Moisture sources tracking of a cold vortex rainstorm over Northeast China using FLEXPART

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Abstract
Water vapor sources and related transport processes are fundamental to the understanding of precipitation mechanisms. This study focuses on a typical Northeast Cold Vortex (NECV) rainstorm on July 25, 2016, which brought floods and huge economic losses to Northeast China. Using the Lagrangian flexible particle dispersion model (FLEXPART) and the areal source–receptor attribution method, the moisture sources and transport characteristics during this event were analyzed. The results show that this NECV rainstorm occurred under a favorable atmospheric circulation background, and particles in the rainstorm area mainly came from the Indo-China Peninsula, South China Sea, Bay of Bengal, and central China at relatively low levels. The largest water vapor uptake and release were found in central China, which was the primary moisture source of this NECV precipitation. Although the Indian Subcontinent–Bay of Bengal–Indo-China Peninsula had a higher moisture intake than the South China Sea–the Philippines, a considerable amount of moisture in the former was released during transport, making the moisture contributions of the two equivalents. Furthermore, the Northeast rainstorm area had a non-negligible precipitation recycling process. All examined sources contributed more than 90% of the moisture in the rainstorm area.

KEYWORDS
NECV rainstorm, moisture sources, quantitative contribution, FLEXPART

1 INTRODUCTION

The Northeast Cold Vortex (NECV), a cutoff low that frequently exists along northern China–Siberia–Northwest Pacific coast with strong quasi-static and persistent characteristics, is often responsible for excessive rainfall in Northeast China (Zheng et al., 1992). The NECV rainstorm can lead to flood disaster (Sun et al., 1994; Wang et al., 2007; Zhao et al., 1980), posing a huge threat to the agricultural production of the northeast area and the life and property safety of residents. However, Liu et al. (2021) found the ECMWF model showed relatively poor prediction skills for heavy precipitation in Northeast China. Thus, it is crucial to explore the mechanism of heavy rain from the source, particularly the NECV rainstorm. As the basic condition for the occurrence, development, and maintenance of rainstorms, abundant water vapor is indispensable (Zhu et al., 1981). Not only is the
local water vapor content high during a rainstorm, but there is also a steady stream of water vapor transit and convergence (Tao, 1980). Northeast China is located at the northernmost end of the East Asian monsoon region, where moisture from low latitudes and tropical oceans needs to travel across most of China to gather. In addition, processes associated with moisture modify the intensity and variability of precipitation that plays a crucial role in the atmospheric water cycle, and vice versa (Eltahir & Bras, 1996; Langhamer et al., 2021). Therefore, figuring out the moisture sources and the water vapor transportation path of the NECV rainstorm is of great significance.

At present, several approaches have been developed for moisture tracking of precipitation events, including isotopic analysis (Bonne et al., 2014; Pfahl & Wernli, 2008), Eulerian (Ding et al., 2020; Munday et al., 2021), and Lagrangian method (Chen et al., 2013; Hu et al., 2020; Huang & Cui, 2015a, 2015b; Liang et al., 2011; Sodemann et al., 2008; Vázquez et al., 2020; Wang et al., 2021; Xu et al., 2017; Xue & Cui, 2020; Zhang et al., 2021; Zhao & Mand, 2021). Regarding the NECV rainstorms, plenty of studies are based on the Eulerian method (Li et al., 2017; Qi et al., 2020; Sun et al., 2002; Wang et al., 2014; Wang & Wei, 2014; Yang et al., 2018), namely, using the vertically integrated moisture flux (VIMF). Others adopt the concept of “atmospheric rivers” to explain the water vapor transportation from the tropical ocean to Northeast China (Pan & Lu, 2020; Ralph et al., 2020; Sun et al., 2018). However, the detailed and quantitative moisture source-sink structure remains unclear (Jiang et al., 2011; Sun & Wang, 2014). Recently, Jiang et al. (2020) employed the Eulerian source-tagging method in the Community Atmosphere Model, version 5 (CAM5), to quantitatively identify the moisture sources of precipitation in Central Asia, but the results highly depend on the performance of the model to reproduce the hydrological cycle. Furthermore, some scholars used the Lagrangian method, such as the Hybrid Single-Particle Lagrangian Integrated Trajectory model, to investigate the moisture origins of the NECV rainstorm (Ma et al., 2017; Sun et al., 2018; Wei et al., 2015). Until now, there are still few studies on the quantitative moisture transport and budget characteristics of NECV rainfall. In this study, the Lagrangian flexible particle dispersion model (FLEXPART) and the quantitative analysis method are utilized to reveal the moisture sources, transport characteristics, and the contribution of each source region to the precipitation during a typical NECV rainstorm on July 25, 2016. This NECV rainstorm was accompanied by thunderstorm gale, hail, and other severe convective weather, leading to reservoirs flood and huge economic losses (Jing et al., 2017). This study is aimed to provide a comprehensive knowledge of the variations between different moisture sources in the NECV rainstorm, which will serve as a solid foundation for a better understanding of the NECV rainfall mechanism.

2 | DATA, MODEL, AND METHODS

2.1 | Data

1. The precipitation data were derived from the hourly 0.1° grid dataset of China automatic weather station merged with the Climate Prediction Center MORPHing technique (CMORPH) satellite (Pan et al., 2012; Shen et al., 2013).

2. The final version of the National Centers for Environmental Prediction (NCEP FNL) global reanalysis data with a spatial resolution of 1° × 1° on 26 vertical levels (https://rda.ucar.edu/datasets/ds083.2/), were acquired every 6 h for circulation situation analysis and driving FLEXPART.

2.2 | Model settings

We employed the Lagrangian Particle Transport model—FLEXPART v9.02, which has been widely used in the study of air pollution dispersion and atmospheric transport processes (Stohl & James, 2004, 2005). To investigate the overall atmospheric transport process of the rainstorm, the simulation area was set to 40°E–160°E, 10°S–60°N, as shown in Figure 1. Using the “domain-filling” mode (Stohl & James, 2004), a total of 1.2 million particles with the same mass and proportional to the air density were released into the area. FLEXPART was run forward for 10 days, which is the average residence time of moisture in the atmosphere (Nieto & Gimeno, 2019; Numaguti, 1999). Specifically, the simulation integral period was from 0000 UTC July 16, 2016 to 0000 UTC July 26, 2016. Then, the particles move freely with the wind field, which incorporates analyzed winds and random motions to account for turbulence (Stohl & James, 2004). A zero-acceleration scheme is adopted in FLEXPART to determine the trajectories’ position of particles (Stohl et al., 1998). Some other physical parameters, such as potential vorticity, specific humidity, temperature, and so on, are obtained through spatial interpolation of reanalysis data (Chen et al., 2011) and recorded every 3 h.

As a result, inevitably there exists truncation error and a certain interpolation error. Note that as the tracing
time goes on, the calculation errors of trajectories rise (Stohl, 1998). The trajectories can be considered to be of acceptable accuracy throughout the 10-day tracking period (Sun & Wang, 2014). Even 12–14 days in East Asia can be tracked (Cheng & Lu, 2020; van der Ent & Tuinenburg, 2017).

### 2.3 Identification of target particles

The Lagrangian analysis method can be applied to track the particles that make significant contributions to precipitation (called the target particles), where the moisture of target particles rises water vapor sources of precipitation can be identified. To select target particles, we referred to the method used by Chen et al. (2011) and Huang and Cui (2015a), which mainly covers the following steps.

1. According to the precipitation period, determine the selection time of target particles: 0000 UTC July 25, 2016 to 0000 UTC July 26, 2016.
2. Based on the rainfall distribution, choose the target area: 117.5°E–126.5°E, 37°N–43.5°N, as shown in the yellow box in Figure 1.
3. From the particles selected in the above two steps, screen out the particles whose precipitation is greater than 2 mm at the grid point.
4. According to the particles picked in the third step, find the particles with a specific humidity change of less than $-1 \text{ g kg}^{-1}$ over 3 h.

### 2.4 Quantitative contribution analysis of moisture sources

From the perspective of Lagrange, the change of moisture content of a particle can be expressed as (Stohl & James, 2004, 2005)

$$e - p = \frac{m dq}{dt}. \quad (1)$$

Wherein, $e$ and $p$ represent the increase and decrease rate of water vapor of a particle during transportation, respectively; $m$ is the mass of a particle; $q$ is the specific humidity; and $t$ is the time. If there exist $N$ particles in an air column with an area of $A$, their moisture changes can be accumulated as

$$E - P \approx \frac{\sum_{i=1}^{N} (e_i - p_i)}{A} = \frac{\sum_{i=1}^{N} m_i \frac{dq}{dt}}{A}, \quad (2)$$

where $E - P$ denotes surface freshwater flux, and $E$ and $P$ stand for the evaporation rate and precipitation rate of surface per unit area, respectively. When assuming the precipitation and evaporation cannot occur simultaneously at the same place in a short time interval, the instantaneous evaporation (precipitation) rate $E (P)$ can be diagnosed separately (Stohl & James, 2004), which is reasonable in heavy precipitation (Huang & Cui, 2015a; Stohl & James, 2004). Thereby if $E - P > 0$, $E$ and $P$ are indicated that there is a net uptake of water vapor, which can be identified as a moisture source; otherwise, $P - E$ and it is a rainfall area.
In order to quantitatively investigate the moisture budget as the target particle moves along its trajectory, the water vapor absorbed from the source region (Uptake) is divided into three parts (Sun & Wang, 2015): the water vapor lost in the transfer process (Loss), the water vapor released in the target region (Released), and the water vapor not released despite arriving in the target region (Unreleased). Using the “areal source–receptor attribution method” proposed by Sun and Wang et al. (2014), we can estimate the values of Uptake, Loss, and Released. Then, Unreleased is obtained by

\[
\text{Unreleased} = \text{Uptake} - \text{Loss} - \text{Released}. \quad (3)
\]

Moreover, the total released moisture in the target area is also calculated (\(\text{Released}_{\text{total}}\)), which is regarded as the precipitation. Therefore, the contribution of moisture in the source to the precipitation of the target region can be expressed as

\[
\text{C} = \frac{\text{Released}}{\text{Released}_{\text{total}}} \times 100\%. \quad (4)
\]

The ratio of the water vapor intake in the source region to the total water vapor release in the target region is \(\frac{\text{Uptake}}{\text{Released}_{\text{total}}} \times 100\%\). Accordingly,

\[
\frac{\text{Uptake}}{\text{Released}_{\text{total}}} \times 100\% = \frac{\text{Loss}}{\text{Released}_{\text{total}}} \times 100\% + \frac{\text{Released}}{\text{Released}_{\text{total}}} \times 100\% + \frac{\text{Unreleased}}{\text{Released}_{\text{total}}} \times 100\%. \quad (5)
\]

As a result, we can quantitatively compare the moisture budgets of diverse source areas.

3 | RESULTS

3.1 | Large-scale circulation and precipitation

The NECV emerged on July 23, 2016, reached the mature stage on July 24, 2016, and lasted until July 30, 2016. During this period, middle and high latitudes (east of 90°E, north of 45°N) at 500 hPa presented a situation of “two ridges and one trough” (Figure 1a). Two blocking highs can be found in the western Mongolia plateau and the Sea of Okhotsk. Accompanied with a cold center, the NECV was located in the east of Lake Baikal, stable and less moving. At the bottom of NECV, there existed an upper-level jet stream. Northeast China was in front of the cold vortex trough, favoring upward movement.

North of 15°N, subtropical high controlled central and southern China. The low-level warm and moist air from southeast China was transported to the target region, where it met with the high-level dry and cold air behind the cold vortex, increasing atmospheric instability. Furthermore, the convergence of cold and warm air also boosts the atmosphere’s baroclinicity, which promotes the development of rainstorm weather-scale systems or mesoscale systems (Tao, 1980), facilitating this intense rainfall.

Furthermore, Figure 1b shows the average VIMF (VIMF = \(\frac{1}{\rho} \int_{p_{s}}^{300 \text{ hPa}} q \mathbf{v} \cdot d \mathbf{p}\), where \(\rho\) is the gravitational acceleration, \(p_s\) is the surface pressure, \(q\) is the specific humidity, \(p\) is the pressure, and \(\mathbf{v}\) is the horizontal wind vector) and VIMF divergence (\(\nabla \cdot \text{VIMF}\)) from 0000 UTC July 16, 2016 to 0000 UTC July 26, 2016. It indicates a strong Somali trans-equatorial jet transported moisture from west to east to the Indian Subcontinent, the Bay of Bengal, and the Indo-China Peninsula. Then, the moisture from the Indo-China Peninsula merged with that from the Northwest Pacific Ocean, forming a strong core of water vapor flux from South China to Northeast China. On July 25, 2016, the target area had strong water vapor flux convergence in the lower troposphere (not shown), providing adequate water vapor for the precipitation.

The precipitation from 0000 UTC July 25, 2016 to 0000 UTC July 26, 2016 is presented in Figure 2a. It indicates that the main rain belt was northeast-southwest, mainly located in the Northeast Plain (Figure 2b). The largest precipitation centers were in the Bohai and the central and eastern part of Liaoning Province, with maximum precipitation of more than 100 mm. According to the above precipitation distribution characteristics, the target region was selected as 117.5°E–126.5°E and 37°N–43.5°N (the black box area in Figure 2a), which basically contained locations with 24 h accumulated precipitation greater than 50 mm.

3.2 | Particle trajectories

Following Dorling et al. (1992), we clustered the particle trajectories based on the non-hierarchical clustering algorithm, and the deviation between each trajectory and its average clustering trajectory was summed up as the root mean square deviation (RMSD). As shown in Figure 3, RMSD did not increase gradually or monotonically as the number of clusters decreased, but sudden interruptions were evident. When the number of clusters decreased from 8 to 7, RMSD changed greatly for the first time, with a
percentage change of more than 5%. Therefore, the particle trajectories were divided into eight categories.

Figure 4 provides the target particles’ trajectories and the clustered trajectories. It shows that the target particles mainly originated from the Indo-China Peninsula, the South China Sea, and the Bay of Bengal in turn, together accounting for more than 50%. Central China was responsible for 9.37% of the particles, and the above types all came from relatively low levels (the height is lower than 4000 m). There were also particles from the western Pacific, central Eurasia, and area around Balkhash Lake in the upper atmosphere. Generally, the trajectories of target particles are related to the northward advance of the East Asian summer monsoon and the circulation systems at corresponding levels. Compared with the Eulerian method (Figure 1b), the intense water vapor transport over the Arabian Sea did not be reflected in Figure 4, which may due to so long-distance that this part of moisture did not contribute significantly to the rainstorm in Northeast China. Instead, the Lagrangian trajectory tracking model could accurately track the particles that make crucial contributions and capture the key moisture sources.

3.3 | Moisture sources and quantitative contribution

According to the $E - P$ distribution diagnosed from FLEXPART (Figure 5a), the target particles experience multiple water vapor intake (the red part in Figure 5a, $E - P > 0$) and release processes (the blue part in

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**FIGURE 2** (a) Accumulated precipitation distribution (shading, units: mm) from 0000 UTC July 25, 2016 to 0000 UTC July 26, 2016 (black box represents target area). (b) Topography of Northeast China and related provinces

**FIGURE 3** The change of the percentage of root mean square deviation (PC in RMSD, blue dot) and root mean square deviation (RMSD, pink square) with the number of clusters
Further presents the moisture budget distribution method (Sun & Wang, "areal source–receptor attribution method"; 2014). We quantified the contribution of various moisture sources to the target area (Figure 5b) and estimated the contribution of local water vapor in the target area ("T" in Figure 5). It can be found that region C (central China) made the largest contribution to precipitation, accounting for up to 54.15%. Region D (eastern and coastal areas of mainland China) ranked second. Note that most particle trajectories passed through Regions C and D (Figure 4), where evaporation can be produced by water bodies such as the Yangtze River, Yellow River, and Dongting Lake. Moreover, some re-evaporation occurs as a result of precipitation from water vapor transfer upstream of these areas. Thus, abundant moisture was absorbed in Regions C and D (Figure 5a). The terrain in regions C and D is relatively flat. They are also closer to the target region, leading to less en-route moisture loss and significant moisture contributions to the target region. The target region (9.24%) was slightly less than Region D (10.58%), implying that local evaporation also plays a non-negligible role. In addition, the moisture contribution of Region E (the Indian subcontinent–Bay of Bengal–Indo-China Peninsula) and F (South China Sea–the Philippines) was 7.06% and 5.24%, respectively, which may be attributed to the far distance to the target region leading to the loss of much moisture during transport. Moreover, Regions A, B, and G also contributed a minor amount, which may be caused by the less moisture content in the upper atmosphere. In general, the total contribution of all sources to the precipitation in the target region reached 90.69%, which well explained most of the moisture sources in the precipitation process. The remaining moisture probably exists in the particles before the tracking 10 days or from moisture sources not been covered in this study.

Figure 5c further presents the moisture budget conditions of all sources (terms in Equation 5). And the proportion of each part of moisture received by the source area to the total uptake is also provided (the numbers on histogram). Region C (central China) had the greatest proportion of the total water vapor uptake, and meanwhile, it also released the most moisture in the target region, accounting for 22.53% of the moisture uptake in this region. Region A (central Eurasia), as a drier area in the mid-latitude westerly, also had obvious water vapor intake, which was comparable with Region D (eastern and coastal areas of mainland China), but the former has more en-route loss, causing a greater moisture contribution in Region D. For Region D, 44.63% of total moisture uptake was unreleased, which may be released elsewhere due to atmospheric circulation. Although Region E (the Indian subcontinent–Bay of Bengal–Indo-China Peninsula) had more total moisture uptake than region F (South China Sea–the Philippines), the en-route loss in Region E (79.81%) was greater than that in F (63.85%). With the equivalent proportion of the unreleased, the final moisture contributions of regions E (7.06%) and F (5.24%) were comparable. Especially, there was a certain amount of moisture uptake in the target region, of which 30.16% contributed to precipitation, implying the importance of the precipitation recycling process in the target region.
region (According to Eltahir and Bras (1996), precipitation recycling describes the contribution of local evaporation to local precipitation). Overall, region C (central China) had the most moisture intake and was the principal moisture source for this NECV precipitation.

4 | CONCLUSIONS

In this study, the Lagrangian trajectory tracking model FLEXPART and quantitative contribution analysis method were used to investigate the moisture sources, transport path, and quantitative contribution and budget process of each source during an NECV rainstorm on July 25, 2016. The large-scale circulation background was also analyzed. Compared with the traditional Eulerian method, we more clearly illustrated the water vapor transport characteristics related to the NECV precipitation. The main conclusions are as follows.

1. This NECV rainstorm occurred under favorable large-scale atmospheric circulation, with decent water vapor conditions. Through backward tracking of target particles, we found the majority of target particles came from the Bay of Bengal, Indo-China Peninsula, South China Sea, and central China, and these particles were all from the low levels. Particles from higher altitudes were also identified in the western Pacific, central Eurasia, and near Lake Baikal.

2. Quantitative contribution analysis demonstrated that region C (central China) contributed the most moisture to the precipitation, followed by the eastern and
coastal areas of mainland China (D) and the target rainfall area (T). The Indian subcontinent—Bay of Bengal–Indo-China Peninsula (E) and the South China Sea—the Philippines (F) also played a role. The moisture from all sources can account for 90.69% of the precipitation in the target region.

3. Central China (C) had the largest water vapor uptake and release. Although region E (the Indian subcontinent—the Bay of Bengal–Indo-China Peninsula) had higher moisture uptake than F (South China Sea—the Philippines), a large amount of moisture in region E was released along the way so that the moisture contribution of the two roughly equivalent. Furthermore, the target area had a non-negligible precipitation recycling process.

Land region (central China) turned out to be a dominant moisture source for this NECV precipitation, which may challenge the conventional wisdom that monsoons deliver plenty of water vapor from tropical oceans (Ding et al., 2020; Tao, 1980). However, Cheng and Lu (2020) revealed that terrestrial sources can be equally or more competitive than oceans for multiple East Asia land regions such as North China. They argued these vital terrestrial sources are maintained by the prevailing south-westerly monsoons across basins during the wet season, but were often overlooked and deserve further examination. Moreover, some studies also highlighted the importance of continental sources (Hu et al., 2018; Nie & Sun, 2022; Sun & Wang, 2014). Consequently, the terrestrial regions adjacent to the precipitation area could provide a rich source of water vapor.

Accompanied by global warming, the number of NECV days has decreased significantly (Lian et al., 2016). However, as the temperature rises, so does the amount of moisture in the atmosphere, increasing the severity of precipitation and making extreme precipitation events more frequent (Vázquez et al., 2020). Meanwhile, the global and regional water cycles have been enhanced (Skliris et al., 2016). In the future, from the perspective of statistics, various NECV precipitation cases for a long period need to be analyzed to further discuss the moisture transport characteristics in the context of global warming, which may provide some precursor signals before precipitation as well (Huang & Cui, 2015b).

**AUTHOR CONTRIBUTIONS**

**Yuting Yang:** Data curation; formal analysis; investigation; methodology; software; validation; visualization; writing – review and editing. **Qiangli Zou:** Methodology; software; validation; visualization.

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