Potential impacts of climate extremes on snow under global warming conditions in the Mongolian Plateau

Chunlan Li, Xinwu Xu, Hongyu Du, Debin Du, Walter Leal Filho, Jun Wang, Gang Bao, Xiaowen Ji, Shan Yin Yuhai Bao and Hossein Azadi

(Author affiliations can be found at the end of the article)

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Abstract

Purpose – The paper aims to investigate the possible changes in mean temperature in the Mongolian Plateau associated with the 1.5 and 2°C global warming targets and how snow changes in the Mongolian Plateau when the mean global warming is well below 2°C or limited to 1.5°C.

Design/methodology/approach – In total, 30 model simulations of consecutive temperature and precipitation days from Coupled Model Inter-comparison Project Phase 5 (CMIP5) are assessed in comparison with the 111 meteorological monitoring stations from 1961–2005. Multi-model ensemble and model relative error were used to evaluate the performance of CMIP5 models. Slope and the Mann–Kendall test were used to analyze the magnitude of the trends and evaluate the significance of trends of snow depth (SD) from 1981 to 2014 in the Mongolian Plateau.

Findings – Some models perform well, even better than the majority (80%) of the models over the Mongolian Plateau, particularly HadGEM2-CC, CMCC-CM, BNU-ESM and GFDL-ESM2M, which simulate best in consecutive dry days (CDD), consecutive wet days (CWD), cold spell duration indicator (CSDI) and warm spell duration indicator (WSDI), respectively. Emphasis zones of WSDI on SD were deeply analysed in the 1.5 and 2 °C global warming period above pre-industrial conditions, because it alone has a significant negative relation with SD among the four indices. It is warmer than before in the Mongolian Plateau, particularly in the southern part of the Mongolian Plateau, indicating less SD.

Originality/value – Providing climate extremes and SD data sets with different spatial-temporal scales over the Mongolian Plateau. Zoning SD potential risk areas and proposing adaptations to promote regional sustainable development.

Keywords Adaptation, Impacts, 1.5°C and 2°C global warming above pre-industrial conditions, Consecutive temperature and precipitation days, Mongolian Plateau

Paper type Research paper

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported over the past decades that most land areas of the world have experienced climate extremes, such as fewer cold days/nights (and frost days) and more hot days/nights (and heat waves) in terms of temperature extremes, and a larger proportion of annual total rainfall over most areas due to heavy precipitation events in terms of precipitation extremes (Klein Tank *et al.*, 2009). Moreover, scientists are virtually certain (99%) that there will be more hot days and fewer cold days by the end of the 21st century, and it is very likely (90% certain) that there will be longer or more intense heat waves (or both) (IPCC, 2014). Climate extremes and the resultant impacts have been occurring in every corner of the globe, such as North America, Central America, South America, Europe, the Mediterranean region, Africa, Asia and Australia/New Zealand (Seneviratne *et al.*, 2012), which have already caused considerable devastating impacts as well as severe societal losses across the globe.

The IPCC Fifth Assessment report points out that the cryosphere is a natural integrator of climate variability and provides some of the most visible signatures of climate change. As the key component of the cryosphere, snow plays a fundamental role in global climate due to its high albedo and cooling effect (Qin *et al.*, 2018). In addition, the change of snow caused by regional climate change would have serious consequences for the economic development and fragile ecosystem in arid areas. As one of the predominate grassland ecosystems within the "Belt and Road" region (NRSCC, 2017), the rangeland in the Mongolian Plateau (MP) represents nearly 515 million acres (203 million ha), which account for 12% of the rangeland area across the Asian continent (Angerer *et al.*, 2008). Herding provides the primary source of income in this region and relies on the natural resources from grassland (Miao *et al.*, 2015), which are affected mainly by snow change. Therefore, snow changes under the context of climate extremes have a significant effect on economic development and residents' lives.

Among others, the social impacts of climate extremes are those that directly affect residents' physical and emotional well-being, including health effects, water and food scarcity, and impacts on livelihoods that can lead to displacement. The differential effects on residents are a critical aspect of the social nature of climate change, a phenomenon that has only recently entered the climate change discourse. Literature increasingly demonstrates that climate change disproportionately impacts individuals and groups that have scarce resources or are socially isolated (Winchester and Szalachman, 2009). In particular, severe weather events can severely damage a wide range of assets on which residents depend to preserve their livelihoods, including natural resources, health, infrastructure and financial capital (Carleton and Hsiang, 2016).

To avoid suffering from more severe climate extremes and to reduce the risks and impact of climate change, the Paris Climate Agreement proposed a goal to limit the mean global surface temperature. Stemming from the Paris Agreement, there is a concerted effort within the international community to limit the increase in the average global temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. But, what are the possible changes of mean temperature in the MP associated with the 1.5 and 2°C global warming targets? What does this mean for snow change in the MP when the mean global warming is well below 2°C or limited to 1.5°C? There are still some questions that need to be answered. Moreover, for a given increment in mean global temperature, local climate impacts can vary from one region to another (Shi *et al.*, 2017), and therefore, the relevance for global-scale policy recommendations and mitigation strategies is not a helpful metric for impacts assessment and adaptation planning at the regional scales (Karmalkar and Raymond, 2017). Thus, adaptation strategies for regional climate extremes in the context of sustainable development should be made separately.

Recently, with the availability of the Coupled Model Inter-comparison Project Phase 5 (CMIP5) model output (Taylor *et al.*, 2012), which has the outputs of dozens of models' historical experiments and future projections under different Representative Concentration Pathways (RCPs), several studies have been investigating the current or future climate extremes (Sillmann *et al.*, 2013a, 2013b). These outputs provide a good opportunity to evaluate the capacity of coupled models to simulate extreme climate events in the MP, as well as project their future changes. There are a lot of models, but which one is suitable for climate extreme simulation and projection in MP? Thus, studying how these models perform in the MP and then finding the best model is a vital step. The impacts of climate extremes are not only related to their frequencies and/or intensities but are also associated with their continuous days, but most of them were focused on the frequency and/or intensity of extreme climate (Shi *et al.*, 2018). Compared with the occasional extremes, more than three days of consecutive temperature or precipitation extremes may cause more catastrophes, and even more serious threats to our daily life (Shi *et al.*, 2018). As such an important element of climatic extremes, the consecutiveness or continuousness of the extremes has been seldom studied, with no mention about combining the past with the future changes of climate extremes and analyzing their potential effects. Through a literature review, it was found that there has been some research on climate extremes in the MP (John *et al.*, 2013), but the previous problem remained, that few studies have focused on the consecutiveness or continuousness of climatic extremes changes, particularly in their potential effects. Numerous studies have demonstrated that recent and potential future increases in global temperatures are likely to affect the cryosphere (Smith and Bookhagen, 2018), but there are few studies from the perspective of extreme climate change. The average snow depth (SD) is not only an indicator of water resources but also a major indicator for comprehensive research on snow distribution. Therefore, it is essential to perform a systematic study on the duration of climate extremes and their potential effects on snow change in this region under the conditions of 1.5 and 2°C of global warming above pre-industrial conditions.

This paper is organized as follows. Section 2 describes the study area, and Section 3 explains the data and method. Section 4 provides the results and discussions, and Section 5 presents a concluding summary and a discussion on the uncertainties associated with the model.

2. Study area

The MP consists of Mongolia and Inner Mongolia, China (Li *et al.*, 2018). It is located in an arid to semiarid area in northeastern Asia and lies in the transition zone between the westerlies and the East Asian Monsoon, which cumulatively makes it climatically sensitive. In addition, due to its special geographic location and geomorphological features, the East Asian Inland Plateau is the region always threatened by most kinds of extreme events, such as drought, dzuds, and heavy snowfall (Miao *et al.*, 2015). In this area, low mountains are located in the east, while high mountains are distributed in the west, the Yinshan mountain ranges to the south and the Sayan and Hentiy mountain ranges to the north.

3. Data and method

3.1 Data

3.1.1 Model data. Consisting of a large variety of climate data, the CMIP5 model outputs can greatly benefit climate change studies (Wu *et al.*, 2017), with higher horizontal and vertical resolutions in comparison to the Coupled Model Inter-comparison Project Phase 3 (CMIP3). The coupled climate model outputs – such as climate indices and near-surface temperature – in this study are taken from the CMIP5 multiple model data archive, and more details on the models can be found on the CMIP5 website (http://cmip-pcmdi.llnl.gov/cmip5/availability.html).

Model data derive from RCP4.5 and RCP8.5 during 1850–2005, and they were selected from the 30 models because they are the top-priority emission scenarios for global modeling studies under the framework of the CMIP5 (Kim *et al.*, 2018). Although some models performed multiple runs starting from different initial conditions, the first realization (i.e. r1i1p1), as the first-order assessment, in these 30 models was used to treat all models equally, and the outputs of these 30 models are used in Table 1.

3.1.2 Observation data. The recorded daily maximum and minimum temperatures and precipitation data in 111 meteorological monitoring stations of the MP (43 in Inner Mongolia and 68 in Mongolia) from 1961–2014 were analyzed to verify the accuracy of the model simulation data, and thereby retaining the observation data of the longest period. Comparing the model data from 1850–2005 with the observation data from 1961–2014, the longest data set is 1961–2005. Thus, this study collected data from 1961–2005 for deep analysis. The observation data were used to calculate the consecutive indices of temperature and precipitation whose definition is from Li *et al.* (2018), and these indices were then used to validate the model data. When validating the model data against the observations, a regional mean value from 1961 to 2005 was calculated from the 111 sites, because extremes indices derived directly from these daily data at the stations are expected to preserve better performance without being subject to horizontal interpolation, so as to avoid secondary errors when compared to grids.

3.1.3 Snow depth data. SD data came from recent global reanalysis products, namely, the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 (https://climate.copernicus.eu/climate-reanalysis), and its older counterpart, the ERA-Interim, (hereafter ERA-I). The aforementioned analyses were chosen because they belong to the latest generation and have demonstrated strong validation with several network observations (Orsolini *et al.*, 2019). Comparing the SD from 1981–2019 with the climate extremes data from 1961–2014, the longest data set is 1981–2014. Therefore, the research time scale of SD and extreme indices should be consistent, with 1981–2014.

3.2 Method

3.2.1 Multi-model ensemble (MME) and model relative error. Some analyses found that a multi-model ensemble (MME) can nearly always outperform any individual model when simulating climate variables, because of its ability to enable point-wise averaging over the multi-model ensemble of simulations, which can offset deviations of single models and thus provide statistically superior estimates (Kim *et al.*, 2018). Thus, in this study, an MME was used to find out which periods had global mean warming of 1.5 and 2°C above pre-industrial conditions and to determine the mean temperature in the MP during these periods. There are two main ways to construct an MME, including unweighted averaging and weighted averaging. This research used unweighted averaging to create an MME of the CMIP5 models because it is the easiest way (Kim *et al.*, 2018). The bilinear interpolation method is applied to interpolate model outputs with different horizontal resolutions to a common grid ($1° \times 1°$) with the help of ArcGIS (Tian *et al.*, 2015).

Root-mean-square error (RMSE) analysis was shown to be a better method for evaluating the performance of CMIP5 models, not only on a global scale (Sillmann *et al.*, 2013a) but also on a regional scale. This paper also used RMSEs to evaluate the performance of CMIP5 models to simulate and project climate extremes in the MP, and then find the most suitable model (based on the evaluation results) in each index for further analysis. At first, the annual index data from 1961–2005 was calculated from both observation and modeling. Then the RMSE *(m,o)*) of each model was obtained, and its expression is as follows:

Model full name	Institution and country	Atmospheric resolution (lon × lat)
ACCESS1.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) – Bureau of Meteorology (BOM)/Australia	$1.875° \times 1.25°$
BNU-ESM	Global Change and Earth System Science (GCESS)/China	$\sim 2.8° \times 2.8°$
CanCM4	Canadian Center for Climate Modeling and Analysis/Canada	$0.75° \times \sim 0.75°$
CESM1-FASTCHEM	National Science Foundation, US Department of Energy and National Center for Atmospheric Research (USA)	$1.25° \times \sim 0.9°$
CMCC-CESM	Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC)/Italy	$3.75° \times \sim 3.7°$
CMCC-CM	Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC)/Italy	$0.75° \times \sim 0.75°$
CMCC-CMS	Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC)/Italy	$1.875° \times \sim 1.9°$
CNRM-CM5	Centre National de Recherches Météorologiques–Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (France)	$\sim 1.4° \times 1.4°$
CSIRO-Mk3-6–0	CSIRO in collaboration with the Queensland Climate Change Center of Excellence (Australia)	$1.875° \times \sim 1.9°$
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University (China)	$\sim 2.8° \times \sim 2.8°$
FGOALS-s2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University (China)	$\sim 2.8° \times \sim 2.8°$
GFDL-CM3	Geophysical Fluid Dynamics Laboratory (GFDL)/USA	$2.5° \times 2°$
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory (GFDL)/USA	$2.5° \times 2°$
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory (GFDL)/USA	$2.5° \times 2°$
HadCM3	Met Office Hadley Center (MOHC)/UK	3.75×2.5
HadGEM2-CC	Met Office Hadley Center (MOHC)/UK	$1.875° \times 1.25°$
HadGEM2-ES	Met Office Hadley Center (MOHC)/UK	$1.875° \times 1.25°$
INM-CM4.0	Institute of Numerical Mathematics (INM)/Russia	2×1.5
IPSL-CM5A-LR	Institute Pierre-Simon Laplace/France	$3.75° \times \sim 1.9°$
IPSL-CM5A-MR	Institute Pierre-Simon Laplace/France	$2.5° \times \sim 1.3°$
IPSL-CM5B-LR	Institute Pierre-Simon Laplace/France	$3.75° \times \sim 1.9°$
MIROC4h	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology (Japan)	$\sim 0.56° \times 0.56°$
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)	$\sim 1.4° \times 1.4°$
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)	$\sim 2.8° \times 2.8°$
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental Studies (Japan)	$\sim 2.8° \times 2.8°$
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)/Germany	$1.875° \times \sim 1.9°$
MPI-ESM-MR	Max Planck Institute for Meteorology (MPI-M)/Germany	$1.875° \times \sim 1.9°$
MPI-ESM-P	Max Planck Institute for Meteorology (MPI-M)/Germany	$1.875° \times \sim 1.9°$
MRI-CGCM3	Meteorological Research Institute/Japan	$1.125° \times \sim 1.1°$
NorESM1-M	Norwegian Climate Center (NCC)/Norway	$2.5° \times \sim 1.9°$

Table 1.
Basic information on the 30 coupled model intercomparison project Phase 5 global coupled climate models

$$RMSE_{(m,o)} = \sqrt{\langle (M - O)^2 \rangle} \tag{1}$$

where M is the model data, O is the corresponding observation data and the angular bracket denotes spatial averaging in the MP.

Third, the relative model error for each model ($RMSE'_{(m,o)}$) (Gleckler *et al.*, 2008) was derived based on the result from the second step.

$$RMSE'_{(m,o)} = \frac{RMSE_{(m,o)} - RMSE_{median}}{RMSEmedian} \tag{2}$$

where $RMSE_{median}$ is the median of $RMSE_{(m,o)}$ for the individual model. Negative $RMSE'_{(m,o)}$ indicates that the corresponding model performs better than the majority of the models.

3.2.2 Definition of the time to reaching 1.5 and 2°C global warming thresholds. The recent response in the Paris Agreement under the United Nations Framework Convention to the challenge of additional magnitudes of global warming provides a promising framework for global climate protection. Thus, it is necessary to understand fully what statements the Paris Agreement has made. According to the Paris Agreement, the thresholds of mean global warming of 1.5 and 2°C above pre-industrial conditions are relative to the climate change in the pre-industrial period; therefore, in this study, the years 1861–1900 are used as the quasi pre-industrial baseline to calculate the year when global warming would reach the 1.5 and 2°C targets under the various RCP pathways. In detail, first, 31-year time slices were used to smooth the time series of global mean temperatures. Second, the first year when the temperature exceeds 1.5 and 2°C above pre-industrial conditions for the individual GCMs was defined as the threshold year of global warming of 1.5 and 2°C above pre-industrial conditions. Third, two 15-year spans around the threshold year were chosen to compare with the reference period (1975–2005) to assess the changes in climate extremes and to exclude the interannual variability of temperature, making sure that this period is a relatively stable climate condition (Shi *et al.*, 2017).

For the choice of the model, this paper is different from previous studies. First, comparing the simulated data and observation data of different extreme indices, the best model of each variable was determined and then an MME for the optimal models was produced based on the first step. Subsequently, the average global warming threshold years of 1.5 and 2°C above pre-industrial conditions were calculated based on MME. In this way, it can not only eliminate the differences between the models that are inaccurate for research extreme indicators, but also reduce the noise and improve predictive capabilities in the future prediction period of mean global warming of 1.5 and 2°C above pre-industrial conditions. Moreover, the problems of uncertainty are mainly attributed to the model itself, avoiding secondary errors and thereby providing some reliable evaluation results.

4. Results and discussion

4.1 Assessment of Coupled Model Inter-comparison Project Phase 5 models' performance

$RMSE'_{(m,o)}$ values for all indices (rows) and all models (columns) relative to the station-based observation are shown in Figure 1. Before analysis, it is worth noticing that the colors characterize the magnitudes of the $RMSE'_{(m,o)}$ values: colder colors indicate models that perform better than others on the average level, and vice versa. Figure 1 summarizes the general performance of individual models based on the $RMSE'_{(m,o)}$ values, and it also shows that the simulation abilities of individual models vary widely, including different models simulating the same indicator, and the same model simulating different indicators. For CDD, the first three models performing relatively well are HadGEM2-CC, HadGEM2-ES and MRI-CGCM3. For CWD, CMCC-CM, CMCC-CMS and MPI-ESM-P, they appear to perform better than the others. BNU-ESM, CanCM4 and CMCC-CMS are the first three models that performed well when simulating CSDI. For WSDI, the best performing models are GFDL-ESM2M, GFDL-ESM2G and MIROC5. Overall, some of the models perform well, even better than the majority (80%) of models. This paper thereby selected only the best model for each index, i.e. the HadGEM2-CC, CMCC-CM, BNU-ESM and GFDL-ESM2M models simulating CDD, CWD, CSDI and WSDI work best, respectively, and are considered here as the best approximation of the ground truth.

In addition, the four models under RCP 4.5 and RCP 8.5 are used together to calculate the average global temperature in a fixed time window of 31 years to determine when the global mean temperature rises to 1.5 and 2.0°C thresholds above pre-industrial conditions. Two 15-year spans around the threshold year were chosen for this paper to find comparatively stable climate conditions.

4.2 Threshold surpassing times of 1.5 and 2.0°C global warming above pre-industrial conditions

It is a key scientific problem related to the trend of global climate change to estimate the changes of SD in the MP when the global temperature rises by 1.5 and 2.0°C above pre-industrial conditions, to quantitatively assess the response of snow change to climate warming and to respond expediently to the risks brought by its feedback effect.

The mean global air temperature anomalies relative to pre-industrial levels (1861–1900) and the surpassing year of 1.5 and 2°C global warming above pre-industrial conditions under RCP 4.5 and RCP 8.5 scenarios are shown in Figure 2. From Figure 2, it can be easily concluded that the temporal trend of mean global air temperature anomalies under both scenarios are similar, showing an apparent increase. However, the year reaching the 1.5 and 2°C threshold above pre-industrial conditions is largely different among models and RCPs. Under RCP4.5, the ensemble mean of the mean global temperature steadily surpasses 1.5 and 2°C warming after 2029 and 2049, respectively. Under the RCP 8.5 scenario, the ensemble mean of the mean global temperature steadily surpasses 1.5 and 2°C warming after 2025 and 2038, respectively. The time when the average surface temperature of the MP exceeded the threshold of 1.5 and 2°C was nearly ten years earlier than the global scale, indicating the sensitivity of climate change in the MP and the need to study the region.

4.3 Identifying regions at snow depth-risk based on climate extremes

4.3.1 Changes of snow depth in the Mongolian Plateau in the past. The depth of snow in the MP from 1981–2014 begins in September and lasts until May of the year with a maximum in

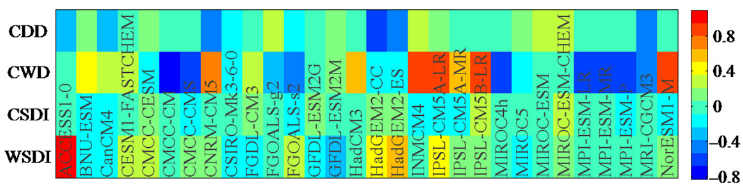

Figure 1. The 'portrait' diagram indicating relative $RMSE'_{(m,o)}$ values of the extreme climate indices simulated by the CMIP5 models concerning the station-based observation during the period of 1961–2005

January (Figure 3). SD decreased significantly during the study period, and in spring and autumn, it changes significantly with downward trends. In winter, it showed moderate changes with no significant change (Figure 4). The annual change trend of SD is consistent with Bi *et al.* (2020), who found SD in a decreasing trend during 1982–2015 by using data from SMMR, SMM/I, SSMIS and the observations.

Distributions of mean long-term annual SD indicated a strong latitudinal zonality (Figure 4). Generally, mean long-term annual SD increased with northward latitude in the MP, which was consistent with high elevation and the NDVI distribution. Spatial distributions of trend coefficients of mean annual SD in the MP showed that the most significant decreasing trends were observed in the southwest region, indicating that the decreasing rate was greater in other regions.

4.3.2 Snow depth risk area under the conditions of 1.5 and 2.0°C global warming. Only one model simulated SD among the four models, so this study did not directly use the results of the model simulation to analyze the future change of SD, but only indirectly

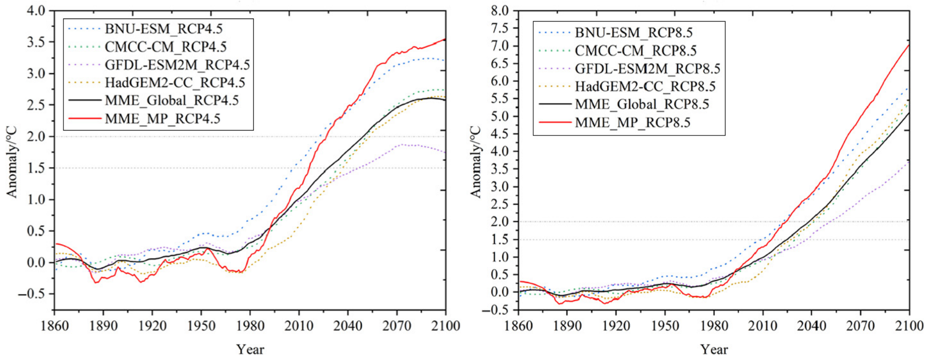

Figure 2.
Time series of 31-year-slipping-mean in annual mean global surface air temperature anomalies simulated from the individual model and MME under RCP4.5 and RCP8.5, the years when global anomalies of individual model and MME reached 1.5 and 2°C (the anomalies relative to 1861–1900)

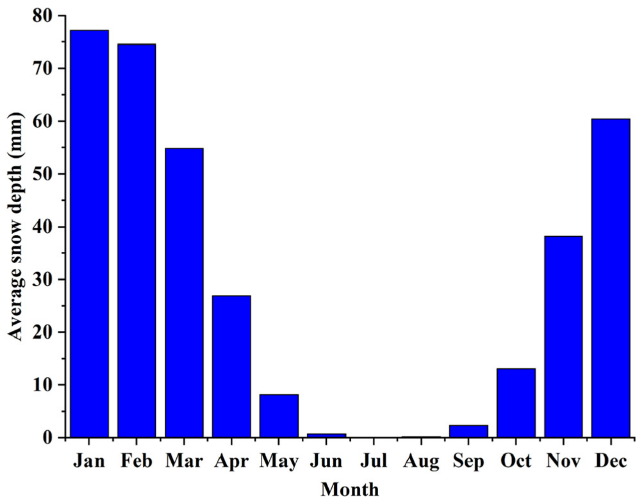

Figure 3.
Monthly SD in the MP from 1981–2014

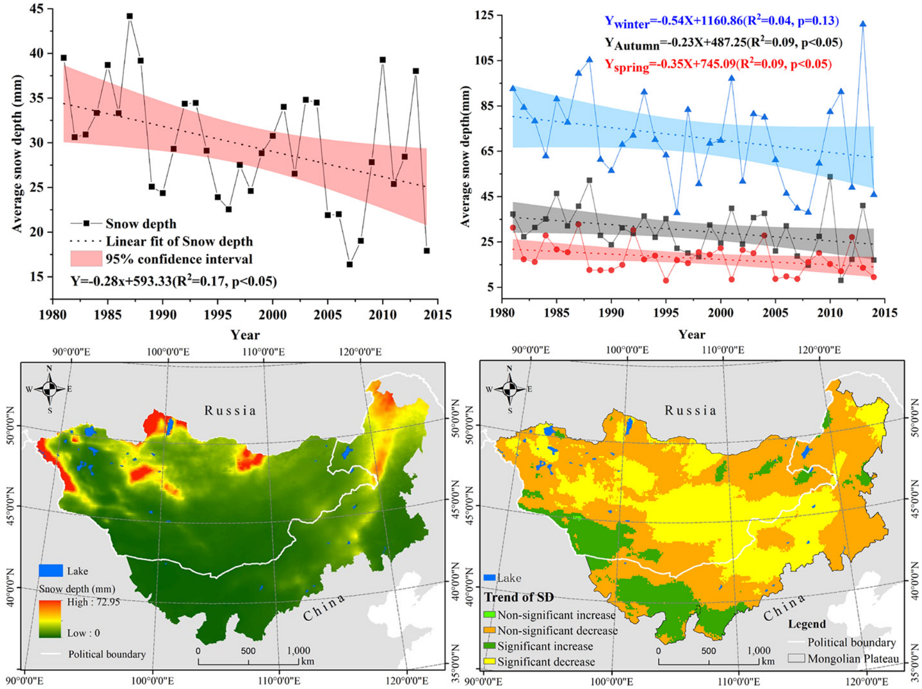

Figure 4.
SD changes in the MP from 1981–2014

analyzed the related extreme climate indicators (Table 2). Warmer air leads to a greater supply of moisture forming the air and decreases the SD. The above-mentioned factors and related uncertainties may explain the regional and temporal differences in mean long-term SD status. This cascade-like effect, in combination with consecutive temperature and precipitation days, will cause the decrease of snow to continue and to then affect vegetation growth, which can influence the economic development of the animal husbandry-dominated areas. However, specific contributions need to be further explored, which is not the focus of this study.

Compared to 1975–2005, WSDI in MP was larger at the 2°C level than at the 1.5°C level, in both RCP 4.5 and RCP 8.5. It indicates that it was warmer than before in the MP, particularly in the southern part of the MP. Based on the relationship between SD and WSDI (Table 2), under the conditions of 1.5 and 2.0°C global warming, SD in the northern part of the MP will increase, while decreasing in the southern region. It is easy to identify that the risk areas of SD in the MP under the conditions of 1.5 and 2.0°C global warming are the southern areas (Figure 5).

Table 2.
Relationship between SD and consecutive temperature and precipitation days

	CDD	CWD	CSDI	WSDI
SD	−0.204	0.238	0.123	−0.432*

Note: *Represents significance at 0.05 level

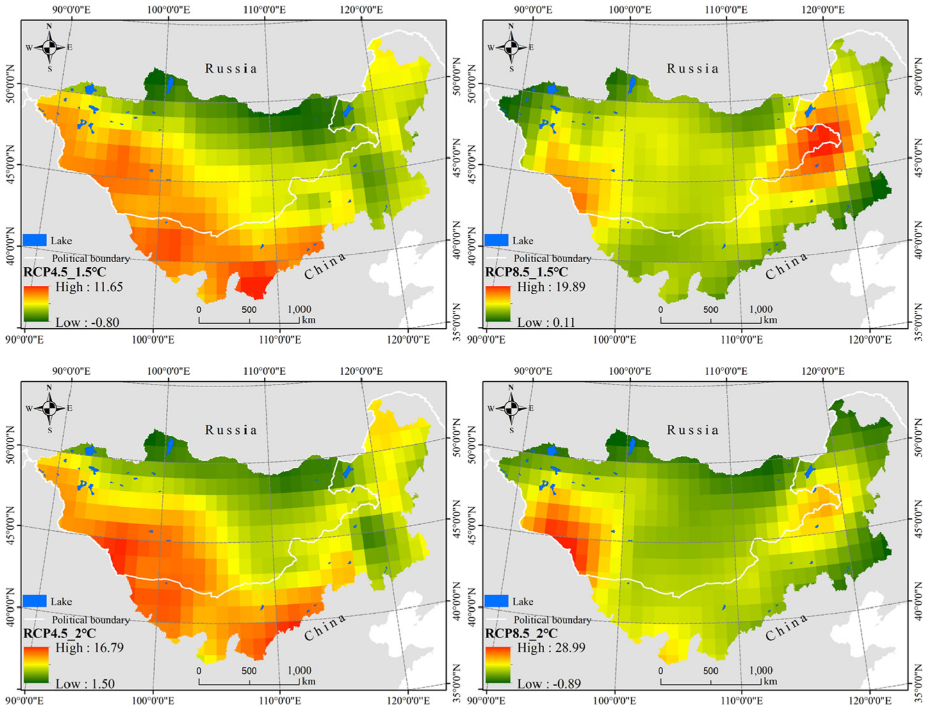

Figure 5.
Distributions of WSDI relative to 1975–2005 under the conditions of 1.5 and 2.0°C global warming over MP

5. Adaptation options and limitations

5.1 Adaptation options

Possible SD effects must be dealt with during the design of any mitigation, and adaptation options that have certain flexibility with respect to the magnitude of potential effects should be selected. SD reduction can result in a freshwater shortage; thus, early warning measures for water shortages should be taken in the southern part of the MP. Increasing SD means that more water content will increase soil moisture and promote vegetation productivity (Wang *et al.*, 2018). Therefore, in future ecological projects, various types of vegetation will be planted to improve the structure of the existing mature and artificial pure forest to ensure biodiversity and avoid various potential ecological crises in the northern region.

Through empirical research, the unique nature of inter-related social and economic climate change impacts within affected areas is becoming increasingly clear. Climate change, particularly with the climate extremes, can act as a threat multiplier to SD in the MP at present. First, the risks of climate extremes often seem to be exacerbated by the various current ecological and economic challenges, along with their impacts on snow depth-affected vegetation. The grassland in the MP is one of the largest grassland regions in the world, accounting for approximately 50% of the land in the MP, and it is vulnerable to climate change. Second, people who live in the MP, regardless of climate change, are facing poverty and hunger, increasing the demand for resources and creating a financial crisis. The region's animal husbandry activity is the most important source of income for pastoral livelihoods. Evidence suggests that the dzud will make it harder to address these challenges in the MP because they will perpetuate poverty. Dzud can result in poverty, unemployment and unplanned migration to central areas in Mongolia (Ganzorig and Narantsetseg, 2013). Recurring dzud conditions force many herders, who used to live a nomadic life amid Mongolia's vast plains and mountains, to migrate to a marginalized urban area to seek alternate employment (CD, 2017). This migration exacerbates poverty and unemployment because they are lacking in work skills. The UNDP (2019) noted that one-third of Mongolia's population already lives below the poverty line.

Climate extremes, snow and the dzud in the MP can hinder affected areas that are on their pathway to approaching sustainable development. The capacity of affected areas to deal with these challenges depends on a variety of governance levels, adaptation options and an adequate understanding of local vulnerabilities. Therefore, good governance, adaptation and mitigation measures are needed in this pathway.

One way to address some of the climate extremes challenges is to focus on plateau-level issues. Taking the entire MP as a unit of the study area can also contribute to a greater social understanding of resilience and a profound understanding of gaps and limitations in existing programs. Resilience is often seen only as the ability of the ecosystem to withstand and recover from damage. This neglects resilience as a social process and as the capability of communities to absorb changes (Oliver-Smith, 2016). Immediate actions should be designed and built to properly function under future new climatic conditions to reduce future costs and impacts.

5.2 Limitations

Comparing gridded GCM simulations against station-based observations can be problematic. Annual mean data represented changes in the entire MP, thus resulting in a loss of variation detail in inter-annual change.

Based on these results, relative mitigation and adaptation can be put forward effectively. The accuracy is always affected by underlying surface conditions and algorithms. However, uncertainties and potential biases in spatial interpolation can be introduced due to specific algorithms, especially in complex terrain areas.

As a consequence, the purpose of this paper is to fill the gap that hampers the local understanding of the effect of consecutive temperature and precipitation days on SD in the past, and then to find out the risk area under the conditions of 1.5 and 2.0°C global warming only, rather than to provide a comprehensive scientific analysis on gaps in general. Despite these limitations, the results obtained in this study can help to better understand the potential influences of climate extremes on SD. The evaluation of climate models against observed data is an important step in building confidence in their use for future impact assessments (Bannister *et al.*, 2020).

6. Conclusions

This paper assessed the CMIP5 models' performance of consecutive temperature and precipitation days, established the threshold surpassing times of 1.5 and 2°C global warming, and investigated trends in SD changes in temporal and spatial scales and their responses to climate extremes. Compared with previous studies, the novelty of this research is that it has considered possible snow change adaptation options in face of the climate extremes under the conditions of 1.5 and 2.0°C global warming.

In this study, consecutive temperature and precipitation days between 1961 and 2005 from 30 coupled model simulations of Phase 5 of the CMIP5 are assessed in comparison with the 111 meteorological monitoring stations of the MP. The results show that some of the models perform well, even better than the majority (80%) of models. This paper thereby selected only the best model for each index, i.e. the

HadGEM2-CC, CMCC-CM, BNU-ESM and GFDL-ESM2M models simulating CDD, CWD, CSDI and WSDI performing best, respectively, were chosen for simulation under RCP8.5 and RCP4.5 to analyze the consecutive temperature and precipitation day impacts in both the 1.5 and 2°C global warming periods. For the four consecutive extreme indices, only WSDI has a significant negative effect on SD. Therefore, the emphasis zones of WSDI on SD were deeply analyzed under the conditions of the 1.5 and 2.0°C global warming periods. It was found that it is warmer than before in the MP, particularly in the southern part of the MP, indicating less SD. Adaptation measures should be effectively taken in these areas.

As far as adaptation strategies are concerned, these are deemed as important because they can increase local resilience and prevent disturbances in industry and community life. Climate extremes can interfere with economic activities, so improved knowledge may lead to greater preparedness.

The implications of this study are twofold. It shows the extent to which climate conditions in the MP are changing and how this change affects SD. Also, the study showed that the models used perform well and that data deriving from them may offer a basis for decision-making.

In terms of future directions, it is important that industry practitioners, policymakers, government bodies and researchers are made better aware of the potential impacts of climate extremes on snow or other cryosphere elements under global warming conditions, as they may affect the well-being of the populations in the MP.

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Author affiliations

Chunlan Li, School of Urban and Regional Sciences, East China Normal University, Shanghai, China and State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy Sciences, Beijing, China

Xinwu Xu, China Meteorological Administration, Beijing, China and University of Chinese Academy of Sciences, Beijing, China

Hongyu Du, Institute of Ecology and Sustainable Development, Shanghai Academy of Social Sciences, Shanghai, China

Debin Du, School of Urban and Regional Sciences, East China Normal University, Shanghai, China

Walter Leal Filho, Hamburg University of Applied Sciences, Research and Transfer Centre "Sustainable Development and Climate Change Management", Hamburg, Germany and School of Science and the Environment, Manchester Metropolitan University, Manchester, UK

Jun Wang, Key Laboratory of Geographic Information Sciences of Ministry of Education, East China Normal University, Shanghai, China and School of Geographical Sciences East China Normal University, Shanghai, China

Gang Bao, College of Geographical Sciences, Inner Mongolia Normal University, Huhhot, China and Key Laboratory of Remote Sensing and Geographic Information System, Inner Mongolia, Huhhot, China

Xiaowen Ji, School of Environment and Sustainability, University of Saskatchewan, Saskatoon SK, Canada

Shan Yin and Yuhai Bao, College of Geographical Sciences, Inner Mongolia Normal University, Huhhot, China and Key Laboratory of Remote Sensing and Geographic Information System, Inner Mongolia, Huhhot, China

Hossein Azadi, Department of Geography, Ghent University, Ghent, Belgium

Corresponding author
Chunlan Li can be contacted at: 15598022233@163.com