Warming over the North Pacific can intensify snow events in Northeast China

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ABSTRACT

The variation of winter snowfall intensity over Northeast China and its relationship with the autumn North Pacific SST are investigated for the period 1960–2012. An upward trend is apparent for the winter snowfall intensity over Northeast China during the last half-century, coinciding with an increasing autumn SST over the North Pacific. Their interannual correlation coefficient reaches up to 0.58 for the past five decades, and 0.42 after their trends are removed. Further analyses indicate that the warming SST during autumn may persist into winter. Correspondingly, large parts of East Asia and the North Pacific are dominated by an anticyclonic anomaly, which can induce an anomalous southeasterly over Northeast China, weaken the northerly wind, then warm the surface, increase the water vapor content and intensify snowfall events. Thus, the autumn North Pacific SST can be considered as a key predictor for winter snowfall events over Northeast China. Results from leave-one-out cross-validation and independent validation both show a significant correlation and a small RMSE between prediction and observation. Therefore, the autumn SST over the North Pacific is suggested as a potential predictor for winter snowfall intensity in Northeast China.

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1. Introduction

Intense snowfall events, generally coinciding with persistent low temperature, can cause large economic losses, ecosystem damage, disruption to society, and even a threat to human lives (Cattiaux et al. 2010; Changnon and Changnon 2006; Wang, Liu, and Lee 2010). Early studies indicated that winter snowfall in Northeast China (NEC) has experienced an increasing trend since the mid-1980s (Wang and He 2013), as well as its annual variability; however, this trend is not significant (Sun et al. 2010). There have been many studies that focused on intense snowfall cases over China and their corresponding atmospheric circulations have been comprehensively revealed (e.g. Sun, Wang, and Yuan 2009; Wang, Yu, and Yang 2011; Wen et al. 2009; Xie et al. 2010), and these have increased our understanding of the formation and mechanisms of snowfall events over China.

The East Asian winter monsoon (EAWM) is considered to be the critical synoptic system influencing winter snowfall over NEC (Wang and He 2012, 2013), and is characterized by strong northwesterly flow along the eastern edge of the East Asian coast, with a robust Siberian high appearing over the Asian continent and a strong Aleutian low over the North Pacific (Wu and Wang 2002). Early studies indicated that ENSO (e.g. Webster and Yang 1992; Zhang, Sumi, and Kimoto 1996) and the Arctic Oscillation (AO) (e.g. Gong, Wang, and Zhu 2001; He 2015; Wu and Wang 2002) both have significant impacts on the winter snowfall over northern China by influencing the intensity of the EAWM. However, the relationship between the EAWM and AO experienced a seesaw counterpart change against that between the EAWM and ENSO (Wang, He, and Liu 2013). Furthermore, Liu et al. (2012) suggested that the recent occurrence of cold and snowy winters is tightly associated
with the recent decline in autumn Arctic sea ice, which is consistent with the viewpoint of Song et al. (2012).

Previous studies also showed that the SST over some regions presents a close connection with the precipitation variations over China. For instance, Xiao, Yan, and Li (2002) pointed out that summer precipitation over China is affected by a dipole SST anomaly over the Indian Ocean through the Pacific–Japan wave train. Zhao and Qian (2009) discovered that the North Pacific, Indian Ocean–South China Sea, and the central and eastern equatorial Pacific are the three key regions whose preceding winter SST anomalies present an important influence on precipitation over China. Recently, a study by Li, Xiao, and Li (2012) indicated a significant positive correlation between North Atlantic SST (30–50°N, 10–40°W) and the leading two principal components of snowfall over NEC in winter, despite the correlation coefficients exhibiting an obvious spatial difference. However, studies concerning winter snowfall over NEC rarely involve any discussion on snowfall intensity. As intense snowfall events usually cause more damage than mild ones, it is of great value to pay more attention to snowfall intensity. In this paper, we analyze the variation of winter snowfall intensity over NEC and its relationship with SST over the North Pacific. Results reveal that the autumn North Pacific SST over the midlatitudes has a close connection with the snowfall intensity over NEC, suggesting the autumn SST over the North Pacific can be considered as a useful predictor for improving winter climate forecasts over NEC.

2. Data and method

The station data used in this study were obtained from the China Meteorological Administration, which are based on daily records of 756 gauge stations over China. The gridded data include the NCEP monthly reanalysis data-set for 1960–2012 (horizontal resolution: 2.5° × 2.5°) (Kalnay et al. 1996) and HadISST1 (horizontal resolution: 1° × 1°) (Rayner et al. 2003).

In this study, the winter (December–January–February) snowfall intensity for each station is considered as the mean snowfall amount of all the snowfall events during the whole winter. A snowfall event is defined according to the station data based on the following three criteria: (1) the gauged daily precipitation should be equal or more than 0.1 mm; (2) the station’s daily mean surface air temperature should be below 0 °C; and (3) the station’s daily mean ground temperature should also be below 0 °C. The last two criteria ensure that precipitation will be in the form of snow and result in snow cover on the ground. Considering the missing data for most stations before 1960, this study only focuses on the period of 1960–2013. For daily precipitation and air temperature data, the stations whose missing records amount to more than 5% of total records covering the 54 years have been rejected, and thus 538 stations are selected. Missing records of daily precipitation and air temperature data are replaced by the climatological values of the selected period; for the ground temperature data, missing records are considered lower than 0 °C when the corresponding daily air temperature is below −3.0 °C, while fixed to climatological values of the selected period when the corresponding daily air temperature is equal to or above −3.0 °C. Snowfall intensity data covering 53 winters from 1960 to 2012 for each station are picked out in this paper. The NEC region is defined as being north of 40°N and east of 120°E, and there are 78 stations out of the total 538 stations located in this region, which are extracted for further study.

3. Results

Figure 1(a) is the first EOF mode of winter NEC snowfall intensity. It can explain about 28.5% of the total variance and has uniform positive loadings over the NEC region, which means that the uniform changes of snowfall intensity over NEC is the main feature. The largest loadings are located along the south coast region of NEC, which implies snowfall intensity here has a larger variability than in other regions. Figure 1(c) shows the normalized time series of the first principal component of the EOF and the corresponding regional mean winter snowfall intensity over NEC. Both series show a significant increasing trend after the late 1980s. The winter regional mean snowfall intensity is highly correlated with the winter total snowfall amount, with the coefficient reaching up to 0.80. However, the winter snowfall amount does not show an obvious trend.

Yang and Lau (2004), based on SVD analysis, suggested that the specific precipitation modes over China might be associated with the specific modes of Pacific SST during boreal spring and summer. Thus, the relationships between the NEC winter snowfall intensity and the Pacific SST are investigated. Figure 2(a) shows the correlation map of autumn Pacific SST anomalies with the winter NEC regional mean snowfall intensity. A large area of significant positive correlation coefficients can be seen over the North Pacific, and this significant positive correlation can also be found during winter (Figure 2(b)). This implies that autumn SST anomaly signals can sustain to winter (Figure 2(c)), and then influence winter climates.

A key region (30–50°N, 130°E–140°W) is apparent for the Pacific SST that presents a close association with the NEC winter snowfall intensity, and thus the North Pacific SST index (NPSSTI) is defined as the mean SST of this region for further analysis. Clearly, the time series of autumn NPSSTI displays a strong upward trend, especially after the late 1980s (Figure 1(d)), presenting a similar change.
Figure 1. (a) First EOF mode of winter NEC snowfall intensity. (b) Correlation map between autumn NPSSTI and winter snowfall intensity during 1960–2012 (dots with a cross mark mean correlations significant at the 90% confidence level). (c) Normalized time series of the first principal component (PC1, blue line) and winter NEC regional mean snowfall intensity (red line) during 1960–2012. (d) Time series of the autumn NPSSTI anomaly during 1960–2012 (units: °C).

Figure 2. Correlation between (a) autumn and (b) winter North Pacific SST anomalies and winter NEC regional mean snowfall intensity. (c) Correlation of SST anomalies between autumn and winter during 1960–2012.
Notes: Shadings means correlation is significant at the 95% confidence level. Note that all data were detrended prior to computation.
Figure 3. Linear regression of (a) winter SLP (units: hPa), (b) 500 hPa geopotential height (units: m) and (c) 850 hPa wind (units: m s\(^{-1}\)) on the detrended autumn NPSSI anomaly. Panels (d–f) are the same as (a–c) but for linear regression on detrended winter NEC regional mean snowfall intensity.

Note: Shaded areas indicate the regression is significant at the 90% confidence level.

Figure 4. (a) The observed (blue line) and predicted (red line) winter NEC regional mean snowfall intensity anomaly (mm), based on leave-one-out cross-validation, for the period 1960–2012. (b) As in (a) but for the result of an independent sample test for the period 1990–2012.
characteristic to that of winter NEC snowfall intensity (Figure 1(c)). The statistical correlation between them can reach up to 0.58 for the original series, and 0.42 after trends are removed, both significant at the 99% confidence level. The correlation coefficient between autumn NPSSTI and winter snowfall intensity for each station in NEC has also been computed (Figure 1(b)). The result shows uniform positive correlations over NEC, as well as the correlations in the southern part being relatively large. This close relationship indicates that the autumn North Pacific SST may, via certain physical processes, have a strong impact on winter NEC snowfall intensity.

The regression maps of winter atmospheric circulation fields on the autumn NPSSTI anomaly are shown in Figure 3(a)–(d). The positive autumn SST anomalies over the North Pacific can persist into winter and sustainably heat the local air. According to the ideal equation $P = \rho \times R \times T$ (where $P$ is the pressure of the ideal gas, $\rho$ is its density, $R$ is the constant, and $T$ is the temperature), warmer air temperature can evoke extensively positive SLP and 500 hPa height anomalies throughout the mid–high latitudes over the North Pacific and East Asia (Figure 3(a) and (b)). The positive anomalies of SLP and 500 hPa height can weaken the Aleutian low and the East Asian trough, consequently weakening the EAWM. Additionally, this anticyclonic anomaly appearing over the North Pacific can result in the delivery of southeasterly wind anomalies over NEC (Figure 3(c)). This anomalous southeasterly wind abates the cold and dry northwesterly wind from the high latitudes and increases local air temperature, which is conducive to local evaporation. Furthermore, the increased evaporation over the ocean surface due to the SST warming together with the anomalous southeasterly can result in more water vapor being transported from the North Pacific to NEC, providing favorable conditions for the intensification of snowfall events.

To depict the atmospheric conditions corresponding to intensified snowfall winter, we further regressed the winter atmospheric circulation fields on the synchronous winter NEC regional mean snowfall intensity anomaly (Figure 3(d)–(f)). The results show that when the winter NEC snowfall intensifies, a positive SLP and a positive 500 hPa height anomaly is apparent over the North Pacific and the East Asian continent (Figure 3(d) and (e)), which show quite similar patterns to the results from the regressions on NPSSTI. A correspondingly strong anomalous anticyclonic circulation at 850 hPa appears, inducing an anomalous southeasterly from the ocean to NEC, which can help bring water vapor from the Pacific (Figure 3(f)).

As discussed above, the autumn North Pacific SST may provide a useful predictor for winter snowfall intensity over NEC. We therefore use the NPSSTI as a predictor to calibrate the prediction model for the winter snowfall intensity over NEC using the linear regression method. The validation is implemented via leave-one-out cross-validation and independent sample testing.

Figure 4(a) presents the predicted result based on leave-one-out cross-validation and the corresponding observed snowfall intensity anomalies over NEC during 1960–2012. The observed interannual variability of the snowfall intensity can be predicted well and the correlation coefficient with the observation can reach up to 0.54, which is significant at the 99% confidence level. Furthermore, the upward trend of snowfall intensity is also reproduced by the prediction, especially after the late 1980s. Additionally, the correlation between the prediction and observation is 0.37 after trends are removed, also significant at the 99% confidence level, and with a low RMSE of only 0.16 mm.

The prediction scheme is further validated by conducting an independent sample test. In this case, the data of the first 30 years are used to establish the prediction model and then the prediction is implemented for the remaining years. Figure 4(b) shows the time series of predicted and observed snowfall intensity for the period 1990–2012. Their correlation can reach up to 0.45, significant at the 95% confidence level, and with a low RMSE of 0.15 mm. However, the correlation is only 0.21 after trends are removed, suggesting relatively strong skill in predicting its linear trend but relatively weak skill in predicting the interannual variation from the independent scheme, mainly due to poor prediction in recent years. This implies that the relationship between autumn SST and winter NEC snowfall intensity may be unstable and more studies are needed.

4. Conclusions

This paper has analyzed the winter snowfall intensity variation over NEC and its relationship with the autumn North Pacific SST over the midlatitudes during the period 1960–2012. The results show that the winter snowfall intensity over NEC experienced an upward trend during the last half-century, coinciding with a warming trend of autumn North Pacific SST. Their correlation can reach up to 0.42, significant at the 99% confidence level. Further analysis demonstrates that the autumn SST over the midlatitudes of the North Pacific is partly responsible for the winter NEC snowfall intensity variation from the interannual perspective. The warming anomalies over the North Pacific can be observed as spanning from autumn to winter and present obvious impacts on local atmospheric circulations as well as its adjacent regions. The persistent warming can change the winter atmospheric conditions by evoking extensively positive air pressure anomalies and an anomalous anticyclonic circulation over large parts of East Asia and the North Pacific. An anomalous southeasterly wind over NEC is then induced, abating the northerly wind from the high
latitudes. This pattern can warm the surface and increase the water vapor content, consequently favoring the occurrence of intense snowfall.

Accordingly, the autumn North Pacific SST is suggested as a potential predictor for winter snowfall events over NEC. Results from leave-one-out cross-validation and independent sample testing both present a high correlation with the observation, coinciding with a low RMSE.

Limitations of this study should be acknowledged, and there are still some issues that need further investigation in the future. First, whether the relationship between the autumn North Pacific SST and the winter snowfall intensity over NEC is stable needs to be clarified. Second, the impacts of other teleconnection factors on snowfall events in China need to be further explored, such as AO and Arctic sea ice, although some studies have already mentioned these aspects (e.g. Liu et al. 2012). Additionally, the impacts of anthropogenic warming on snowfall events in China are also deserving of further study, because of its different influences varying from region to region across China (Sun et al. 2010; Wang et al. 2012).

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