Past and Projected Freezing/Thawing Indices in the Northern Hemisphere

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ABSTRACT

Freezing/thawing indices are useful for assessments of climate change, surface and subsurface hydrology, energy balance, moisture balance, carbon exchange, ecosystem diversity and productivity. Current freezing/thawing indices are inadequate to meet these requirements. We use 16 Coupled Model Intercomparison Project phase 5 (CMIP5) models available for 1850–2005, three representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5) during 2006–2100, and Climatic Research Unit gridded observations for 1901–2014, to assess the performance of freezing/thawing indices derived from CMIP5 models during 1901–2005. We also analyzed past spatial patterns of freezing/thawing indices and projected these over three RCPs. Results show that CMIP5 models can reproduce the spatial pattern of freezing/thawing indices in the Northern Hemisphere but that the thawing index slightly underestimated observations and the freezing index slightly overestimated them. The thawing index agreed slightly better with observations than did the freezing index. There is significant spatial variability in the freezing/thawing indices, ranging from 0° to 10 000°C day. Over the entire Northern Hemisphere, the time series of the area-averaged thawing index derived from CMIP5 output increased significantly at about 1.14°C day yr^{−1} during 1850–2005, 1.51°C day yr^{−1} for RCP2.6, 5.32°C day yr^{−1} for RCP4.5, and 13.85°C day yr^{−1} for RCP8.5 during 2006–2100. The area-averaged freezing index decreased significantly at −1.39°C day yr^{−1} during 1850–2004, −1.2°C day yr^{−1} for RCP2.6, −4.3°C day yr^{−1} for RCP4.5, and −9.8°C day yr^{−1} for RCP8.5 during 2006–2100. The greatest decreases in the freezing index are projected to occur at high latitudes and high altitudes, where the magnitude of the decreasing rate of the freezing index is far greater than that of the increasing rate of the thawing index.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) reported that the global mean air temperature (combined ocean and land surface) has warmed by 0.85°C during 1880–2012 (IPCC 2013). Considering only land surface air temperature change, temperatures have increased by 0.75°C during 1906–2005, which corresponds to the fast rise of anthropogenic greenhouse gas concentrations in the atmosphere (Wang et al. 2011; Chen and Frauenfeld 2014a; Devaraju et al. 2015; Betts et al. 2016). Relative to the global mean temperature, the rate and magnitude of temperature rise were much greater at high latitudes (Symon et al. 2004; Screen and Simmonds 2010) and in

high-altitude regions (Pepin et al. 2015; Guo and Wang 2016; Wang et al. 2016).

Permafrost regions and regions with seasonally frozen ground occupy about 24.91×10^6 km² (25.6%) and 48.12×10^6 km² (50.5%) of the exposed land surface in the Northern Hemisphere, respectively (Zhang et al. 2003). Climate change has meant greater warming at high-latitude and high-altitude regions that have frozen ground. Influenced by a warming climate, permafrost warming and thawing (Romanovsky and Osterkamp 1995; Romanovsky et al. 2010; Smith et al. 2010; Wu and Zhang 2010; Wu et al. 2015, 2016; Zhao et al. 2010), active layer thickness deepening (Zhang et al. 2005; Shiklomanov et al. 2012; Luo et al. 2016), and reducing soil freezing depth (Frauenfeld et al. 2004; Frauenfeld and Zhang 2011; Streletskiy et al. 2015) will affect these regions.

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Although much work has been done on permafrost responses to a warming climate, most studies have been done using observational datasets from sites that cannot fully represent the changes of frozen ground. Further, a warming climate is spatially heterogeneous such that site-scale research has difficulty demonstrating spatial variability of frozen ground at a region scale. In such cases, freezing/thawing indices can be widely used on frozen ground to contribute to mapping and predicting permafrost distribution (Nelson and Outcalt 1987), estimating soil freezing depth (Peng et al. 2016), and computing active layer thickness (Nelson et al. 1997; Zhang et al. 2005; Park et al. 2016).

A number of freezing/thawing-index studies have been conducted. Luo et al. (2014) reported that the multiyear average thawing index ranged between 1902.7° and 2990.1°C day and that the freezing index ranged between 1729.5° and 3606.1°C day in northeastern China as based on 21 observational sites. Jiang et al. (2008, 2015) found that there was a significant increasing trend of thawing at a rate of 19.83°–45.6°C day (10 yr)^{−1} at the Qinghai-Xizang Railway during 1966–2004 and an obvious upward trend of thawing in the Tianshan Mountains of China. Wu et al. (2011) reported that the annual surface freezing index generally increases but that no significant trends were detected during 1987–2005 at 20 sites in Mongolia. Frauenfeld et al. (2007) used reanalysis datasets to assess the freezing/thawing indices in different regions; for example, in the Arctic (the area north of 50°N), the long-term mean thawing index is 1387°C day when based on the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) as compared with 1232°C day from CRU and 1220°C day from the climatologically aided interpolation (CAI) dataset. This suggests that the ERA-40 dataset has a warm bias. To summarize previous studies, most focus on the point scale and do not represent the spatial heterogeneity of climate change (e.g., latitude and altitude). Most also have not considered the evolution of past freezing/thawing indices using CMIP5 output. Last, few studies have used projected freezing/thawing indices in the Northern Hemisphere. These unfulfilled tasks are important for evaluating past and projecting future climate change, permafrost distribution, soil freezing depth, and active layer thickness at the hemispheric scale. Therefore, the scientific questions and motivations of this study are completely different from previous studies.

In this study, we investigate freezing/thawing indices for the Northern Hemisphere derived from 16 general circulation models (GCM) from CMIP5 output, available during 1850–2100, and a CRU dataset for 1901–2014.

The research question focuses on spatiotemporal changes of freezing/thawing indices over the Northern Hemisphere and divides into three parts: First, how well will freezing/thawing indices derived from CMIP5 output compare to one computed from the CRU dataset? Second, what is the temporal (past and future) and spatial pattern of freezing/thawing indices? Third, how did freezing/thawing indices change in the past and what is the projected pattern of freezing/thawing indices in the Northern Hemisphere?

2. Data and methods

a. CRU surface air temperature

The CRU TS3.23 time series observational dataset of surface air temperature used in this study was developed by the University of East Anglia (<http://www.cru.uea.ac.uk/data>). It comprises monthly grids of observed climate data for 1901–2014 with spatial resolution 0.5° × 0.5°. We use the CRU air temperature data to compute freezing/thawing indices and as the observational dataset to evaluate the CMIP5 dataset.

b. CMIP5 surface air temperature

We used output from 16 CMIP5 models developed by internationally recognized research institutes that had already released their CMIP5 outputs (<https://esgf-node.llnl.gov/projects/esgf-llnl/>; Joetzer et al. 2013). Detailed information for each model is shown in Table 1. These models' datasets are from different institutions and countries, with different spatial resolutions, but are from the same period (1850–2100). The CMIP5 models' outputs include four experiments, one historical experiment covering 1850–2005 and three future emission scenarios from 2006 to 2100. The three future scenarios are representative concentration pathways (RCP) developed for the IPCC AR5 (RCP2.6, RCP4.5, and RCP8.5). Different forcings were used in these four experiments. RCP8.5 is characterized by a radiative forcing pathway at 8.5 W m^{−2} in 2100, RCP4.5 uses 4.5 W m^{−2} in 2100, and RCP2.6 reaches 2.6 W m^{−2} in 2100. The historical forcing experiment was the observational atmospheric composition change (Taylor et al. 2012). To convert CMIP5 model datasets to the same resolution, we re-gridded all CMIP5 models' output to a 0.5° × 0.5° resolution by using a bilinear interpolation method (Wang and Chen 2014; Chen and Frauenfeld 2014b). Here the monthly CMIP5 outputs are used in this study for two reasons. First, the monthly CRU datasets are used to evaluate the freezing/thawing indices derived from CMIP5 outputs. To match CRU, the monthly CMIP5 outputs are used in this study. Second, use of daily

TABLE 1. Information about the CMIP5 climate models that were used in this study.

Model	Institution and country	Spatial resolution
CCSM4	National Center for Atmospheric Research; United States	192×288
CanESM2	Canadian Centre for Climate Modeling and Analysis; Canada	64×128
FIO-ESM	The First Institute of Oceanography; China	64×128
GISS-E2-H	NASA Goddard Institute for Space Studies; United States	90×144
GISS-E2-R	NASA Goddard Institute for Space Studies; United States	90×144
IPSL-CM5A-LR	Institute Pierre Simon Laplace; France	96×96
IPSL-CM5A-MR	Institute Pierre Simon Laplace; France	143×144
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology; Japan	64×128
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies; Japan	64×128
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology; Japan	128×256
MPI-ESM-LR	Max Planck Institute for Meteorology; Germany	96×192
MPI-ESM-MR	Max Planck Institute for Meteorology; Germany	96×192
MRI-CGCM3	Meteorological Research Institute; Japan	160×320
NorESM1-M	Norwegian Climate Centre; Norway	96×144
BCC_CSM1.1(m)	Beijing Climate Center, China Meteorological Administration; China	160×320
BCC_CSM1.1	Beijing Climate Center, China Meteorological Administration; China	64×128

CMIP5 outputs to calculate the freezing/thawing indices would require a daily observational dataset to evaluate them. However, the coarse spatial resolution of CMIP5 outputs limits using the observational daily dataset from the meteorological stations for evaluation. There are uncertainties in using a single-point dataset to evaluate a $0.5^\circ \times 0.5^\circ$ gridcell area extent.

c. Freezing/thawing-index estimation

Frauenfeld et al. (2007) have described the methods for calculating the freezing/thawing indices. Among the various methods of computing a freezing (thawing) index, the approach of summing all temperatures below (above) 0°C during the freezing (thawing) periods is suitable and plausible (Wu et al. 2011; Luo et al. 2014). We define the freezing period to be from July to June of the following year to sum the freezing index during a continuous cold season. The thawing period is defined as from 1 January to 31 December (Wu et al. 2011; Peng et al. 2016). We derived the freezing/thawing indices from the CRU dataset and CMIP5 model outputs. Annual freezing (thawing) index values at each 0.5° grid cell were calculated as follows: when the mean monthly air temperature (MMAT) was below (above) 0°C , we multiplied MMAT by the number of days within that month and then summed the monthly freezing (thawing) index values over the calendar year. The annual freezing/thawing index based on monthly data is thus

$$\text{FI} = \sum_i^{N_F} |T_i| \times D_i, \quad T_i < 0^\circ\text{C}, \quad \text{and} \quad (1)$$

$$\text{TI} = \sum_i^{N_T} T_i \times D_i, \quad T_i > 0^\circ\text{C}, \quad (2)$$

where T_i is the mean air temperature for the month, D_i is the number of days in that month, the freezing period is $i = 1, 2, \dots, N_F$, and the thawing period is $i = 1, 2, \dots, N_T$.

d. Analysis method

To quantify the agreement of freezing/thawing indices derived from CMIP5 model outputs and from the CRU dataset, basic statistical methods and error analysis are employed, including the mean, the number of cases N , the intercept and slope of the least squares regression between simulated and observed, mean error (ME), mean absolute error (MAE), root-mean-square error (RMSE), standard deviation of the error (SDE), and Pearson correlation coefficient R . The correlation coefficient is a statistical index able to detect relationships among variables. RMSE is frequently used as a measure of the differences between values predicted by a model and observations, and it is recognized as a good measure of the accuracy of simulated results (Willmott 1982). To calculate the whole domain-averaged freezing/thawing indices, all of the cells of the Northern Hemisphere boundary were included. We used a linear regression and a test of statistical significance at the 95% confidence level to understand the trends of past and projected freezing/thawing indices in the Northern Hemisphere.

To analyze the spatial distribution of historical freezing/thawing-indices changes, we computed the 30-yr mean freezing/thawing indices derived from the CRU dataset and historical CMIP5 data during 1971–2000.

TABLE 2. Evaluation of thawing index derived from CMIP5 models relative to CRU dataset by mean, number of cases, slope and intercept of the least squares regression, mean error, mean absolute error, root-mean-square error, and standard deviation of the error; Here N is the number of years of the dataset (1901–2005).

Model	Mean (°C day)	N	Slope	Intercept	ME (°C day)	MAE (°C day)	RMSE (°C day)	SDE (°C day)	R
CRU	3767.5	105	—	—	—	—	—	—	—
CCSM4	3771.8	105	1.11	−406.3	4.3	42.8	57.1	35.8	0.80
CanESM2	3956.9	105	1.03	85.4	189.4	189.4	196.4	201.5	0.80
FIO-ESM	3738.4	105	0.87	453.4	−29.1	53.1	65.5	38.5	0.72
GISS-E2-H	3895.2	105	0.67	1375.6	127.7	127.7	135.4	141.0	0.76
GISS-E2-R	3893.9	105	0.71	1219.9	126.4	126.8	134.4	139.7	0.76
IPSL-CM5A-LR	3438.5	105	1.08	−618.4	−328.9	328.9	333.5	321.3	0.80
IPSL-CM5A-MR	3571.1	105	0.23	2695.0	−196.3	196.3	206.9	189.9	0.38
MIROC-ESM-CHEM	3939.2	105	0.68	1362.0	171.7	171.7	178.0	184.0	0.75
MIROC-ESM	3946.9	105	0.75	1110.5	179.4	179.4	185.6	191.6	0.76
MIROC5	4117.6	105	0.68	1558.6	350.1	350.1	355.7	360.9	0.62
MPI-ESM-LR	3695.8	105	1.02	−138.3	−71.7	83.7	96.5	70.5	0.73
MPI-ESM-MR	3736.3	105	1.11	−446.1	−31.1	55.7	66.4	39.6	0.79
MRI-CGCM3	3620.8	105	0.56	1527.7	−146.7	147.0	156.5	141.3	0.64
NorESM1-M	3513.2	105	0.76	661.8	−254.2	254.2	258.7	247.1	0.76
BCC_CSM1.1(m)	3773.6	105	1.12	−459.3	6.1	46.5	57.0	36.5	0.81
BCC_CSM1.1	3520.8	105	1.11	−678.9	−246.7	246.7	251.2	239.6	0.85
Ensemble	3758.1	105	0.84	581.5	−9.4	27.0	34.3	33.0	0.88

We also analyzed their changes with latitude and longitude on the basis of four profiles. Spatial differences in the freezing/thawing indices derived from CRU and CMIP5 output can clarify their spatial evaluation. We also estimated their historical spatial trends during 1901–2005.

To project freezing/thawing-indices changes in the twenty-first century, we first computed the spatial distribution of freezing/thawing indices during 2006–2100 in three RCP experiments. Second, we derived the time series of area-averaged freezing/thawing indices and their spatial patterns during 2006–2100 in three RCP experiments. Last, we computed the trends in individual CMIP5 output.

3. Results

a. Evaluation of the freezing/thawing indices

There is generally good agreement for the thawing index between the CMIP5 and CRU datasets (Table 2). The thawing indices derived from CRU and CMIP5 were not statistically different (the Pearson correlation coefficient was between 0.38 and 0.85), with an RMSE between 57.0° and 355.7°C day. The slopes of the thawing index for almost one-half of the models are around 1, with large variability in the intercept. Mean error values for the thawing index indicate that it is underestimated by seven models and overestimated by nine models relative to the CRU thawing index. For both the MAE and SDE, the largest value is for MIROC5 and the smallest value is for CCSM4. For the average ensemble of the 16 CMIP5 models, the ME shows that the thawing index

is underestimated. The MAE, RMSE, and SDE of the ensemble CMIP5 models are all smaller than those of the individual models. Furthermore, the correlation coefficient is 0.88. Thus, the thawing index from the average ensemble CMIP5 models is in good agreement with the CRU thawing index.

There was generally good agreement of the freezing index between each CMIP5 model and the CRU dataset (Table 3). The freezing index derived from CMIP5 output correlated with the freezing index derived from the CRU dataset at Pearson correlation coefficients between 0.13 and 0.65, with an RMSE between 82.7° and 278.6°C day, and the slope for all models is less than 1. The ME of the average ensemble freezing index is only 27.2°C day, which means it is overestimated relative to the CRU dataset. The correlation coefficient is 0.70, which is higher than that for each of the individual CMIP5 models. These results indicate that the average ensemble freezing index is in good agreement with the freezing index derived from the CRU dataset.

Although the evaluation results of the freezing/thawing indices show good agreement, the indices do underestimate and overestimate the CRU dataset, respectively. The thawing index derived from CMIP5 output is in slightly better agreement with CRU than is the freezing index.

b. Historical freezing/thawing indices

1) CLIMATOLOGY OF THE THAWING INDEX

The thawing index derived from CRU dataset shows that it ranges from 0° to more than 10 000°C day (Fig. 1a).

TABLE 3. As in Table 2, but for freezing index.

Model	Mean ($^{\circ}\text{C day}$)	N	Slope	Intercept	ME ($^{\circ}\text{C day}$)	MAE ($^{\circ}\text{C day}$)	RMSE ($^{\circ}\text{C day}$)	SDE ($^{\circ}\text{C day}$)	R
CRU	2009.3	105	—	—	—	—	—	—	—
CCSM4	2175.6	105	0.7	732.3	166.3	173.9	196.6	150.8	0.48
CanESM2	1997.8	105	0.6	803.8	−11.5	64.6	82.9	69.9	0.52
FIO-ESM	1958.0	105	0.7	623.0	−51.3	73.9	94.7	97.8	0.57
GISS-E2-H	1988.4	105	0.8	366.5	−20.9	68.0	82.7	75.6	0.63
GISS-E2-R	2060.3	105	0.6	790.5	51.0	75.6	94.1	62.9	0.56
IPSL-CM5A-LR	2137.1	105	0.5	1076.8	127.7	134.3	153.1	116.2	0.48
IPSL-CM5A-MR	1973.5	105	0.1	1790.8	−35.9	78.6	96.3	85.9	0.13
MIROC-ESM-CHEM	1739.2	105	0.6	593.3	−270.2	270.2	278.6	303.0	0.60
MIROC-ESM	1704.8	105	0.5	623.2	−304.5	304.5	315.0	336.8	0.50
MIROC5	2099.2	105	0.5	1010.5	89.9	102.2	125.1	85.6	0.47
MPI-ESM-LR	2082.3	105	0.8	491.0	72.9	92.7	113.2	74.0	0.59
MPI-ESM-MR	2005.2	105	0.8	319.1	−4.2	65.8	82.8	66.2	0.63
MRI-CGCM3	2259.1	105	0.4	1429.0	249.8	249.8	265.3	230.0	0.39
NorESM1-M	2225.7	105	0.6	1069.6	216.4	217.3	235.5	197.9	0.46
BCC_CSM1.1(m)	2033.4	105	0.9	259.6	24.1	82.1	105.8	58.3	0.56
BCC_CSM1.1	2145.5	105	1.1	−7.6	136.2	145.1	168.1	123.5	0.65
Ensemble	2036.6	105	0.6	748.3	27.2	49.8	64.3	58.3	0.70

The smallest appears on the Greenland Ice Sheet, almost 0°C day , and the largest is in the tropical regions at more than 8000°C day . Around the Arctic Ocean and Tibetan Plateau regions, it is less than 1000°C day . In Siberia and Alaska, it is less than 2000°C day . In North America, most areas are less than 7000°C day , except in Mexico. In Europe, it varies, falling to less than 6000°C day and even to less than 1000°C day in northern Europe. In Asia, it varies from 1000° to more than $10\,000^{\circ}\text{C day}$ because of the vast span of latitude and altitude. Overall, as latitude and altitude increase, the thawing index clearly decreases. Similar spatial patterns in the thawing index also occur in the ensemble average CMIP5

models (Fig. 1b). The spatial difference of thawing index between historical CRU and CMIP5 data (Fig. 1c) shows that most regions have positive values. This suggests that the thawing index derived from ensemble-averaged CMIP5 is underestimated. However, there are also some negative values in the Tibetan Plateau, Mongolian Plateau, and near the equatorial zone, meaning that the thawing index is overestimated in these regions.

The thawing index derived from both the CRU dataset and the ensemble-averaged CMIP5 output shows dramatic changes along different longitudinal and latitudinal gradients in the Northern Hemisphere (Fig. 2). The

FIG. 1. Spatial distribution of 30-yr mean thawing index across the Northern Hemisphere: (a) calculated from the CRU dataset for 1971–2000, (b) mean ensemble of 16 CMIP5 models in the historical experiment for 1971–2000, and (c) its difference between CRU and CMIP5 for 1971–2000.

FIG. 2. Thirty-year mean thawing-index variability in different sections: (a) 30°N profile, (b) 65°N profile, (c) 85°W profile, and (d) 95°E profile. The magenta symbols represent thawing index derived from CRU for 1971–2000, and the green symbols are from CMIP5 for 1971–2000.

thawing indices measured by CRU or CMIP5 are similar in the same profile. Along the 30°N transect (Fig. 2a), the thawing index was greater in areas of 115°–82°W (North America) and 10°W–80°E (North Africa and the Indian peninsula). This latter spatial pattern is followed by a sharp decrease as a result of its location adjacent to the Tibetan Plateau, followed again by a strong increase. The overall section of the 65°N transect (Fig. 2b) indicates some patterns of variability, including up and down changes. In the 85°W transect, there is a decline in variability of the thawing index from low to high latitude (Fig. 2c) in North America. Along the 95°E transect (Fig. 2d), the thawing index initially declines, then it increases, followed again by a decrease. This transect directly follows thawing-index variation from low-latitude regions, through the high-altitude Tibetan Plateau, ending in the high-latitude Siberian regions in the Eastern Hemisphere.

2) CLIMATOLOGY OF THE FREEZING INDEX

Spatial freezing-index patterns from the historical ensemble CMIP5 dataset are similar to that of the CRU data during 1971–2000 (Figs. 3a,b), but there are notable differences (Fig. 3c). The freezing indices with the lowest values are largely located in low-latitude and low-altitude

regions. A freezing index of less than 1000°C day occupies most of the area, mainly located south of 45°N, except for the Tibetan Plateau. The highest value occurs on the Greenland Ice Sheet, with greater than 5000°C day. Overall, the freezing index has a positive relationship with latitude and altitude. The negative bias is mainly located in the Tibetan Plateau and western Siberia, while positive bias occurs in other regions. This indicates that the ensemble-averaged CMIP5 output was overestimating the freezing index in the Tibetan Plateau but underestimating it in most high-latitude regions.

The freezing index derived from both the CRU dataset and the ensemble-averaged CMIP5 output shows dramatic changes along different longitudinal and latitudinal gradients in the Northern Hemisphere (Fig. 4). The 30°N transect (Fig. 4a) shows that the freezing index is mostly zero except between 80° and 100°E for the high-altitude regions. The 65°N transect (Fig. 4b) indicates some variability, including up and down changes that result from the profile going through the west mountains in the North America and then to the plateau of eastern Europe, central Siberia, and eastern Siberia. Figure 4c shows continuous increasing changes from south to north in the 85°W transect, which mainly reflects

FIG. 3. As in Fig. 1, but for freezing index.

the character of the freezing index in North America. The 95°E transect shows complicated variability in the freezing index because of the profile through the Tibetan Plateau, Mongolian Plateau, and high-latitude regions.

Four freezing/thawing-indices transects showed opposing patterns, and opposing spatial patterns of

freezing/thawing indices occurred due to latitude and altitude.

3) SPATIAL TREND OF FREEZING/THAWING INDICES

To analyze the long-term changes of thawing index, we estimated the spatial patterns of 1901–2005 thawing-index

FIG. 4. As in Fig. 2, but for freezing index.

FIG. 5. Spatial variability of trends in the Northern Hemisphere for the (top) thawing and (bottom) freezing index for (a),(d) the index based on the CRU dataset for 1901–2005, (b),(e) the index from the mean ensemble of 16 CMIP5 models in the historical experiments for 1901–2005, and (c),(f) the trend difference between CRU and the CMIP5 ensemble dataset for 1901–2005. The stippled regions indicate statistically significant trends (95% level).

trends (Figs. 5a–c). The analysis showed a statistically significant increasing trend in most grids. Exceptions included some located on the Greenland ice sheet and other minor areas that were not statistically significant (Figs. 5a,b). The trends for thawing index range from less than 0° to $10^{\circ}\text{C day yr}^{-1}$. It is clear that the trend is largely between 2° and $4^{\circ}\text{C day yr}^{-1}$ in most grids. The trend in the spatial distribution is between 0° and $1^{\circ}\text{C day yr}^{-1}$ in northern North America (including Alaska), Siberia, and the Tibetan Plateau. In other regions, the trend is more than $1^{\circ}\text{C day yr}^{-1}$, reaching greater than $3^{\circ}\text{C day yr}^{-1}$ in some regions. The difference in thawing-index trend is near zero in most regions and is negative in some lower-latitude regions (Fig. 5c).

The freezing index measured from the CRU dataset (Fig. 5d) shows a statistically significant decreasing trend in most areas north of 30°N . It is not statically significant south of 30°N , with a rate of approximately zero. The decline rate mainly ranges between -10° and $-1^{\circ}\text{C day yr}^{-1}$.

There is a similar spatial pattern for the freezing index evident from the historical CMIP5 dataset (Fig. 5e). There is a relatively higher rate of decline of the freezing index located in the Tibetan Plateau and north of 55°N , especially north of 66.5°N at less than $-4^{\circ}\text{C day yr}^{-1}$. The freezing-index trend difference is almost around zero, and some high-latitude regions have positive values (Fig. 5f).

Therefore, statistically significant increasing and decreasing trends were the main historical patterns in the thawing and freezing indices, respectively.

c. Projections of freezing/thawing indices for the twenty-first century

1) SPATIAL VARIATIONS OF FREEZING/THAWING INDICES

The spatial pattern of the 30-yr (2071–2100) climatology of thawing index, derived from the ensemble-averaged

FIG. 6. Spatial distribution of 30-yr mean (top) thawing index across the Northern Hemisphere in the future during 2071–2100 and (bottom) thawing-index difference for 2071–2100 relative to the historical period of 1971–2000 calculated from the (a),(d) RCP2.6, (b),(e) RCP4.5, and (c),(f) RCP8.5 experiments.

CMIP5 output for the three RCPs (Figs. 6a–c), demonstrates that the spatial patterns in three RCP experiments are similar to those calculated from historical data. Relative to the historical thawing index, these RCP experiments show an increased trend but at a different magnitude. There is a generally large spatial heterogeneity in thawing-index values, most likely due to the latitude and altitude. A substantial difference between the three RCP experiments during 2071–2100 and the historical experiment during 1971–2000 (Figs. 6d–f) is evident. Positive differences were found in all regions in the Northern Hemisphere, indicating a greater thawing index in the future for all RCP experiments. Greater differences are found at lower latitude and altitude and with higher forcing levels from RCP2.6 to RCP8.5. Taking the Tibetan Plateau as an example, it differs between 100° and 200°C day between RCP2.6 and the historical experiment, it ranges from 300° to 400°C day in RCP4.5, and is greatest in RCP8.5, being

between 500° and 800°C day. These differences demonstrate that thawing index is increasing.

The spatial patterns of freezing index in three RCP experiments across the Northern Hemisphere are similar to that in the historical period (Figs. 7a–c). However, differences are evident among three the RCP experiments relative to the historical experiment. The freezing index decreases from the historical experiment to the RCP2.6, RCP4.5, and RCP8.5 experiments. The Tibetan Plateau once more gives an example: the freezing index is usually greater than 3000°C day in the historical experiment, but the areal extent of values of the freezing index of greater than 3000°C day declines in RCP2.6. The freezing index ranges largely between 2000° and 3000°C day in RCP4.5 and is less than 2000°C day in RCP8.5.

Negative differences of the freezing index between the historical experiment and the three RCP experiments are found in most regions except south of 30°N as a result of the

FIG. 7. As in Fig. 6, but for freezing index (2070–99) and freezing-index difference (2070–99 relative to 1971–2000).

freezing index south of 30°N being about zero (Figs. 7d–f). Further, a relatively smaller value of freezing-index differences occurs at high-altitude and high-latitude regions, such as the Tibetan Plateau and north of 60°N.

2) PROJECTED TRENDS IN FREEZING/THAWING INDICES

The spatial pattern of thawing-index trends derived from ensemble average CMIP5 output in RCP2.6, RCP4.5, and RCP8.5 is similar to that in the historical experiment. The main difference is the increasing rate. In RCP2.6 (Fig. 8a), the rate of change is greater than 1°C day^{yr}^{−1} in most grids; it is greater than 4°C day^{yr}^{−1} in most grids in RCP4.5 (Fig. 8b) and is greater than 7°C day^{yr}^{−1} in most grids in RCP8.5, sometimes even exceeding 20°C day^{yr}^{−1} (Fig. 8c). The rate of increases of thawing index in the high-latitude and high-altitude regions are relatively less than in other regions.

The spatial pattern of freezing-index trends derived from CMIP5 output in RCP2.6, RCP4.5, and RCP8.5 is

similar to those in the historical experiment. In RCP2.6 (Fig. 8d), the rate of change is more than −1°C day^{yr}^{−1} for most areas; it is more than −4°C day^{yr}^{−1} for most areas in RCP4.5 (Fig. 8e) and is more than −10°C day^{yr}^{−1} for most areas in RCP8.5, sometimes even being more than −20°C day^{yr}^{−1} (Fig. 8f). In these three RCP experiments, taking the high-altitude Tibetan Plateau and high-latitude Alaska as examples, the declining rate of freezing index is greater than for the other regions.

Figure 9 shows the time series of area-averaged freezing/thawing-index anomalies in the Northern Hemisphere from the CRU dataset and from CMIP5 output in the historical, RCP2.6, RCP4.5, and RCP8.5 experiments. There is a statistically significant increase of about 1.14°C day^{yr}^{−1} during 1850–2005 from the historical experiment and about 1.98°C day^{yr}^{−1} during 1901–2014 from the CRU dataset. The RCP8.5 scenario exhibits the largest increase of 13.85°C day^{yr}^{−1} for 2006–2100. The RCP4.5 and RCP2.6 scenarios

FIG. 8. Spatial variability of trends in three RCP experiments across the Northern Hemisphere for (top) thawing and (bottom) freezing index in (a),(d) RCP2.6, (b),(e) RCP4.5, and (c),(f) RCP8.5. The stippled regions indicate statistically significant trends (95% level).

show a relatively smaller positive trend, at a rate of $5.32^{\circ}\text{C day yr}^{-1}$ and $1.51^{\circ}\text{C day yr}^{-1}$, respectively, over the same period (Fig. 9).

There is a statistically significant declining trend of freezing index derived from CRU and CMIP5 output in the three historical RCP experiments (Fig. 10). The rate of area-averaged freezing index derived from the CRU dataset is $-1.83^{\circ}\text{C day yr}^{-1}$ during 1901–2013. The ensemble area-averaged freezing index decreased at a rate of $-1.39^{\circ}\text{C day yr}^{-1}$ during 1850–2004. In the other three RCP experiments, the rate of ensemble area-averaged freezing-index decline is $-1.20^{\circ}\text{C day yr}^{-1}$ in RCP2.6, $-4.3^{\circ}\text{C day yr}^{-1}$ in RCP4.5, and $-9.8^{\circ}\text{C day yr}^{-1}$ in RCP8.5 during 2006–99.

3) FREEZING/THAWING-INDICES TREND IN INDIVIDUAL MODELS

The area-averaged freezing/thawing-index trends show substantial differences among the 16 models

(Figs. 11 and 12). The thawing-index trends of the 16 models show virtually the same significant increasing pattern for the historical experiment and also for the three future scenarios. Two exceptions are the FIO-ESM and GISS-E2-R in RCP2.6. The freezing-index trends of the 16 models show virtually the same significant declining pattern for the historical experiment and also for the three future scenarios.

4. Discussion

a. Comparisons with previous research

Previous studies have focused on long-term variation and trends in freezing/thawing indices at point and regional scales. For example, at the point scale, most studies use observational air temperature data from meteorological stations to calculate freezing/thawing indices and analyze variability (Jiang et al. 2008,

FIG. 9. Time series of thawing index in the Northern Hemisphere from the CRU dataset (green line), the CMIP5 historical experiment (black line), and projected from different CMIP5 experiments during 1850–2100 for RCP2.6 (yellow line), RCP4.5 (blue line), and RCP8.5 (red line).

2015; Wu et al. 2011; Luo et al. 2014). At the regional scale, reanalysis of air temperature datasets has also been used to compute freezing/thawing indices (Frauenfeld et al. 2007; Peng et al. 2016). Frauenfeld et al. (2007) reported basic differences in freezing/thawing indices derived from daily or monthly air temperature, but that trends can be basic consistent with each other. Building on the work of previous studies, the comprehensive evaluation of freezing/thawing indices derived from CMIP5 output indicates good agreement with that derived from the CRU dataset. Not only is this the case using long-term freezing/thawing indices measured from CRU during 1901–2014, and CMIP5 output during 1850–2005, but our work also projects the long-term freezing/thawing indices at three forcing levels during 2006–2100. Therefore, our study comprehensively improves on previous freezing/thawing indices.

b. Climate indicators

In the past, temperature has been the most popular and common indicator of climate change. The IPCC AR5 has reported, on the basis of temperature records, that the climate is warming. Spatial heterogeneity of climate warming has also been demonstrated, however. High-latitude regions are experiencing faster warming, as indicated by a pattern known as Arctic amplification (Serreze and Barry 2011). In high-altitude regions, the Mountain Research Initiative EDW (Elevation Dependent Warming) Working Group (in 2015) also reported that there was an amplifying effect. Thus, high-mountain environments have experienced a more rapid rise in temperature than have lower-elevation

FIG. 10. As in Fig. 9, but for freezing index.

regions (Guo et al. 2016). In this study, the spatial pattern of freezing-index differences between three RCP experiments and the historical experiment display a remarkable consistency in high-latitude and high-altitude regions, with greater declines. The spatial pattern of the freezing-index trend derived from CRU and CMIP5 also exhibits a faster decreasing trend in high-latitude and high-altitude regions. Although the thawing-index spatial pattern difference and trend in these regions are not larger than in other regions, the magnitudes of the difference and trend are far less than in the freezing index. Thus, given a greater freezing-index decline and smaller thawing-index increase in high-latitude and high-altitude regions when compared with other regions, we can clearly project greater warming in high-latitude and high-altitude regions. Except for the amplifications referred to earlier, an increasing thawing index and decreasing freezing index can also indicate a warming climate in the Northern Hemisphere. Therefore, freezing/thawing indices can be good climate indicators for use in future climate change research.

c. Application of freezing/thawing indices in frozen ground

Freezing/thawing indices are two of the most important parameters in cold-region engineering (Daniel et al. 2018) and environmental research because of their sensitivity and wide application. Their main application is to map the distribution of permafrost and seasonally frozen ground, estimate soil freezing depth, and measure active layer thickness. Nelson and Outcalt (1987) have developed a surface freezing-index model to map permafrost distribution:

$$F = \frac{\sqrt{FI}}{\sqrt{FI} + \sqrt{TI}} \quad (3)$$

FIG. 11. Trends in regional-average thawing index across the Northern Hemisphere from different CMIP5 experiments during 1850–2100: historical (1850–2005) (black bar), RCP2.6 (2006–2100) (yellow bar), RCP4.5 (2006–2100) (blue bar), and RCP8.5 (2006–2100) (red bar).

A value of 0.5 for the ratio F is the boundary between continuous and discontinuous permafrost. The ratio of 0.5 is only for a ground-surface freezing index for the snow-cover insulation effect in the freezing period. The advantage of this model is that it needs few parameters and does not require surface information such as vegetation, soil texture, and so on. It has been widely used to investigate permafrost distribution (Nan et al. 2012; Guo et al. 2016).

Another application is to estimate the soil freezing depth and active layer thickness. The Stefan solution to compute the soil freezing depth and active layer thickness, which is based on freezing/thawing indices, is a widely used method in frozen-ground research. Previous studies have largely focused on basin or regional scales and decadal past time scales (Nelson et al. 1997; Shiklomanov and Nelson 1999, 2002; Zhang et al. 2005; Park et al. 2016; Peng et al. 2016). Our current, past, and projected freezing/thawing-indices products have been developed and are useful for estimating

soil freezing depth and active layer thickness in the Northern Hemisphere for 1850–2100.

d. Implications of freezing/thawing indices on plant growth

Plant growth, which is one part of terrestrial ecosystems, plays a significant role in the energy balance, hydrological process, carbon cycle, and thermal and water transfer (Piao et al. 2003; Godínez-Alvarez et al. 2009). Vegetation has a carbon sequestration effect that will regulate the carbon balance and reduce greenhouse gases (Piao et al. 2003; Hu et al. 2010). Variability in vegetation growth has been reported regionally and at continental scales and has potential drivers (Zhu et al. 2016). Some studies have also reported that plant growth changes in high-latitude and high-altitude regions as a result of permafrost degradation. Examples are shrub expansion in the Arctic tundra ecosystem (Tape et al. 2006; Lawrence and Swenson 2011; Elmendorf et al. 2012) and greening in the Tibetan Plateau (Zhang et al. 2013).

FIG. 12. As in Fig. 11, but for freezing index.

Potential impact factors are air temperature and precipitation, which are the most important for vegetation growth. However, plant growth depends upon the magnitude of temperature and long-time exposures to certain temperatures. That is precisely what the freezing/thawing indices measure and is why the indices are important in a cold environment, especially as sensitive indicators of permafrost status (Guo et al. 2016). Plant growth is argued to be a greening response to changes in land cover type as measured by an increasing thawing-index trend and decreasing freezing-index trend. An increasing thawing index and declining freezing index can indicate more energy for vegetation growth. Thus, variability in freezing/thawing can have a significant impact on plant growth. It should also be noted that plant growth may itself contribute to freezing/thawing variability through impacts on surface albedo and the sensible heat flux (Foley et al. 1994; Levis et al. 2000; He et al. 2014).

5. Summary and conclusions

This study investigated past freezing/thawing indices in the Northern Hemisphere using an observational CRU dataset and a CMIP5 historical experiment. The indices projected future changes using CMIP5 output in three RCP experiments. In the Northern Hemisphere, the freezing/thawing indices derived from CMIP5 output are in good agreement with results from the CRU dataset. However, thawing and freezing indices slightly under- and overestimated observations. The thawing index is in slightly better agreement with observations than is the freezing index.

The spatial pattern of freezing/thawing indices computed from CMIP5 output can accurately reproduce the spatial pattern in the Northern Hemisphere. However, uncertainties in CMIP5 models are still evident. The thawing index derived from CMIP5 output is underestimated in most regions, but overestimated in the Tibetan Plateau, Mongolian Plateau, and near the equatorial zone. The freezing index estimated from CMIP5 output is overestimated in the Tibetan Plateau but is underestimated in most high-latitude regions.

In the Northern Hemisphere, the climatological range of the thawing index is from 0° to greater than 10 000°C day, and the freezing index ranges from 0° to more than 10 000°C day. Among the three RCP experiments, the thawing index increased with higher forcing levels, inversely to the freezing index. The spatial pattern of freezing/thawing-indices variability is dominated by latitude and altitude.

Combined with the freezing/thawing indices derived from CRU and ensemble-averaged CMIP5 output, there is an increasing trend in thawing index and a decreasing

trend in freezing index in the Northern Hemisphere. The greatest decrease in the freezing index occurs in high-latitude and high-altitude regions, with a relatively smaller increase of thawing index in these regions. However, the magnitude of decreasing rate in the freezing index is far greater than the increasing rate of thawing index.

Time series of ensemble area-averaged freezing/thawing indices show that there is a generally increasing trend in thawing index and decline in freezing index across the Northern Hemisphere. By the end of the twenty-first century, the thawing index will significantly increase by 143.5°–1315.8°C day and the freezing index will significantly decrease by from −114° to −931°C day. The 16 individual CMIP models largely capture the freezing/thawing-indices trend, with the exception of the FIO-ESM and GISS-E2-R models.

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