Comparison of Snowfall Variations over China Identified from Different Snowfall/Rainfall Discrimination Methods

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ABSTRACT

Based on the snowfall observations at 836 surface weather stations in China and the Daily Surface Climate Variables of China version 3.0 dataset for 1961–2013, capability of five methods with different objective criteria for identifying wintertime snowfall is evaluated, to provide reference for application of these methods in snowfall/rainfall discrimination. Methods I, II, III, IV, and V use the daily average surface air temperature (T_a), wet-bulb temperature (T_w), dynamic threshold T_w, 0-cm ground temperature, and 700–850-hPa thickness, respectively, to identify the snowfall. The results show that the climatological distribution of snowfall can be well produced by Methods I, II, and III. Method IV underestimates the snowfall days in eastern Tibetan Plateau (ETP), and Method V cannot yield the actual large numbers of snowfall days and amounts. Accordingly, the linear trends of snowfall days estimated from Methods I, II, and III largely agree with the observations, while a discrepancy is found in the linear trend of snowfall amounts over southeastern China (SEC). For interannual and decadal variations of snowfall, Method V shows the worst performance. It is more reasonable to use T_w to distinguish snowfall from rainfall instead of T_a, 0-cm ground temperature, and 700–850-hPa thickness; and the reference thresholds of T_w in northeastern China (NEC), northwestern China (NWC), ETP, and SEC are −1.5, −1.5, −0.4, and −0.3°C, respectively. The above results are beneficial to identifying snowfall in short-term climate prediction.

Key words: snowfall/rainfall discrimination method, wintertime snowfall, wet-bulb temperature (T_w), threshold, comparison

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1. Introduction

As the main form of precipitation in the top and high latitudes during the wintertime, snowfall is critical to crop growth, air quality, and water supply in those areas (Barnett et al., 2005). Heavy snowfall (larger than 10 mm day^{-1}) usually results in huge losses in transportation, electricity, economy, and human life (Changnon et al., 2006; Li et al., 2015; Yang and Liu, 2016). The accumulated snowfall on the ground can also increase the surface albedo and alter the surface energy budget, thus further affecting the land surface processes (Loth et al., 1993; Dai, 2008; Box et al., 2012). Consequently, change in snowfall has been of great interest in many research fields, including meteorology, hydrology, ecology, environment, and so on.

In recent years, a number of studies have been devoted to the climatic features, influential factors, and physical mechanisms of snowfall over different regions. For example, recent studies found that the abnormal 2009/2010 winter snowfall event and the 2013 winter snowstorm in the Middle East are both closely related to the anomalous activity of the North Atlantic Oscillation (NAO; Seager et al., 2010; Luo et al., 2015). The adjust-

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ment of circulation on the hemispheric scale by the Arctic Oscillation (AO) results in the heaviest snowfall or icy rainfall in southern China in the beginning of 2008 (Wang et al., 2009). It has been highlighted that the Arctic sea-ice decline in autumn can affect snowfall anomalies in the mid–high latitudes by altering water vapor transport and large-scale circulations (Wu et al., 2011; Liu et al., 2012; Wu, 2018; Chen et al., 2019). The weakening of the East Asian winter monsoon (Wang and He, 2013), the strengthening of the Hadley circulation (Zhou et al., 2017), the warming of the Pacific Sea Surface Temperature (SST; Feng and Chen, 2016), and the anomalous activity of the Scandinavian Atmospheric Teleconnection Pattern (Zhu and Chen, 2019) have been revealed to play significant roles in the snowfall change in China.

Different methods have been adopted by relevant studies to identify snowfall. For example, the snowfall observation data have been employed in quite a few studies (Liu et al., 2013; Sun et al., 2019), while Wang and He (2013) used winter precipitation to replace snowfall in northeastern China (NEC), and Dong et al. (2010) identified precipitation with a daily average temperature lower than 0°C as snowfall. In addition, the wet-bulb temperature (T_w) was also used to separate snowfall from precipitation in China (Zhang et al., 2016). Generally, the methods for snow identification fall into two categories. One is to record snowfall based on practical weather phenomena. The other is to use certain objective criteria to distinguish snowfall. In China, the station observations record snowfall according to the weather phenomena, but reliable ground data are sparse and require manual observation. In addition, the sharing of observed snowfall data is not timely. Therefore, it is necessary to develop the objective criterion method to identify snowfall from historical precipitation data.

A number of objective criterion methods have already been developed to select snowfall from the historical precipitation data. For instance, meteorological variables such as the 700–850-hPa thickness (Heppner, 1992; Xu et al., 2019), surface temperature (Bourgouin, 2000; Sun J. Q. et al., 2010), and T_w (Yamazaki, 2001) are commonly used to distinguish the precipitation phase. Recent studies have shown that T_w is much closer to the actual temperature of precipitation particles than the air temperature (T_a), making it potentially more suitable for the estimation of snowfall (Behrangi et al., 2018). Other meteorological variables such as humidity and vertical temperature lapse rate have also been considered as the key parameters affecting the phase of precipitation (Sims and Liu, 2015; Harpold et al., 2017a). Meanwhile, the threshold methods are widely applied to snowfall identification in many hydrological models, including the single threshold method (Refsgaard et al., 1992; Yang et al., 1997; Arnold et al., 1998) and dual-threshold method (Wigmosta et al., 1994; Kang et al., 1999; Chen et al., 2008). Though there are many objective criterion methods to distinguish the precipitation types, which are more convenient for identifying snowfall than observation, these methods need to be validated carefully before their practical application (Harpold et al., 2017b). If results of the objective criterion method and the observation differ, deviation will occur in the understanding of relevant scientific issues. Existing studies have already evaluated the objective criterion method. Comparing several methods for determining precipitation phase in the Owyhee Mountains of Idaho, USA, Marks et al. (2013) found that the dual-threshold approach (T_a) predicts too much snow, while results of T_a, dewpoint temperature, and T_w lower than 0°C are generally similar. Behrangi et al. (2018) compared the skills of several predictors including various atmospheric variables and their combinations when identifying surface precipitation phase in 33 snowfall subregions poleward of 35°S/N, and found that among all single predictors, T_w yields the highest skill score for determining precipitation phase and can reduce uncertainties resulting from regional differences. But few studies pay attention to the evaluation of different snowfall/rainfall discrimination methods in China. Therefore, based on the snowfall observation data, this study is motivated to conduct a detailed comparison among the snowfall in China identified with different objective criterion methods, with the aim to test the accuracy of the snowfall/rainfall discrimination methods.

The remainder of this paper is organized as follows. Section 2 introduces the data and snowfall/rainfall discrimination methods. Section 3 presents the capability of five objective criterion methods for describing the characteristics of wintertime snowfall, including the spatial distribution, long-term trend and interannual variations, the skill scores of various objective criterion methods, and the distribution of snow and rain with respect to the discrimination factors. The major findings of this study are finally summarized in Section 4.

2. Data and snowfall/rainfall discrimination methods

The observed daily snowfall data at 836 stations over China from the China Meteorological Administration (CMA) after quality control are used in this study and serve as a benchmark for the comparison. In this dataset, the snowfall is identified by the weather phenomena, and a snowfall day refers to as a day when the snowfall phenomenon occurs but rainfall does not. Meanwhile, the snowfall amount is measured as the snow water equivalent on the snowfall day (Wang and Zhou, 2018; Zhou et al., 2018).

The daily meteorological data (including precipitation, T_a, relative humidity, and air pressure) used for identification of snowfall with the objective criterion methods are from the version 3.0 of Daily Surface Climate Variables of China developed by the CMA. In this study, five objective criterion methods are adopted to identify the snowfall, and are evaluated and compared with the observed snowfall identified by the weather phenomena (abbreviated as OBS).

If the temperature near the ground is high, the snow falling in the air will melt, so the objective criterion method distinguishes snowfall from rainfall by giving a low threshold of low-level air condition. The five objective criterion methods given below, which have been used in relevant research and models, can all ensure a low-level temperature cold enough to meet the temperature conditions of snowfall. The specific identification criteria for the methods are as follows:

Method I: T_a is the most easily observed and obtained variable among the meteorological data. It is widely used in the objective criterion method. Dong et al. (2010) employed 0°C as the threshold to identify snowfall. Therefore, a day on which daily precipitation is more than 0.1 mm and daily average T_a is less than 0°C is defined as a snowfall day.

Method II: T_w is an important variable reflecting the air condition. Marks et al. (2013) used the 0°C T_w to distinguish snowfall from rainfall, and the result was satisfactory. Therefore, a day on which daily precipitation is more than 0.1 mm and daily average T_w is less than 0°C is identified as a snowfall day.

Method III, the dual-threshold method proposed by Ding et al. (2014): The precipitation type is determined by comparing T_w with the threshold temperature ($T_{\min}$ and $T_{\max}$). The threshold temperatures are calculated by the altitude, relative humidity, and average air pressure.

$$\text{type} = \begin{cases} \text{snow}, & \text{if } T_w \leqslant T_{\min}, \\ \text{sleet}, & \text{if } T_{\min} < T_w < T_{\max}, \\ \text{rain}, & \text{if } T_w \geqslant T_{\max}. \end{cases} \quad (1)$$

For this method, a day with daily precipitation more than 0.1 mm and T_w less than $T_{\min}$ is distinguished as a snowfall day.

Method IV: Low temperature near the ground is a prerequisite for the snowfall formation. Sun J. Q. et al. (2010) used 0-cm ground temperature lower than 0°C to identify snowfall in China. With this method, a day with daily precipitation more than 0.1 mm and daily average 0-cm ground temperature (T_0) below 0°C is distinguished as a snowfall day.

Method V: Compelling evidence suggests that the 700–850-hPa thickness could reflect lower-tropospheric temperature profiles that are critical in the determination of precipitation types (Heppner, 1992). Therefore, when the daily precipitation is more than 0.1 mm and the 700–850-hPa thickness is less than 1550 m, this day can be identified as a snowfall day.

Precipitation on the snowfall day distinguished by the five objective criterion methods is regarded as the corresponding snowfall amount. Considering the unity of the two sets of data, this research uses data of 681 stations, and defines four subregions (Fig. 1): NEC (north of 40°N, east of 115°E, including 118 stations), northwestern China (NWC; north of 40°N, west of 95°E, including 46 stations), eastern Tibetan Plateau (ETP; 28°–37°N, 90°–105°E, including 50 stations), and southeastern China (SEC; 28°–38°N, east of 110°E, including 158 stations). Our study focuses on the wintertime snowfall during 1961–2012. The wintertime period is defined as October of a specific year to April of the following year.

The Heidke skill score (HSS) proposed by Heidke (1926) is used in this study. It indicates that the accuracy of actual forecast is better than that of random forecast, and its value range is within [−1, 1]. When the forecast is completely correct, the value is 1. The specific calculation is as follows:

$$\text{HSS} = \frac{N_{11} + N_{00} - C}{N_{11} + N_{10} + N_{01} + N_{00} - C}, \quad (2)$$

where N_{11} indicates the number of events that is predicted as snowfall by the objective criterion method and actually observed as snowfall; N_{10} represents the number of events predicted to be snowfall and actually observed to be rainfall. If the forecast is rainfall but the actual observation is snowfall, this condition is classified as N_{01}. When both the forecast and the actual observation are rainfall, the event is expressed by N_{00}. The variable C is calculated as below:

$$C = \frac{(N_{11} + N_{10})(N_{11} + N_{01}) + (N_{01} + N_{00})(N_{10} + N_{00})}{N_{11} + N_{10} + N_{01} + N_{00}}. \quad (3)$$

In this study, the false alarm rate (R_{FA}) and missing report rate (R_{MR}) are used as test indices. These statistics can reflect the deviation of the objective criterion method in judging snowfall, and are calculated as:

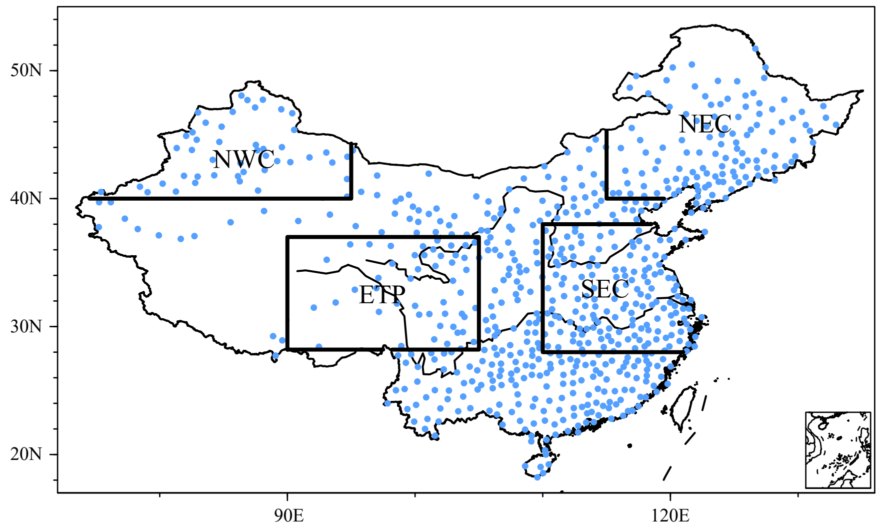

Fig. 1. Spatial distribution of stations (dots) in this study and domains of the four subregions (black lines): northeastern China (NEC; north of 40°N, east of 115°E, including 118 stations), northwestern China (NWC; north of 40°N, west of 95°E, including 46 stations), eastern Tibetan Plateau (ETP; 28°–37°N, 90°–105°E, including 50 stations), and southeastern China (SEC; 28°–38°N, east of 110°E, including 158 stations).

$$R_{FA} = \frac{N_{10}}{N_{11} + N_{10}}, \tag{4}$$

$$R_{MR} = \frac{N_{01}}{N_{11} + N_{01}}. \tag{5}$$

3. Results

3.1 *Spatial distribution*

Figure 2 shows the climatological distributions of snowfall days and amounts in China during the wintertime of 1961–2012, which are obtained from the OBS and aforementioned methods. As shown in Fig. 2a, distribution of the snowfall days exhibits obvious regional differences. The large values of snowfall days are mainly located in NWC, NEC, and ETP (Fig. 2a), which is consistent with previous studies (Sun X. Z. et al., 2010; Zhang et al., 2016). To be more specific, the number of snowfall days is more than 20 in NEC, and even exceeds 70 near the Greater Khingan Range of NEC. The number of snowfall days in NWC is more than 30. It increases gradually northward and reaches above 50 in the northernmost area. In ETP, more than 30 days are snowy, with a great value of over 70 appearing in parts of the Bayan Hara Mountains. The distribution of the snowfall amounts (Fig. 2b) is similar to that of the snowfall days. This similarity suggests that the great amounts of snowfall in these regions may largely result from the frequent occurrences.

In comparison, the snowfall days estimated from Methods I, II, and III (Figs. 2c, e, g) generally have a good agreement with the OBS in terms of the spatial pattern. These methods can well capture the distribution characteristics of snowfall days in China. The distributions of snowfall days obtained by using 0-cm ground temperature (Method IV) and 700–850-hPa thickness (Method V) are consistent with the OBS in northern China. The snowfall days gained from Method IV show an underestimation in the amplitude over ETP (Fig. 2i). For the estimation of snowfall days with Method V (Fig. 2k), relatively large values are seen in the top and lower reaches of the Yangtze River, suggesting an overestimation of the snowfall days there.

As for the geographic distribution of the snowfall amount, estimations from the five objective criterion methods essentially agree with the OBS in northern China. However, the value of large snowfall amount in the ETP estimated from Method III is relatively larger as compared to the OBS. For Method IV, the estimation in the ETP is far less than the OBS. Method V can faithfully show the distribution of large values of snowfall amount in northern China but overestimates the snowfall amount near the Changbai Mountain. Therefore, it can be concluded that results from all the methods are generally consistent in terms of the distribution of snowfall amount in northern China, while obviously differentiated in the ETP.

To more intuitively and quantitatively measure the differences between various objective criterion methods and observations, we classify the snowfall into four categories based on the classification of the CMA, i.e., light snowfall (0.1–2.5 mm day^{-1}), moderate snowfall (2.5–5 mm day^{-1}), large snowfall (5–10 mm day^{-1}), heavy snowfall (larger than 10 mm day^{-1}), and their average in

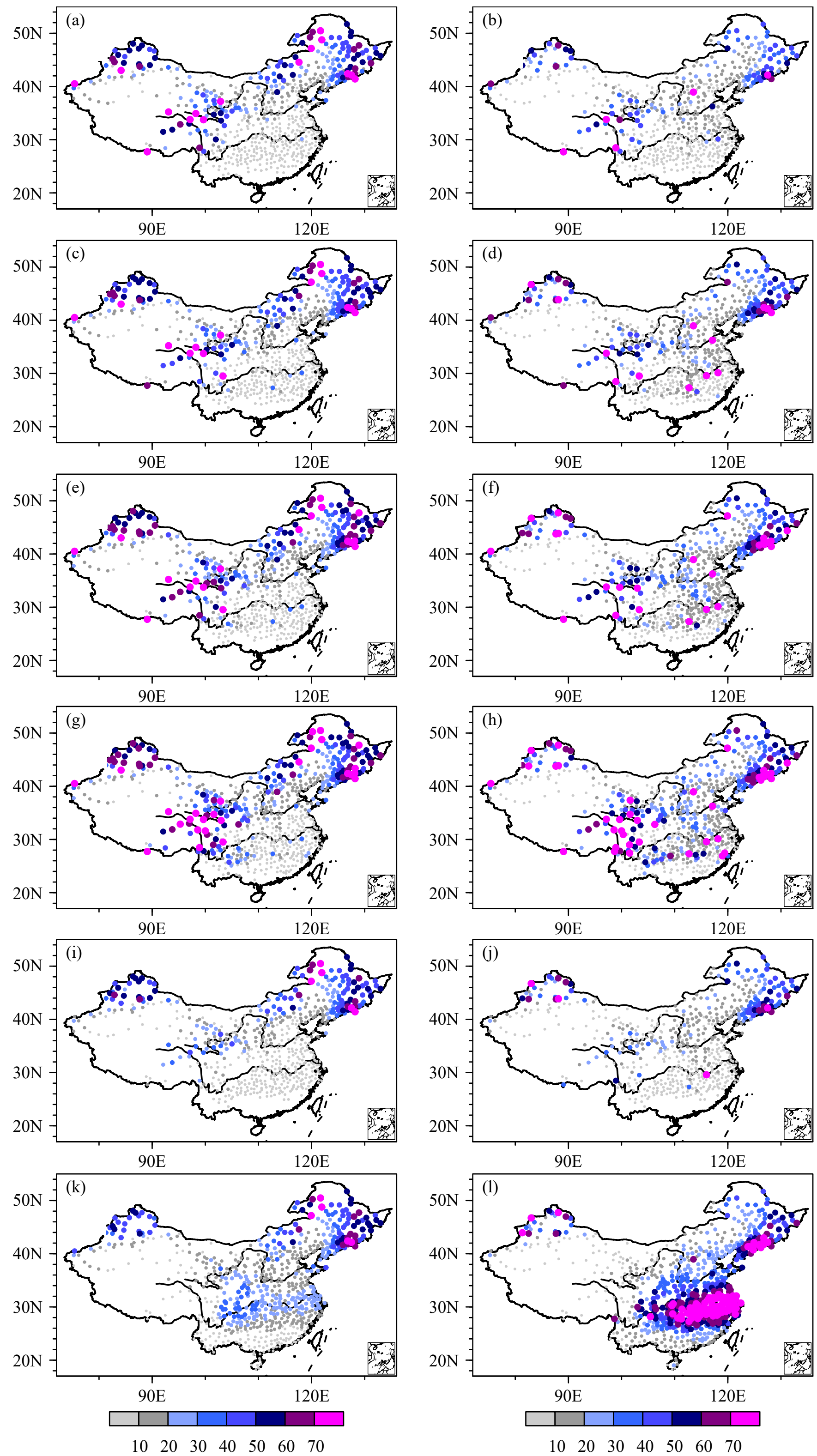

Fig. 2. Climatology of the number of snowfall days (left panel; day yr^{-1}) and snowfall amounts (right panel; mm): (a, b) OBS, (c, d) Method I, (e, f) Method II, (g, h) Method III, (i, j) Method IV, and (k, l) Method V.

NCE, NWC, ETP, and SEC. Figure 3 shows the climatology of the number of days for different categories of snowfall in the four subregions. The methods with which snowfall is identified by T_w (Methods II and III) overestimate the numbers of days and amounts of the four categories of snowfall in different grades in NEC, NWC,

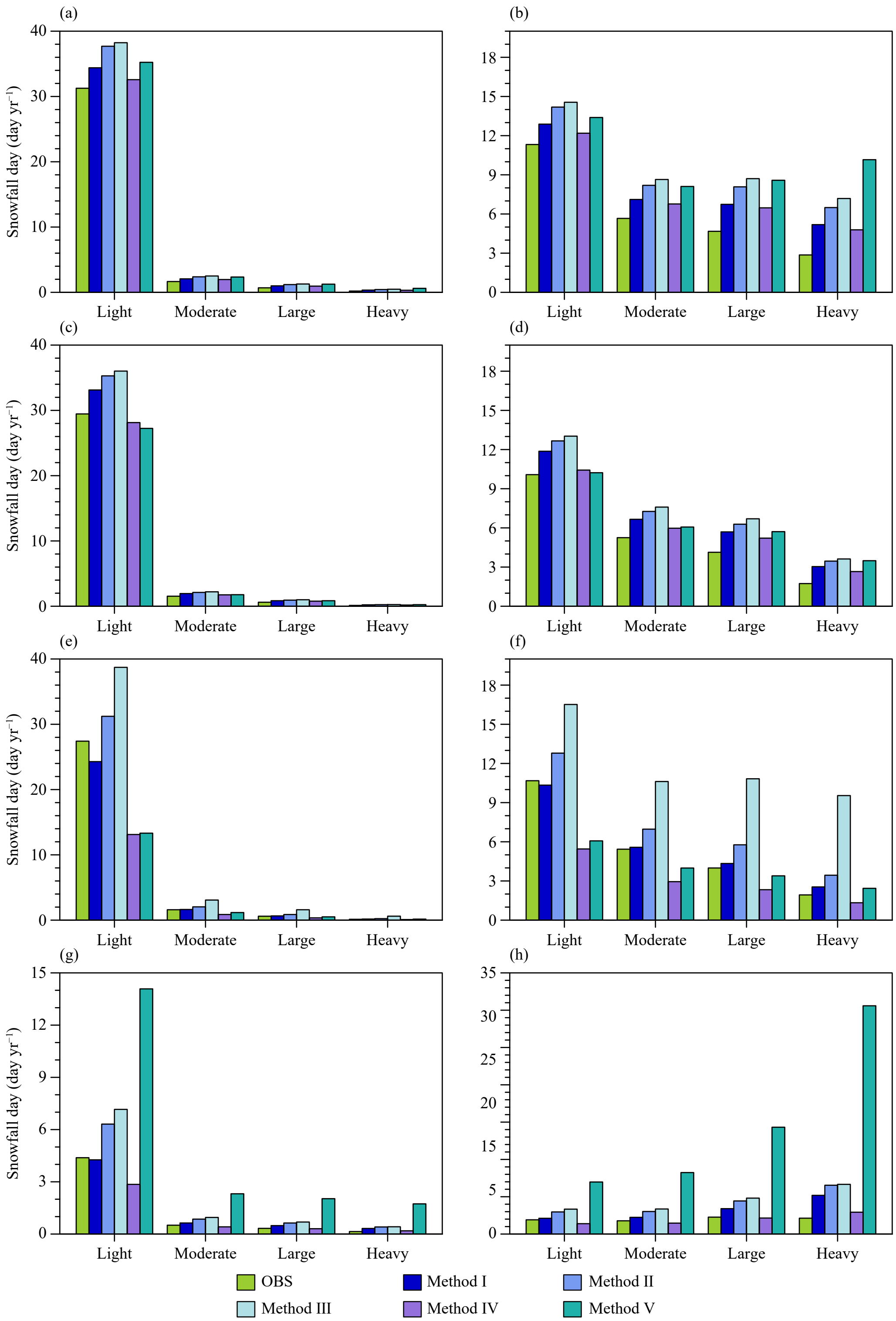

Fig. 3. Climatology of different categories of snowfall days (left panel; day yr^{-1}) and snowfall amounts (right panel; mm) over (a, b) NEC, (c, d) NWC, (e, f) ETP, and (g, h) SEC.

ETP, and SEC. For the estimation from Method I, snowfall days and amounts of all four categories in NEC and NWC are more than the observations, while an underestimation of light snowfall days and amounts in the ETP is suggested. It can be clearly seen that the days and amounts of different snowfall categories in the ETP and SEC obtained by 0-cm ground temperature (Method IV) are less than the observed data. When 700–850-hPa thickness is used to distinguish snowfall (Method V), the numbers of snowfall days and amounts in the ETP are underestimated, and the days and amounts of different snowfall categories in SEC are overestimated to a large extent.

Seen from the climatology of different categories of snowfall, there is no significant discrepancy in each category among results of different snowfall/rainfall discrimination methods in NWC and NEC, while all the methods show obvious differences in ETP and SEC.

3.2 *Long-term trend and interannual variations*

The trend of snowfall is one focus of the snowfall research. To better evaluate the performance of objective criterion methods in describing secular changes of the wintertime snowfall, we plot the linear trends of snowfall days and amounts in Fig. 4. As revealed in the OBS (Figs. 4a, b), the number of snowfall days in China shows an overall decreasing trend, and the snowfall amounts in the east of NCE, NWC, and ETP show an increasing trend. It can be seen from the OBS that the trend of snowfall days is not completely consistent with that of the snowfall amounts, which has been explained by previous studies (Zhou et al., 2018). Methods I, II, and III can show the general decreasing trend of snowfall days in China, while Methods IV and V demonstrate a significant downward trend only in NEC. The increasing trend of the snowfall amounts in NEC, NWC, and ETP gained from the objective criterion methods generally corresponds with the OBS, but the results are quite different between them in SEC.

Among snowfall studies, many focus on the interannual and interdecadal variations. In order to provide reference for the accuracy of the objective criterion method in analyzing the interannual and interdecadal snowfall variations in China, Fig. 5 shows the detrended time series of the snowfall days and amounts in the four main snowfall areas from the OBS and the objective criterion methods, which represent the interannual variation of wintertime snowfall. As observed in Fig. 5, in NEC and NWC, the correlation coefficient between the objective criterion method and the OBS shows a high positive value of over 0.9 except for Method V. The interannual variations of the snowfall days and amounts obtained by Methods I–IV are generally consistent with those of the OBS. Methods I and II show an interannual variation in the ETP that is the closest to the OBS. For the snowfall days and amounts, the correlation coefficients between Method II and OBS are 0.96 and 0.89 in SEC, respectively, which are the highest among results of the five objective criterion methods.

Figure 6 shows the 11-yr Gaussian filtered time series of the snowfall days and amounts in the snowfall subregions from the OBS and objective criterion methods, which reflect the interdecadal variation of snowfall. For the snowfall days and amounts, the decadal variations estimated with Methods I, II, III, and IV agree with the OBS in NEC. It can be seen that the decadal variation of the snowfall days in NWC is generally similar before the mid-2000s between the OBS and results of Methods I, II, and III, while it significantly differs after the mid-2000s among them (Fig. 6c). In the ETP (Figs. 6e, f), the results of Methods I and II can match the OBS best. The decadal variation of snowfall in SEC obtained by Method II is the most consistent with the OBS. It is worth noting that the interannual and decadal variations obtained from Method V (700–850-hPa thickness less than 1550 m) in subregions are not accurate compared with the OBS. This evaluation can be considered as a reference when using the objection criterion method to analyze the interannual and decadal variations of snowfall, and the failure to represent interannual and decadal variations deserves further discussion and explanation.

3.3 *The skill scores of various methods with objective criteria*

In order to evaluate the objective criterion method quantitatively, taking the weather forecast scores as reference, Fig. 7 shows the HSS of the five snowfall identification methods in different subregions. The results show that the scores of Method I in NEC and NWC are more than 0.8, indicating better performance than that in ETP and SEC. Method II, which uses a uniform threshold of T_w to distinguish snowfall, yields high scores in all four subregions, among which the score in ETP is the highest compared to results of other methods. This method is not very sensitive to regional differences, and the effect is relatively stable. The dynamic threshold of T_w is used in Method III to distinguish snowfall, producing high scores for all subregions except ETP. Although the dynamic threshold value considers the influence of altitude, relative humidity, and air pressure, Method III has lower scores than Method II, which shows that it still needs to be improved. Using 0-cm ground temperature to distinguish snowfall from rainfall (Method IV), the score is solely high in NEC with a number more than 0.7, while it is low for other subregions, especially ETP. Among the five methods, Method V has the lowest scores, and its effect in distinguishing between rain and snow is relatively poor, especially in ETP. It can be seen from Fig. 7 that the skill scores show obvious regional dependence, indicating regional differences in the effects of snowfall/rain-

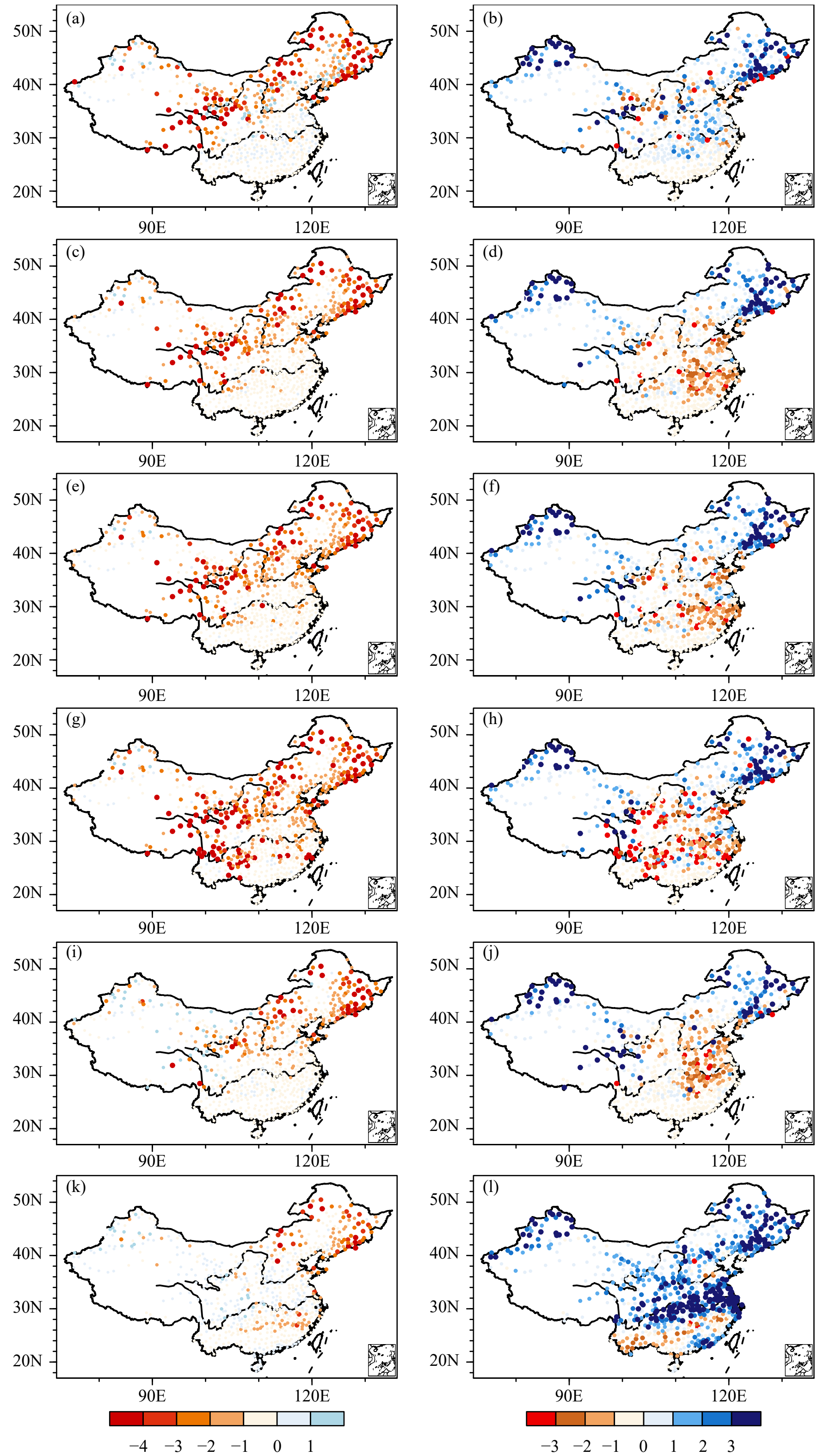

Fig. 4. Linear trends of the snowfall days (left panel; day decade^{-1}) and snowfall amounts (right panel; mm decade^{-1}): (a, b) OBS, (c, d) Method I, (e, f) Method II, (g, h) Method III, (i, j) Method IV, and (k, l) Method V.

fall discrimination methods. The scores obtained by different methods in NEC and NWC are generally higher than those in ETP and SEC. Using T_w to identify snowfall can reduce the impact of regional change, and the performance is relatively stable.

The HSS is an overall evaluation method. For more

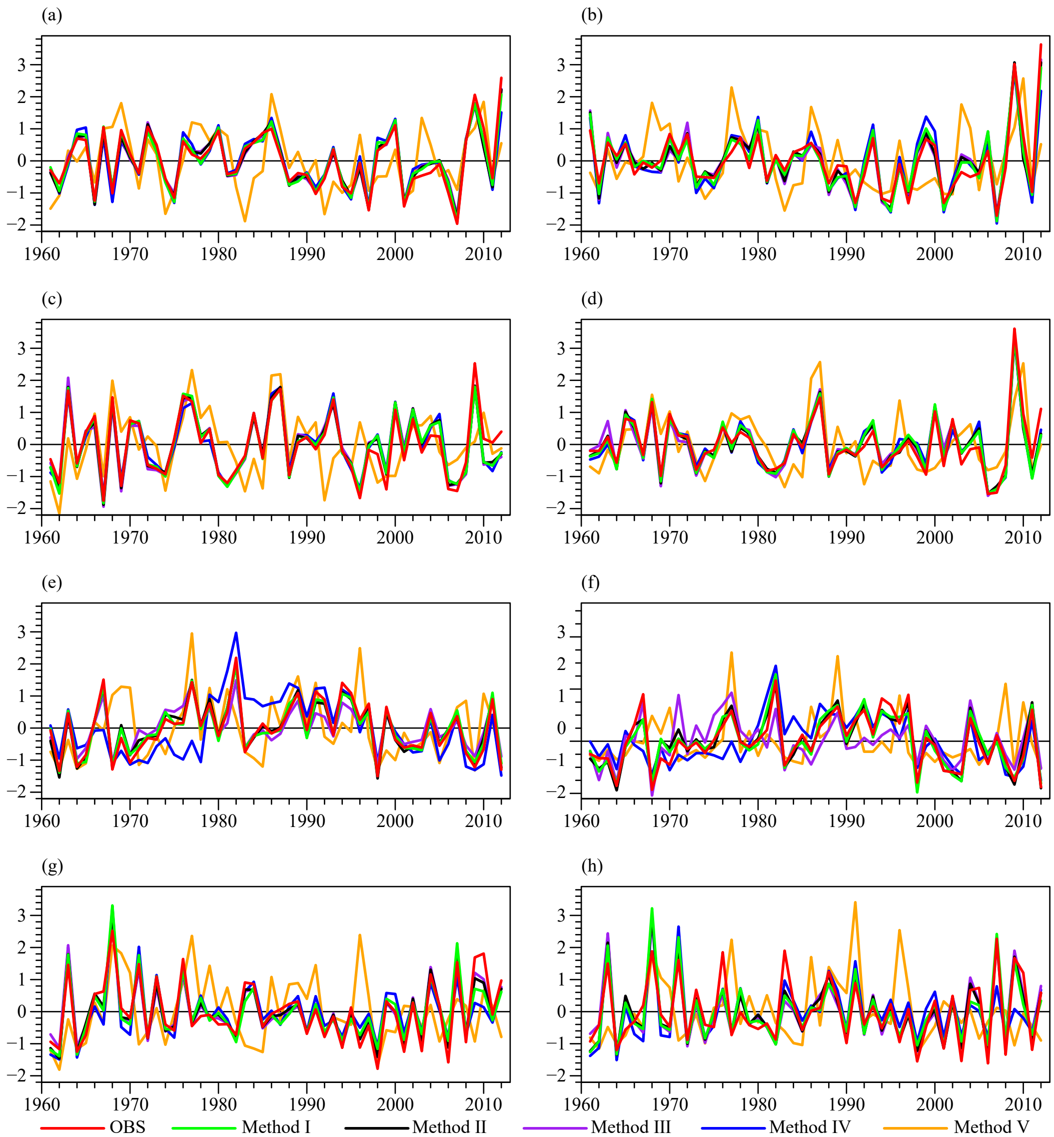

Fig. 5. The detrended time series of snowfall days (left panel) and snowfall amounts (right panel) identified over (a, b) NEC, (c, d) NWC, (e, f) ETP, and (g, h) SEC with different methods.

detailed evaluation of various snowfall/rainfall discrimination methods, the contingency table of R_{FA} and R_{MR} is given in Table 1. R_{FA} and R_{MR} can reflect the deviation of snowfall judgment. From Table 1, it can be seen that the two methods by which T_w is adopted to distinguish snowfall from rainfall (Methods II and III) have lower R_{MR} values than other methods, but their R_{FA} values are the 2nd (Method III) and 3rd (Method II) highest, following that of Method V. Methods II and III identify more rainfall events as snowfall events. Using 0-cm ground temperature to distinguish snowfall (Method IV) leads to a lower R_{FA}, and R_{MR} is the highest except for that of Method V. More snowfall events are identified as rainfall events by Method IV. The variables R_{FA} and R_{MR} are the highest when using Method Ⅴ to distinguish the snowfall, so the corresponding comprehensive skill score is also the lowest among those methods. This further explains the overestimation or underestimation of snowfall days by those five objective criterion methods in Section 3.1. The variables R_{FA} and R_{MR} also reflect the threshold value. A high threshold value leads to a high R_{FA}, while a low threshold value result in a high R_{MR}. Based on the above analysis, the threshold of Method I is suitable because of the small difference between R_{MR} and R_{FA} in NEC and NWC, but the threshold of 0°C is low in ETP and SEC. The thresholds of Methods II and III in the four snowfall subregions are too large, and when employing T_w to distinguish snowfall, a reasonable threshold should be lower than 0°C. Similarly, a reasonable threshold greater than 0°C should be adopted when 0-cm ground

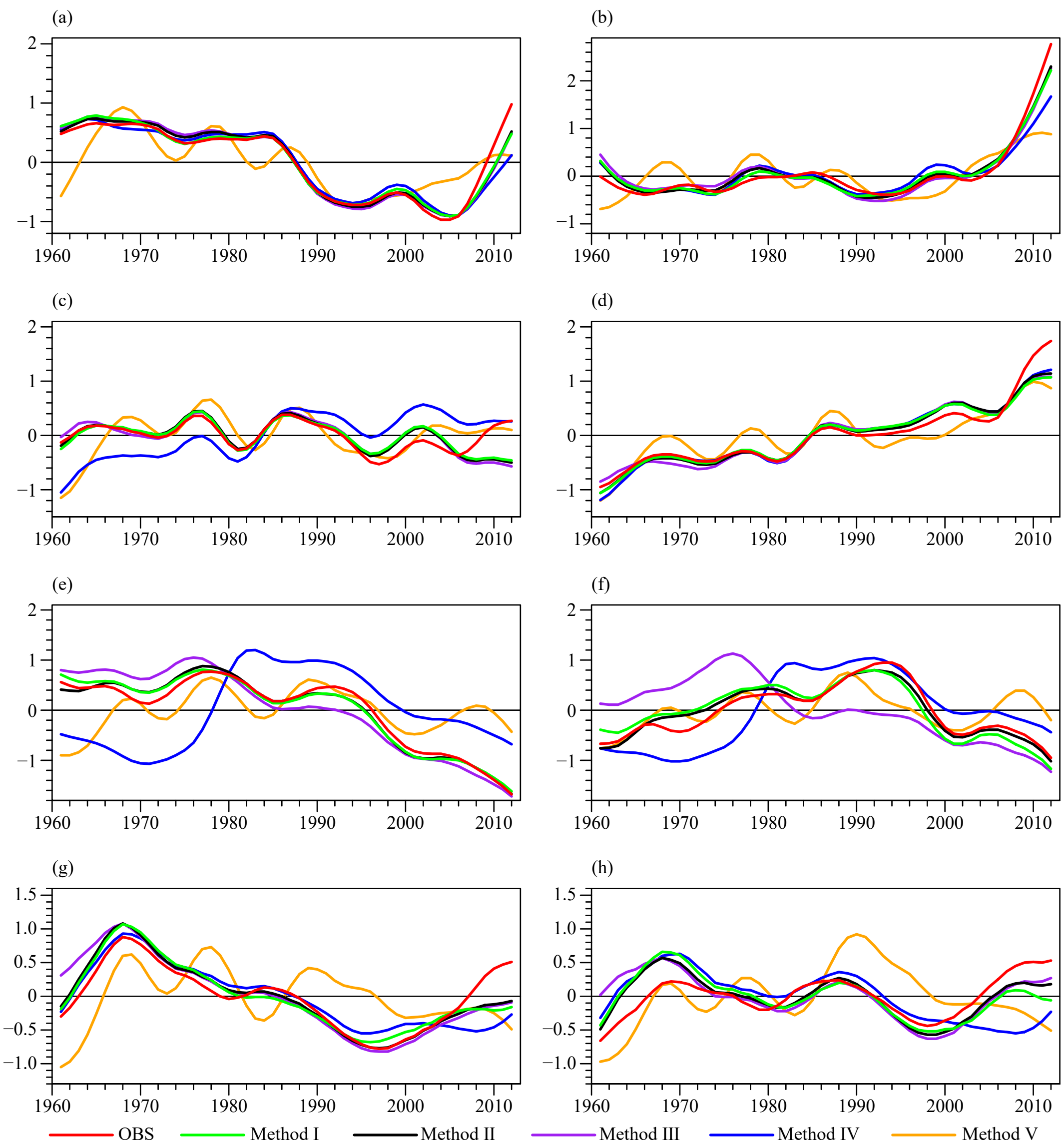

Fig. 6. The 11-yr Gaussian filtered time series of light snowfall days (left panel) and light snowfall amounts (right panel) over (a, b) NEC, (c, d) NWC, (e, f) ETP, and (g, h) SEC generated by different methods.

temperature is used to discriminate snowfall from rainfall. The poor performance of Method V is due to the selection of discriminant variable, and the 700–850-hPa thickness is not a reasonable variable for snowfall identification.

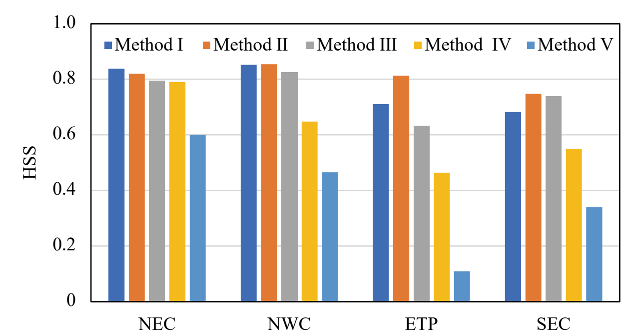

Fig. 7. The Heidke skill scores (HSS) of various snowfall/rainfall discrimination methods in the four subregions.

3.4 *Distributions of snow and rain with respect to the discrimination factors*

The five objective criterion methods mentioned above respectively use daily average T_a, daily average T_w, daily average T_w with threshold, daily average 0-cm ground temperature, and 700–850-hPa thickness to identify snowfall. In order to determine which variable is more reasonable to distinguish snowfall from rainfall in different subregions, Figs. 8, 9 show the sample size distributions of snow and rain with respect to those four variables. A snowfall event refers to a day when only snow-

Table 1. The contingency table of the false alarm rate (R_{FA}; %) and missing report rate (R_{MR}; %)

Method	NEC		NWC		ETP		SEC	
	R_{FA}	R_{MR}	R_{FA}	R_{MR}	R_{FA}	R_{MR}	R_{FA}	R_{MR}
I	5.58	6.27	3.87	5.14	11.09	24.42	20.79	36.05
II	10.05	1.65	6.62	1.45	14.78	6.73	27.90	16.78
III	11.52	1.41	8.19	1.05	31.12	3.23	31.98	12.70
IV	5.08	10.89	3.67	20.42	4.80	56.40	15.35	56.24
V	15.37	13.03	10.79	27.01	47.40	75.16	70.55	21.36

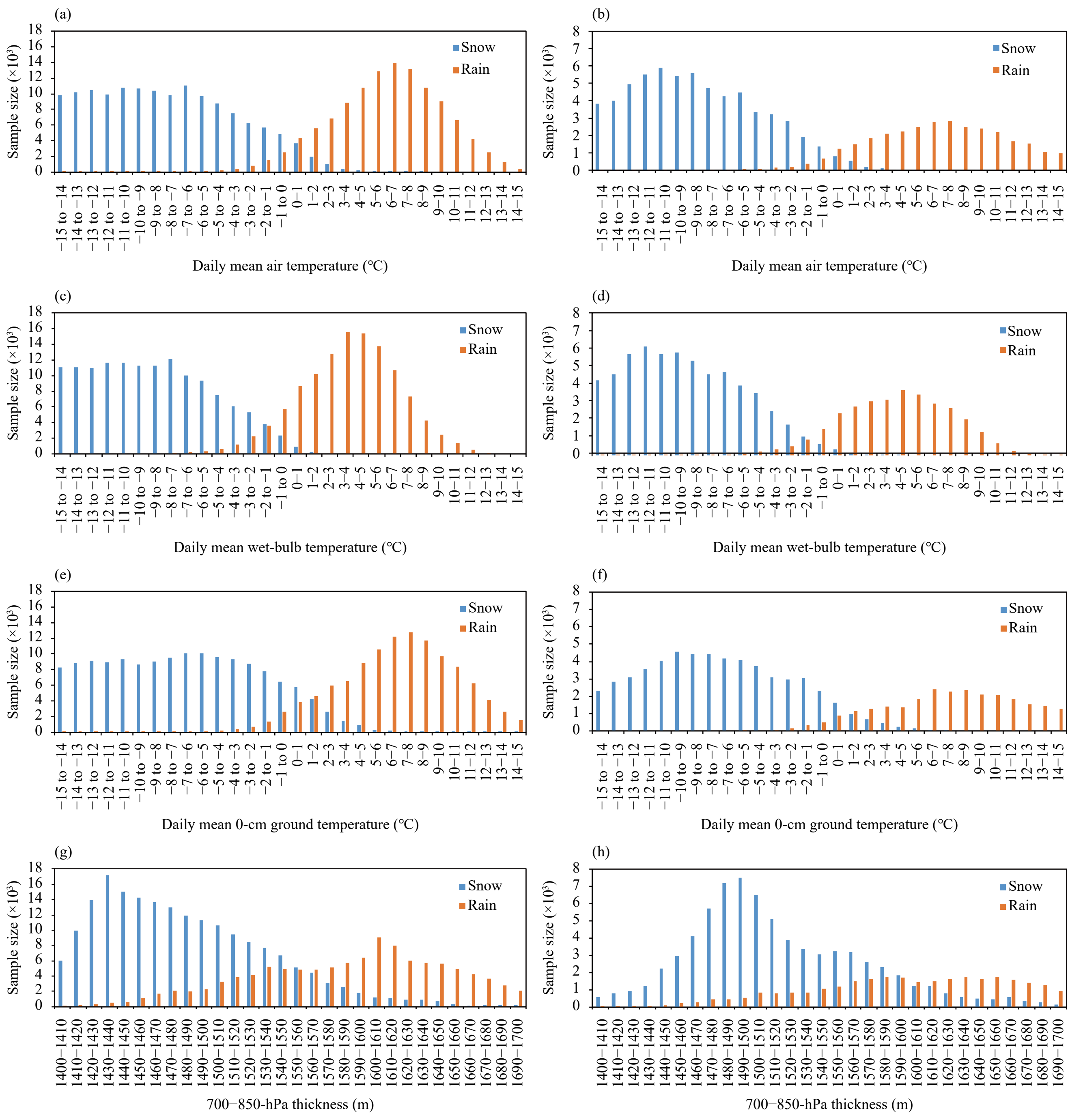

Fig. 8. Sample size distributions of snow and rain with respect to (a, b) daily mean air temperature (T_a), (c, d) daily mean wet-bulb temperature (T_w), (e, f) daily mean 0-cm ground temperature, and (g, h) 700–850-hPa thickness over NEC (left panel) and NWC (right panel).

fall is observed. If there are both snowfall and rainfall on that day, it is regarded as a rainfall event. In NEC, when $T_a \geqslant -3$°C, 98.9% of the samples are rainfall events, while the ratio of snowfall events can reach 99.4% when

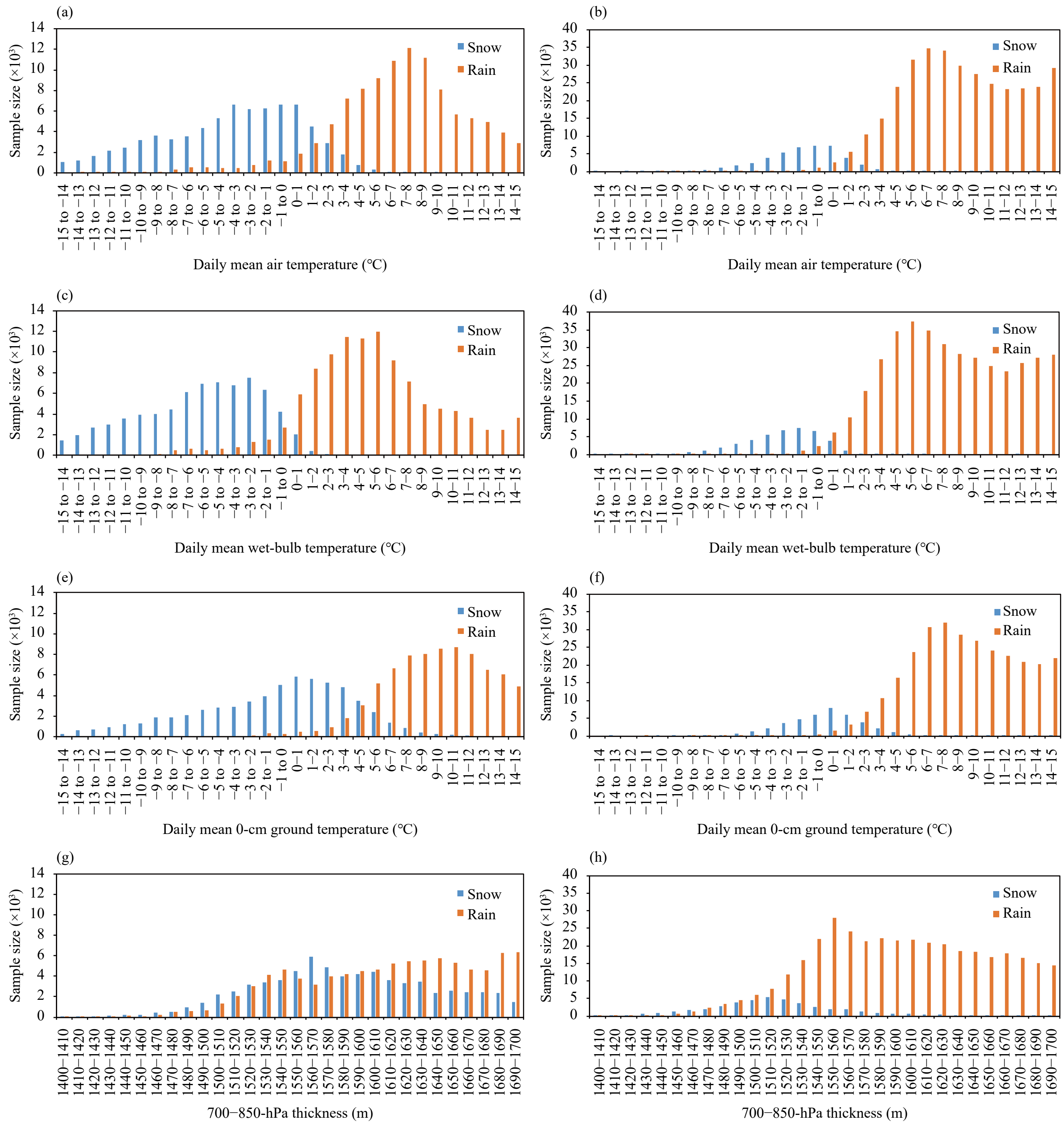

Fig. 9. As in Fig. 8, but for over ETP (left panel) and SEC (right panel).

T_a < 3°C. There are 23,574 snow events and 21,701 rainfall events in the range of −3 to 3°C (Fig. 8a). With the daily average T_w, 98.6% of the samples are rainfall events when $T_w \geqslant -4$°C, and 99.8% are snowfall events when T_w < 1°C; 18,472 snowfall events and 21,439 rainfall events can be found in the range of −4 to 1°C (Fig. 8c). Seen from the distribution of rain and snow events in NEC corresponding to 0-cm ground temperature (Fig. 8e), 98.5% of the events are rainfall events when $T_0 \geqslant -2$°C, while 99.4% of them are snowfall events when T_0 < 5°C. Within the range of −2 to 5°C, there are 29,050 snowfall events and 33,850 rainfall events. It can be seen from Fig. 3g that the overlapping range of snowfall and rainfall events with respect to 700–850-hPa thickness is large, and the accuracy is poor compared with that of the other objective criterion methods.

In NWC, 98.6% of them are rainfall events when $T_w \geqslant -4°C$, while 99.3% are snowfall events when $T_w < 0°C$; 5931 snowfall events and 3229 rainfall events are found in the range of −4 to 0°C (Fig. 8d). Over the ETP, the proportion of rainfall events is 98.2% when $T_w \geqslant -5°C$, while that of snowfall events is 99.8% when $T_w < 2°C$. In the range of −5 to 2°C, there are 34,424 snowfall events and 21,318 rainfall events (Fig. 9c). Meanwhile, 99.8% of the events in SEC are rainfall events when $T_w \geqslant -2°C$, while 99.0% of them are snowfall events when $T_w < 2°C$, and 19,299 snowfall events and 20,156 rainfall events occur in the range of −2 to 2°C (Fig. 9d). The same conclusion can be obtained in all four subregions. It can be seen that the samples in the overlap of rainfall and snowfall events with respect to T_w are the least, followed by those related to daily average T_a and daily average 0-cm ground temperature. In addition, the samples in the overlapping range of rain and snowfall events with respect to 700–850-hPa thickness are the most.

Therefore, it is more reasonable to apply T_w instead of T_a, 0-cm ground temperature, or 700–850-hPa thickness to snowfall identification. In Method II, T_w is adopted to distinguish snowfall, but its threshold is larger than the actual threshold value, which makes more rainfall be recognized as snowfall and results in the failure to show the actual condition. Method III uses the dynamic threshold of T_w to distinguish snowfall. The dynamic threshold considers the influence of altitude, relative humidity, and air pressure, but the resultant score is lower than Method II, which shows that this method still needs to be improved.

In order to find the reasonable thresholds for snowfall identification in the four subregions with T_w, we take each 1°C T_w as a cell, and select the cell with the smallest overlap of rain and snow events so as to determine the threshold according to the proportion of samples of rain and snow events in this cell. Table 2 shows the minimum overlapping range of rain and snow events with respect to T_w and the reasonable thresholds in different subregions. In NEC, the numbers of both rain and snow samples in T_w range of −2 to −1°C are the least, which are 3769 and 3633, respectively. According to the proportion, the threshold of T_w can be determined as −1.5°C. Similarly, in NWC, the samples of rain and snow events in T_w range of −2 to −1°C are 1051 and 876, respectively, and the threshold is −1.5°C. In the ETP, there are 4228 rain and 2725 snow events in the cell of −1 to 0°C, and the threshold is −0.4°C. A reasonable T_w threshold for SEC is −0.3°C.

Using the improved T_w threshold to identify snowfall, the HSS are 0.847 and 0.857 respectively in NEC and NWC, which are higher than the results of the five methods mentioned above. When this improved method is employed to determine snow in ETP and SEC, the HSS are 0.811 and 0.743, respectively, slightly lower than 0.813 and 0.748 in Method II. However, through calculation and comparison, it is found that the values of R_{FA} and R_{MR} for the improved T_w method are close. Compared with Methods II and III, which have high R_{FA} and low R_{MR}, the improved threshold can effectively reduce the possibility of mistaking rainfall for snowfall, so it can be concluded that the improved T_w threshold is more reasonable. This improved T_w threshold, which is based on the distribution of observed rain and snow, can be applied in relevant studies for snowfall identification.

4. Conclusions

It is reliable to distinguish snowfall from rainfall according to observed weather phenomena in station data, but the sharing of observed snowfall data is often not timely. Therefore, the objective criterion method is usually used to separate snowfall from precipitation in snowfall research. Despite the convenience of the method, its applicability has not been evaluated in detail. In order to provide reference for the applicability of the objective criterion method in China, this paper evaluates the capability of five objective criterion methods to describe the characteristics of wintertime snowfall. The main conclusions are summarized as follows.

The distribution of snowfall in China has obvious regional characteristics. The large numbers of snowfall days produced by the Methods I, II, and III, which are consistent with the OBS, are mainly located in NWC, NEC, and ETP considering the climatology. The climatological distribution of snowfall amounts can be well produced by those three methods, although the amount is overestimated in SEC. Method IV underestimates the

Table 2. The minimum overlapping range of rain and snow events with respect to wet-bulb temperature (T_w) and the reasonable threshold in different subregions

	NEC	NWC	ETP	SEC
Minimum overlap cell	(−2°C, −1°C)	(−2°C, −1°C)	(−1°C, 0°C)	(−1°C, 0°C)
Snow sample	3769	1051	4228	6712
Rain sample	3633	876	2725	2377
Threshold of T_w	−1.5°C	−1.5°C	−0.4°C	−0.3°C

number of snowfall days in the ETP, resulting in less snowfall, and Method V cannot produce the actual large numbers of snowfall days and amounts.

The linear trends of the snowfall days estimated from Methods I, II, and III substantially agree with that in the OBS as they all show an overall decreasing trend. Methods IV and V only produce a significant decrease of snowfall days in NEC. In contrast, the snowfall amounts in NEC, NWC, and ETP produced by five objective criterion methods present the same increase trend as the OBS, but there is a discrepancy in SEC.

In this snowfall study, Methods I–IV can show the interannual and decadal variations of snowfall in NEC and the interannual variation in NWC. When analyzing the snowfall in the ETP, Methods I and II yield results closer to the observations. Differences exist between the snow variation characteristics derived from Method V and the OBS, which should be a focus of the related study. The findings are instructive for application of the objective criterion method in short-term climate prediction.

For the discrimination factors, it is more reliable to choose T_w to distinguish snowfall instead of T_a, 0-cm ground temperature, and 700–850-hPa thickness. When using T_w, a spatially consistent threshold is unreasonable, and regional differences should be considered. The reference thresholds of T_w in NEC, NWC, ETP, and SEC are −1.5, −1.5, −0.4, and −0.3°C, respectively. Since snowfall is affected by various meteorological variables including altitude, temperature, relative humidity, and vertical temperature lapse rate, how to establish an objective and easy method for snowfall/rainfall discrimination is still an open issue in future studies.

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