Simulated Historical (1901–2010) Changes in the Permafrost Extent and Active Layer Thickness in the Northern Hemisphere

Donglin Guo1,2,3 & Huijun Wang2

1Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, 2Key Laboratory of Meteorological Disaster, Ministry of Education/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China, 3Joint Laboratory for Climate and Environmental Change, Chengdu University of Information Technology, Chengdu, China

Abstract A growing body of simulation research has considered the dynamics of permafrost, which has an important role in the climate system of a warming world. Previous studies have concentrated on the future degradation of permafrost based on global climate models (GCMs) or data from GCMs. An accurate estimation of historical changes in permafrost is required to understand the relations between changes in permafrost and the Earth’s climate and to validate the results from GCMs. Using the Community Land Model 4.5 driven by the Climate Research Unit -National Centers for Environmental Prediction (CRUNCEP) atmospheric data set and observations of changes in soil temperature and active layer thickness and present-day areal extent of permafrost, this study investigated the changes in permafrost in the Northern Hemisphere from 1901 to 2010. The results showed that the model can reproduce the interannual variations in the observed soil temperature and active layer thickness. The simulated area of present-day permafrost fits well with observations, with a bias of $2.02 \times 10^6$ km$^2$. The area of permafrost decreased by 0.06 ($0.62) \times 10^6$ km$^2$ decade$^{-1}$ from 1901 to 2009 (1979 to 2009). A clear decrease in the area of permafrost was found in response to increases in air temperatures during the period from about the 1930s to the 1940s, indicating that permafrost is sensitive to even a temporary increase in temperature. From a regional perspective, high-elevation permafrost decreases at a faster rate than high-latitude permafrost; permafrost in China shows the fastest rate of decrease, followed by Alaska, Russia, and Canada. Discrepancies in the rate of decrease in the extent of permafrost among different regions were mostly linked to the sensitivity of permafrost in the regions to increases in air temperatures rather than to the amplitude of the increase in air temperatures. An increase in the active layer thickness of 0.009 (0.071) m decade$^{-1}$ was shown during the period of 1901–2009 (1979–2009). These results are useful in understanding the response of permafrost to a historical warming climate and for validating the results from GCMs.

1. Introduction

Permafrost occupies approximately 25% of the land area of the Northern Hemisphere. It is estimated that approximately 1,830 Pg of soil organic carbon is stored in permafrost soils, equivalent to approximately 2.2 times more carbon than is present in the Earth’s current atmosphere (Ciais et al., 2013; Mu et al., 2015). Zhang et al. (1999) estimated that approximately $11.4–36.6 \times 10^9$ m$^3$ of ground ice is stored in permafrost in the Northern Hemisphere. In addition, large populations and engineering facilities have expanded into permafrost regions in recent decades as a result of their abundant natural resources in these regions (Nelson, Anisimov, & Shiklomanov, 2002). Seasonally freezing and thawing processes in the active layer of permafrost are closely related to the surface ecology, hydrology, and energy budget of these regions (Guo et al., 2015; Guo, Yang, & Wang, 2011a, 2011b; Yi et al., 2014). Permafrost has a large sensitivity to climate change and is distributed in regions with the greatest recorded warming, which makes it likely that permafrost will begin to thaw in response to global climate change (Collins et al., 2013; Guo et al., 2017; Guo & Wang, 2012; Tian & Jiang, 2015; Zhou et al., 2016). The thawing of permafrost can result in the release of soil organic carbon, the melting of ground ice, and changes in the seasonal soil freezing and thawing processes. These changes will, in turn, affect the climate (Li & Chen, 2013; Schuur et al., 2015), the hydrology and availability of water resources (Guo, Wang, & Li, 2012; Lijedahl et al., 2016), the stabilization of engineering facilities underlain by permafrost (Guo & Sun, 2015; Guo & Wang, 2016b; Nelson et al., 2002), and the terrestrial ecosystem (Qin, Zhou, & Xiao, 2014; Yang et al., 2010). Therefore permafrost has an important role in the climate system of a warming world.
A growing body of research has simulated the potential thawing of permafrost (Anisimov & Nelson, 1996; Guo & Wang, 2013; Guo & Wang, 2016a; Koven, Riley, & Stern, 2013; Lawrence et al., 2011, 2008; Liu & Jiang, 2016; Slater & Lawrence, 2013; Stendel & Christensen, 2002; Zhang, Chen, & Riseborough, 2008). An early simulation using a diagnostic model in conjunction with data from three global climate models (GCMs) suggested a reduction of 25–44% in the area of permafrost in response to a 2°C increase in global temperatures (Anisimov & Nelson, 1996). Reductions in permafrost area of 33% (Representative Concentration Pathway (RCP) 2.6), 49% (RCP4.5), 62% (RCP6.0), and 72% (RCP8.5) were also projected using the fully coupled Community Climate System Model, version 4.0 (Lawrence et al., 2012). More recently, multiple GCMs or data from multiple GCMs have been used to estimate future permafrost variation and the results have suggested that the area of permafrost will decrease by 37 ± 11% (RCP2.6), 51 ± 13% (RCP4.5), 58 ± 13% (RCP6.0), and 81 ± 12% (RCP8.5) by 2080–2099 (Koven et al., 2013; Slater & Lawrence, 2013). Permafrost variations among different permafrost subregions have also been projected using a diagnostic model driven by the outputs from multiple GCMs (Guo & Wang, 2016a).

These studies have mostly considered future permafrost variation based on GCMs. Although historical changes in permafrost are also referred in these studies, they lack accuracy because the results include a bias caused by simulated climate bias, which may amplify the rate of degradation of permafrost by 29% in the warmest case scenario of RCP8.5 (Lawrence et al., 2012). In addition, the results include unrealistic interannual variations in the extent of permafrost because GCMs are not designed to replicate variations in temperature for individual years. Some regional details in changes in the extent of permafrost cannot be captured as a result of the relatively coarse resolution of GCMs (usually ≥0.9° × 1.3°). An accurate estimation of the historical changes in permafrost is therefore required to compare or validate the results from GCMs. Research on historical changes in permafrost is useful in uncovering the response of permafrost to climate change and could help to advance our understanding of the future behavior of permafrost. For example, it has been shown that air temperatures in permafrost regions experienced a temporary increase during the 1930s and the 1940s (Guo, Li, & Hua, 2017). A study of the response of permafrost to this temporary increase in air temperatures would help our understanding of the range of increase in air temperatures required to cause the thawing of permafrost.

This study investigated historical changes in the extent of permafrost and the active layer thickness from 1901 to 2010 using the latest version of the Community Land Model (CLM4.5) driven by a set of new, high-resolution Climate Research Unit National Centers for Environmental Prediction (CRUNCEP) data set at a simulation resolution of 0.5° × 0.5°. The simulated results were validated based on observations of changes in soil temperatures and the active layer thickness and present-day extent of permafrost. In section 2, a description of the data, model, experimental design, and methods is provided. In section 3, the studied results with regard to validation of model, change in permafrost areas, and change in active layer thickness are presented. Discussions on potential sources of possible bias in the results are given in section 4, followed by conclusions of this study in section 5.

2. Data, Model, Experimental Design, and Methods

2.1. Data

CRUNCEP is a new, high-resolution atmospheric forcing data set (Viovy, 2011) combining the Climate Research Unit (CRU) TS3.2 monthly climatology with a resolution of 0.5° × 0.5° (Mitchell & Jones, 2005; Sun, 2017) and the National Centers for Environmental Prediction (NCEP) six-hourly reanalysis data with a resolution of 2.5° × 2.5° (Fan, Xie, & Xu, 2016; Gao, 2017; Kalnay et al., 1996). The CRUNCEP data set includes air temperature, precipitation, pressure, wind, specific humidity, downward short-wave radiation, and downward long-wave radiation. The data have a spatial resolution of 0.5° × 0.5° and a temporal resolution of 6 h over the time period of 1901–2010. Currently, there are five versions of CRUNCEP, version 4, that were used in this study. The data set has been used to drive the CLM for research on vegetation growth and evapotranspiration (Mao et al., 2013; Shi et al., 2013).

Daily soil temperature data from Russian meteorological stations were used to validate the simulated soil temperature (http://meteo.ru/english/climate/soil.php). The soil temperature was measured at depths of 0.02, 0.05, 0.1, 0.15, 0.2, 0.4, 0.6, 0.8, 1.2, 1.6, 2.4, and 3.2 m. The data at the depth of interest of 1 m were calculated using simple linear interpolation between known values. The data cover the period from 1963.
to 2011, although the observation period varied between stations and some stations covered a shorter observation period. Only data from 1981 to 2009 were used in this study because the majority of stations had continuous data available for this period. Strict quality control was performed in creating the data so it is considered to be reliable.

Yearly active layer thickness observations were obtained from the Circumpolar Active Layer Monitoring network (Brown, Hinkel, & Nelson, 2000). These data cover the period of 1990–2015, but not all stations had records for the entire period. The data from 1996 to 2007 were used because most of the stations had continuous data during this period. These observations are available from http://www.gwu.edu/~calm/ and have previously been used to validate the results of climate models (Guo & Wang, 2016b; Koven et al., 2013; Lawrence et al., 2012).

The observations of the extent of permafrost used to validate the simulated present-day permafrost distribution were obtained from the Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997). The data are available at http://nsidc.org/data/docs/fgdc/ggd318_map_circumarctic/index.html at a resolution of 0.5° × 0.5°. These data classify permafrost into continuous, discontinuous, isolated, and sporadic. However, it is argued that only continuous and discontinuous permafrost can be identified by climate models as a result of their coarse resolution (Burn & Nelson, 2006). Therefore, only these two types of permafrost were used for comparison with the simulated results. However, if the resolution of a climate model is sufficiently high, then other types of permafrost may be identified.

2.2. Model

The model used in this study was the latest version of the CLM, CLM4.5 (Oleson et al., 2013), which is an update of CLM4.0. A series of modifications has been performed in the CLM since version 3.0 to eliminate deficiencies in the simulation. The modifications relevant to permafrost simulation include an explicit treatment of soil freezing and thawing processes. The thawing begins when soil temperature is above 0°C and soil ice content is above 0, while the freezing begins when the soil temperature is below 0°C and soil liquid water content is above the maximum unfrozen water content. An expression for freezing point depression was used to calculate the maximum unfrozen water content to allow liquid water to coexist with ice over a wide range of soil temperatures below 0°C (Niu & Yang, 2006). The thermal and hydraulic properties of soil organic matter are represented to decrease the warm bias in the simulated soil temperature (Nicosky et al., 2007). The soil has been extended to approximately 50 m depth, with a total of 15 layers, to account for thermal inertia from the cold, deep permafrost layers (Alexeev et al., 2007). The cold region hydrology process was improved from CLM4.0 to CLM4.5 for moderately dry near-surface organic soils (Swenson et al., 2012). These modifications have greatly improved the accuracy of frozen ground simulations and have made CLM4.5 one of the most sophisticated models for simulating the dynamics of permafrost (Koven et al., 2013; Lawrence et al., 2008; Lawrence et al., 2011).

2.3. Experimental Design

Six atmospheric forcing variables (air temperature, precipitation, pressure, wind, specific humidity, and downward short-wave radiation) required by the model as input data were obtained from the CRUNCEP data set. A global simulation was carried out with the CLMCRUNCEP chosen as the DATM (Data Atmosphere). The output of the model was set with a spatial resolution of 0.5° × 0.5° and a temporal resolution of 24 h. The simulation was initiated by cyclically running the model for 100 years with CRUNCEP data in 1979. The final model state was saved and taken as the initial conditions; the model was then cyclically run for 5 years with CRUNCEP data in 1901. The interannual change in soil temperature was <0.003°C at all soil levels when the initiation process ended, indicating that the model reached a steady state. The final state of initialization run was taken as the new initial conditions; the transient simulation was conducted for the period of 1901–2010.

2.4. Methods

Permafrost was defined as the ground where the monthly soil temperature in at least one soil layer in the upper 10 layers (3.8 m) remains below 0°C for 24 consecutive months (Lawrence et al., 2012). According to this definition, permafrost in this study refers to “near-surface permafrost.” The active layer thickness was calculated as the maximum depth of thaw for permafrost over the course of a year using daily soil temperature data (Lawrence et al., 2008).
The model validation was based on a comparison between the simulated grid-mean results and individual site observations. A scale mismatch was therefore present in this validation, which may contribute to the bias between the simulations and observations. In spite of this, our comparison was based on the average of observations across all sites as the regional mean. This may moderate some of the effect of the scale mismatch on the validation.

The correlation coefficient and the Nash-Sutcliffe efficiency (NSE) were used to quantitatively assess the level of agreement between the simulations and observations (Nash & Sutcliffe, 1970). The NSE is calculated as follows:

\[
\text{NSE} = \frac{\sum_{i=1}^{T} (Q_{\text{obs}} - Q_{\text{sim}})^2}{\sum_{i=1}^{T} (Q_{\text{obs}} - \bar{Q}_{\text{obs}})^2}
\]

where \(Q_{\text{obs}}\) represents observations, \(Q_{\text{sim}}\) represents simulations, and \(T\) represents the total samples. NSE is a normalized index that indicates how closely the plot of the simulated and observed results fits the 1:1 line. It has a range of \(-\infty\) to 1; the simulated results are more accurate when the NSE is closer to 1 and the value 1 implies a perfect agreement of the simulated results with the observations.

The linear trend was the slope of the linear regression calculated by the least squares fitting method with a MATLAB function. The statistical significance of the trend was assessed by Student’s t test.

Based on the different geographical characteristics controlling the formation of permafrost, permafrost can be classified into high-latitude and high-elevation permafrost subregions (Cheng & Wang, 1982). This study used the Tibetan Plateau to represent high-elevation permafrost region because typical and major high-elevation permafrost is distributed on the Tibetan Plateau. However, permafrost in some higher-latitude mountainous regions (e.g., the Alps) is also considered to be high-elevation permafrost. Given the great concern of permafrost-rich countries about the fate of their own permafrost as a result of local effects of thaw of permafrost, we classified the permafrost regions into four subregions with respect to the countries with large areas of permafrost: Russia, Canada, Alaska, and China.

### 3. Results

#### 3.1. Validation of Model

The model reasonably captured the observed interannual change in soil temperature and active layer thickness (Figure 1). The change in the simulated soil temperature was in close agreement with observations at a depth of 1 m, with a correlation coefficient of 0.90 and an NSE of 0.78. The trend in the simulated soil temperature was 0.48°C decade\(^{-1}\), which is close to, but slightly larger than, the trend of 0.45°C decade\(^{-1}\) in the observations. The simulated change in the active layer thickness also fits well with the observed values, with a correlation coefficient and an NSE of 0.73 and 0.21, respectively. The simulated trend was close to, but smaller than, the observed trend.

The simulated present-day (mean from 1981 to 2000) permafrost distribution largely corresponds to the observed distribution (Figure 1c). The discrepancies between the simulated and observed distribution of permafrost were mainly located on the eastern Tibetan Plateau. Permafrost in the eastern Tibetan Plateau cannot be fully identified in accordance with our definition of near-surface permafrost in the upper 3.8 m of soil as a result of the deep active layer thickness in this region. The simulated area of permafrost was 17.26 × 10^6 km\(^2\), which compares reasonably with the observed area of 15.24 × 10^6 km\(^2\) with a bias of 2.02 × 10^6 km\(^2\). For different permafrost subregions, the simulated area of permafrost were 16.3 (high latitude), 0.97 (high elevation), 8.77 (Russia), 4.42 (Canada), 1.05 (Alaska), and 1.24 (China) × 10^6 km\(^2\), which are comparable with the observed area of 14.34 (high latitude), 0.90 (high elevation), 8.20 (Russia), 4.02 (Canada), 1.06 (Alaska), and 1.05 (China) × 10^6 km\(^2\), with biases of 1.96 (high latitude), 0.07 (high elevation), 0.57 (Russia), 0.40 (Canada), −0.01 (Alaska), and 0.19 (China) × 10^6 km\(^2\).

#### 3.2. Change in Permafrost Areas

Permafrost in different regions of the Northern Hemisphere has experienced a statistically significant decrease in area from 1901 to 2009 (Figure 2). Over the entire permafrost region, the area of permafrost decreased by 0.06 × 10^6 km\(^2\) decade\(^{-1}\) from 1901 to 2009. The decrease was more significant for the period
of 1979–2009, with a trend of $-0.62 \times 10^6$ km$^2$ decade$^{-1}$. Permafrost subregions also uniformly showed a decrease in area from 1901 to 2009 and a more significant decrease from 1979 to 2009 (Figures 2b–2g).

There was a clear decrease in the extent of permafrost in response to increasing air temperatures over the entire permafrost region from the 1930s to the 1940s (Figure 2a). For the subregions of permafrost, high-latitude and high-elevation permafrost and permafrost in Canada and China showed a clear response to increasing air temperatures from the 1930s to the 1940s (Figures 2b–2g). Permafrost in Alaska appears to present a lagging response to increasing air temperatures, whereas permafrost in Russia does not show a clear response to increasing air temperatures. These results confirm that permafrost responds to increasing air temperatures, even if these persist for a relatively short period of time, except for the permafrost in Russia.

From a spatial perspective, permafrost decreased the most in the northern part of the Western Siberian Plain in Russia, the southern edge of the permafrost in Canada, and the northwestern Tibetan Plateau during the period of 2001–2010 relative to the 1900s (Figure 3a). A slight increase in the extent of permafrost was seen in northeastern China (Figure 3a). Although the changes were smaller, the places where either increases or decreases in permafrost occurred from 1935 to 1945 relative to the 1900s correspond well with those from 2001 to 2010 relative to the 1900s (Figure 3b). This indicates that these regions are likely to be the most sensitive to climate change. The decreases in permafrost during the periods 2001–2010 and 1935–1945 relative to the 1900s are caused by increasing local air temperature in each month of 24 consecutive months used to identify permafrost (not shown). The increase in permafrost are caused by increasing local summer precipitation rather than air temperature that show increase in all 24 consecutive months except for August (1935s–1900s) (Figures 4a and 4b). The increasing summer precipitation infiltrate into soil to result in an increase in soil liquid water (Figures 4c and 4d). The more liquid water produces a cool summer soil column because of its large thermal capacities (Figures 4e and 4f), which causes the increase in permafrost.

Comparisons of the rate of thawing of permafrost between different subregions showed that high-elevation permafrost thaws faster than high-latitude permafrost. Permafrost in China showed the fastest rate of thaw, followed by permafrost in Alaska, Russia, and Canada (Figure 5a). These differences are consistent with the predictions of Guo and Wang (2016a). The trends in the percentage decrease in area of permafrost in different regions had a statistically significantly positive correlation (correlation coefficient 0.93, exceeding the
significance level of 95%) with the sensitivity of permafrost in their own region to increasing air temperatures, but had a statistically significantly negative correlation (correlation coefficient 0.83, exceeding the significance level of 95%) with the rate of increase in air temperature in their own region (Figures 5b and 5c). This indicates that differences in the speed of thawing among different subregions are related to the sensitivity of permafrost in these areas to changes in air temperatures rather than to the amplitude of the change in air temperatures.

The sensitivity of permafrost to changes in air temperatures in different subregions are also related to their thermal conditions. Permafrost is defined as occurring when the soil temperature remains below 0°C for 24 consecutive months. In other words, as areas of permafrost warm and exceed 0°C, they can no longer be defined as permafrost. Given this definition, warmer permafrost more easily exceeds 0°C and becomes nonpermafrost than colder permafrost if temperature increases the same degree for both warmer and colder permafrost. This indicates that warm permafrost has a larger sensitivity to changes in air temperature than colder permafrost. According to the European Centre for Medium-Range Weather Forecasts Reanalysis Interim (ERA-Interim) data set (Dee et al., 2011), high-elevation permafrost is 6.77°C warmer than high-latitude permafrost. Permafrost in China (−2.39°C) is the warmest, followed by permafrost in Alaska (−6.54°C), Russia (−8.61°C), and Canada (−10.30°C). This corresponds to the speed of thawing of permafrost in these subregions.
3.3. Change in Active Layer Thickness

The active layer thickness over the entire permafrost region showed a statistically significantly increasing trend from 1901 to 2009 at a rate of 0.009 m decade−1. The rate of increase intensified from 1979 to 2010 with a rate of 0.071 m decade−1 (Figure 6). A response to increasing air temperatures from about the 1930s to the 1940s can also be clearly seen in the change in the active layer thickness (Figure 6). The linear changes in the active layer thickness in permafrost subregions were similar to those over the entire permafrost region, except for Alaska, where the active layer thickness did not show a clear response to increasing air temperatures from about the 1930s to the 1940s (Figure 6).

Figure 3. Changes in areal extent of permafrost in (a) the 2000s relative to the 1900s and (b) in the decade from 1935 to 1945 (1935s) relative to the 1900s. Four countries and the Tibetan Plateau (TP), consisting mostly of permafrost, are outlined by gray dashed lines.

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Figure 4. Differences in (a and b) air temperature (°C) (red), precipitation (mm day−1) (blue), (c and d) soil liquid water (kg m−2), and (e and f) soil temperature (°C) between the period 1935–1945 (1935s) and 1900s (Figures 4a, 4c, and 4e) and between the 2000s and 1900s (Figures 4b, 4d, and 4f), as averaged over the grid cells with increasing permafrost. The x axis represents the 24 consecutive months used to identify permafrost.
From a spatial perspective, the majority of permafrost regions showed a significantly positive trend in active layer thickness during the period of 1901–2009. However, there were some regions where negative trends appeared, such as northwestern Canada, the northern edge of Greenland, and the northern part of the Siberian, Russia (Figure 7). Although the trends in active layer thickness during the period of 1979–2009 were distinctly larger, their spatial patterns were similar to those during the period of 1901–2009. Overall, the trends in active layer thickness decreased with increasing latitude, which is consistent with the future change in active layer thickness in the 2°C warming scenario reported by Guo and Wang (2016b).

4. Discussion

Biases in permafrost simulations are generally related to unrealistic representations of the physics of frozen ground in the models, low accuracy in the atmospheric data, and coarse resolution in the simulation. The CLM has undergone a series of improvements with respect to the process relevant to frozen ground, including the incorporation of soil organic matter, deepening of the soil layer, and corrections to the cold region hydrology scheme (Oleson et al., 2013). These improvements have enhanced the ability of the CLM to simulate frozen ground (Lawrence et al., 2012). A new higher-resolution atmospheric data set, CRUNCEP, has been developed as input data for land surface models (Viovy, 2011). CRUNCEP data and a simulation resolution of 0.5° × 0.5° were used in the latest version of the CLM (CLM4.5) to obtain a reliable estimate of historical changes in permafrost in the Northern Hemisphere. Longer-term series (29 years for soil temperature and 12 years for the active layer thickness) of the observed changes in permafrost were used to validate the simulated results rather than climatology observations that were generally used for validation in the papers with respect to simulation of frozen ground (e.g., Lawrence et al., 2012). The simulated results fitted well to observations, indicating that the simulated results are reasonable.

There was a relatively larger bias in the distribution of permafrost in the eastern Tibetan Plateau. This bias can be partially attributed to our definition of near-surface permafrost in the upper 3.8 m of soil. Using this definition, some of the permafrost cannot be identified because the thickness of the active layer (the permafrost table) is greater than 3.8 m in some permafrost regions of the Tibetan Plateau (Wu, Zhang, & Liu, 2010; Zhao et al., 2010). The simulated distribution of permafrost on the eastern Tibetan Plateau was closer to the observed distribution when the permafrost in deeper 4.7 m soil layers was considered (not shown). Surface data in the model may contribute to this bias to some extent. In our previous studies based on CLM4.0, a band with an unchanging active layer thickness was encountered as a result of bias in the soil organic matter content. The disappearance of the band in this study indicates an improvement in the data for soil organic matter. However, Han et al. (2015) and Gao, Shi, and Giorgi (2016) suggested that the vegetation cover within the CLM has some bias in the Tibetan Plateau, which may affect the transfer of water and heat into the soil and may further contribute to uncertainties in this simulation.
An absence of excess ground ice in this model may be a source of uncertainty in this simulation. Previous studies have argued that the inclusion of excess ground ice may delay the speed of thawing of permafrost (Burn & Nelson, 2006). Lee et al. (2014) have shown that the inclusion of excess ice can delay the thawing of permafrost at 3 m depth by approximately 10 years in most regions with a high excess of ground ice. Excess ground ice has not been accounted for in the version of the CLM used in this study, and this contributes to the possible uncertainties in the simulation. The presence of excess ground ice can facilitate the prediction of thermal settlement hazard by this model—a hazard that seriously threatens the stabilization of engineering facilities underlain by permafrost and is caused by the degradation of permafrost (Guo & Wang, 2016b). It is therefore expected that excess ground ice will be incorporated into the next version of the CLM.

5. Conclusions

The dynamics of permafrost in the Northern Hemisphere were investigated using CLM4.5 driven by CRUNCEP data at a simulation resolution of 0.5° × 0.5°. Changes in the observed soil temperature and active layer thickness and the present-day extent of permafrost were captured well by this simulation, indicating that the simulated results are reasonable.

The area of permafrost decreased by 0.06 (0.62) × 10^6 km² decade\(^{-1}\) and the active layer thickness increased by 0.009 (0.071) m decade\(^{-1}\) during the period 1901–2009 (1979–2009). A clear decrease in the area of permafrost and an increase in the active layer thickness were found in response to increasing air temperatures from about the 1930s to the 1940s, indicating that permafrost is sensitive to even short-term warming of the Earth’s climate.

High-elevation permafrost thaws faster than high-latitude permafrost. Permafrost in China had the fastest rate of thawing, followed by Alaska, Russia, and Canada. These regional differences in the rate of thawing are closely correlated to the sensitivity of permafrost in these regions to increases in air temperature, which is related to local thermal conditions.

These results provide an insight into the historical dynamics of permafrost in the Northern Hemisphere. They will be useful for understanding the response of permafrost to climate warming and can be used to validate the corresponding results from GCMs. The use of CLM4.5, the CRUNCEP data set, and a relatively high resolution are conducive to this simulation. Possible uncertainties in this study may be related to less accurate surface data and an absence of excess ground ice in the model. Previous simulations of permafrost have concentrated on the prediction of the future degradation of permafrost based on GCMs (Anisimov & Nelson, 1996; Guo & Wang, 2016a; Koven et al., 2013; Lawrence et al., 2012; Stendel & Christensen, 2002;
Zhang et al., 2008). This study focused on the historical dynamics of permafrost based on a surface land model and atmospheric data. Future work is planned to examine the evolution of permafrost between typical historical cold and warm periods.

Acknowledgments
This research was jointly supported by the External Cooperation Program of BIC, the Chinese Academy of Sciences (134111KYSB20150016), the National Key R&D Program of China (2016YFA0600704), and the National Natural Science Foundation of China (41775076 and 41405087). We thank the National Snow and Ice Data Center (Boulder, CO, USA), which provided the Circum-Arctic Map of Permafrost and Ground-Ice Conditions (https://nsidc.org/data/docs/fgdc/ggd318_map_circumarctic/index.html).

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