LETTER

Anthropogenic influence would increase intense snowfall events over parts of the Northern Hemisphere in the future

Huopo Chen1,2, Jianni Sun1,2 and Wenqing Lin1,3

1 Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People’s Republic of China
2 Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University for Information Science and Technology, Nanjing, People’s Republic of China
3 University of Chinese Academy of Sciences, Beijing, People’s Republic of China

E-mail: chenhuopo@mail.iap.ac.cn

Keywords: snowfall, anthropogenic influence, attribution, projection, CMIP6

Abstract

Snowfall is an important element of the climate system and generally has particularly large economic and human impacts. Simulations with climate models have indicated a decline in mean snowfall with warming in most regions. The response of intense snowfall events to a changing climate, however, is unclear. Thus, the degree which anthropogenic influence is responsible for intense snowfall change and how intense snowfall will respond to the changing climate in the future are addressed here using new simulations from Coupled Model Intercomparison Project phase 6 models. The results show that anthropogenic influences on changes in snowfall are detectable across the lands of the Northern Hemisphere and generally result in a decreasing trend in snowfall events. However, increased anthropogenic activity has increased intense snowfall occurrences over most parts of Asia, North America, and Greenland. With additional warming in the future, while the length of the snowy season will be shortened and the areas where snowfall occurs will be reduced, the occurrence probability of an intense snowfall event is projected to significantly increase with a level of high confidence over these regions by the end of this century. This suggests that these regions, including most parts of northern China, would suffer from more intense snowfall events in the future due to a continuous increase in anthropogenic influence.

1. Introduction

In the context of climate warming, intense snowfalls have frequently affected large parts of the continents in the Northern Hemisphere in recent winters, resulting in particularly large economic and human impacts. For example, the severe snowstorm that occurred in southern China in early 2008, the largest snowstorm over America since 2007 that occurred in 2017, and the deadly winter storm that blasted Europe in early 2020, have all caused large economic losses and homelessness (e.g. Ding et al 2008). However, snowfall is also an important occurrence that has significant impacts on human life, as approximately one-sixth of the world’s population depends on snowmelt for water (Vavrus 2007). Recognition of the cause of snowfall change is therefore urgent for the public and governments and may help to establish public awareness of climate change and drive policy decisions for climate adaptation.

Numerous studies have been devoted to understanding the causes and physical mechanisms of snowfall changes across the lands of the Northern Hemisphere. Studies have shown that recent occurrences of snowy winters are closely linked to the intensification of the Hadley circulation (Zhou et al 2017), the diminishment of Arctic sea ice (Liu et al 2012), the increase in the stratospheric polar vortex disturbance (Lu et al 2016), and the strong negative phase of the North Atlantic Oscillation (Seager et al 2010) or the Arctic Oscillation (Cohen et al 2010). Large-scale atmospheric circulation anomalies, including the persistent Ural blocking high, an intensified Middle East jet stream, a strengthened
western Pacific subtropical high, and the positive phase of the Antarctic Oscillation, are mainly responsible for the occurrence of and changes in snowfall events across China during the past decades (Ding et al 2008, Sun et al 2009, Wen et al 2009, Zhang et al 2012, Wang and He 2013). These findings have largely improved our understanding of changes in snowfall events.

There is also overwhelming evidence that the anthropogenic fingerprint is involved in increasing risks of climate extremes at the regional to global scale, especially heat events (Min et al 2011, Zhang et al 2013, Sun et al 2014, Diffenbaugh et al 2017, Li et al 2017, 2020, Chen and Sun 2017a, 2017b, Dong et al 2020). With further warming in the future, anthropogenic influence on changes in climate extremes across the world would be amplified, causing heat events, heavy precipitation, and droughts to become much stronger and to occur more frequently in the future (King and Karoly 2017, Coffel et al 2018, Gao et al 2018, Wang et al 2019, Chen et al 2019, 2020a). In response to anthropogenic warming, the occurrence of daily snowfall events is projected to decrease across much of the Northern Hemisphere, including the regions of Europe, China, Japan, and USA, and to slightly increase at the highest latitudes such as northern Canada, northern Siberia, and Greenland (Sun et al 2010, Krasting et al 2013, O’Gorman 2014, Danco et al 2016, Zhou et al 2018, Ohba and Sugimoto 2020). However, the degree to which anthropogenic influence is responsible for snowfall change as the climate warms remains unclear, especially for intense snowfall, which is the main topic of this study.

Recently, simulations from models of the new phase of Coupled Model Intercomparison Project (CMIP6) have been released progressively. Compared to those of models from the earlier phase of CMIP5, the dynamic processes of these models are substantially better and generally use finer horizontal and vertical resolutions (Erying et al 2016), allowing the models to better simulate climate extremes (Chen et al 2020b, Jiang et al 2020, Zhu et al 2020). Thus, different forcing experiments as well as 21st century scenario simulations from CMIP6 are employed here to address the above mentioned key issues.

2. Data and methods

2.1. Dataset

Two data sources are used in this study. Gridded daily precipitation and daily maximum temperature, which is provided by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC), are used here for the observations. This dataset is constructed from data from approximately 16,000 stations around the world and satellite observations using the optimal interpolation approach (Chen et al 2008). It contains data from 1979 to the present, with a high horizontal resolution of 0.5° longitude-latitude.

The daily outputs from 10 CMIP6 models (table S1 (available online at https://stacks.iop.org/ERL/15/114022/mmmedia)) that include historical, natural, aerosol, and greenhouse gases forcing simulations are used here. The historical simulations (ALL) include both anthropogenic forcings (such as greenhouse gases and aerosols) and natural forcings (such as volcanic aerosols and solar outputs); the greenhouse gases (GHG) simulations include only greenhouse gases emissions; the aerosol (AER) simulations include only aerosol emissions; the natural (NAT) simulations include only natural forcings. The time slices spanning from 1950 to 2014 for different forcing simulations are conductive to the attribution analyses. Additionally, the 21st century scenarios of the new shared socioeconomic pathway (SSP) 5–8.5 and SSP1–2.6 are also used. Changes in snowfall at the end of this century (2081–2100) are generally estimated with respect to the current state during the period of 1995–2014. It should also be noted that only the first run of ‘r’l1i1p1f1’ from CMIP6 simulations is employed here for the analyses. All these data are resampled to a common 1.5° × 1.5° grid using a first-order conservative remapping procedure using the Climate Data Operator (CDO) software (https://code.mpimet.mpg.de/projects/cdo).

2.2. Snowfall definitions

Precipitation generally has two main phases, namely, solid precipitation (i.e. snowfall) and liquid precipitation (i.e. rainfall). In general, solid precipitation can be difficult to measure. One common method is the use of a rain gauge to collect snow and measure it as liquid precipitation after it melts, usually alongside a separate record of the weather phenomenon of snowfall. However, such records are not easy to collect by the observers, and there is often large error. Thus, snowfall is generally distinguished by the temperature threshold method (Yang et al 1997, Sun et al 2010, Krasting et al 2013, Ding et al 2014, O’Gorman 2014, Bai et al 2019, Ohba and Sugimoto 2020), because snow forms when the surface air temperature is close to the freezing point.

The rain-snow transition does not occur precisely at a surface temperature of 0 °C because frozen precipitation does not immediately melt as it falls past the melting level and because there is temperature variability within the accumulation period (O’Gorman 2014). Thus, an empirical relationship (Rawlins et al 2006) between the fraction of precipitation falling as snow and temperature is applied here to produce large-scale gridded estimates of snowfall for the Northern Hemisphere continents.

\[ S = f(T) P \]
where \( f(T) \) is the fraction of precipitation \((P)\) that falls as snow \((S)\), as determined by the surface air temperature \((T)\). In this study, the surface air temperature is replaced by the daily maximum surface air temperature for snowfall statistics. Snowfall may be underestimated according to this definition but this method ensures that the precipitation falling to the ground is solid snow. Another assumption of a uniform 10:1 snow-to-liquid ratio in converting liquid precipitation to a snowfall depth equivalent \((O’Gorman 2014)\) is also applied here, although this ratio may have substantial regional variations \((Baxter et al 2005)\). Finally, snowfall days are considered days having a daily snowfall greater than 0.1 cm, while intense snowfall days are defined as days having a daily snowfall exceeding 5.0 cm.

Most snowfall events over the Northern Hemisphere generally happen from the autumn season of the current year to the spring of the next year. Thus, the first day of snowfall is identified as the first date when snowfall occurs after the month of September, and the last day of snowfall is defined as the last date of snowfall during the snowy season. The duration interval of snowfall is identified as the difference during the snow year. Trends of these characteristics are estimated by the Theil-Sen median method, and the significance is evaluated by the non-parametrical Mann-Kendall test at the 95% confidence level.

### 2.3. Attribution metrics

To explore the potential anthropogenic influence on snowfall, two metrics proposed by Stott et al \((2004)\), namely, the ‘probability ratio’ \((PR)\) and ‘fraction of attributable risk’ \((FAR)\), are used here. \(PR\) is a measure of the probability change of an event, and \(FAR\) indicates the fraction attributable to humans. These frameworks have been widely used to quantify the anthropogenic influence on the occurrence of individual heat waves \((Otto et al 2012, Lewis and Karoly 2013)\), dry spells \((Sippel and Otto 2014)\), and heavy precipitation \((Pall et al 2011)\), as well as long-term changes in these events \((Fischer and Knutti 2015, Chen and Sun 2017a)\).

\[
PR = \frac{P_1}{P_0}
\]

\[
FAR = 1 - 1/PR
\]

where \(P_1\) is the occurrence probability of extreme event in the current climate or during future periods and \(P_0\) is the probability of event generally identified during the pre-industrial (PI) control period. However, the NAT forcing simulation rather than the PI experiment is used here as the ‘counterfactual’ world without anthropogenic influence because few models have the daily outputs of the PI simulation until now. Furthermore, NAT and PI simulations are similar, and the NAT simulation can isolate the anthropogenic influence during the historical period well \((Diffenbaugh et al 2018)\). For example, if the occurrence probability of an event is 0.01 in the NAT simulation and the probability increases to 0.02 in the historical simulation, then the PR is 2, implying that the anthropogenic influence doubles the occurrence probability of this extreme event.

For the future projection of snowfall, we adopted three ways to express the confidence levels of the results. First, the model agreement of all models analyzed with the same changing directions as the multi-model median ensemble is displayed for the changes in the patterns of snowfall and snowfall days. Second, the interquartile model spread, i.e. the range between the 25th and 75th percentiles of the model ensembles, is shown for the change in regional average over continents of the Northern Hemisphere to represent the confidence level. Third, the time point of the significant changing signal emergence is shown for the snowfall change for each model. The point of emergence is identified using the pairwise \(t\) test with the 21-yr window advocated by Krasting \((2013)\). The analysis first determined if the SSP5-8.5 transient climate simulation in the final 21 yr \((2080–2100)\) is statistically different from that in the current state \((1994–2014)\) in the historical simulation. If it is significant, the 21-yr window is shifted backward in time by 1 yr \((e.g. 2079–2099)\) until there is no longer a significant difference between the analysis period and the present climate, and the time point is considered the starting time of the significant change in signal emergence.

### 3. Results

#### 3.1. Assessment of model ability

Compared to observational estimates of snowfall, the historical simulations from the CMIP6 models capture the magnitudes and many of features of mean snowfall and snowfall days with the respective pattern correlations of 0.84 and 0.93 (figure 1). The observed high values are mainly located over the mid to high latitudes of the Northern Hemisphere, centering over the regions of Siberia, Greenland, and the Labrador Plateau. The finding is similar for the historical simulations, but generally with an overestimation for both the mean snowfall and snowfall days over these regions. Snowfall biases in the models may be partly associated with temperature biases and inadequate spatial resolution in regions with high terrains. We also note that there is a large discrepancy in snowfall and snowfall days between CMIP6 simulations and observations in regions with high mountains, including the Tibetan Plateau. This may mainly result from
observations because there are not many stations in these high mountain regions.

Furthermore, in both observations and simulations, climate warming causes widespread decreases in snowfall and intense snowfall days across most regions of the Northern Hemisphere, particularly Eurasia, which is also consistent with earlier findings (O’Gorman 2014). Additionally, the historical simulations also capture the uniform responses of changes in the first and last days of snowfall to warming in recent decades well (figure S1), with snowfall starting later and ending earlier. This strong similarity between simulation and observation substantially increases the robustness of the following attribution and projection results.

3.2. Anthropogenic influence on snowfall changes
A key question is to what degree anthropogenic influence, in addition to effects of internal variability of climate systems (Cohen et al 2010, Seager et al 2010, Liu et al 2012, Lu et al 2016, Zhou et al 2017), is responsible for snowfall change. To clearly address this issue, we implement comprehensive attribution analyses using the different forcing simulations from CMIP6 models, including historical experiments, greenhouse gases simulations, AER forcing simulations, and NAT simulations. The two attribution metrics PR and FAR are employed here, which have been widely used to quantify the anthropogenic influence on the occurrence of climate extremes across the world (Fischer and Knutti 2015, Chen and Sun 2017a).

Historical forcing has already decreased the occurrence probability of snowfall relative to natural forcing over most grids of the Northern Hemisphere, including Europe, Alaska, Canada, and some parts of China (figure 2). In contrast, the PR in northern Asia, Greenland, and eastern North America tends to be slightly increased, implying more snowfall days over these regions in response to the warming in recent decades, which is in agreement with earlier findings from CMIP5 simulations (IPCC 2013). According to the Clapuyron–Clausius equation, the increase in atmospheric moisture capability is partly responsible for the snowfall increases over these regions due to warming, which could increase the occurrence probability of precipitation event during the cold seasons. Certainly, the increase in temperatures due to anthropogenic influence have reduced snowfall occurrence, but this is limited to regions of the mid-low latitudes in the Northern Hemisphere. For high-latitude regions, daily temperatures are still much lower than the freezing point during the cold seasons, although increases in temperatures occur much more quickly in response to the warming in high-latitude regions than in the low-latitude regions. Additionally, the climate system anomaly also shows some responsibilities. For example, the reduction in Arctic sea ice can modulate the atmospheric circulation anomalies over the Eurasian continent, such as blocking highs, and provide an increased moisture source for snowfall (Liu et al 2012).

As expected, among anthropogenic influences, increased GHG emissions contribute largely to the decrease in the number of snowfall days, with the PR being substantially decreased across most lands of the Northern Hemisphere. Particularly for the mid-latitude regions, including southern Europe, southern China, and USA, it has been reported that the occurrence probability of snowfall has significantly decreased in the past decades due to GHG emissions and that the PR is reduced less 0.7. This suggests that the increase in GHG emission has contributed to more than 30% (FAR) of the decrease in snowfall days in these regions during the past decades. In the high-latitude regions, the change in snowfall days is more much weakly associated with GHG emissions. In contrast, we can see the increasing probability of snowfall in response to AER forcing across the Northern Hemisphere, especially over the mid-latitude regions. This is closely connected to the cloud effects of AERs that generally leads to a decrease in temperature. Furthermore, increasing AER emissions has also increased the occurrence probability of intense precipitation events, or more specifically, intense snowfall events during the cold season.

Relatively strong responses of intense snowfalls to anthropogenic influence are expected across the Northern Hemisphere (figure 3). The occurrence probability of intense snowfalls is found to obviously increase with climate warming in ALL forcing simulations, especially over regions of most parts of Asia, North America, and Greenland, in which FARs are estimated to increase by at least 10%, possibly even exceeding 20%. Thus, the increased anthropogenic activity in the past decades is partly responsible for the increase in intense snowfall events over these regions. The findings for the GHG forcing simulations are similar, but the PR is relatively high, implying a larger contribution of GHG emissions among the anthropogenic influences to changes in intense snowfalls. FARs over some parts of the Northern Hemisphere, particularly Greenland, exceed 20%. However, for USA, the AER forcing (positive) exerts a greater impact on the changes in intense snowfalls than GHG emissions (negative), resulting in an increased probability of intense snowfall events.

Additionally, a uniform effect of increased GHG emissions on the dates of the first and last occurrences of snowfall events can be observed across the lands of the Northern Hemisphere, with an increasing trend for the first snowfall day and a decreasing trend for the last snowfall day (figure S2). In the other words, over the past decades, the first occurrence of snowfall has been delayed and the end date has tended to be earlier due to GHG emissions. The opposite case can be found for the AER forcing simulations, but with a relatively weak response. Thus, anthropogenic influence has decreased the length of
the snowfall season over the Northern Hemisphere in the past decades.

Briefly, anthropogenic influences, especially GHG emissions, have exerted significant impacts on changes in snowfall and intense snowfall events over the lands of the Northern Hemisphere. However, it is unclear whether snowfalls and intense snowfalls will increase or decrease in response to further warming in the future. To clearly address this issue, the 21st century scenario projections of the new Shared Socioeconomic Pathway (SSP) 5–8.5 (high) and SSP1-2.6 (low) are used in the next section.

3.3. Snowfall change in response to future anthropogenic warming

By the end of this century (2081–2100), annual snowfall and snowfall days are expected to significantly decrease with a high confidence level across the lands of the Northern Hemisphere (figure 4), especially over the mid-latitude regions, including southern Europe, southern China, Japan, and USA, in which snowfall and snowfall days will decrease by at least 50% under the SSP5-8.5 scenario compared to the current state (1995–2014). However, some regions of northern Asia and Greenland are projected to experience increasing snowfall and snowfall days by the end of this century. Similar changes are featured in the low scenario of SSP1-2.6 but with a relatively smaller change in magnitude. For regional averages, annual snowfall and snowfall days are projected to tend to significantly decrease in the future, and changes began to be noticeable since early this century. By the end of the 21st century, annual snowfall is estimated to decrease by approximately 26% and snowfall
days are projected to decrease by approximately 26% under the SSP5-8.5 scenario with respect to the current climate.

Similar patterns are observed for future changes in intense snowfalls (figure 4). However, it is noticeable that the areas in which intense snowfall will increase are much larger. Such increases in response to future warming are observed not only in regions of Greenland and northern Asia but also over northern China and the Tibetan Plateau. Furthermore, the increases in both intense snowfall and intense snowfall days over these regions are projected to be much stronger than those in snowfall and snowfall days, with an increase of at least 50% over most grids of these regions under the SSP5-8.5 scenario. This implies an increasing probability of intense snowfall events over these regions despite rapid warming in the future. Further estimation shows that the future increases in intense snowfall days are largely contributed by the anthropogenic influences, by at least 20% over most grids of these regions and even exceeding 40% (figure S3).

Continuously increasing anthropogenic emissions in the future would further delay the first occurrence of snowfall events across the Northern Hemisphere, especially for the high-latitude regions (figure S4). In contrast, the dates of the last occurrence of snowfall would tend to significantly decrease in response to future warming, resulting in a uniform decrease in the length of the snowfall season in the future. By the end of 21st century, the first occurrence of snowfall would be delayed by an average of approximately 25 d over the Northern Hemisphere and the last occurrence of snowfall would be approximately 29 d earlier. Correspondingly, the length of the snowfall season would be decreased by approximately 54 d compared to that in the current climate. These change signals are also robust in the low scenario of SSP1-2.6 (figure S5), but with a relatively smaller change in magnitude.

Furthermore, snowfall events would happen further north in the future, and the regions that experiencing snowfall events would be obviously reduced (figure S6). For some southern, previously snowy regions in the Northern Hemisphere, it is possible that there would no longer be snowfall events experienced by the end of this century. Northward movement would be much more apparent for intense snowfall events, and there would be only rare events experienced in the future over southern parts of Europe, China, and USA (figure 5). Further estimation from the grids shows that the area percentage of intense snowfall events would decrease from approximately 46% across the Northern Hemisphere in the present to approximately 36% by the end of this century.

4. Conclusion and discussion

Snowfall is an important aspect of weather and climate that generally poses a great threat to society, the ecosystem, and humans, often causing large economic losses. It is thus of great importance to the publics and governments to improve the understanding of changes in and the occurrence of snowfall events, especially regarding the impacts of anthropogenic influences. To clearly address this key issue, the new outputs of CMIP6 simulations that include different forcing experiments and 21st century scenario simulations are employed in this study.

Our analyses show that the effects of anthropogenic influences on changes in snowfall are detectable across the lands of the Northern Hemisphere, generally resulting in a decreasing trend in snowfall events. Additionally, the length of the snowfall season
Figure 4. Changes in annual snowfall, snowfall days, intense snowfall and intense snowfall days by the end of this century (2081–2100) under the SSP5-8.5 scenario with respect to the current state (1995–2014). The right column shows the corresponding changes averaged over the lands of the Northern Hemisphere in future years under the SSP5-8.5 (red) and SSP1-2.6 (blue) scenarios. The white dots in the left panels indicate similar change signals for all models with the MME that implying a high confidence level. The shaded areas in the right column show the interquartile model spread, i.e. the range between the 25th and 75th percentiles of the model ensemble, representing the confidence level. The diamond symbols for the models (small) and MME (big) denote the years when the climate change signal emerges under the SSP5-8.5 scenario. Units: %.

Figure 5. Future changes in grid ranges of intense snowfall occurrences. (a) The shaded areas indicates grids in which at least one intense snowfall event is reported to occur in the present, and the red dots indicate grids with no intense snowfall event by the end of this century under the SSP5-8.5 scenario. (b) This panel displays the percentage of grids with intense snowfall over the lands of the Northern Hemisphere. The shaded areas show the interquartile model spread, i.e. the range between the 25th and 75th percentiles of the model ensemble, representing the confidence level.
shows a decrease in response to anthropogenic warming in the historical period, with snowfall events tending to occur later and end earlier. However, increased anthropogenic activity has increased the occurrence of intense snowfall over regions of most parts of Asia, North America, and Greenland, and this increase is largely attributed to the impacts of increased greenhouse gases emissions. With further warming in the future, while the length of snowfall seasons would be shortened and the areas of snowfall occurring would be reduced, the frequency of snowfall events is projected to slightly increase in the high-latitude regions of the Northern Hemisphere, including some parts of Asia, North America, and Greenland. This result is in line with the early findings from CMIP5 simulations (Krasting et al. 2013, Danco et al. 2016). The increase is much significant for intense snowfall event and the occurrence probability is projected to significantly increase with a high confidence level over these regions by the end of this century under different warming scenarios. This suggests that these regions, including most parts of northern China, would experience more intense snowfall events in the future, due to the continuous increase in anthropogenic influence.

We should also note that some assumptions and limitations used here may impact the conclusions in this study. First, the daily mean temperature that was generally used for the definition of snowfall events in previous studies was replaced by the daily maximum temperature. Snowfall may be underestimated according to this definition but this method ensures that the precipitation falling to the ground is the solid snow. Second, the assumption of a uniform 10:1 snow-to-liquid ratio is applied here to convert liquid precipitation to a snowfall depth equivalent, as previous studies have suggested (e.g. Krasting et al. 2013, Danco et al. 2016). This ratio may in fact have substantial regional variations (Baxter et al. 2005) and also vary based on time period, especially in future periods with rapid warming. More research is therefore needed to improve the understanding of the snowfall formation processes that affect this ratio. Third, while dynamic processes and horizontal resolution are substantially better in CMIP6 models than in earlier phases, many of these models still suffer from temperature biases and precipitation biases, which may impact changes in snowfall. Additionally, there is also a large discrepancy of snowfall between CMIP6 simulations and observation, especially in the high mountain regions, including the Tibetan Plateau (figure 1). This discrepancy may result from observations because there are only a few stations in these high-altitude regions, leading to large uncertainties in observations, suggesting that other datasets on the regional and sub-regional scales should be used in the future (e.g. Shi et al. 2011). To reduce this uncertainty, especially for the future projection of snowfall, it is suggested that simulations from more models (including global circulation models and regional climate models) be used in the future to increase robustness (e.g. Giorgi et al 2018).

Acknowledgments

This research was jointly supported by the National Natural Science Foundation of China (Grant Nos. 41991284, 41922034, 41825010), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant Nos. XDA23090102), and the National Key Research and Development Program of China (Grant Nos. 2016YFA0600701, 2016YFA0602401).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://esgf-node.llnl.gov/search/cmip6/.

ORCID iD

Huopo Chen https://orcid.org/0000-0003-0760-8353

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