A new method for determining the single threshold temperature of precipitation phase separation

Yulian Liu[a,b] Guoyu Ren[a,c] Xiubao Sun[a,c] Xiufen Li[d,e] Hengyuan Kang[f,]

[a] Department of Atmospheric Science, School of Environmental Science, China University of Geosciences, Wuhan 430074, China;
[b] Heilongjiang Climate Center, Harbin 150030,China;
[c] Laboratory for Climate Studies, National Climate Center, CMA, Beijing100081,China;
[d] Innovation and Opening laboratory of Regional Eco-Meteorology in Northeast, China Meteorological Administration
[e] Heilongjiang Provincial Institute of Meteorological Sciences, Harbin 150030,China.
[f] Harbin Meteorological Bureau, Harbin 150028,China.

Corresponding author: G. Ren (guoyoo@cma.gov.cn)

Submitted to *hydrology and earth system sciences* for possible publication

Abstract

Separating the solid precipitation from liquid precipitation in existing historical precipitation observation data is a key problem in the monitoring and study of climate anomaly and long-term change of extreme precipitation events in difference phases. Based on the comprehensive analysis of the historical daily air temperature, precipitation data, and visual observations of precipitation phase in the northern areas of Mainland China (north of 30 °N), this paper proposes a Snowday-Direct-Definition-Mothod (SDDM) to determine the threshold temperature of rainfall and snowfall for a complex and diverse geographical and climatic region. A statistical model of separating solid from liquid precipitation was established. The main conclusions include: (1) in northern China, the threshold temperature range of the daily mean temperature of rain and snow determined based on weather phenomenon records was from -1.2 ℃ to 6.3 ℃, with a difference of 7.5 ℃ among areas, and a mean threshold value of 2.8 ℃ for the whole region. The temperature in the northern Tibetan Plateau was the highest (generally higher than 4 ℃). The low threshold temperature values appeared in eastern Northeast China, North China, and northern Xinjiang Autonomous Region, which were less than 2 ℃. (2) The threshold temperature decreased with increase in longitude east of 100 °E, but it was more dispersed in the areas west of 100 °E. The threshold temperature was generally higher and more variable in the low-latitude, and lower and more concentrated in the high-latitude. The threshold temperature generally increased with altitude. (3) There was a negative correlation between the threshold temperature and the annual precipitation. It was also negatively correlated with the annual average relative humidity. (4) The multivariate regression fitting model developed based on the annual mean temperature, altitude, and annual precipitation was able to simulate the threshold temperature of the precipitation phase in northern China well. The calculated threshold temperature based on the model has a smaller relative error for snow days and snowfall, and the stations with less than 10% of relative error reached 97% and 92%, respectively. The results of this study can therefore be applied for the separation of solid and liquid precipitation events in the areas without sufficient weather phenomenon records.

Key words: Northern China; Precipitation; Phase; Separation; Statistical model; Regional differences

1. Introduction

Precipitation is an important parameter used to characterize climate characteristics and climate change, and it is one of the key components of the Earth's water and energy cycles (Loth et al., 1993). The influence of different phases of precipitation on the surface water and energy cycles is enormous (Vavrus, 2007; Wu et al., 2009), as more than 50% of the global meteorological disasters are closely related to abnormal precipitation, including extreme intense rainfall, heavy snowfall or blizzards, freezing rain and droughts (WMO, 2013; Wang et al., 2005). Under the similar precipitation amount, the effect of different phases of precipitation on the Earth's surface system and the social and economic system is clearly different, thus it is important to distinguish and understand the characteristics and anomalies of snowfall or mixed-phase events and their causes. In addition, in monitoring long-term changes in extreme precipitation events on sub-continental to global scales, it is also necessary to distinguish rainfall and snowfall events from historical precipitation data.

To date, many studies have been published on the characteristics and multi-decadal variation of snowfall in China (e.g. Jiang et al., 2003; Yang et al., 2005; Qin et al., 2006; Liu et al., 2012, 2013; Zhang et al., 2015). Also, many studies on both the global and Asian regional total precipitation and extreme precipitation events and their long-term change have been reported (Becker et al., 2012; Noake et al., 2012; Polson et al., 2013; Blanchet et al., 2009; O'Hara et al., 2009; Kunkel et al., 2009; Ren, 2007, 2015, 2016; Liu et al., 2011; Fang et al., 2011; Zhong et al., 2013; Wan et al., 2013; Yu et al., 2014; Xiao et al., 2015; Dang et al., 2015). The analyses of precipitation change generally showed a detectable trend toward more precipitation amount and more frequent extreme rainfall events over the last decades. All of these studies have greatly enriched the understanding of global precipitation and snowfall climatology and the climate change and variability in different regions and varied scales.

There are few direct observations of precipitation phase at the global scale. Researchers can partition precipitation phase, but there are difficulties in doing so at air temperatures near freezing (Ding et al., 2014; Jennings et al., 2018; Stewart et al., 2015). Even in the case of relatively abundant meteorological observational data in China, some works often need to use certain methods to separate the different phases of precipitation in historical precipitation data.

Previous works have discussed the phase identification of precipitations. Bourgouin (2000) introduced the area-method in separating different precipitation phases, which is based on the vertical thermal structure of the atmosphere, the distribution of condensation nuclei of water vapor, and the descent velocity to predict the precipitation phase. Dai (2008) analyzed the temperature range of precipitation phase change on the continent and the ocean, and discussed the relationship between the phase change temperature and the pressure. Kienzle et al. (2008) proposed to use two input variables (temperature and range) to estimate daily snowfall from precipitation data. Ye et al. (2013) suggested the site-specific threshold values of air temperature and dewpoint to discriminate between solid and liquid precipitation for improving snow and hydrological modeling. Froidurot et al. (2014) pointed out that surface air temperature and relative humidity show the greatest explanatory power. Sims and Liu (2015) proposed that atmospheric moisture impact precipitation phase and that wet-bulb temperature, rather than ambient air temperature, be used to separate solid and liquid precipitation. Harpold et al. (2017) and Jennings et al. (2018) pointed out that a humidity phase prediction method had similar or more effective accuracy compared to temperature phase prediction method in separating snowfall from precipitation data. This was also shown by other authors (e.g., Ding et al., 2014; Harder and Pomeroy, 2013, 2014; Marks et al., 2013; Feiccabrino et al., 2015).

However, in a larger scale study, it is usually difficult to obtain the observational records in the global dataset. To study the separation methods of precipitation phrase on the continental and global scales, only the surface air temperature data are more easily available. Dew point temperature and relative humidity data, for example, can be used only in regional scale investigation, despite their good suitability as indicators of precipitation phrase separation (Harpold et al., 2017a,b; Jennings et al., 2018).

In some hydrological models, the solid-liquid precipitation separation used the double threshold temperature method (Wigmosta et al., 1994; Kang et al., 1999, 2001; Chen et al., 2008) and the single threshold temperature method (Arnold et al., 1998; Wang et al., 2004). The customized threshold temperature method has a larger error (Marks et al., 2013; Han et al., 2010). Han et al. (2010) developed an insurance probability method to determine the single threshold temperature and a fitted model in China.

In this work, we used the daily observational data of the national stations for years 1961–2013 in mainland China, including the long-term records of air temperature, precipitation, relative humidity and visual observations of precipitation phase. We applied the Snowday Direct Definition Method (SDDM) to determine the single threshold temperature values of rainfall and snowfall in northern China (north of 30 °N). A statistical model of the threshold temperature was established to provide a tool for use in studies of large-scale snowfall climatology and climate change, weather forecasting, and hydrological model parameterization. It is believed that China has sub-continental scale characteristics of lands and natural conditions, and a diversity of climates and topographic types, and the phase separating methods developed in mainland China should have a better universality in continents and the world.

2. Data and methods

2.1 Data

The main purpose of this study was to develop an easy and convenient method for separating solid and liquid precipitation, so that the objective separation of solid and liquid parts of precipitation can be achieved without exhaustive reference of observational data. International exchange data generally only contain the daily temperature and precipitation, with no other reference data, so we have only used the indicators related to temperature and precipitation to develop a method of separation.

The data was obtained from the National Meteorological Information Center of China Meteorological Administration (CMA). The air temperature, precipitation and relative humidity data were derived from the “China Land Daily Climatic Dataset

(V3.0)’’. The precipitation phase observation was derived from “China Land Climatic Data Daily Weather Phenomena Dataset’’. All the data have been quality controlled. Collected since January 1951, the “China Land Daily Climatic Dataset (V3.0)’’ contains the daily data of air pressure, surface air temperature (daily mean, daily maximum and daily minimum), precipitation, pan-evaporation, relative humidity, wind speed, sunshine hours, and 0-cm ground temperature from 839 stations The “China Land Climatic Data Daily Weather Phenomena Dataset’’ is the daily records encoded by the 752 national stations in mainland China since 1951. Cross comparison of the two datasets and the examination of station information was performed, and any incomplete temperature, precipitation, relative humidity and weather phenomena data were removed. There are total 623 stations selected for use in the study, all of which meet the demand to have information integrity, sequential continuity, and records of more than 20 years in climate reference period (1981–2010). The data may contain inhomogeneities caused by the relocation and other factors, but they would exert little influence on the analysis results, so the data are not adjusted for homogeneity.

First, the precipitation caused by fog, dew, and frost as well as the trace precipitation was removed, and daily precipitation greater than or equal to 1 mm was taken as the effective precipitation. In this regard, the main consideration is that the international exchange precipitation data only contains no less than 1 mm of daily precipitation. In the separation of daily rainfall (pure rain), mixed-phase events, and snow (pure snow) events, ‘pure rain’ was recorded when the weather phenomenon data indicate that only rain occurred on that day without snow and mixed-phase events; it was registered as ‘pure snow’ when only snowfall occurred without rain and mixed-phase events, and ‘mixed-phase events’ when there is rain and snow in the same day, in the records of weather phenomenon data. The daily maximum and minimum temperature during an occurrence of mixed-phase events at each station were recorded as the reference thresholds for the snow and rain temperature threshold values.

When there is less snowfall at the station in lower latitude zone or more arid regions, there may be arbitrary cases of snowfall. An example is from Lijiang station, Yunnan, located in 26°N, at which pure snow occurred only six times in the 30 years from 1981 to 2010. The representation of the threshold temperature would be poor in these cases. In order to ensure that the snowfall frequency is great enough and the threshold temperature is representative, we took 324 stations (Fig. 1) in northern China for use in this study. They are generally located north of the Yangtze River, approximately consistent with the January mean temperature isotherm of 3 ℃ or the 30°N parallel. The days with the snowfall records during 1981-2010 were greater than or equal to 100d for each of the stations. In order to avoid the influence of extreme values on the determination of threshold temperature, the maximum and minimum daily mean temperature in each of the precipitation phases were not counted.

For the cases of extreme large rain and snow records at the stations, comparison was made to ensure that the minimum and maximum temperature was correct by examining the weather phenomena, surface air temperature and precipitation on the same day. When mixed-phase events occurred, the range of daily mean temperature was generally large. Threshold temperature was determined only for pure rain and pure snow; the daily mean temperature on a mixed-phase event day was only taken as the reference temperature threshold value.

2.2 Methods

According to the method of China's physical geographical regionalization, mainland China is divided into three natural geographical regions: Eastern Monsoon Region (I, 231 stations), Northwest Arid Region (II, 67 stations), and Qinghai-Tibetan Plateau Region (III, 26 stations) (Fig. 1). More stations are distributed in Eastern Monsoon Region, and there air only 26 stations in Qinghai-Tibetan Plateau Region. A vast region of western part of the Qinghai-Tibetan Plateau is the well-known no-man land without climatic observations, and this would affect the analysis in some extents. The representative station of the Eastern Monsoon Region is Zhaozhou station (Zhaozhou-I hereafter) in Heilongjiang province, which has the lowest threshold temperature of snowfall and rainfall in the country. The representative station of the Qinghai-Tibet Plateau Region is Shiquanhe station (Shiquanhe-II hereafter) in Tibet Autonomous Region, which has the highest threshold temperature of snowfall and rainfall in the country. There are relatively fewer precipitation events in the Northwest Arid Region, and Balikun station (Balikun-III hereafter) in Xinjiang Autonomous Region was selected as the representative station because it observed relatively more precipitation events, and the rain, mixed-phase events, and snow events were evenly distributed. The station is also far from the two other regions (Table 1).

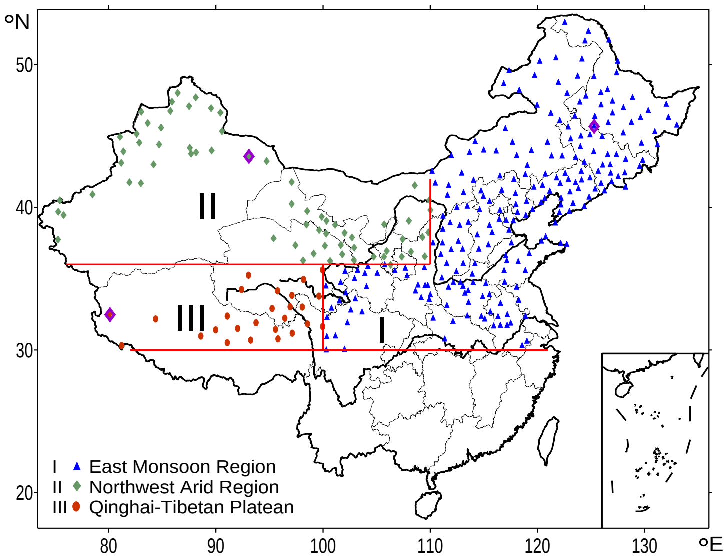


FIG.1. Regionalization and distribution of 324 national stations north of 30 ˚N in mainland China (I: East Monsoon Region; II: Northwest Arid Region; III: Qinghai-Tibetan Plateau; Blue triangle: stations in the East Monsoon Region; Green diamond: stations in the Northwest Arid Region; Red circle: stations in the Qinghai-Tibetan Plateau. The purple diamond denotes the representative stations in different regions: Zhaozhou of Region I; Balikun of Region II; Shiquanhe of Region III)

Table 1 Information of representative stations in the three regions

Station name	Zhaozhou	Balikun	Shiquanhe
Province	Heilongjiang	Xinjiang	Tibet
Climate zone	I	II	III
Elevation(m)	148.7	1679.4	4278.6
Latitude(N)	45° 42′	43° 36′	32° 30′
Longitude(E)	125° 15′	93° 03′	80° 05′

The relative error (RE) of snow days (snowfall) was defined as the percentage (%) of the difference between simulated snow days (snowfall) and observational (true) snow days (snowfall) to the observational (true) snow days (snowfall), which could be used to indicate the effectiveness of simulated results.

The establishment of model was realized using the stepwise regression analysis method included with the SPSS Statistics 17.0. The advantage of stepwise regression is that the number of the arguments contained in the regression equation is fewer, it is easy to apply, the root mean squared error (RMSE) is small, and the model created is more stable.

The maximum daily mean temperature at the occurrence of snowfall at the weather station is Tsm, the minimum daily mean temperature at the time of rainfall is Trn; the number of snowfall days between Trn and Tsm is Sn, the number of rain days is Rn, and the total number of rain and snow days between Trn and Tsm is Nsr = Sn + Rn; the single critical temperature of rain and snow days is Tt-d, that is, the precipitation event that occurs when the daily mean temperature is lower than Tt-d is considered to be a snowfall event, otherwise it is considered as a rainfall event; the single critical temperature estimated by the statistical model is Tt-p.

Using the Snowday-Direct-Definition-Mothod (SDDM) to define the threshold temperature of precipitation phase, the calculation steps were as follows:

First, find the Trn and Tsm in the dataset of the 623 stations, and count Sn, Rn, and Nsr. Second, calculate the daily average temperature of Nsr and sort it in ascending order. Last, the average of daily mean temperature of the Sn^{th} day and the $(Sn+1)^{th}$ day was calculated, and it was taken as the threshold temperature (Tt-d) of the rain and snow days. For the area where pure rain and snow events did not overlap ($Tsm<Trn$, that is, the snowfall and rainfall events did not intersect in the sorted daily average temperature series), the average of Tsm and Trn was taken as the Tt-d. The average of Tt-d and the daily mean temperature of mixed-phase events day was taken as the Tt-d when Tt-d was not in the range of mixed-phase events day daily mean temperature. The Tt-ds values in this study were all within the daily mean temperature

of mixed-phase events day, however, and this operation was not required.

3. Threshold temperature

3.1 Daily mean temperature corresponding to precipitation in different phases

Figure 2 and Table 2 show phase temperature distribution of precipitation events at the stations. The total precipitation events at 324 stations were included in the statistical calculations, and their corresponding daily mean temperature values (Fig. 2a) were examined: only snowfall occurred when the daily mean temperature was below -12.9 ℃; only rainfall occurred when the daily mean temperature was higher than 22.1 ℃; and the three phases of snow, rain, and mixed-phase events occurred when the temperature was between -12.9 ℃ and 22.1 ℃.

In northern China, pure snow (snowfall) events occurred when the daily mean temperature was below 8.5 ℃, and 95% of the snowfall events occurred when the daily mean temperature was lower than 2.7 ℃ and higher than -16.6 ℃ (Fig. 2a). All pure rain events (rainfall) occurred when the daily mean temperature was higher than -4.9 ℃, and 95% occurred when the temperature was lower than 26.0 ℃ and higher than 6.4 ℃. All mixed-phase events appeared in the temperature range of -12.9–22.1 ℃, with 95% occurring when the daily mean temperature was lower than 8.3 ℃ and higher than -1.6 ℃.

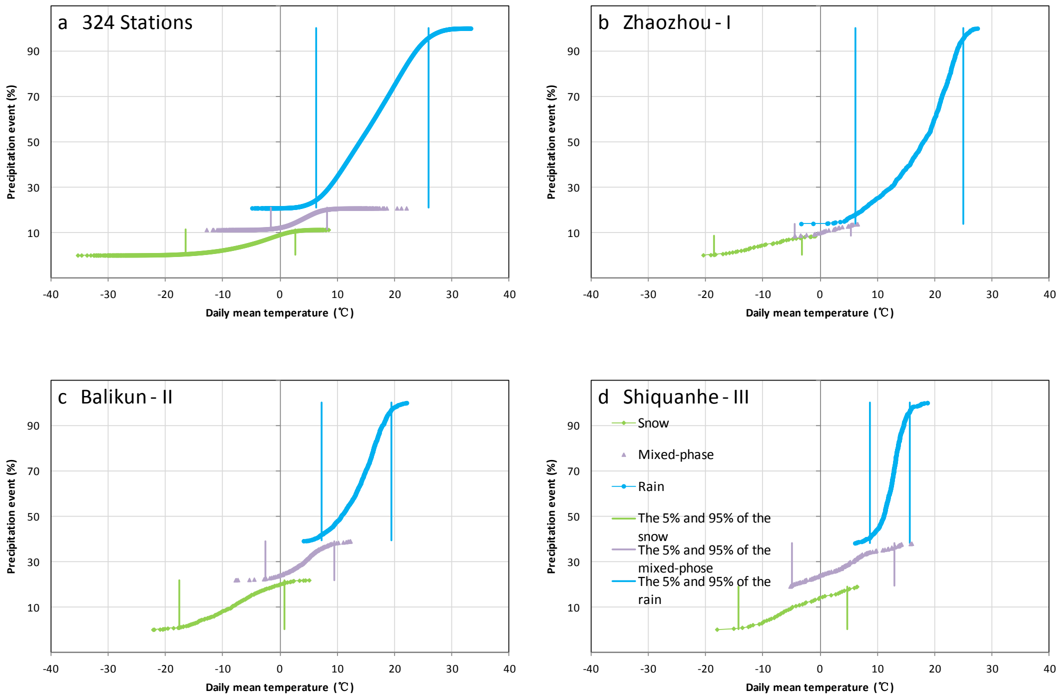


FIG.2. Precipitation phase temperature distribution of regional average and representative stations (a-324 stations; b-Zhaozhou-I; c-Balikun-II; d-Shiquanhe-III)

At Zhaozhou-I station (Fig. 2b), the pure snow events all occurred when the daily mean temperature was lower than -0.9 ℃, pure rainfall occurred when the daily mean temperature was higher than -3.4 ℃, and mixed-phase events occurred in case of -4.5–6.5 ℃. Zhaozhou-I station had the lowest threshold temperature (-1.2 ℃) of snowfall and rainfall in the study region. At Balikun-II station (Fig. 2c), the pure snow events all occurred when the daily mean temperature was lower than 5.1 ℃, pure rain events occurred when the daily mean temperature was higher than 4.1 ℃, and mixed-phase events occurred within a temperature range of -7.8–12.3 ℃. At Shiquanhe-III station (Fig. 2d), the pure snow events all occurred when the daily mean temperature was lower than 6.4 ℃, pure rainfall occurred when the daily mean temperature was higher than 6.1 ℃, and mixed-phase events occurred when the temperature was from -5.3 ℃ to 16.0 ℃. Shiquanhe-III station had the highest threshold temperature (6.3 ℃) of snowfall and rainfall in the whole region.

Table 2 The distribution range of daily mean temperature under different phases of precipitation at stations

Station	Snow day mean temperature (℃)					Mixed-phase events day mean temperature (℃)					Rain day mean temperature (℃)				
	Max	Min	Ave	5% value	95% value	Max	Min	Ave	5% value	95% value	Max	Min	Ave	5% value	95% value
All	8.5	-35.4	-5.2	-16.6	2.7	22.1	-12.9	3.6	-1.6	8.3	33.3	-4.9	16.3	6.4	
Zhaozhou-I	-0.9	-20.5	-10.2	-18.6	-3.3	6.5	-4.5	1.6	-4.5	5.5	27.5	-3.4	17.8	6.1	25
Balikun-II	5.1	-22.2	-8.2	-17.6	0.8	12.3	-7.8	4.1	-2.5	9.5	22.1	4.1	14.3	7.3	19.4
Shiquanhe-III	6.4	-18.1	-4.4	-14.3	4.8	16	-5.3	4.3	-5	13.1	18.7	6.1	12.6	8.7	15.7

It can be seen from Fig. 2 and Table 2 that there is a larger difference of the maximum daily mean temperature of snowfall (extreme threshold temperature of snowfall) and the minimum daily mean temperature of rainfall (extreme threshold temperature of rainfall) among the stations.

Figure 3 shows that there is a common spatial distribution feature in the Tsm, Trn and the average daily mean temperature of mixed-phase events in northern China, with the high values generally in the Tibetan Plateau and southern Xinjiang, while the low values mostly in eastern and northern Xinjiang. At the stations analyzed, most have a relationship of Trn<Tsm, that is, the minimum daily mean temperature at the time of a rain event is lower than the maximum daily mean temperature at the time of a snowfall event. Only in a few of places in Northwest Arid Region, is the maximum daily mean temperature of a snow day lower than the minimum daily mean temperature of a rain day, indicating that the pure rain and snow events do not

overlap.

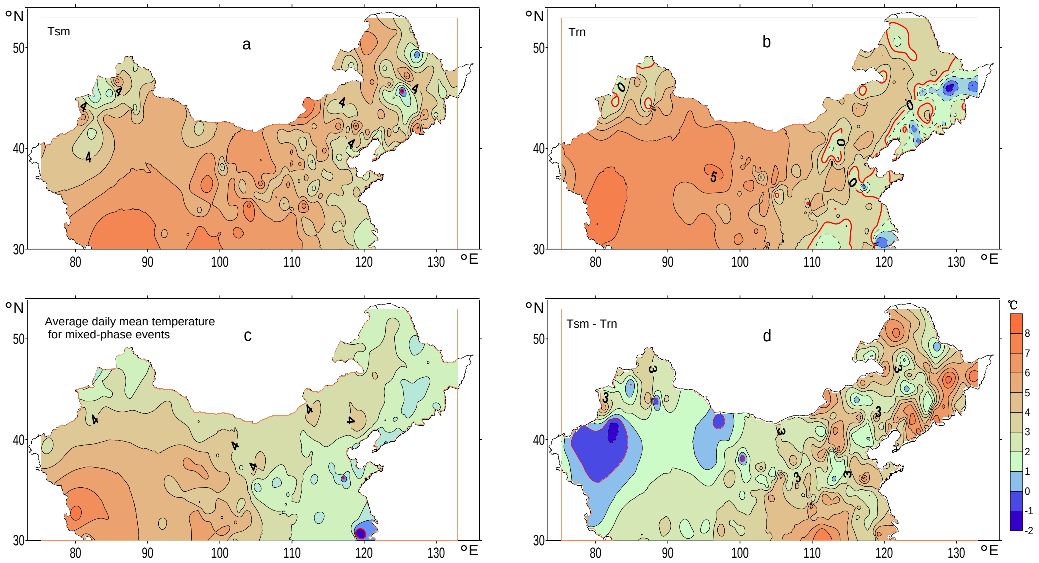


FIG.3. The distribution of daily mean temperatures when precipitation occurs (a. Tsm; b. Trn; c. average daily mean temperature of mixed-phase events; and d. difference between Tsm and Trn) (Red thick line represents 0℃ isotherms)

3.2 Threshold temperature determination

Figure 4 shows the distribution of the relative error of the snow days and snowfall in northern China, determined by the threshold temperature as mentioned in section Data and Methods, to the actual snow days and snowfall counted by using weather phenomenon records. The relative error of snow day was smaller. This is due to the definition of threshold temperature being directly determined by snow-day mean temperature. Since the daily mean temperature of the Sn^{th} day and the $(Sn+1)^{th}$ (or more) day is the same under this definition, however, there will be a slight positive bias in the threshold temperature of the same temperature day, with a range of relative errors (0, 2.3%).

The spatial distribution of the relative error of the snowfall was mainly positive, which is due to the systematic deviation of the method. Larger deviation appeared in eastern part of the Qinghai-Tibetan Plateau and the Yangtze-Huaihe River Basins. These areas have more precipitation and sufficient water vapor. Under the same water vapor condition, the observed rainfall was greater than the observed snowfall, and the amount of snowfall determined by the threshold temperature was slightly large, with the certain sites even larger. Small values occurred in the southeastern Northeast China, the border zone between Inner Mongolia and Xinjiang, and western Xinjiang, with the main reason related to the less precipitation and insufficient water vapor. Overall, the relative error of snowfall is between -5% and 20%. There were 312 stations (more than 96%) with deviation less than or equal to 10%, and the absolute value of the relative error was less than 5% in most areas.

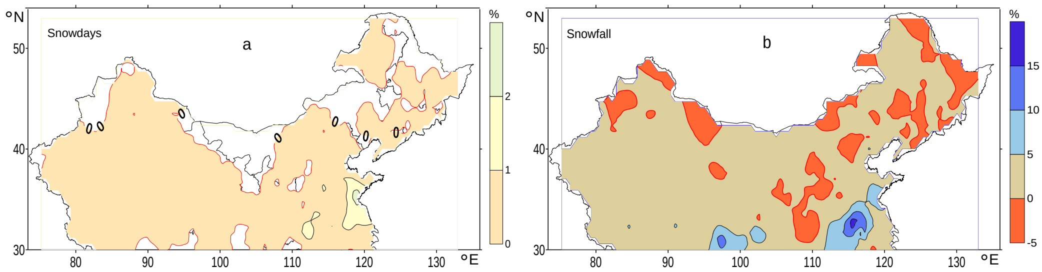


FIG.4. The spatial distribution of the relative error of the days (a) and amount (b) of snowfall determined by the threshold temperature (Tt-d) in northern China

The spatial distribution of the threshold temperature (Tt-d) of rain and snow at the stations north of 30 °N are shown in Fig. 5. The average Tt-d is 2.3 ℃ for Eastern Monsoon Region, 3.4 ℃ for Northwest Arid Region, and 5.2 ℃ for the Qinghai-Tibetan Plateau. The highest threshold temperature of the study region is 6.3 ℃ (Shiquanhe-III, Fig. 2d), the lowest is -1.2 ℃ (Zhaozhou-I, Fig. 2b), the threshold temperature range was 7.5 ℃, and the average threshold temperature for the whole region was 2.8 ℃. The high-values were in the northern Qinghai-Tibetan

Plateau, with a threshold temperature of more than 4 ℃, and the low-values were generally in eastern Northeast China, North China, and northern Xinjiang with the threshold temperature mostly less than 2 ℃. The threshold temperature west of 100 °E showed an approximately zonal distribution, and it decreased with the increase of latitude; the east of 100 °E had a meridional distribution, and the threshold temperature decreased with increasing longitude. There are some uncertainties on the distribution of the threshold temperature in the Qinghai-Tibetan Plateau and northwestern deserts mainly due to the interpolation in the regions with sparser observations.

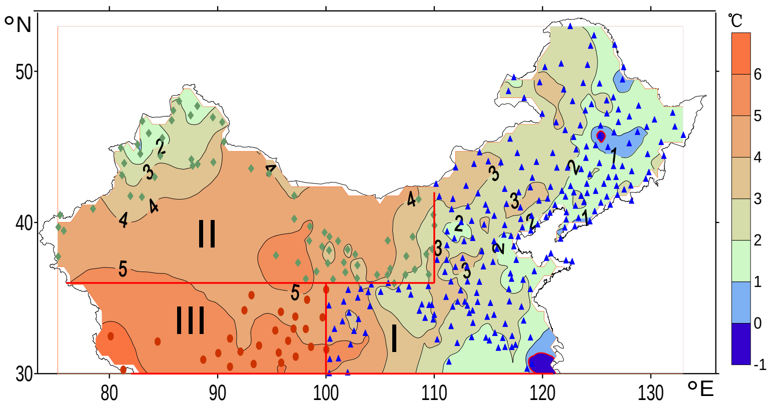


FIG.5. Spatial distribution of threshold temperature of precipitation phases in northern China (I: East Monsoon Region; II: Northwest Arid Region; III: Qinghai-Tibetan Plateau. Unit: ℃)

3.3 Correlation between threshold temperature and geographical/climatic factors

The threshold temperature (Tt-d) is related to the longitude, latitude, altitude, annual precipitation, annual mean air temperature, and annual relative humidity of the observational sites, with a positive correlation with altitude and a negative correlation with the other factors. All the correlations passed the significant test (p=0.05) (Fig 6). In areas where the annual mean temperature is lower, the threshold temperature was generally higher and more variable, while in areas with higher annual mean temperature, it was generally slightly lower and relatively less variable. The threshold temperature had a decreasing trend with increase of annual mean air temperature (Fig. 6a). In lower altitude area, the threshold temperature was lower, while it was higher in mountains and plateaus, and a highly significant increasing trend of threshold temperature with altitude can be seen (Fig. 6b). There was a negative correlation between the threshold temperature and the annual precipitation, and a more significant negative correlation with the annual relative humidity (Fig. 6c, d).

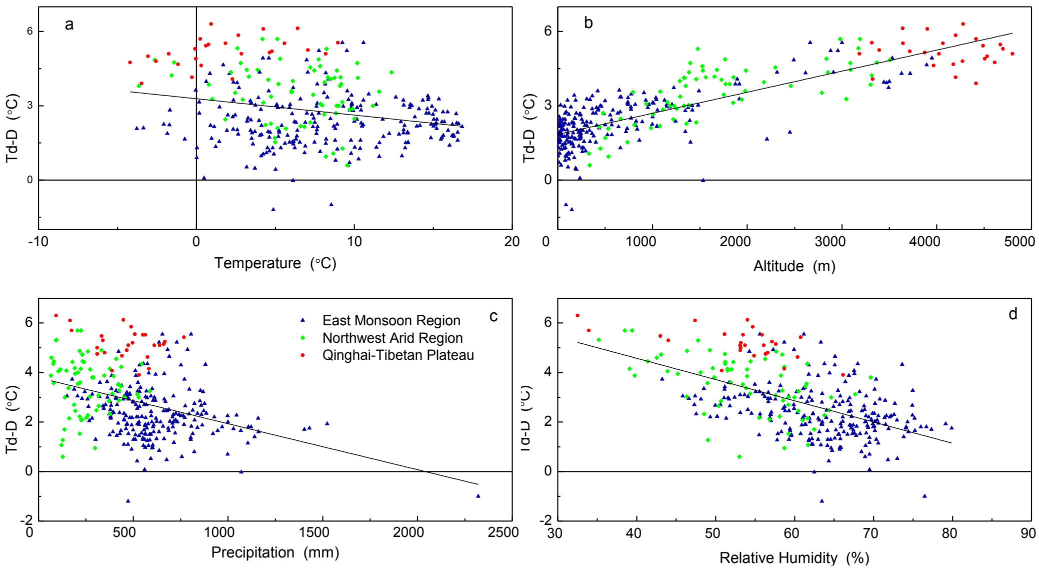


FIG.6. Relationship of the threshold temperature (Tt-d) with temperature (a), altitude (b), annual precipitation (c) and annual mean relative humidity (d) in northern China
(Blue triangle: East Monsoon Region; Green diamond: Northwest Arid Region; Red circle: Qinghai-Tibetan Plateau)

It is possible that the relationship of the threshold temperature with longitude and latitude is also related to the variations of altitude and relative humidity in the study region. The altitude and relative humidity generally decrease from west to east and from south to north, and the altitude and relative humidity have better correlations with the threshold temperature, which may be the reason why threshold temperature decreases with the increase of the longitude and latitude. Therefore, altitude and relative humidity may be the more important factors in determining the threshold temperature.

The threshold temperature was positively correlated with altitude, which may mainly be because the ground surface receives stronger solar radiation, causing the boundary-layer atmosphere to heat rapidly in the high altitude areas during daytime. However, the upper air temperature is low, the temperature lapse rate is larger, the cloud bottom-height is low, and the path of snowflakes is short, so the snowfall phenomenon can also be more frequently observed when the daytime surface air temperature is high.

The threshold temperature was negatively correlated with annual precipitation in particular with relative humidity, which may be related to the low latent heat flux and high sensible heat flux in arid area. When the sensible heat flux is high, the ground surface air temperature is high, and the temperature lapse rate is large. In the case of the same condensation height or cloud bottom-height, snowfall is more likely to occur under the condition of higher surface air temperature. It is also possible that the higher the threshold temperature in arid area than in humid area is caused by a difference of the more complicated microphysical processes around the snowflakes between the two climatic conditions.

3.4 Establishment of the threshold temperature model

Considering that the relative humidity data of some areas is difficult to obtain, the precipitation factor was selected as the independent variable. Using the SPSS software stepwise regression analysis method, a statistical model of threshold temperature was established with annual mean air temperature, altitude, and annual precipitation as influential factors. The model, which passed the significant test (*p*=0.05), can be expressed as follow:

$$Tt\text{-}p = 1.69147 + (.09585) * T + (.001311) * H + (-0.00172) * R \qquad (1)$$

where Tt-p is the simulated threshold temperature (℃), T is the annual mean air temperature (℃) of the station, H is the altitude of the station (m), and R is the annual precipitation of the station (mm).

The correlation coefficient between Tt-p and Tt-d (threshold temperature determined by using the synoptic phenomena) is 0.88. The median and standard deviation of the simulated threshold temperature (Tt-p) were 2.54℃ and 1.17℃, which were close to the median (2.64℃) and standard deviation (1.33℃) of the Tt-d. The maximum simulated threshold temperature was 5.9 ℃, minimum was -0.4 ℃, temperature range was 5.5 ℃, and average simulated threshold temperature was 2.8 ℃ for the whole region. The maximum positive deviation of the Tt-p to the Tt-d was 2.9 ℃, and the minimum negative deviation was -1.8 ℃. The numbers of stations with relative error less than 10% for snow day and snowfall reached 97% and 92% respectively.

In the East Monsoon Region (Region I), the simulated threshold temperature was generally lower than the Tt-d (0.026 ℃ lower in Region I on average). However, it was higher in the Northwest Arid Region (Region II) (0.063 ℃ higher on average) and the Qinghai-Tibetan Plateau Region (0.065 ℃ higher on average) (Fig. 7).

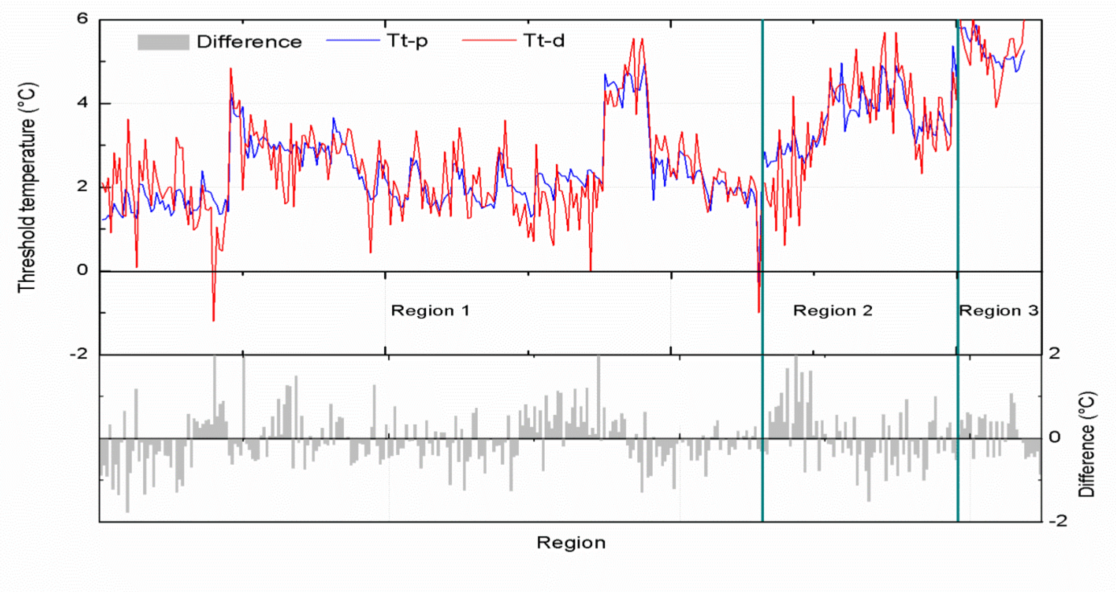
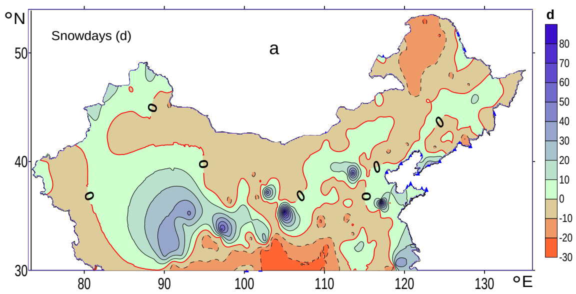


FIG.7. Simulated threshold temperature (Tt-p), threshold temperature (Tt-d) and their difference for observational stations in different regions of northern China (Region 1: East Monsoon Region; Region 2: Northwest Arid Region; Region 3: Qinghai-Tibetan Plateau Region)

The mean absolute errors (MAE) of threshold temperature of the simulated snowfall are 0.476℃ for East Monsoon Region, 0.560℃ for Northwest Arid Region, and 0.435℃ for Qinghai-Tibetan Plateau Region. Fig. 8 (and also Table 3) shows the spatial distribution of the absolute errors of threshold temperature of the simulated snowfall and snow days. Larger positive errors can be seen in the Northwest Arid Region and western Qinghai-Tibetan Plateau Region for snow days.



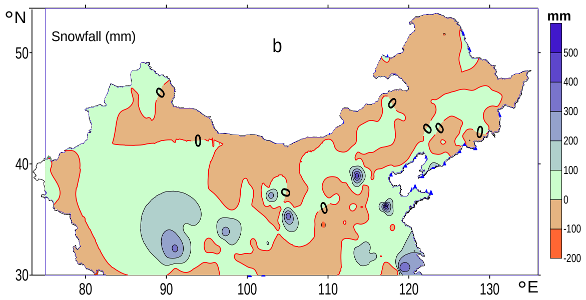


FIG. 8. Absolute error distribution of snowfall days (a) and snowfall (b) for the simulated threshold temperature Tt-p

Table 3 Comparison of statistics and the errors resulting from the simulated threshold temperature Tt-p

		North of China	Region I	Region II	Region III
Snowday	Correlation	0.999	0.998	0.999	0.999
	MAE (d)	7.77	7.52	5.21	16.69
	MRE (%)	2.71	2.98	1.68	2.98
	RMSE (d)	3.9	4.3	2.3	3.6
Snowfall	Correlation	0.997	0.996	0.999	0.998
	MAE (mm)	37.18	37.7	19.67	77.6
	MRE (%)	3.71	4.09	2.1	4.44
	RMSE (mm)	73.78	76.13	43.81	95.24

Figure 9 shows spatial distribution of the relative error of the simulated snow days (Fig. 9a) and snowfall (Fig. 9b) relative to the actual snow days and snowfall at the stations. The relative error range of snowfall days in northern China was between -16.8% and 17.0%, with an average of -0.1%; the relative error was smaller in mid-southern parts of the study region, and larger in the coastal areas and the northern Qinghai-Tibetan Plateau. In the Qinghai-Tibetan Plateau Region, the medians of the simulated snow days were smaller than those of the actual snow days, and the relative errors were larger. This may be related to the fact that the snowfall days in northern Tibetan Plateau fluctuated greatly, with some years with larger numbers of snowfall days. The relative error range of snowfall in the whole region was between -15.5% and 29.0% with an average of 1.1%, and the spatial distribution was basically the same as that of the relative errors of snow days.

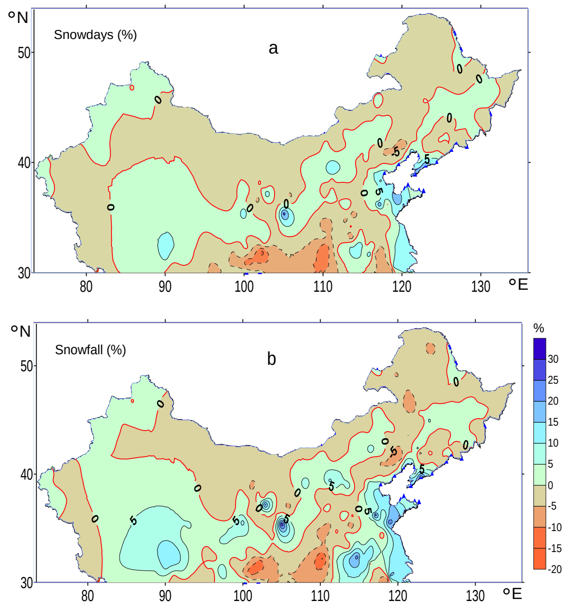


FIG.9. Relative error distribution of snowfall days (a) and snowfall (b) defined by the simulated threshold temperature Tt-p

Affected by the extremely low air temperature and the abnormally deficient water vapor due to the East Asian winter monsoon, the snow days (snowfall) with only snowfall weather were relatively less frequent (low) in northern China, as compared to other regions of the same latitude; therefore, it is more likely that the relative error is large in the study region. However, the relative error range shown here is acceptable, and the fitting effect is generally good.

The RMSE of the relative error of snow days was 3.9, and the RMSE of the relative error of snowfall was 5.6. The annual snow days and the amount of snowfall were less in the mid-southern parts of the study region which had negative relative errors of the simulated snow events; however, snow days and snowfall were slightly more numerous in the northern part of the Sichuan Basin. The number of snow days and snowfall was less in the coastal area which had positive relative errors of the simulated snow events, while there were more snow days and snowfall in the northern Qinghai-Tibetan Plateau. The relative error of snow days (snowfall) and the threshold temperature had a correlation coefficient of -0.40 (-0.32); both passed the significant test (p=0.05). It can be seen that the relative error in the area with low threshold temperature tends to be positive, and that relative error in the area with high threshold temperature is generally negative.

4. Discussion

China has a vast territory. The study region across the latitude range 30–54 °N, and a longitude range of 73–136 °E, with various climate types of temperate monsoon zone, continental arid zone and alpine including the highest mountainous system of the Qinghai-Tibetan Plateau. The complex and diverse geophysical and climatic condition makes the region ideal for understanding the transition of precipitation phrase and developing a method to separate the different precipitation phrase.

We made an attempt to develop such a method to separate the precipitation phases by using a high-quality daily observational dataset in this paper. Our study not only determined the threshold temperature with more reliable results, but also tested the statistical model of threshold temperature, provided the results of the model and the relative error range for different regions, and confirmed the applicability of the method in the complex geographic area with diverse climate types.

With the method of determining threshold temperature developed in this paper, the relative error of snow days and snowfall calculated for most of the stations was very small, and the stations with less than 10% relative errors accounted for 97% and 92%, respectively. This method could be used to better determine the snow days than the snowfall, with the relative error of snowfall was slightly larger in the Huaihe River basin. This is mainly because, when using the threshold temperature to calculate the amount of snowfall, rain days with a daily mean temperature below the threshold temperature could be identified as the snow day, and also some snow days with a daily mean temperature above the threshold temperature could be classified as rain days. In the frequent transformation of the precipitation phases (early spring and early winter), precipitation on a rain day is often greater than that on a snow day, so the priority to ensure the determination of a snow day, the estimated relative error of snowfall would be a little larger.

Han et al. (2010) used the insurance probability method to determine the single threshold temperature of rain and snow, taking the daily mean temperature of the 98.5% insurance probability of rainfall and snowfall, 50% insurance probability of mixed-phase events as the threshold temperature. For comparison of SDDM and the insurance probability method, the number of snow days (Sn) and rain days (Rn) between Trn and Tsm was calculated, respectively, using the two methods. The corresponding daily mean temperature at the insurance probability of the snow and rain days between [Trn, Tsm], X (x∈ (0–99%)) (at 1% intervals), was estimated. For example, the number of rain days and snow days between Trn and TSM is 100d respectively; when x = 90% is taken, the rain day temperature Tr90 corresponds to the insurance probability of 90%, that is, to ensure the minimum daily mean temperature in the event of 90% rain days between Trn and TSM, while Ts90 is to guarantee that the maximum daily mean temperature in the event of 90% snowfall days is between Trn and TSM. The arithmetic mean of each station's Trx and Tsx is defined as the threshold temperature Tt-x at the station's insurance probability x.

The threshold temperature (Tt-x) was calculated according to the insurance probability method, and the threshold temperature (Tt-d) was obtained based on the definition in this paper; the relative error comparison is presented in Table 4. For simplicity, the insurance probability interval in the table was taken as 10%. The maximum, minimum, and range of the threshold temperature (Tt-x) under different insurance probability, and of the (Tt-d), in northern China, are given in the table; at the same time, the maximum, minimum, and range of the relative error of the snow days and snowfall, as well as the number of stations with a relative error less than or equal to 10%, are also given.

Table 4 Comparison of statistics and the relative errors resulting from threshold temperature Tt-x and Tt-d

	Threshold temperature (℃)			Relative error of snow days (%)				Relative error of snowfall (%)			
	max	min	max-min	max	min	max-min	Stations <10%	max	min	max-min	Stations <10%
Tt-0	6.4	-2.3	8.7	30.2	-11.1	41.3	311	36.6	-15.3	51.9	280
Tt-10	6.4	-2.3	8.7	25.1	-11.1	36.3	313	29	-11.8	40.8	284
Tt-20	6.5	-2.3	8.8	25.1	-9.5	34.6	316	29	-9.7	38.7	287

Tt-30	6.5	−2.2	8.7	23.6	−7.1	30.7	314	31.5	−15.3	46.8	287
Tt-40	6.4	−2.2	8.6	23.6	−5.8	29.4	316	31.5	−8.4	39.9	289
Tt-50	6.5	−2	8.5	21.1	−5.7	26.8	312	32.2	−9.7	41.9	286
Tt-60	6.4	−1.5	7.9	19.1	−6.5	25.6	313	32.2	−9.7	41.9	289
Tt-70	6.4	−1.4	7.8	15.6	−6.5	22.1	314	30.2	−6.2	36.4	283
Tt-80	6.7	−1.4	8.1	18.3	−5.8	24	307	45.2	−8.4	53.6	282
Tt-90	6.5	−1.2	7.7	23	−7	29.9	306	33.4	−9.7	43.1	276
Tt-d	6.3	−1.2	7.5	2.6	0	2.6	323	20.2	−4.3	24.5	312

Table 4 shows that, using the insurance probability method, the test results of the threshold temperature (Tt-70), obtained when the insurance probability x = 70% was taken, represented the best values, as the difference between the minimum and maximum values of the threshold temperature was small, and the relative errors were small, with the relative error of the snow days at 314 stations ≤10%, and that of the snowfall at 283 stations ≤ 10%.

The range of threshold temperature Tt-d of snow days determined in this paper was less than that of the Tt-70. The relative error of snow days was obviously small, and the relative error of snowfall was much less than that of the Tt-70, with more stations having the relative errors ≤10% for both snow days and snowfall. Therefore, the method developed in this paper has an advantage over the insurance probability method developed in the previously works.

Ding (2014) used a similar method as that in this paper to determine the precipitation types with daily mean wet-bulb temperature, relative humidity and surface elevation as predictors. Compared to the other nine schemes used in hydrological and land surface models, their method showed a better accuracy. Our analysis also finds the better correlations of relative humidity and surface elevation with the real thresholds in the study region, but wet-bulb temperature has not been assessed in our work.

In order to compare to the two works, the accuracy of Tt-d in our work and that of Ding et al. (2014) is tested over the same air temperature range. The results are shown in Table 5. The Tp-CH in our work is the Tt-p of all stations in the study area. The Tp-R1 is the Tt-p of stations in East Monsoon Region, the Tp-R2 is the Tt-p of Northwest Arid Region, and the Tp-R3 is the Tt-p of the Qinghai-Tibetan Plateau.

Table 5 Accuracy (%) of methods by Ding et al. (2014) and this work (SDDM) for the air temperature range [0℃, 4℃]

	Ding et al. (2014)	Tp-CH	Tp-R1	Tp-R2	Tp-R3
China	59.3	87	87	84	84
R1	53.1	83	83	78	80
R2	60.1	89	89	90	88
R3	66.1	99	99	99	99

Ding et al. (2014) separated rain, snow and sleet or mixed-phase events, but our work only separates rain and snow. This may be the reason that the accuracy of our method is higher. However, the test result of Tt-p for each region is relatively stable. Therefore, the SDDM as developed in this paper is stable and reliable for the separation of rain and snow. More importantly, the SDDM has potential to be applied in a broader area where the daily wet-bulb temperature and relative humidity data are unavailable. Liu and Ren et al. (2018) recently tested the possibility of extrapolating the statistical model of separating solid precipitation from liquid precipitation. Considering less snowfall in the lower latitudes and less rainfall in the higher latitudes, the proposed area for use of the method is between 30 °N to 60 °N in the latitude range, and areas outside this range may have large deviation.

When building the statistical model of threshold temperature, we actually also built a model containing the relative-humidity as predictor for possible use in the region where the daily mean relative-humidity data can be obtained.

$$Tt\text{-}p = 2.572889 + (.089936) * T + (-.01646)*U + (.000931) * H + (-0.00089) * R \quad (2)$$

where U is daily mean relative humidity (%) of the observational station, and the other terms are the same as Formula (1).

The test of this model showed that the Formula (2) is indeed relatively better than the formula (1), but the advantage is not so obvious. Modeled thresholds using the formula including relative humidity have a very similar spatial distribution pattern with that determined by the formula without the term. In most areas where the relative-humidity data cannot be obtained, therefore, Formula (1) can be confidently used, which has little effect on the separation results.

In this paper, only the two phases of pure snowfall and pure rainfall were determined, however, and the mixed-phase events were not analyzed. In the case of mixed-phase events, the surface air temperature changed greatly during a day; there was probably mixed-phase events, pure rain and pure snow in the same day, the threshold temperature fluctuations were large, and it would be difficult to accurately determine and simulate. Because the method used in this paper did not quantify the mixed-phase events, when precipitation was separated into solid and liquid state, the mixed-phase events will be classified as snow when the daily mean temperature is lower than the threshold temperature, and as rain when the daily mean temperature is higher than the threshold temperature, causing a certain error. However, for the study of large-scale snowfall climatology, especially for studies of the larger than sub-continental scale snowfall climate change, the snow and rain separation method presented in this paper could well meet the needs.

5**. Conclusions**

Based on the analysis of the historical daily temperature, precipitation, and weather phenomenon observation data in northern China, the threshold temperature model for determining the phase of rain and snow was established and tested. The main conclusions are as follows:

(1) The threshold temperature value of rain and snow determined based on weather phenomenon data is between -1.2–6.3 ℃, with a temperature range of 7.5 ℃ and an average value of 2.81 ℃. The high values were in the northern Qinghai-Tibetan Plateau, reaching more than 4 ℃, and the low values were found in Northeast China, North China, and northern Xinjiang Autonomous Region, generally less than 2 ℃. The west of 100 °E showed an approximately zonal distribution, and the threshold temperature decreased with latitude; the east of 100 °E had a meridional distribution, and the threshold temperature decreased with increasing longitude.

(2) The threshold temperature was more variable in the low latitude areas, while it was slightly lower and relatively centralized in the high latitudes, with a clear decreasing trend with increase of latitude. The threshold temperature was lower at low altitudes, higher in the high altitude areas, and increase with altitude. There was a statistically significant negative correlation between the threshold temperature and

annual total precipitation and annual mean relative humidity, with the negative correlation with relative humidity especially significant.

(3) A statistical model based on latitude, elevation, and annual precipitation can be used to simulate the threshold temperature of the precipitation phase in northern China, with less relative error in simulated snow days and snowfall. The stations with relative error less than 10% reached 97% and 92% for the snow days and snowfall respectively.

Acknowledgements: This study is financed by the Ministry of Science and Technology of China (Fund No: 2018YFA0605603) and the Natural Science Foundation of China (NSFC) (Fund No: 41575003 and 41771067).

References

Arnold JG, Srinivasan R, Muttiah RS, et al . 1998: Large area hydrologic modeling and assessment; part I: model development. Journal of the American Water Resources Association, 34(1): 73-89. DOI: 10.1111/j.1752-1688.1998.tb05961.x

Becker A, Finger P, Meyer-Christoffer A, et al. 2012: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901-present, Earth Syst. Sci. Data Discuss., 5, 921–998.

Blanchet J, Marty C, Lehning M. 2009: Extreme value statistics of snowfall in the Swiss Alpine region. Water Resour. Res., 45. DOI:10.1029/2009WR007916

Bourgouin P. 2000: A method to determine precipitation types. Weather and Forecasting, 15(10): 583-592.

Chen RS, Kang ES, Lu SH, et al. 2008: A distributed water-heat coupled model for mountainous watershed of an inland river basin in Northwest China (I) model structure and equations. Environmental Geology, 53: 1299- 1309.

Dai AG． 2008. Temperature and pressure dependence of the rain-snow phase transition over land and ocean. Geophysical Research Letters, 2008, 35: 62-77

Dang HF, Zhao LN, Gong YF. 2015: Temporal and Spatial Distributions of Summer Precipitation Analysis in China, Journal of Chengdu University of Information Technology, 30(6): 609-615.

Ding B, Yang K, Qin J, et al. 2014. The dependence of precipitation types on surface elevation and meteorological conditions and its parameterization. J. Hydrol. 513, 154–163.

Fang XQ, Liu CH, Hou GL. 2011: Reconstruction of Precipitation Pattern of China in the Holocene Megathermal, Scientia Geographica Sinica, 31(11): 1287-1292.

Feiccabrino, J., Graff, W., Lundberg, A., Sandström, N., Gustafsson, D., 2015: Meteorological Knowledge Useful for the Improvement of Snow Rain Separation in Surface Based Models. Hydrology 2, 266–288. https:// doi.org/10.3390/hydrology2040266.

Froidurot S, Zin I, Hingray B, et al. 2014: Sensitivity of precipitation phase over the Swiss Alps to different meteorological variables. Journal of Hydrometeorology, 15: 685-696

Han CT, Chen RS, Liu JF, et al. 2010: A Discuss of the Separating Solid and Liquid Precipitations, Journal of Glaciology and Geocryology, 32(2):249-256.

Harder P, Pomeroy J W. 2013: Estimating Precipitation Phase Using a Psychrometric Energy Balance Method. Hydrological Processes.DOI: 10.1002/hyp.9799.

Harder P, Pomeroy J. 2014: Hydrological model uncertainty due to precipitation-phase partitioning methods. Hydrological Processes. DOI: 10.1002/hyp.10214.

Harpold AA, Rajagopal S, Crews JB, et al. 2017: Relative humidity has uneven effects on shifts from snow to rain over the western U.S. American Geophysical Union. DOI: 10.1002/2017/GL075046.

Harpold, A.A., Kaplan, M., Klos, P.Z., Link, T., McNamara, J.P., Rajagopal, S., Schumer, R., Steele, C.M., 2017a: Rain or snow: hydrologic processes, observations, prediction, and research needs. Hydrol Earth Syst Sci, 21: 1–22.

Jennings KS, Winchell TS, Livneh B, et al. 2018. Spatial variation of the rainsnow temperature threshold across the Northern Hemisphere. Nat. Commun. 9. DOI:10.1038/s41467-018- 03629-7.

Jiang Y, Qian WH. 2003: Regional characteristics of Heavy Snowfall or Snowstorm in Inner Mongolia. ACTA GEOGRAPHICA SINICA. 58 (Suppl.): 38-48.

Kang ES, Cheng GD, Lan YC, et al . 2001: Alpine-runoff simulation of the Yalong River for the South-North Water Diversion. Journ al of Glaciology and Geocryology, 23(2) : 139- 148.

Kang ES, Cheng GD, Lan YC, et al . 1999: A model for simulating the response of run off from the mountainous watershed of inland river basins in the arid area of northwest China to climatic changes. Science in China, Series D, 42 (Suppl.): 52- 63.

Kienzle S, 2008: A new temperature based method to separate rain and snow. Hydrol. Processes, **22**, 5067-5085. DOI: 10.1002/hyp.7131.

Kunkel KE, Palecki MA, Ensor L, et al. 2009: Trends in twentieth-century U.S. extreme snowfall seasons. Journal of Climate, 22(23): 6204-6216.

Loth B, Graf H, Oberhuber JM. 1993: Snow cover model for global climate simulations. Journal of Geophysical Research: Atmospheres. (1984–2012) 98(D6): 10451-10464.

Liu JH, Zhang PZ, Meng CH, et al. 2011: A Comprehensive Study on Precipitation Change Over Monsoon Marginal Areas During Last Five Centuries. SCIENTIA GEOGRAPHICA SINICA, 31(4):401-411.

Liu YL, Ren GY, Yu HM. 2012: Climatology of Snow in China, Scientia Geographica Sinica, 32(10):1176-1185.

Liu YL, Ren GY, Yu HM, et al. 2013: Climatic Characteristics of Intense Snowfall in China with Its Variation. Journal of Applied Meteorological Science, 24(3):304-313.

Liu YL, Ren GY,Sun XB. 2018. Establishment and Verification of Single Threshold Temperature Model for Partition Precipitation Phase Separation. Journal of Applied Meteorological Science. 29(4):449-459.

Marks D,Winstral A,Reba M,et al. 2013. An evaluation of methods for determining during-storm precipitation phase and the rain/snow transition elevation at the surface in a mountain basin, Advanced in Water Resourced,55:98-110. DOI: 10.1016/j.advwatres.2012.11.012.

Noake K, Polson D, Hegerl G, et al. 2012: Changes in seasonal land precipitation during the latter twentieth-century, Geophysical Research Letters, 39 (3): 136-141. DOI:10.1029/2011GL050405.

O'Hara BF, Kaplan ML, Underwood SJ. 2009: Synoptic climatological analyses of extreme snowfalls in the Sierra Nevada. Weather & Forecasting, 24(6): 1610-1624.

Polson D, Hegerl GC, Zhang X, et al. 2013: Causes of robust seasonal land precipitation changes. Journal of Climate, 26 (17): 6679-6697.

Qin D, Liu S, Li P. 2006: Snow cover distribution, variability and response to climate change in western China. J. Clim.. 19, (9): 1820 –1833.

Ren GY. 2007.Climate change and China water resources. Beijing: Meteorological press. 314.

Ren GY, Ren YY, Zhan YJ，et al. 2015: Spatial and temporal patterns of precipitation variability over mainland China: II: recent trends. Advances in Water Science, 26(4): 451-465.

Ren GY,Liu YJ,SUN XB, et al. 2016: Spatial and temporal patterns of precipitation variability over mainland China: Ⅲ: causes for recent trends,. Advances in Water Science, 27(3): 327-348.

Sims EM, Liu G. 2015. A parameterization of the probability of snow-rain transition. Journal of Hydrometeorology, 16: 1466-1477.

Stewart RE, Thériault JM, Henson W, 2015. On the Characteristics of and Processes Producing Winter Precipitation Types near 0°C. Bull. Am. Meteorol. Soc. 96, 623–639. DOI:10.1175

/BAMS-D-14-00032.1

Wan H, Zhang XB, Francis WZ, et al. 2013: Effect of data coverage on the estimation of mean and variability of precipitation at global and regional scales. Journal of Geophysical Research: Atmospheres, 118:534-546. DOI:10.1002/jgrd.50118

Wang SG, Kand ES, Li X. 2004: Progress and Perspective of Distributed Hydrological Models. Journal of Glaciology & Geocryology, 26 (1) :61-65.

Wang CY, Wang SL, Huo ZG, et al. 2005: Progress in research of agro-meteorological disasters in China in recent decade. Acta Meteorologica Sinica, 5:659-671.

Wigmosta MS, Vail LW, Lettenmaier DP. 1994: A distributed hydrology-vegetation model for complex terrain [J] . Water Resources Research, 30(6): 1665- 1679.

WMO. 2013: Reducing and managing risks of disasters in a changing climate. WMO Bulletin, 62(Special Issue): 23-31.

Wu BY, Yang K, Zhang RH. 2009: Eurasian snow cover variability and its association with summer rainfall in China. Advances in Atmospheric Sciences, 26:31-44.

Vavrus S. 2007: The role of terrestrial snow cover in the climate system. Climate Dynamics, 29(1):73-88.

Xiao C, Yu RC, Yuan WH, et al. 2015: Spatial and temporal differences characteristics of the rainy season of Mainland China. Acta Meteotologica Sinica, 73 (1): 84-92.

Yang LM, Yang T, Jia LH, et al. 2005: Analyses of the Climate Characteristics and Water Vapor of Heavy Snow in Xinjiang Region, Journal of Glaciology and Geocryology, 27 (3): 389-396.

Ye H, Cohen J, Rawlins M. 2013: Discrimination of solid from liquid precipitation over northern Eurasia using surface atmospheric conditions. Journal of Hydrometeorology, 14 (4): 1345-1355.

Yu RC, Li J, Chen HM, et al. 2014: Progress in studies of the precipitation diurnal variation over contiguous China. Acta Meteorologica Sinica, 72 (5): 948-968.

Zhang ZF, Xi S, Liu N, et al. 2015: Snowfall change characteristics in China from 1961 to 2012, Resources Science, 37(9): 1765-1773.

Zhong J, Su BD, Zhai JQ, et al. 2013: Distribution Characteristics and Future Trends of Daily Precipitation in China, Progressus Inquisitiones De Mutatione Climatis, 9 (2): 89-95.