

Research Article

Objective Identification Method of Cold-Front Precipitation in Winter Half Years over East Asia

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Cold front is an important weather system that produces precipitation in East Asia. Under the background of global warming, extreme precipitation caused by cold fronts presents a significant increasing trend. Hence, it is very important to quantify the coldfront precipitation that may cause great damages. In this study, an objective identification method is proposed for cold-front precipitation, which can objectively identify the precipitation area affected by cold fronts. Then, the climatological characteristics and trends of cold-front precipitation over East Asia in the winter half years from 1989 to 2018 are investigated by using the ERA-5 reanalysis dataset. Based on the dataset of cold fronts and frontal zones, this method automatically distinguishes the precipitation area affected by cold fronts to quantitatively estimate cold-front precipitation. The results show that this identification method can well describe cold-front activities and associated precipitation during an extreme cold wave event that occurred in southern China in January 2016. In the past 30 years, cold fronts have significantly contributed to the precipitation in East Asia in winter half years. The areas with the maximum cold-front precipitation and maximum contribution rate of cold-front precipitation to total precipitation are located in the North Pacific storm track, cold-front precipitation exceeds 700 mm, and the contribution of coldfront precipitation to total precipitation exceeds 60%. In addition, the contribution rates of cold-front precipitation are also relatively large in the midlatitudes of East Asia, especially in North China and Northeast China, where cold-front precipitation accounts for 50%-60% of total precipitation. In East Asia, the total precipitation in autumn is greater than that in winter; however, cold-front precipitation and its contribution rate in winter are significantly more and larger than those in autumn. As the coldfrontal activity is more frequent and intense in winter, the rainfall in winter depends more on cold fronts. In the past 30 years, the trends of cold-front precipitation and total precipitation are consistent in most parts of East Asia, indicating that cold-front precipitation makes a great contribution to the trend of total precipitation in winter half years.

1. Introduction

Against the background of global warming, extreme weather and climate events occur frequently. Papalexiou and Montanari revealed significant increasing trends in the frequency of precipitation extremes over most of Eurasia, northern Australia, and the American Midwest from 1964 to 2013 [1]. In urban China, the trend of extreme precipitation has also increased significantly over the past 60 years [2]. Floods caused by heavy rainfall can cause enormous economic losses and even casualties [3]. Therefore, understanding the mechanisms responsible for extreme precipitation events is beneficial for the prediction of their changes [4].

Catto et al. revealed that as an important system that affects regional weather changes, and atmospheric fronts are often associated with heavy rainfall and strongly affect its spatiotemporal distribution [5]. Solman and Orlanski suggested that frontal activity is often associated with extreme rainfall events in subtropics and high latitudes [6]. Any changes in the intensity, frequency, or characteristic paths of the fronts have an impact on the local climate, and changes in precipitation are strongly controlled by changes in frontal activity at the midlatitude and subpolar latitude [7–9]. Schemm et al. revealed that the frontal precipitation amount increases with the increased intensity of the frontal zone [10].

According to Hawcroft et al., for midlatitude weather, quantifying precipitation induced by a particular weather system and decomposing the contributions of precipitation brought by different weather systems to the total precipitation in the climate can help grasp the potential influence of the change in intensity or spatiotemporal distribution of precipitation events in the future [11]. Wu et al. studied fronts and cyclones associated with changes in total and extreme precipitation in China. They identified precipitation within a 500 km radius of the front (extratropical cyclone) as frontal precipitation (extratropical cyclone precipitation). The results show that precipitation associated with front and extratropical cyclones accounted for 21.2% and 20.4% of total precipitation, with the largest proportion in June and January, respectively [12]. Catto et al. proposed a method to relate precipitation to atmospheric fronts. If a front occurs in a search box centered at a grid point, the precipitation at this grid point is allocated to the front. This method revealed that more than 90% of extreme precipitation in some parts of the major midlatitude storm-track regions is associated with fronts. On average, 51% of global extreme precipitation events are associated with fronts [5]. Hénin et al. modified an algorithm proposed by Catto et al. to study the frontal precipitation on subdaily timescales over the North Atlantic and Europe. It is revealed that cold fronts mainly contribute to inland precipitation, where cold-front precipitation amounts to 500 mm per year, accounting for 40% of total precipitation. The European continent is less affected by frontal precipitation than North America, but it is still dominated by cold-front-related precipitation [13]. Therefore, cold fronts play an important role in precipitation, and thus, quantifying cold-front precipitation is of great significance in the study of precipitation events.

In East Asia, which is densely populated and concentrated in industrial and agricultural production, continuous rain and extreme precipitation events frequently occur due to cold fronts, which often cause catastrophic damages. So far, there have been many works focusing on the characteristics of frontal precipitation in East Asia. For a frontal rainstorm in Liaoning province of China, Wu et al. suggested that the inflow of dry and cold air into the upper troposphere near the front is more likely to cause severe convective weather such as hail and thunderstorms [14]. Another case study in South China has revealed that frontal precipitation has an obvious baroclinic structure and severe vertical movement [15]. Liang et al. pointed out that the temperature gradient near the frontal zone provides the energy of baroclinic instability for convective activity, and the vertical shear of strong low-level wind makes convection easy to maintain and develop [16]. The above studies have deepened our understanding of frontal precipitation over East Asia. However, there are relatively few quantitative studies on cold-front precipitation over East Asia. Moreover, most of the existing studies on frontal precipitation over East Asia focus on a single process, while the research on coldfront precipitation over East Asia is still scarce from the

climatological point of view. Based on a two-step identification algorithm for cold front [17], this paper presents an objective method to identify cold-front precipitation over East Asia and studies its climatic characteristics and longterm change trend, aiming to obtain an overall understanding of the distribution and trend of cold-front precipitation in East Asia.

The remainder of this paper is organized as follows: Section 2 introduces the data and methods. Section 3 presents a case of identifying the cold-front precipitation in an extreme cold wave event. Section 4 analyzes the characteristics of cold-front precipitation in winter half years. Section 5 further illustrates the trend of cold-front precipitation during this period. Finally, the main conclusions and discussion are provided in Section 5.

2. Data and Methods

2.1. Data. The data used in this paper mainly come from the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA-5) of global climate [18], including the temperature and wind components at 850 hPa, surface wind components, sea-level pressure and hourly precipitation covering the period from September to January of 1989–2018, the hourly snowfall and the sea-level pressure fields at both 00:00 UTC and 12:00 UTC in January 2016, and the sea-level pressure fields at both 00:00 UTC and 12:00 UTC in September 2016. All data have a horizontal resolution of $2.5^{\circ} \times 2.5^{\circ}$.

2.2. Methods

2.2.1. Linear Regression Method. The linear regression method was used in the analysis of trends in the frequency of cold-front activity and precipitation. As an example, the regression equation of the estimated cold-front activity frequency (\hat{y}) versus time (x) was calculated for the trend of cold-front activity frequency, where the sample size of x is n, and the regression equation is as follows:

$$\widehat{y} = bx + a. \tag{1}$$

The regression coefficient a and the constant b are calculated using the least squares method and can be expressed as

$$b = \frac{\sum_{i=1}^{n} x_{i} y_{i} - (1/n) \left(\sum_{i=1}^{n} x_{i}\right) \left(\sum_{i=1}^{n} y_{i}\right)}{\sum_{i=1}^{n} x_{i}^{2} - (1/n) \left(\sum_{i=1}^{n} x_{i}^{2}\right)},$$

$$a = \overline{y} - b\overline{x}.$$
(2)

When a > 0, it means that the frequency of cold fronts tends to increase with time, and when a < 0, it means that the frequency of cold fronts tends to decrease with time.

2.2.2. Two-Step Cold-Front Identification Algorithm. Feng et al. proposed a two-step cold front identification algorithm, which combines the thermal front parameter (TFP) with temperature advection to identify the frontal zone and then the front. This algorithm has a good ability to identify cold fronts in East Asia in recent 30 years and has two steps [17].

First, TFP is combined with temperature advection to locate the cold-frontal zone:

$$TFP = -\nabla |\nabla T| \cdot \frac{\nabla T}{|\nabla T|},$$

$$-\overrightarrow{V} \cdot \nabla T = -\left(u \cdot \frac{\partial T}{\partial x} + v \cdot \frac{\partial T}{\partial y}\right),$$
(3)

where *T* is the temperature at 850 hPa that smoothened 100 times with a five-point smoothing technique, *V* is the wind vector of 850 hPa, and *u* and *v* are the zonal and meridional winds, respectively. It is considered that grid points that satisfy the thresholds of the two variables $(|\text{TFP}| \le 2 \times 10^{-11} K/m^2 \text{ and } -\vec{V} \cdot \nabla T \le -1 \times 10^{-4} K/s)$ belonging to the cold-frontal zone.

Second, the grid points on the easternmost and southern boundaries of each identified cold-frontal zone are determined as warm boundaries. Then, second-order polynomial fitting is applied to these grid points, and each smoothed curve indicates a cold front. For specific steps, see Feng et al. [17].

Hence, an objective dataset of 30-year cold fronts and initial cold frontal areas are obtained by using this method.

2.2.3. Objective Identification Method of Cold-Front Precipitation. Cold-front precipitation can be calculated by using the dataset of cold fronts and initial cold-frontal zones obtained by the two-step cold-front identification method mentioned in Section 2.2.2. To clearly demonstrate the method of this paper, an example where more than one cold front exists over East Asia was chosen. Taking the case of the cold front at 00:00 UTC on September 18 of 2017 as an example, the method proceeds as follows.

(1) Identifying the Cold-Frontal Zone. Figures 1(a) and 1(b) present the initial cold-frontal zones (denoted as cold-frontal zone I) and the cold fronts obtained by the two-step cold-front identification algorithm, respectively. Figure 1(c) shows a combination of cold-frontal zone I and cold fronts shown in Figures 1(a) and 1(b). It can be seen that not all initial cold-frontal zones have cold fronts. Therefore, cold-frontal zone II is obtained by deleting the frontal zones without cold fronts (Figure 1(d)).

(2) Extending the Cold-Frontal Zone. After delineating the cold-frontal zone, all precipitation in the cold-frontal zone can be taken as cold-front precipitation. However, since the cold front is determined by the grid points on warm boundaries of the cold-frontal zone, while the cold-frontal zone is mainly located behind the cold front, taking precipitation falling into the cold-frontal zone as cold-front precipitation will result in an underestimation as precipitation ahead of the cold-frontal zone is ignored. Therefore, it is necessary to extend the cold-frontal zone based on cold-frontal zone II, which is mainly discussed in this section.

Considering the range of precipitation ahead of the cold front and the moving speed of the cold front, three preliminary extension schemes are designed, which extend cold-front area II eastward and southward by one-grid, twogrid, and three-grid spacings (2.5°, 5°, and 7.5°), and they are denoted as schemes 1, 2, and 3, respectively. In order to accurately select the expansion scheme, we analyzed a total of 360 examples from 2014 to 2015. Taking the precipitation process at 00:00 UTC on September 18 of 2017 as an example, the changes in cold-front precipitation under three schemes are discussed to determine an optimum scheme to extend the cold-frontal zone. Figure 2(a) shows that there are three cold fronts located in the West Siberian trough, the periphery of the Baikal high pressure, and the cyclone over Japan. Obvious precipitation occurs near the three cold fronts and along the Qinghai-Tibet Plateau, where precipitation near the cold front located in the cyclone of Japan is the largest with a wide range.

Figures 2(b)-2(i) display the distributions of cold-front precipitation in cold-frontal zone II and those under three extension schemes. From Figures 2(b) and 2(c), it can be seen that the location of cold-front precipitation in coldfrontal zone II is well consistent with each cold front, but the precipitation ahead of cold front cannot be well reflected. Figures 2(d)-2(i) demonstrate the cold-front precipitation under three extension schemes. Comparatively, scheme 1 underestimates the contribution of cold-front precipitation located in the cyclone of Japan to total precipitation. Scheme 2 can well describe precipitation corresponding to each cold front. As far as scheme 3 is concerned, there is little difference compared with scheme 2, but the precipitation over the Qinghai-Tibet Plateau is erroneously classified as coldfront precipitation. Therefore, extension scheme 2 is selected as the optimum scheme for extending the cold-frontal zone, which extends cold-frontal zone II eastward and southward by 5° to obtain cold-frontal zone III.

(3) Cold-Front Precipitation and Its Contribution Rate to Total Precipitation. The precipitation falling into cold-frontal zone III is considered cold-front precipitation pf, and the ratio of pf to total precipitation pa is the contribution rate of cold-front precipitation to total precipitation which is as follows:

$$\operatorname{Con} = \frac{\mathrm{pf}}{\mathrm{pa}} \times 100\%. \tag{4}$$

Similar to the process of identifying cold fronts and coldfrontal zones, cold-front precipitation is calculated twice a day, that is, at 00:00 UTC and 12:00 UTC each day. The cold-front precipitation is calculated as the 12-hour cumulative precipitation of 6 hours before and after the abovementioned two moments. It should be noted that coldfront precipitation over the Tibetan Plateau will not be discussed in this paper as the cold fronts and areas with coldfront precipitation are identified by the dataset at 850 hPa.

(4) Intensity of the Cold Front. The cold front intensity Fs is defined by temperature advection as follows:



FIGURE 1: (a) Cold-frontal zone I, (b) objective cold front, (c) objective cold front and cold-frontal zone I, and (d) objective cold front and cold-frontal zone II obtained by the two-step cold-front identification method at 00:00 UTC on September 18, 2017.



FIGURE 2: Continued.



FIGURE 2: (a) Surface precipitation and objectively identified cold front, (b) cold-frontal zone II, and (c) precipitation falling into cold frontal zone II at 00:00 UTC on September 18, 2017. (d, f, h) The extended cold-frontal zones according to schemes 1–3, respectively. (e, g, i) Precipitation falling into the three extended cold-frontal zones. The blue grids are cold-frontal zone II, the red grids are the extended parts, shading denotes the precipitation (unit: mm), the contour is the sea-level pressure at an interval of 4 hPa, and the blue line indicates the objectively identified cold front.

$$Fs = |-\overrightarrow{V} \cdot \nabla T|.$$
(5)

Among them, $-\vec{V} \cdot \nabla T < 0K/s$, and it is treated by standardization.

(5) *China Regional Division*. In this paper, the geographical extent of each region in China is shown in Figure 3.

3. Identification of Cold-Front Precipitation in a Super Cold Wave Event

Cold air activity frequently occurs over East Asia during winter half years. During cold wave weather events, coldfront precipitation mostly manifests as catastrophic weather such as snowstorms and freezing rain. Under the background of global warming, the frequency and intensity of extreme weather events such as snowstorms and



FIGURE 3: The geographical extent of each region in China.

freezing rain have increased [19], which exert an increasing influence on socioeconomic development. Hence, this phenomenon has attracted great attention from scholars, the public, and government decisionmaking departments. From January 21 to 25, 2016, a super cold wave weather process swept most parts of China, with record-breaking minimum temperatures being observed in many regions [20]. A wide range of rain, snow, and freezing weather occurred in southern China. The city of Guangzhou in China experienced the first snowfall since its meteorological records began [21, 22]. Moreover, snowfall was also observed in Hong Kong and Macau, which is rare in history. Figures 4(a)-4(c)present the sea-level pressure fields, precipitation, snowfall, and cold front from January 22 to 23, 2016. There was a high pressure centered around Lake Baikal, dominating much of the East Asia continent. The cold front on the periphery of the high pressure brought a wide range of rainfall and snowfall; thus, it is an important system causing this freezing rain and snow weather event in southern China.

During this event, the objective algorithm for identifying cold-front precipitation is applied to quantify cold-front precipitation, similar to the quantification of cold-front precipitation, and snowfall taking place within the extended cold-frontal zone is defined as cold-front snowfall (Figures 4(d)-4(f)). At 00:00 UTC on January 22, the cold front was located along the regions from North China to Southwest China. Under the influence of this cold front, heavy snowfall occurred in North China, Central China, and East China (Figure 4(d)). At 12:00 UTC on January 22, the cold front moved eastward and shifted southward, splitting into two sections. Besides, a new cold front appeared in regions from North China to Southwest China. Under the influence of this new cold front, Changsha, Chongqing, Kunming, Hangzhou, and other cities experienced a snowfall weather event (Figure 4(e)). At 00:00 UTC on January 23, cold fronts merged and moved eastward into the sea. Correspondingly, the rain band also moved eastward, and thus, the cold-front snowfall was mainly concentrated in southwest and southeast coastal areas of China (Figure 4(f)).

From the above analysis, it can be concluded that the identification method for cold-front precipitation proposed in this paper can objectively quantify cold-front precipitation during this super cold wave event, and it also has a good ability in identifying the snow generated by the cold front. The identification method helps understand the influence of cold fronts on extreme precipitation events and the evolution characteristics of extreme precipitation events.

4. Characteristics of Cold-Front Precipitation in Winter Half Years

4.1. Winter Half Years. Figure 5 shows the climatological cold-front precipitation and corresponding contribution rates over East Asia during the winter half years of 1989–2018. The maxima of cold-front precipitation and the contribution rate to total precipitation are located in the main storm-track area of the North Pacific Ocean. The maximum precipitation exceeds 700 mm, accounting for more than 60% of total precipitation. Previous studies have also shown that cold fronts are active in the main storm-track regions of the North Pacific, North Atlantic, and Antarctic Oceans, and the large-value areas of cold-front precipitation are also located in these areas [23, 24].

In addition, cold-front precipitation is also relatively large over the regions from Lake Balkhash to Northwest China, North China, and East China (the regions are divided as shown in Figure 3), with precipitation being 100–200 mm. Combining Figures 5(a) and 5(b), it can be found that the total precipitation induced by cold fronts is the largest over the ocean, with the contribution rate exceeding 50%. However, the contribution of cold-front precipitation to total precipitation is not small over the land of East Asia, with the contribution rate being more than 20% in most areas, especially in North China and Northeast China, where cold-front precipitation accounts for 50%-60% of total precipitation. From Lake Balkhash to Northwest China, cold-front precipitation accounts for more than 50% of total precipitation. This indicates that the cold front greatly contributes to winter precipitation.

4.2. Autumn and Winter. Figure 6 shows the climatological cold-front precipitation amounts and corresponding contribution rates during the autumn and winter from 1989 to 2018. The distribution of precipitation in autumn and winter is basically the same. However, cold-front precipitation and corresponding contribution rates in winter are higher than those in autumn. The large values of cold-front precipitation are located in the Sea of Japan and the North Pacific Ocean. Winter precipitation is distributed more southward, where the area with a cold-front precipitation amount of over 100 mm is located to the south of 30°N. The maximum cold-front precipitation reaches 500 mm in winter, and the corresponding contribution rates are more than 70% in a large area from Northeast China to the North Pacific Ocean. In contrast, the maximum cold-front precipitation is only 200 mm in autumn, and the associated contribution rates are weaker than those in winter. However, Figure 7 reveals that the total precipitation in autumn is stronger than that in winter, and the distribution range is relatively wider. The total precipitation in autumn is more in Southwest China, south of the Qinghai-Tibet Plateau, and over the western Pacific Ocean than in winter. As shown in Figure 8, water vapor transport is significantly stronger in autumn than in winter at 850 hPa over Southwest China and south of the Qinghai-Tibet Plateau, and the intensity of water vapor convergence center reaches above -10.10⁻⁷ kg·m⁻²·s⁻¹·hPa⁻¹. In addition, in the western Pacific Ocean, water vapor fluxes are convergent in autumn, while water vapor fluxes are divergent in winter. These factors lead to stronger total precipitation in these regions in autumn than in winter. Therefore, the stronger cold-front precipitation in winter than in autumn may attribute to the stronger cold-front activity in winter.

Figure 9 shows the frequencies of cold-front activity and the intensities of cold-front zones. The cold-front activity in autumn and winter is concentrated in North China, Northeast China, and Japan. The intensities of cold-frontal zones are stronger in Northeast China, Japan, and the North Pacific, and the corresponding contribution



FIGURE 4: The cold wave weather process from 00:00 UTC on January 22 to 00:00 UTC on January 23, 2016. (a–c) The distributions of total precipitation and snowfall at 00:00 UTC on January 22, 12:00 UTC on January 22, and 00:00 UTC on January 23, respectively. (d–f) The cold-front precipitation and cold-front snowfall at 00:00 UTC on January 22, 12:00 UTC on January 22, and 00:00 UTC on January 23, respectively. The contour is the sea-level pressure at an interval of 4 hPa, shading is precipitation (unit: mm), the dotted area is snowfall (unit: mm), and the blue line indicates the objectively identified cold front.

rates of cold-front precipitation to total precipitation are also larger in these regions. The frequency of cold fronts in autumn exceeds 16 in North China, Northeast China, and Japan and reaches 8 in Lake Balkhash and Northwest China. The intensity of cold fronts is strong in North China, Northeast China, and the Sea of Japan, with a maximum value of 70 K/s. Compared to autumn, cold fronts occur more frequently in winter, with a frequency of 30 in Northeast China and the northern Sea of Japan, a frequency of 28 in the southeast coast of Japan, and a frequency of 8 in Southeast China. The intensity of cold fronts is also significantly stronger in winter than in autumn, exceeding 110 K/s in Northeast China, the Korean Peninsula, Japan, and the North Pacific. Therefore, the higher frequency and the stronger intensity of cold fronts in winter result in stronger cold-front precipitation in winter than in autumn. In the results of Berray's study of global cold-front frequency, it can also be found that the frequency of cold fronts is significantly stronger in Southeast China in winter than in autumn [24]. The frequency of cold fronts is stronger in winter than in autumn in Japan [25]. In agreement with the results of this paper, Catto et al. found that the maximum frontal intensity occurs in the western part of the northern hemisphere storm axis, where there is a strong thermal contrast between land and ocean [26].

Advances in Meteorology



FIGURE 5: (a) The cold-front precipitation (unit: mm) and (b) corresponding contribution rate (unit: %) during the winter half years from 1989 to 2018.



FIGURE 6: Climatological means of (a, c) cold-front precipitation (unit: mm) and (b, d) corresponding contribution rates (unit: %) in (a, b) autumns and (c, d) winters of 1989–2018.

5. Long-Term Trends of Cold-Front Precipitation in Winter Half Years

Figure 10 shows the long-term trends of total precipitation and cold-front precipitation from 1989 to 2018. The trends of total precipitation are consistent with those of cold-front precipitation in most areas. Over the ocean, both total precipitation and cold-front precipitation present increasing trends. While on the continent, for regions in the west of Lake Balkhash, the total precipitation and cold-front precipitation over the Bohai Sea of China, Yangtze-Huaihe River basin, and India show decreasing trends. Among them, the total precipitation in the Bohai Sea has decreased by more than 20 mm per ten years, and cold-front precipitation has decreased by more than 12 mm per ten years. For the southeastern coast of China and Mongolia, both total precipitation and cold-front precipitation are increasing, where the total precipitation on the southeastern coast of



FIGURE 7: Climatological means of total precipitation in (a) autumns and (b) winters of 1989-2018 (unit: mm).



FIGURE 8: Climatological means of water vapor flux and water vapor flux dispersion in (a) autumns and (b) winters of 1989–2018. The arrows are water vapor fluxes (unit: $kg \cdot m^{-1} \cdot s^{-1}$); shading is water vapor flux dispersion (unit: $10^{-7} kg \cdot m^{-2} \cdot s^{-1} \cdot hPa^{-1}$).





Advances in Meteorology



FIGURE 9: Climatological means of (a, c) the frequencies of cold front activities and (b, d) the intensities of cold frontal zones in (a, b) autumns and (c, d) winters of 1989–2018.



FIGURE 10: The trends of (a) annual total precipitation and (b) annual cold-front precipitation from 1989 to 2018 (unit: mm/year). The white dots indicate the values that have passed the significance test at a 90% confidence level.

China has increased by more than 20 mm per ten years and cold-front precipitation has increased by more than 12 mm per ten years. In some areas of south of Lake Balkhash, the total precipitation presents a trend opposite to cold-front precipitation; that is, the increasing trends in total precipitation correspond to the decreasing trends in cold-front precipitation.

As shown in Figure 11, the overall trend of cold fronts on the continent of East Asia is decreasing, which significantly decreases by four fronts per decade in parts of northeastern Siberia, Northern, and Northeastern China, and the increasing trend being three fronts per decade can only be found in parts of Mongolia, Central China, and Eastern Qinghai-Tibet Plateau in China. Therefore, it can be concluded that the decrease in total precipitation over regions west of Lake Balkhash, over the Bohai Sea, Yangtze-Huaihe River basin, and around India is related to the decrease in the frequency of cold fronts, while the increase in precipitation in the coastal areas of East Asia and Mongolia is mainly due to the increase in the frequency of cold-front activity. For some areas such as south of Lake Balkhash, although total precipitation has increased, the decrease in the frequency of cold fronts results in the decrease in cold-front precipitation, which thus contributes less to the trend of total precipitation.



FIGURE 11: The trend of cold-front frequency from 1989 to 2018. The white dots indicate the values that have passed the significance test at a 90% confidence level.

Besides, there are few cold fronts in the southern part of the Qinghai-Tibet Plateau (Figure 9), where the contribution rate of cold-front precipitation is below 5%, so the cold-front precipitation in this region has no effect on the trend of total precipitation.

In conclusion, cold fronts have an important influence on precipitation trends, with an overall decreasing (increasing) trend of cold fronts on land (over the ocean), and therefore a decreasing (increasing) trend of cold front precipitation and total precipitation on land (over the ocean) as a whole. The trend of cold-front frequency increases significantly in the storm-track region $(25^{\circ}N-40^{\circ}N, 120^{\circ}E-155^{\circ}E)$, and previous studies have shown this trend [26, 27], so the trend of cold-front precipitation increases in this region. Meanwhile, Hénin et al. showed that cold fronts induce more precipitation than warm fronts globally, with greater differences in winter precipitation, and that the trend in precipitation is significantly correlated with the trend in cold-front precipitation [13].

6. Conclusions and Discussion

Based on the ERA-5 reanalysis data, this paper proposes an objective identification method for cold-front precipitation. The distribution characteristics and trends of cold-front precipitation in winter half years of recent thirty years in East Asia are explored from the climatological point of view. The main conclusions are as follows.

Based on the dataset of 850 hPa cold-frontal zones and surface cold fronts obtained by an objective cold-front identification algorithm, cold-front precipitation can be easily and quickly identified through the objective identification algorithm proposed in this study. The application to a super cold-front weather process on January 22 to 23 of 2016 confirms that this algorithm can well quantify coldfront precipitation and helps understand the influence of cold fronts in extreme precipitation events.

Cold fronts largely contribute to the precipitation in East Asia during the winter half years. The large-value areas of cold-front precipitation and associated contribution rates are located in the main storm-track regions of the North Pacific Ocean, with the maximum exceeding 700 mm, accounting for more than 60% of total precipitation. In East Asia, the contribution rates of cold-front precipitation are more than 20% in most areas, especially in North China and Northeast China, where cold-front precipitation accounts for 50%–60% of total precipitation. For regions from Lake Balkhash to Northwest China, cold-front precipitation also accounts for more than 40% of total precipitation.

In East Asia, the total precipitation in autumn is greater than that in winter due to stronger moisture fluxes in autumn and moisture convergence in the western Pacific. However, cold-front precipitation and corresponding contribution are obviously stronger in winter than in autumn, mainly due to more frequent and stronger cold-front activity in winter. Therefore, the precipitation in winter is more dependent on cold fronts.

Cold-front precipitation and total precipitation present consistent trends over most of East Asia. In particular, there are increasing trends over the ocean, coastal areas of Southeast China, and Mongolia as well as decreasing trends over the Bohai Sea, the Yangtze-Huaihe River basin of China, India, and most areas west of Lake Balkhash. Only for some areas, such as those south of Lake Balkhash, cold-front precipitation shows a decreasing trend, which is opposite to that of total precipitation. In general, cold-front precipitation in East Asia contributes more to the trend of total precipitation in winter half years.

This paper shows that the large-value areas of coldfront precipitation and related contribution rates are located in the storm-track regions of North Pacific. However, the contribution rates of cold-front precipitation to total precipitation are also relatively larger in midlatitudes over the land of East Asia, especially in North and Northeast China, where cold fronts induce more than 40% of total precipitation. Hénin et al. also revealed that global cold fronts contribute more precipitation than warm fronts. The cold-front precipitation in storm-track regions of North Atlantic is the largest. For inland areas, the main contribution to inland precipitation comes from cold fronts, especially in northern United States as well as the southern part and western boundary of Canada, accounting for more than 40% of total precipitation. In addition, the trend of total precipitation is significantly correlated with the trend of cold-front precipitation, except in the Gulf of Mexico and France [13]. In this study, it has been found that the trends of cold-front precipitation and total precipitation are consistent in most regions of East Asia, but there are inconsistencies in regions of East Siberia and west of Lake Balkhash, where the contribution of cold-front precipitation is relatively larger. This remains to be further explored.

The objective identification of cold-front precipitation proposed in this paper involves an extension scheme of the precipitation area, which is extended to account for precipitation located in front of the cold fronts, and precipitation generated during the movement of cold fronts. This extended scheme is generally applicable to most cases but may not be entirely accurate in all instances. In this regard, distinguishing between different types of cold fronts and cold frontal precipitation can further improve the accuracy of identifying cold frontal precipitation and is worth exploring in future work.

Due to cold-front precipitation calculated twice a day, the ERA-5 reanalysis dataset that can provide precipitation data twice a day was used in this paper. Many studies have compared and evaluated reanalysis datasets, observationbased precipitation datasets, and satellite datasets [28–31]. Collectively, these studies highlight the strengths and weaknesses of all types of precipitation data, and the strength of the reanalysis dataset is the long-term broad spatiotemporal coverage of multiple relevant climate variables. For many climate research applications, reanalysis datasets have relatively good physical consistency. Furthermore, the method is based on a single reanalysis dataset; future research will focus on using multiple datasets to improve the accuracy of the method.

Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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