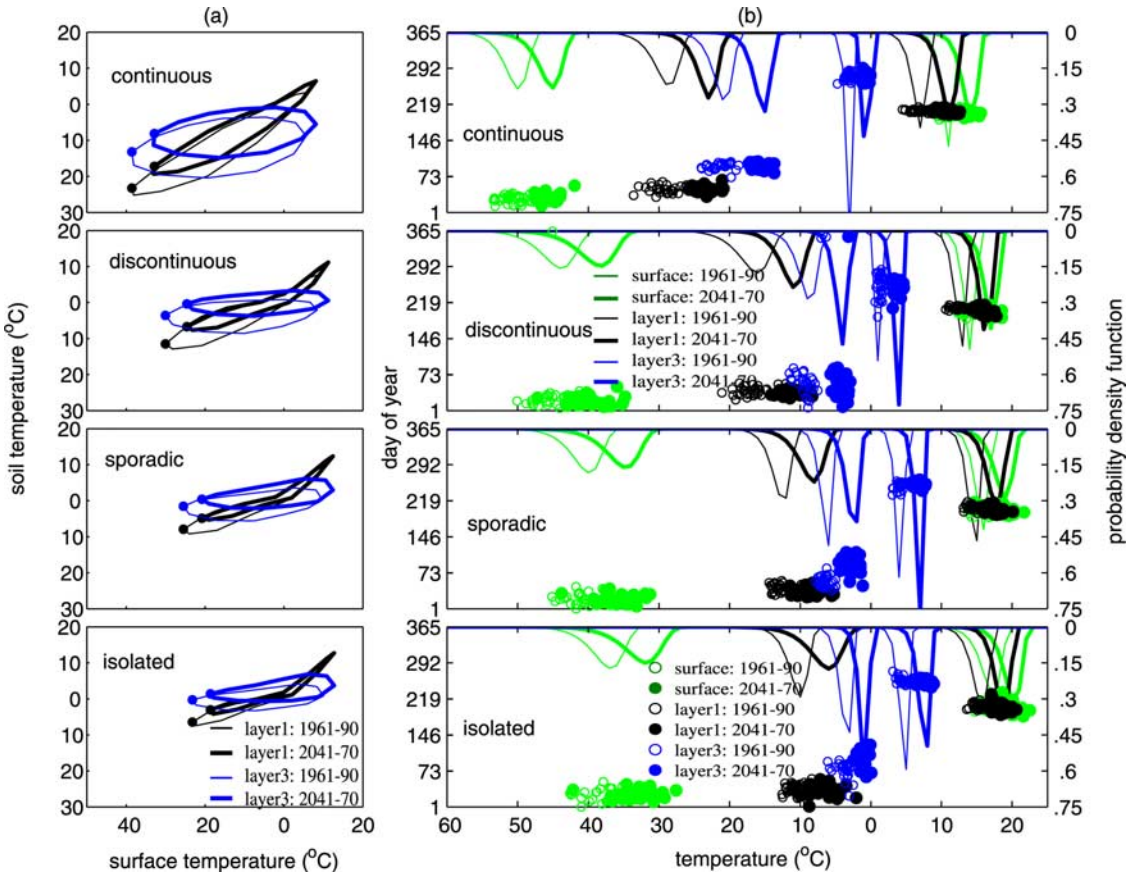

Figure 2. (a) Mean surface/soil thermal orbits for current and future climates, for soil layers 1 and 3, for the various permafrost zones. The dots on the orbits correspond to January and the orbits run anticlockwise through the year. (b) The timing (left axis) of yearly minimum and maximum surface, layer 1 and layer 3 temperatures for current (1961–1990) and future (2041–2070) periods for various permafrost zones. Also shown are the probability density functions (pdfs, right axis) for maximum and minimum surface and soil layer (layers 1 and 3) temperatures, for current and future climates. Note that in each of the subpanels of Figure 2b, the same colour scheme is used for the maximum and minimum temperatures for a given soil-layer/surface, but can be clearly distinguished, with the minimum temperature distributions/timings to the left of those for the maximum temperatures.

variability in the snow-cover from year to year. Layer 3 temperature is phase-shifted with respect to layer 1, as seen by the difference in the orientation of the principal axes of the interception figures for soil layers 1 and 3.

[9] The interception figures for the various permafrost zones for future climate, also shown in Figure 2a, indicate significant changes to the orbits. For layer 1, the differences are predominant from late-winter through early-spring months; shortening of the orbit length on the winter side are associated with the larger temperature increase in winter than for summer. The CRCM4 simulations project a decrease in snow cover for all permafrost zones but the continuous permafrost zone. Though decrease in snow cover by itself could lead to cooling of soil temperatures in winter, the thermal orbits suggest overall warming. The complex response of near surface soil temperatures to snow cover that insulates the soil from the cold atmosphere makes it difficult to explain the projected changes in winter. For the continuous permafrost zone, the thermal orbit corresponding to layer 3 is still mostly below freezing temperature in future climate, while for isolated permafrost zone, the future soil temperature for layer 3 is mostly above 0°C even when surface temperature falls below 0°C.

[10] Changes in the timing and distribution of maximum and minimum surface/soil-layer temperatures are presented in Figure 2b for all permafrost zones. Results corresponding to soil layer 2 are not shown since they are very similar to those for layer 1. The insulating effect of snow cover is reflected in the difference between the surface and layer 1 minimum temperatures, which well exceeds 20°C. The minimum temperatures for layer 1 and layer 3 differ by nearly 10°C on average. The simulated maximum temperatures at the surface and for layer 1 are very similar. The inter-annual variability in the simulated surface and layer 1 minimum/maximum soil temperatures appear to be larger than that for layer 3. In general, the spread in the timing of minimum soil layer temperatures for the discontinuous to isolated permafrost zones are larger than that for the continuous permafrost zone, in both current and future climate. The simulated distributions of minimum and maximum temperatures for both current and future climates appear to be asymmetric and therefore extreme value distribution is employed to study the difference in the shape

of the distribution. The choice of the distribution is not important in this context since we focus on the changes in the shape of the distribution from current to future climate and not on fitting the best distribution. The extreme value distributions for various cases were estimated from the simulated distributions using maximum likelihood method, which are also presented in Figure 2b. For surface minimum temperatures for all four permafrost zones, the probability density functions (pdfs) suggest shifts in the centre of the distributions, indicating a translation towards warmer temperatures in future climate.

[11] For the soil layers, changes to the shape of the pdfs associated with minimum temperatures are noted for all four permafrost zones, in addition to the shift towards warmer temperatures. However, these results are not uniform across the four permafrost zones. For surface maximum temperatures, both the shape and location of the pdfs change for all the permafrost zones, with more pronounced change in the location parameter of the pdfs. Similar to the pdfs of minimum temperatures for soil layers 1 and 3, the pdfs of maximum temperatures change with respect to both location and shape (with more pronounced change for soil layer 3) for all permafrost zones. Based on the results of parametric t-test and non-parametric rank-sum test, it is concluded that the distributions of both the minimum and maximum temperatures at the surface and for the soil layers, for the future climate are significantly different from those for the current climate, for all the four permafrost zones, at a confidence level much higher than the commonly used 90 and 95%. These changes in the average annual, maximum and minimum temperatures discussed above suggest deepening of the active layer for all permafrost zones.

4. Soil Moisture Regime

[12] Any change to the soil thermal regime will likely be reflected in the soil moisture regime and vice-versa. Change in the total soil moisture is important since it can affect the vertical and horizontal fluxes of energy and moisture at the surface. Monthly climatology of the surface water balance components, namely precipitation, evaporation and runoff (defined here as the sum of the surface runoff and deep drainage), are summarized in Figure 3a for both current and future climates. The hydrologic cycle is more intense for the isolated permafrost zone and less intense for the continuous permafrost zone, with maximum precipitation in summer months when atmospheric temperature is higher and hence its potential water holding capacity larger. Being snow dominant regions, the runoff peaks for all four zones occur in spring following snowmelt (Figure 3a). The projections indicate an increase in precipitation for all months, for all four zones, with a 15–20% increase in the annual precipitation. Despite the varying intensity of the hydrologic cycle, evaporation increases from current to future climate for summer months due to increase in temperature and available water. The annual increase in evaporation varies between 13 to 16% for the various zones.

[13] The isolated permafrost zone receives maximum snow of all the four permafrost zones. Future projections indicate a decrease in the snow water equivalent for the discontinuous, sporadic and isolated permafrost zones (Figure 3b). However, a slight increase in the snow water equivalent is projected for the continuous permafrost region. Snow melts earlier in future climate for all permafrost zones, resulting in an increase in the spring runoffs and a decrease in the early summer runoffs (Figure 3a). However, the annual runoffs increase by 15 to 26%, with maximum for the discontinuous permafrost zone. It is interesting to note that these increases in total runoff are caused by increase in both surface runoff and drainage. The general increase in drainage is due to the increased hydraulic conductivity, which is linked to the projected changes in the liquid and frozen soil water contents. The frozen water content is projected to decrease and the liquid water content to increase (figure not shown). Increased drainage in future climate during early fall is due to the decreased frozen water content, while in spring early melt increases drainage. For the continuous and discontinuous permafrost regions, projections indicate a slight decrease (Figure 3b) in the total soil moisture content for the three layers, i.e. integrated over the 4.1 m of soil in CLASS, but these changes are not significant.

5. Discussion and Conclusions

[14] The Canadian RCM projections of soil thermal and moisture regimes for the North American high-latitude permafrost regions, for the 2041–2070 period under the SRES A2 scenario, indicate an increase in the near surface average annual soil layer temperatures by 4 to 6°C for the continuous permafrost region, with respect to the 1961–1990 reference period. The surface/soil thermal orbits for current and future climate for the various soil layers indicate maximum changes during winter. The projected increase in the soil temperatures is reflected in the soil moisture regime. A decrease (increase) in the frozen (liquid) water content is projected to accompany the increased soil temperatures. The projected decrease in the frozen soil moisture content leads to increased drainage due to increased hydraulic conductivity of the soil for all permafrost zones.

[15] Regional climate models (RCMs) are being used in several impact and adaptation studies due to their higher spatial resolution than General Circulation Models (GCMs). However, to make the regional climate model simulations more useful in understanding the subsurface climate, several improvements are required. *Smerdon and Stieglitz* [2006] demonstrated that a lower boundary at several metres influences the behaviour of signals, particularly the annual to decadal signals. The influence of the lower boundary arises because the choice of the zero flux condition imposes a vanishing temperature gradient at the model's bottom boundary. *Stevens et al.* [2007], using a 1-D soil model, showed that shallow boundary conditions can reduce the capacity of the global continental surface to store heat by as much as 1.0×10^{23} Joules during a 110-year simulation with a 10-m deep boundary. The shallow boundary conditions preclude a large amount of heat from being stored in the terrestrial subsurface, possibly allocating heat to other parts of the simulated climate system on long time scales.

[16] However, deeper land surface model are demanding computationally, due to multi layers, in addition to the need for longer spin-up periods. Such modifications are being implemented in the forthcoming versions of CRCM4 and we hope to have climate change simulations with deeper

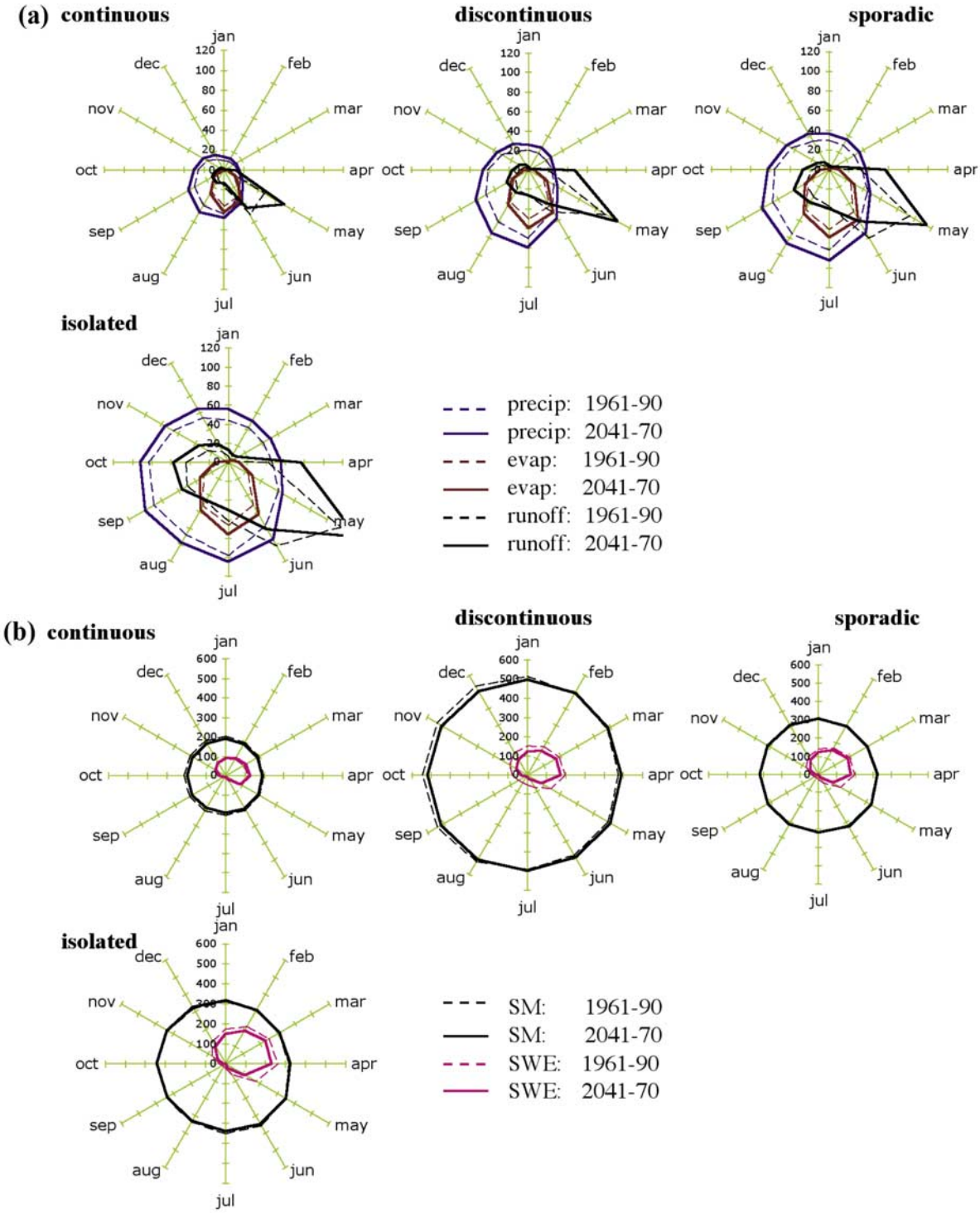

Figure 3. (a) Monthly climatological precipitation (precip), evaporation (evap) and runoff, in mm, for current (1961–1990) and future (2041–2070) climates for various permafrost zones. (b) Total soil water content (SM) for 4.1 m of soil and the snow water equivalent (SWE), both in mm, for the four permafrost zones, for current and future climates.

land surface model available in future. These simulations will also be useful in assessing the impact of a deeper land surface scheme on the land-atmosphere fluxes of water and energy that affect atmospheric calculations. The realism of the simulated regional surface/sub-surface climate can be further increased by incorporating surface processes that both respond to and force the climate through coupled interactions, such as the inclusion of dynamic vegetation and carbon cycle. To improve the simulations, there is also the need for high-resolution soil properties databases. In the current study we have been able to use only one pair of CRCM4 transient climate change simulations. We hope to

have more ensemble members of current and future climate simulations in near future, which can help quantify the uncertainties associated with the climate change projections.

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