THE CHANGES OF PERMAFROST INDUCED BY GREENHOUSE WARMING: A SIMULATION STUDY APPLYING MULTIPLE-LAYER GROUND MODEL

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ABSTRACT

Many of past studies using physically based numerical climate models indicate that increases in atmospheric CO_2 could enhance summer dryness over continental region in middle-high latitudes. However the models used in those studies do not take account of permafrost in high latitudes. We have carried out a set of experiments applying a version of global climate model that can reproduce realistic distribution of the permafrost. From the results, it is indicated that permafrost functions as a large reservoir in hydrologic cycle maintaining dry, hot summer over continents in northern middle-high latitudes, and that the CO_2 warming would reduce this function by causing climatological thawing of permafrost, which would result in moister and cooler summer, and warmer winter in the same region. The present study indicates that an inclusion of very simple description of soil freezing process can make a large difference in a model simulation.

1 INTRODUCTION

The only quantitative tools we have for predicting future climate are physically based mathematical models of climate. At present, the coupled atmosphere-ocean general circulation model (CGCM) is state-of-the-art climate model that is widely used in many research institutes. The CGCM is one of the most complicated numerical models that require maximum computational ability to run, and the parallel processing is a suitable method for the CGCM. In Japan, under development as a national project is the "Earth Simulator" that is a vector parallel computer with a peek speed of 40 T FLOPS. The Earth Simulator is specialized to create a virtual Earth including main structure of a CGCM with a horizontal resolution about 10km. In this study, we used a highly parallel computer to integrate a CGCM.

Permafrost covers 14% of the land surface in the world, functioning as a vast reservoir of inland water with large heat capacity. Therefore, it is expected to have significant effects on climate changes in long time scales. In the global warming induced by increasing greenhouse gases, permafrost would be reduced in some regions, which would impact the thermal and hydrological process of the surface.

Many of past studies indicate that the greenhouse warming could enhance summer dryness on the land surface over continental region in middle-high latitudes [1,2,3,4]. However the numerical models used in those studies do not sufficiently reproduce soil moisture and permafrost of the present climate, because of their simplified representation of ground hydrological processes; not a few of them have only one layer and/or exclude freezing and melting process of soil moisture.

In contrast, Kitoh et al. [5], by using a CGCM that includes a four-layer ground model with freezing and melting process of soil moisture, predicts substantial increase of surface soil moisture over northern high latitudes during summer at times of the greenhouse warming. In this paper, by using the same CGCM, the role of the permafrost is studied based on comparison between runs with and without freezing/melting process of soil moisture.

2 MODELS AND EXPERIMENTS

2.1 Coupled Atmosphere -Ocean Model

The coupled atmosphere-ocean model (CGCM) used for this study is the MRI-CGCM1 [6,7]. The CGCM consists of global general circulation models of the atmosphere and the ocean with a sea-ice model, which incorporates all of possible dynamical and physical processes. The atmospheric component has a 4° by 5° latitude-longitude grid and 15 vertical levels with a top at 1hPa. The ocean component has 21 vertical levels with realistic ocean bottom topography. The horizontal resolution is 0.5-2.0° latitude by 2.5° longitude; the latitudinal grid spacing is reduced near the equator to better simulate El Nino. The model has simulated some aspects of El Nino with dominant peak periods of 3 to 6 years [8]. The sea-ice model predicts ice thickness, concentration and brine rejection. The model simulates seasonal variations of sea-ice concentration and thickness realistically both in the Arctic and in the Antarctic regions [7].

2.2 Multiple Layer Ground Model

The multiple layer ground model consists of four layers with boundaries at 0cm, 10cm, 50cm, 150cm and 10m depth. Soil temperature T at each boundary is predicted by solving the equation of heat conduction. Finite element method is taken for vertical differentiation. In the equation, specific heat and thermal conductivity depend on amount and phase of soil moisture.

Soil moisture contained in each layer is expressed in degree of saturation, i.e., the ratio of available soil moisture to saturated quantity. The partial soil moisture is calculated by the diffusion equation. Freezing (melting) of soil moisture is determined when soil temperature is below (above) freezing point and there is liquid (frozen) soil moisture to freeze (melt). When the uppermost layer is frozen or saturated, all the rainfall and snowmelt become runoff.

2.3 Design of Experiment

To investigate the mechanisms responsible for the permafrost, we have carried out four types of experiments using the MRI-CGCM1 incorporated with the multiple layer ground model. We designate them as F1, F2, NF1 and NF2. F1 and F2 are the runs with freezing/melting process of soil moisture under normal (345 ppm) and doubling (690 ppm) concentration of atmospheric CO_2 respectively, while NF1 and NF2 are their counterparts without the freezing/melting process (Table 1). In NF1 and NF2, the following three major effects of soil freezing are ignored: 1) latent heat of freezing and melting, 2) the impermeability of frozen ground, and 3) the immobility of frozen moisture itself. It takes 20 years for the doubled CO_2 runs (F2 and NF2) to reach their interannual equilibrium states. Therefore, the model is integrated for 30 years for each of the four runs, and the means of last 10 years are used as climatologies for the analysis based on comparison between the runs. We have estimated the effects of freezing and melting process of soil moisture upon the present-day climatology from F1-NF1. F2-F1 and NF2-NF1 are used to study the responses to the CO_2 warming under the respective conditions of soil moisture, and the two of the responses are compared to estimate the impact of freezing and melting process of soil moisture upon the climate change forced by the CO_2 warming.

Table 1. Characteristics of the various experiments.

ID	Atmospheric CO_2	Soil freezing process
F1	345 ppm	Yes
F2	690 ppm	Yes
NF1	345 ppm	No
NF2	690 ppm	No

3 EFFECTS OF SOIL FREEZING ON PRESENT-DAY CLIMATOLOGY

Figure 1 shows climatological seasonal variation of frozen soil moisture zonally averaged over land at the surface layer (0-10cm) and the bottom layer (1.5-10m) in F1. The soil moisture in the surface layer goes through annual cycle of freezing and thawing (Fig. 1a) indicating that seasonally frozen ground is distributed north of 30-40°N. On the other hand, the frozen soil moisture in the bottom layer hardly shows seasonal variation throughout the latitudes (Fig. 1b). Therefore it does not thaw throughout the year in high latitudes, indicating that the permafrost exists north of 50-60°N. Figure 2 shows annually averaged frozen soil moisture at bottom layer. The dashed lines denote 0°C boundary of annually averaged surface air temperature (SAT), suggesting permafrost exists roughly north of 60°N where annual mean SAT is lower than freezing point.

Because of the immobility of the frozen moisture, the permafrost in deep layers has a noticeable effect on the ground surface condition, as shown in Fig. 3. In F1 where soil freezing is included, the soil moisture in the surface layer shows large seasonal variation with a significant summer dryness (Fig. 3a), while the bottom layer is rich in moisture all the year around (figure not shown). On the other hand, in NF1 where soil freezing is excluded, the seasonal variation of surface soil moisture is fairly reduced in amplitude (Fig. 3b) according with the invariability in the bottom layer (figure not shown). The difference between F1 and NF1 is especially striking in north of 50°N, i.e., the permafrost zone, where the summer dryness is dominant in F1 while it is barely seen in NF1. During summer, enhanced evaporation from ground surface leads to decrease of the wetness of upper layers. That induces the upward water diffusion from lower layers to reduce the vertical gradient of the soil moisture ratio. In NF1 where soil moisture does not freeze, the summer dryness is quite moderated especially in high latitudes because a large reservoir in deep layers can supply water with the surface layer. Figure 4 shows F1-NF1 in boreal summer (June-August), which reveals effects of soil freezing on present-day climatology. In middle-high latitudes, during summer, limited available water from lower layers results in enhanced dryness in the surface layer and reduced evapora-

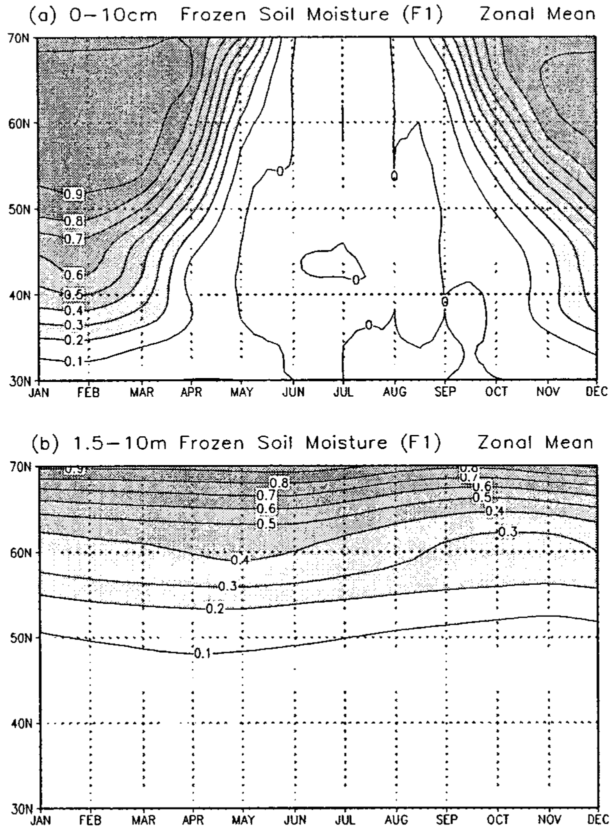

Figure 1. Latitude-month distribution of zonally averaged frozen soil moisture ratio to saturation (a) at the surface layer (0-10cm) and (b) the bottom layer (1.5-10m) in F1.

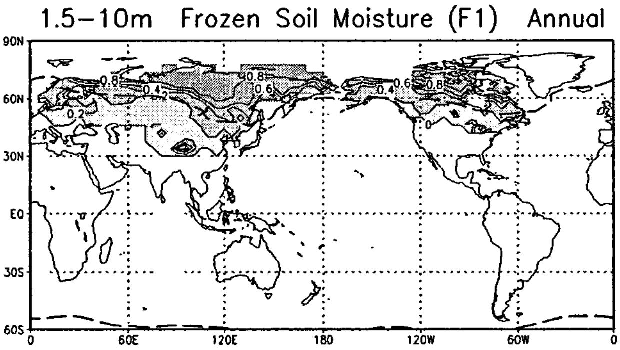

Figure 2. Annually averaged frozen soil moisture ratio to saturation at the bottom layer in F1. Dashed lines denote 0℃ boundaries of annually averaged surface air temperature.

tion from ground surface (figure not shown), which leads to substantial decrease of *in situ* rainfall (Fig. 4a). With reduced cooling effect from the heat of vaporization at surface, SAT marks drastic rise over the permafrost zone (Fig. 4b). Takata and Kimoto [10] shows the similar results

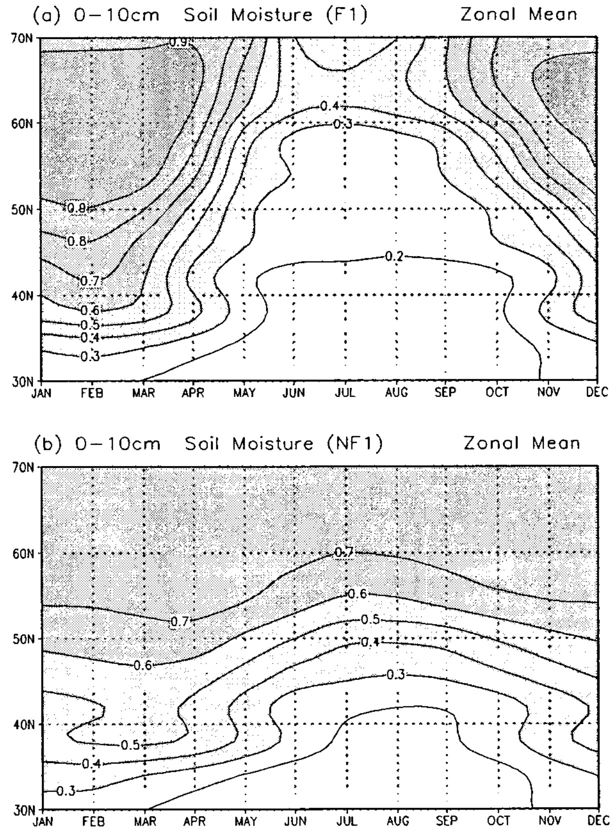

Figure 3. Latitude-month distribution of zonally averaged soil moisture ratio to saturation at the surface layer in (a) F1 and (b) NF1.

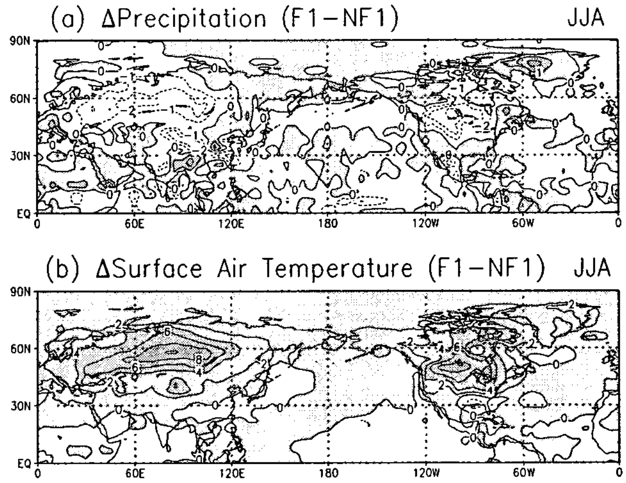

Figure 4. (a) Difference (F1-NF1) in summertime (June- August) averaged total precipitation rate (contour interval: 1 mm/day). Dashed contours denote negative values. (b) As in (a) but for surface air temperature (contour interval: 2 K).

based on the difference between runs with and without soil freezing using an atmospheric general circulation model (AGCM).

4 IMPACTS OF SOIL MELTING ON THE CO_2 CLIMATE CHANGE

The results described above have shown that the permafrost plays a major role in maintaining present-day climatology; in other words, the phase state (solid or liquid) of soil moisture in deep layers determines a fair part of near-surface atmospheric condition. It is therefore speculated that a mass reduction of permafrost induced by CO_2 warming may have a large impact upon the ensuing climate changes.

Figure 5 displays the changes induced by doubling CO_2 (F2-F1) in annually averaged frozen soil moisture at the bottom layer. In high latitudes, frozen moisture shows substantial decrease, which indicates thawing of permafrost induced by CO_2 warming. Figure 6 compares the changes in summertime (June-August) seasonally averaged surface soil moisture induced by doubling CO_2 with and without soil freezing. The difference between them is very clear. The result with soil freezing (F2-F1) predicts substantial increase of surface soil moisture over northern high latitudes (Fig. 6a), while the result without soil freezing (NF2-NF1) shows enhanced summer dryness in the same area (Fig. 6b). In the latter case, since CO_2 warming enhances evaporation, the land surface becomes dryer. Many of the past studies neglecting permafrost indicate the similar results (i.e., enhanced summer dryness). However, when the soil freezing process is considered, CO_2 warming induces permafrost melting in deep layers (Fig. 5) augmenting liquid water available to upper layers, which moderates summer dryness at surface. Figure 7 shows simulated changes in summertime- averaged precipitation induced by doubling CO_2. By comparing the results with soil freezing (Fig. 7a) and without that (Fig. 7b), it is found that the permafrost thawing further accelerates the increase of rainfall over permafrost zone around 60° N. A remote impact of permafrost thawing on the Asian summer monsoon can be seen as a precipitation rise over India.

By including soil-freezing process, which brings on the wetter ground surface causing additional heat capacity of soil moisture with latent heat of phase change, the CO_2 warming in northern high latitude is weakened in summer (Fig. 8a,b), while it is enhanced in winter (Fig. 9a,b). As a result from warmer continental land surface in winter, the Siberian high becomes lower, which induces significant warming in the north Pacific region where the outbreak of its cold air mass reaches.

We can conclude that permafrost functions as a large reservoir hydrologic cycle maintaining dry, hot summer

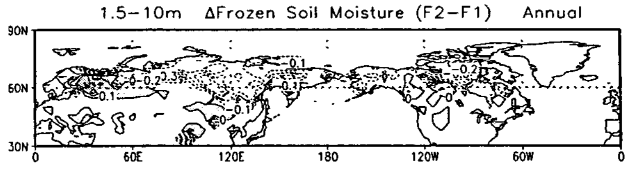

Figure 5. Difference (F2-F1) in annually averaged frozen soil moisture ratio to saturation at the bottom layer (1.5-10m). Dashed contours denote negative values.

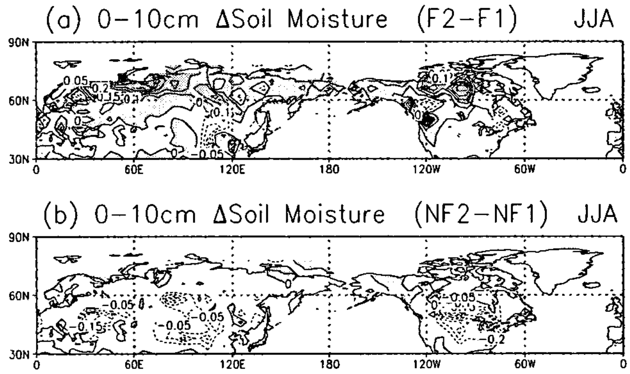

Figure 6. (a) Difference (F2-F1) in summertime (June- August) averaged soil moisture ratio to saturation at the surface layer. Dashed contours denote negative values. (b) Same as in (a) but for NF2-NF1.

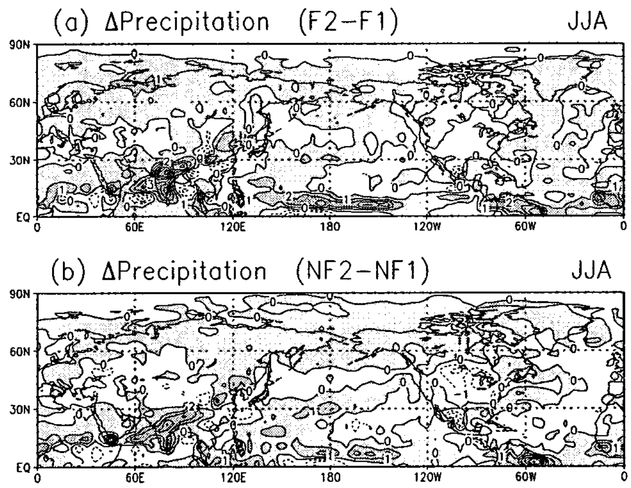

Figure 7. Same as in Fig. 6, but for total precipitation rate (contour interval: 1 mm/day).

over continents in northern middle-high latitudes. The CO_2 warming would reduce this function by causing climatological thawing of permafrost, which would result in moister and cooler summer, and warmer winter in the same region. The present study have indicated that an inclusion

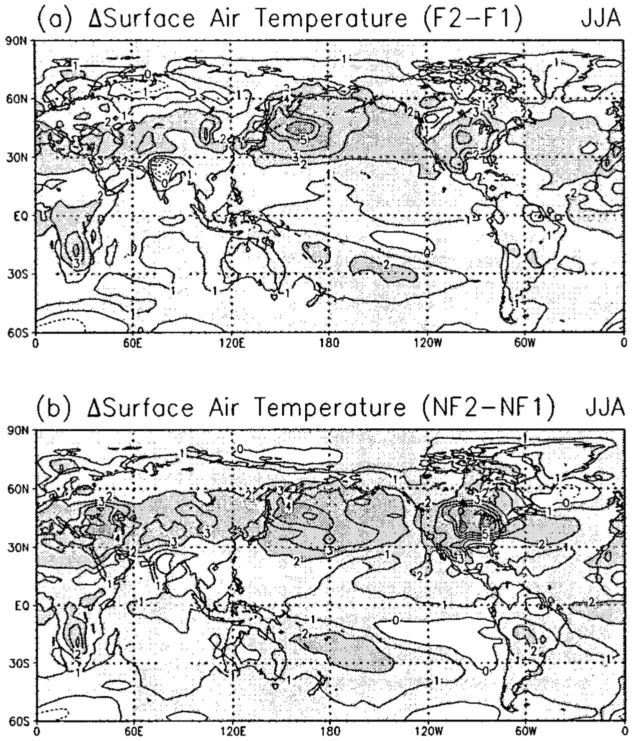

Figure 8. Same as in Fig. 6, but for surface air temperature (contour interval: 1 K).

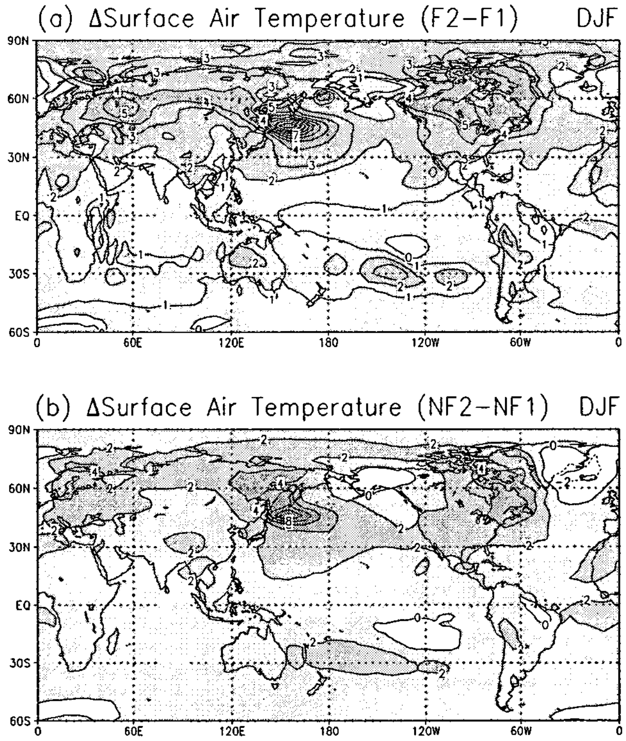

Figure 9. Same as in Fig. 8, but for wintertime (December-February) mean.

of very simple description of soil freezing process can make a large difference in a model simulation, suggesting that climate models with more realistic ground hydrology validated with observational data are needed to study the response to the CO_2 warming in high latitudes.

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