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Thermally-Conditioned Paleo-Permafrost Variations from Global Climate Modeling

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Abstract

The permafrost distribution under Quaternary climate conditions is investigated by a frozen ground classification method based solely upon the near surface air thermal indices as a diagnosing analysis of the Paleoclimate Model Intercomparison Project 2 (PMIP2) output. The methodology is constructed using the present-day distribution of the frozen ground and the thermal (freeze and thaw) index, and showed reasonable capability for large-scale mapping. The frozen ground distribution was reconstructed for 0 ka (pre-industrial), 6 ka (mid-Holocene), and 21 ka (the last glacial maximum; LGM) conditions. The Holocene simulations (0 ka and 6 ka) produced largely similar results. The LGM outputs showed substantial increase of the permafrost area by 49.6% relative to the pre-industrial conditions in median among the models, but also showed insufficient cooling during the cold season in some regions. Across-model variations illustrate the regions that need careful examination in using PMIP2 outputs for further subsurface thermal regime calculations.

1. Introduction

Dynamics of freezing and thawing of the soil is a decisive factor in the eco-climate system in cold regions. Subsurface thermal regimes regulate overall behavior and the seasonality of local hydrology. Depth of the seasonal active layer defines 1) the availability of water and nutrients in the growing season, 2) space available for roots, and 3) the total greenness and productivity of the region. The presence of forest (taiga) or tundra biome modulates the exchange of energy and water between the atmosphere and ground, in contrast to the ice-covered or desert areas. Frozen ground (FG) offers long-term memory of the terrestrial system due to 1) the presence of surface insulation (the organic layer and snow cover) that buffers the heat-conductive ground from the overlying atmospheric changes, and 2) ground ice content. Thus, changes in the distribution of frozen ground in time and space are an important issue in understanding the attribution and consequence of Quaternary climate change. Land process models with physically-based freeze/thaw dynamics can serve as a strong tool for such investigation (Saito 2008a, 2008b; Romanovsky and Osterkamp 1997). We have expertise in testing those models under the current climate conditions. We are about to employ the permafrost dynamics model to the Quaternary conditions to shed light on the abovementioned issues from a climate modeling approach. This is a sub-project in the Paleoclimate Model Intercomparison Project 2 (PMIP2; Braconnot et al. 2007).

This letter reports the result of our preliminary step, i.e., analysis of the PMIP2 surface air temperature outputs to examine the thermal contribution to ground freezing under different climate environment (0 ka, 6 ka, and 21 ka), which will eventually constitute a basis of the forcing data in our successive integration studies with the freeze/thaw dynamics.

2. Numerical models and observational data

The outputs from the PMIP2 atmosphere-ocean coupling (AO) integrations are used in the analysis. The numbers and members of the models producing the results are different between the eras, so different sets of the models are used: for 0 ka– nine integrations, i.e., CCSM, CNRM, CSIRO, ECHAM5, MIROC3.2, MIROC 3.2.2, MRI-fa, MRI-nfa, and UBRIS; for 6 ka– seven, i.e., CCSM, CSIRO, ECHAM5, MIROC3.2, MRI-fa, MRI-nfa, and UBRIS; and six realizations for 21 ka, i.e., CCSM, CNRM, HadCM3, IPSL, MIROC3.2, and MIROC3.2.2. The ice sheet distribution for each era was specified commonly in all the integrations. The details and explanations of each model/institute can be found at the official PMIP2 site at http://pmip2.lsce.ipsl.fr/. Monthly surface air temperature (Tas) data, as well as the land/ocean mask and topography data for each participating model's integration are obtained from the PMIP2 database. Since the length of integrations and the horizontal resolution are different between models, the monthly climatology calculated for Tas from the last 10 years of the integration is used for analysis, and the model outputs were interpolated and mapped onto the T42 truncation grids (128 by 64 grids in the longitudinal and latitudinal direction with the starting longitude on 0°E) before the analysis.

The freeze index (FI) and the thaw index (TI) for the current climate were taken from the National Snow and Ice Data Center (NSIDC) database (Zhang et al. 2005). The annual indices, given on the 25 km resolution Equal-Area Scalable Earth grid, are defined as the cumulative number of degree-days when surface air temperatures are below and above the freezing point (0 °C) and based on the monthly mean values compiled at the Climate Research Unit (CRU) by Mitchell and Jones (2005). The climatology of surface air temperature, and the FIs and TIs were used in the following analysis for the period 1981 to 2000. The FIs and the TIs of the PMIP2 outputs were calculated from the monthly mean

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values in the same manner explained in Frauenfeld et al. (2007).

Distribution and classification of the permafrost (continuous, discontinuous, sporadic, and isolated) are based on the International Permafrost Association map (IPA map; Brown et al. 1997). "No frost" zones are defined as the area with zero freeze index value, i.e., the minimum monthly mean surface air temperature being above the freezing point, which is equivalent to the procedure taken in Saito et al. (2007).

3. Frozen ground classification by the current climate indices

A classification of frozen ground by the FIs and TIs was constructed based on the occurrence frequency of the continuous or discontinuous permafrost or seasonal frost under the present-day distribution (Fig. 1). An advantage of the thermal index classification method is the simplicity and intuitiveness. It can also separate the cold and warm season characteristics in contrast to the annual mean. Because permafrost is especially vulnerable to warming in the snow-free season when there is no overlying snow for insulation, the ability to isolate the relative importance of summer thaw (thaw index) is a considerable advantage over the use of annual means. However, a methodology relying solely on temperature has known limitations in that it neglects contributions from other important factors that control the subsurface thermal regime, such as snow cover, surface vegetation, soil, and subgrid-scale topography (Fig. 2). Uncertainties resulting from those factors are represented by the transitional areas.

4. Thermally-conditioned distribution of frozen ground from PMIP2 outputs

The index-based classification constructed in Section 3 was then applied to the PMIP2 outputs to determine the modeled 'thermally-conditioned' frozen ground distribution under the 0 ka (pre-industrial), 6 ka (mid-Holocene), and 21 ka (the Last Glacial Maximum; LGM) climate conditions. The 0 ka result (Fig. 3b) shows reasonable consistency with the map applied back onto the NSIDC FI-TI climatology (Fig. 3a).

The transitional areas roughly correspond to the southern discontinuous, sporadic and isolated permafrost regions in the IPA map. Expectedly, the largest area of permafrost zones was reconstructed for the LGM case (Fig. 3d), while 0 ka and 6 ka show similar size of distribution except some regional differences (e.g., east of the Ural. Velichko 1984).

An atlas for the LGM period (Frenzel et al. 1992) shows a zone of continuous permafrost with periglacial tundra north of Alps in western Europe, which Fig. 3d lacks. Similar results are found to the south of the Laurentide ice sheet. Examination of the PMIP2 Tas-derived freeze and thaw indices indicates that the modeled cold season tends not cold enough to produce permafrost.

Figure 4a shows the median and ranges of the FIs and TIs over the Northern hemisphere ice-free land (NH land). Compared to the observed values in the present-day climate (1981–2000), the pre-industrial realizations tend to be cooler in both seasons. The distribution is alike between 0 ka and 6 ka for the warm season, though the 6 ka integrations show a cooler distribution with a slightly greater inter-model variation in the cool season. The LGM simulations show much cooler climate and smaller across-model variations in both seasons.

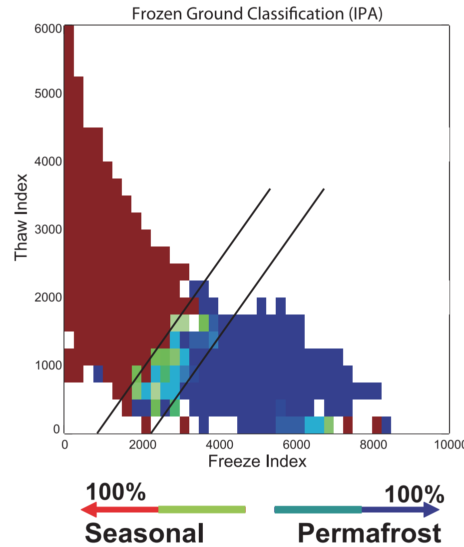

Fig. 1. Frequency of occurrence of continuous/discontinuous permafrost and seasonal frost (seasonally frozen ground) at grid points for a given combination box of the FI and TI values. The width of each box is 250 for the both indices. The locations at which the FI-TI pair falls in the areas above the left line are classified as seasonal frost, and if the pair drops in the areas below the right line it is permafrost. The areas between the two lines are categorized as "transitional" regions. The results are robust against the choice of the box width. The position and the slope of the left and right lines are based upon the optimization in terms of the misclassification rate for seasonal frost and permafrost, respectively.

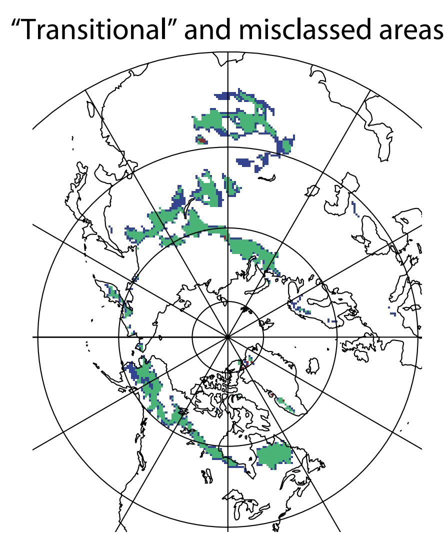

Fig. 2. Distribution of the "transitional" areas (green; 2.43×10^6 km^2). Types and locations of the erroneous classification under the current climate condition are also shown. The IPA Permafrost areas that are categorized as seasonal frost (blue; 0.94×10^6 km^2 or 0.97% of ice-free land in Northern hemisphere) are mainly high mountains, e.g., Himalaya, Tienshan, Hindu Kush and Kavkas Mountains, while the seasonal frost areas categorized as permafrost (red; 0.05×10^6 km^2 or similarly 0.05 %) are coastal areas in Greenland and northeastern Tibet.

The distribution of the area of the classified frozen ground zones among the models is shown in Fig. 4b. It is consistent with the results shown in Fig. 4a indicating that the area classified as permafrost by the mode among the pre-industrial simulations is relatively larger

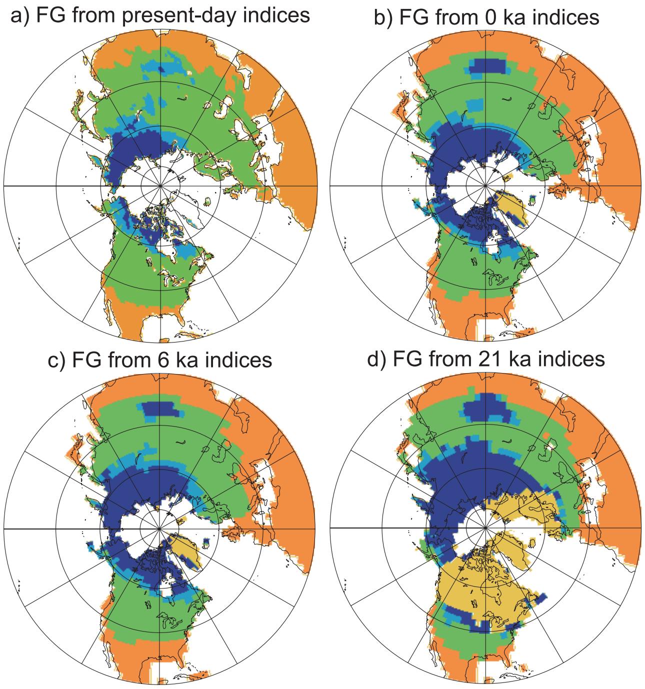

Fig. 3. Frozen ground classification (Fig. 1) is applied to the freeze/thaw index combination a) derived from the NSIDC 1981–2000 monthly climatology for the current climate, and from the last-ten-year monthly climatology for PMIP2 outputs for b) 0 ka, c) 6 ka, and d) 21 ka. The present-day coastlines are drawn commonly for reference in all the figures. The different classification zones are separated by colors: the glacial ice sheet (yellow), permafrost (dark blue), transitional (light blue), seasonal (green) and no (orange) frost zones. In the maps for 0 ka, 6 ka and 21 ka, the mode (i.e., most frequent) type among the integrations at a grid is taken. Variations of the classified type at each grid are shown in Fig. 5.

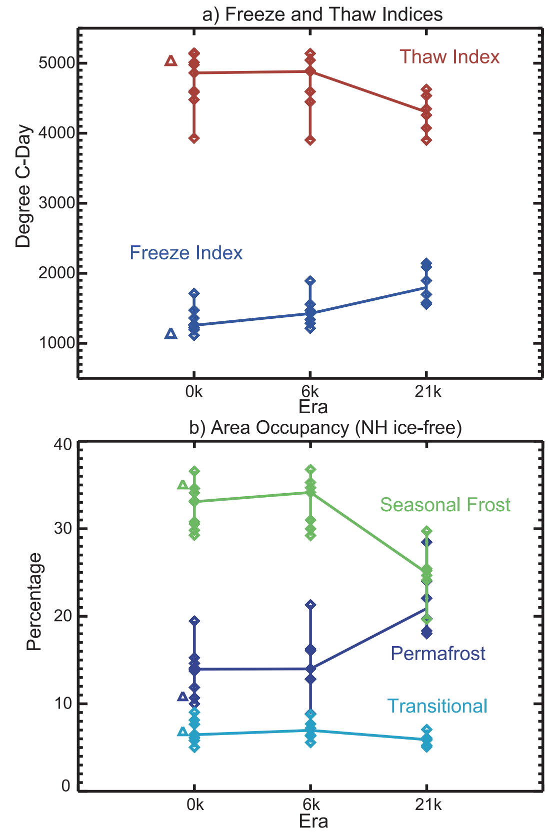

Fig. 4. a) Medians and variations of the modeled TIs (red) and FIs (blue) averaged over the Northern hemisphere ice-free land area for three eras. The observed value derived from NSIDC is shown by triangles. b) Medians and variations of the percentage of NH total land for permafrost (dark blue), transitional (pale blue) and seasonal frost (green) for three eras. The observed values calculated from the IPA map are shown by triangles.

compared to the value based upon the present-day observation, while that for the seasonal frost is smaller. The occupancy of the permafrost zones in the NH land for 21 ka is substantially larger than that of 0 ka (1.50 times larger relative to the 0 ka in median), and the seasonal frost occupancy smaller by a factor of 0.75. Area of the transitional zones varies little between glacial and inter-glacial periods.

Figure 5 illustrates how and where the classified frost zones are diverse among the models, measured in terms of the quantity H defined by the classification probability p: $H = -\Sigma p \ln(p)$. Since there are four possible types (permafrost, transitional, seasonal, and no frost) at an ice-free land grid, the theoretical maximum value (for the most uncertain, diversified case) would be 1.386. The most southern band of 'diversity' around 30°N is mainly the border between seasonal and no frost, while the northern band between 45°N and 65°N is the transitional zone merged with its own boundaries with permafrost to the north, and seasonal frost to the south. The geographical location of the 'diverse' zone is similar between 0 ka and 6 ka, with the larger across-model diversity for 6 ka. The lack of permafrost in the 50–60 °N band (incl. north of Alps) for LGM seems unanimous among the analyzed integration sets.

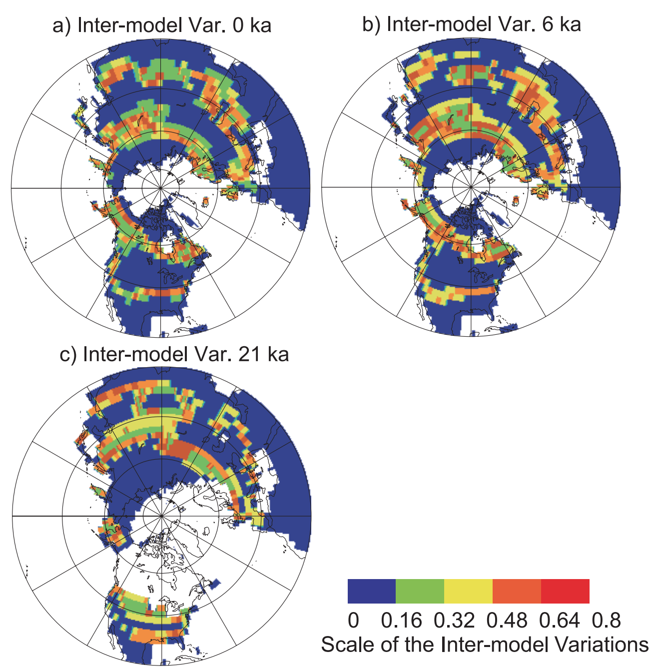

Fig. 5. Variations of the classified types of the frozen ground among the integrations for a) 0 ka, b) 6 ka, and c) 21 ka measured by H. Details are found in text.

5. Discussions

There have been numerous attempts to relate the frozen ground condition to some climatic parameters, and they have proved some usefulness of the approach. However, no single method that takes only atmospheric thermal conditions into account is known to work perfectly because there are other factors that control the presence and absence of frozen ground. Those factors include snow cover, vegetation, soil characteristics, and topography. Deep snow cover, and vegetation, including the top organic layer, modify thermal inputs from the atmosphere thermodynamically and hydrologically. The local soil (e.g., porosity, hydraulic and thermal properties) and topographic characteristics (e.g., aspect and flatness) alter subterranean responses. When the temporal window is small, the time-scale difference can preclude a simple relationship between the overlying atmosphere and the subsurface conditions. Despite those shortcomings, the proposed method demonstrated a successful diagnostic skill test to examine the climate model Tas outputs to be used in subsurface thermal regime calculations, and also produced likely distributions for most of the areas with allowable rate of mismapping.

With different model implementation strategies, horizontal resolutions and the land/sea distribution among the participating models, Tas outputs showed a wide range of variations, with weak cooling during the LGM cold season in some common regions. Another big issue for the LGM is the presence or absence of an explicit Beringia among integrations. This can greatly impact the comparison between the modeled results and the paleo-records in our area of interest (i.e., Alaska and east Siberia) for the period.

We will need to investigate those local to regional aspects of the modeled climate states in the high-latitude/high-altitude areas in more detail to determine how to process the PMIP2 outputs to construct the atmospheric forcing data that are to be prescribed in our future off-line simulations as well as the oceanic forcing data to be used for land-atmosphere coupled experiments.

6. Conclusion

Classification of frozen ground solely by the surface air temperature condition (air freeze and thaw index) was constructed from and tested against the present-day observations. The obtained FG map for the current climate is reasonable, with the intrinsic uncertainties reflected by the transitional zones, which roughly correspond to the southern border of discontinuous permafrost, sporadic, and isolated permafrost zones.

The PMIP2 Tas outputs for 0 ka showed a cooler tendency than the present-day climatology, which likely led to a larger area for permafrost and a smaller seasonal frost area in the classification.

The distributions of categories of frozen ground for 0 ka and 6 ka are similar, although the latter showed larger across-model variations.

Surface air was substantially cooler in the LGM (21 ka) outputs, resulting in larger permafrost and smaller seasonal frost area. Comparison with the reconstructed data, however, implies weak cooling in some common regions. Across-model variation in seasonal-no frost boundary is smaller than in the case of the warmer climate (0 ka and 6 ka).

Next steps include a) detailed examination and comparison of the 6 ka and 21 ka modeled output with the paleo-records, especially available for Alaska and east Siberia, b) construction of the forcing data set to be prescribed in the off-line simulations with physically-based dynamical freeze/thaw models, and similarly, c) preparation for simulations coupled to the land models with an atmosphere model (with prescribed SST), and an atmosphere-ocean model.

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