The Moisture Sources and Transport Processes for a Sudden Rainstorm Associated with Double Low-Level Jets in the Northeast Sichuan Basin of China

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Abstract: A sudden rainstorm that occurred in the northeast Sichuan Basin of China in early May 2017 was associated with a southwest low-level jet (SWLJ) and a mountainous low-level jet (MLLJ). This study investigates the impact of the double low-level jets (LLJs) on rainfall diurnal variation by using the data from ERA5 reanalysis, and explores the characteristics of water vapor transport, including the main paths and sources of moisture, by using the HYSPLIT-driven data of the ERA—interim, GDAS (Global Data Assimilation System), and NCEP/NCAR reanalysis data. The analysis shows that the sudden rainstorm in the mountain terrain was located at the left side of the large-scale SWLJ at 700 hPa, and at the exit region of the meso-scale MLLJ at 850 hPa. The double LLJs provide favorable moisture conditions, and the enhancement (weakening) of the LLJs is ahead of the start (end) of the rainstorm. The capacity of the LLJ at 850 hPa with respect to moisture convergence is superior to that at 700 hPa, especially when the MLLJ and the southerly LLJ at 850 hPa appear at the same time. The HYSPLIT backward trajectory model based on Lagrangian methods has favorable applicability in the event of sudden rainstorms in mountainous terrain, and there is no special path of moisture transport in this precipitation event. The main moisture sources of this process are the East China Sea–South China Sea, the Arabian Sea–Indian Peninsula, the Bay of Bengal, and the Middle East, accounting for 38%, 34%, 17% and 11% of the total moisture transport, respectively. Among them, the moisture transport in the Bay of Bengal and the South China Sea–East China Sea is mainly located in the lower troposphere, which is below 900 hPa, while the moisture transport in the Arabian Sea–Indian Peninsula and the Middle East is mainly in the middle and upper layers of the troposphere. The moisture changes of the transport trajectories are affected by the topography, especially the high mountains around the Sichuan Basin.

Keywords: sudden rainstorm; double low-level jets; moisture convergence; Lagrangian methods; moisture

1. Introduction

Heavy rainfall is the most serious meteorological disaster in the Sichuan Basin, and it has always been a hot topic in extreme weather research. In particular, sudden rainstorms in the mountainous terrain around the Sichuan Basin, which are a kind of strong convective weather, have become a point of difficult when forecasting severe weather due to their short duration, small spatial scale, high intensity of precipitation, and sudden burst.
In all weather systems in the south or north of China, low-level jets are most closely related to precipitation, with a correlation rate of 80% [1]. A large number of scholars have carried out research on the correlation between low-level jets (LLJs) and heavy rainfall [2–5]. The LLJs not only trigger the rainstorm [6,7], but also act as the channel of water vapor transport for precipitation events [8–10], causing stable water vapor convergence [11–13]. According to the height of the maximum wind speed axis of LLJs, they can be divided into free-atmospheric LLJs at 850–600 hPa and boundary layer low-level jets (BLJs) at 850 hPa or below 1500 m [14]. Du et al. [15,16] suggest that the LLJs over southern China could be classified into two types: synoptic-system-related low-level jets (SLLJ) at 900–600 hPa, and the BLJ, with both of them having different formation mechanisms and characteristics. Du and Chen [17,18] indicate that the two types of LLJs play an important role in the water vapor transport of heavy rains in southern China, and their coupling plays a key role in convective initiation (CI). The LLJ has the characteristic of obvious diurnal variation, and it is found by Chen et al. [19] that the daily of precipitation is greatly influenced by the low-level wind speed.

Determining the process of water vapor transport and the sources of extreme precipitation events has always been a meaningful but difficult problem, and Tao and Chen [20] found that moisture transportation from the Bay of Bengal and the South China Sea is an important condition for summer rainstorms in China. Some methods, such as isotope analysis [21–23] and atmospheric numerical model simulations [24–26], have been proposed for the study of moisture transport. Both the former, which is relatively accurate but requires a great quantity of manpower and material resources, and the latter, which has obtained some valuable results but with a strong dependence on the accuracy of the atmospheric model simulation of the process of the water cycle, have disadvantages. Some studies that use vertically integrated moisture flux to estimate the moisture transport for the precipitation [27,28] are based on the Eulerian method, which can only provide the moisture transport path, and cannot quantitatively distinguish the contributions of each moisture source in precipitation [29,30]. Recently, research based on the Lagrangian method has provided a good means to carry out research into moisture transport and its source-sink. Some scholars have diagnosed the primary moisture sources of severe weather processes in North America, Antarctica, Sweden, the Mackenzie River Basin, the Appalachian Mountains and the South China by using the Lagrangian method [31–36]. Jiang et al. [37–39] analyzed the contribution of moisture for major paths over the Huaihe River Basin, the difference of moisture transport between normal years and abnormal years over the Yangtze-Huaihe River, and a comparison of the climatic characteristics of moisture transport between the Meiyu season over the Yangtze-Huaihe River and the Huabei rainy season by using the HYSPLIT v4.9 model. With respect to the Sichuan Basin, Huang and Cui [40,41] found that there were four paths of moisture transport—the Arabian Sea, the Bay of Bengal, the Indo-China Peninsula and the Sichuan Basin—during the precipitation in the Sichuan Basin from 2009 to 2013. Taking an extreme precipitation event in the Sichuan Basin in 2013 as an example, they found that the water vapor was mainly from the Arabian Sea, followed by the Indian Peninsula and the Bay of Bengal-South China Sea.

Tao et al. [42] pointed out in the previous work that LLJs of different scales do not exist in isolation; however, most researchers only give one jet center, because they designate different standards for LLJs. With the increase in data accuracy, it is necessary to think about how the free-atmospheric LLJs at different altitudes can affect the moisture convergence of the rainstorm area. This paper intends to address the following issues by comprehensively analyzing a sudden rainstorm in the northeast Sichuan Basin in early May 2017: How the daily variation of the SWLJ (southwest low-level jet) and the mountainous low-level jet (MLLJ) affects diurnal variations of sudden rainstorms; How the locations of double LLJs affect the rainstorm, as well as their different contribution rates to moisture convergence; Whether the HYSPLIT model applies to a local sudden rainstorm, and if applicable, whether there are abnormal moisture transport paths during a sudden rainstorm; What the variation is in the major paths of moisture transportation, and the contribution of major sources. The data, methodology and the case are described in detail in Section 2. Section 3 further reveals the effect of the SWLJ and MLLJ
on moisture convergence. The paths and sources are analyzed in Section 4, and the conclusion and discussion are provided in Section 5.

2. Data, Methodology and the Case of Sudden Rainstorms

2.1. Data

The data used in this paper included the ERA5 hourly reanalysis data at a resolution of 0.25° × 0.25° provided by ECMWF, including ground pressure, geopotential height, temperature, relative humidity, specific humidity, vertical speed and horizontal wind; precipitation observations by automatic weather stations (AWS) in China merged with satellite data using the CPC morphing technique (CMORPH) with a high spatial (0.1° × 0.1°) and temporal (1 h) resolution; the ERA-interim reanalysis data at a resolution of 0.75° × 0.75°, including geopotential height, temperature, specific humidity and three-dimensional wind, six hourly reanalysis data of the Global Data Assimilation System (GDAS) at 0.5° horizontal, including geopotential height, temperature, specific humidity and three-dimensional wind and the NCEP/NCAR reanalysis data with time resolution of six hours and spatial resolution of 2.5° × 2.5°, including the geopotential height, temperature, specific humidity, zonal wind and meridional wind, three of which drive the HYSPLIT trajectory model. Figures 1 and 2 used the merged precipitation data, Figures 3–7 used the ERA5 reanalysis data, Figure 8 used the ERA5 reanalysis data and the ERA-interim reanalysis data, Figure 9 used the NCEP/NCAR, GDAS and the ERA-interim reanalysis data, and Figures 10–12 used the ERA-interim reanalysis data.

2.2. Methodology

Firstly, with respect to the definition of sudden rainstorms in mountainous terrain, this is given by the Wuhan Rainstorm Research Institute of the China Meteorological Administration, who suggest that a sudden rainstorm has the following characteristics: it takes place in the western mountainous region of China, the precipitation area is less than 200 km in diameter, the cumulative rainfall is more than 20 mm in one hour, and the cumulative rainfall is more than 50 mm in 3 h (the cumulative rainfall in 1 h is more than 10 mm and the cumulative rainfall in 3 h is more 25 mm in the Tibetan Plateau and its western region). With respect to range and intensity, this paper selects a sudden mountainous rainstorm event in the northeast Sichuan Basin that took place in early May 2017 as a case study (Figures 1 and 2). The relationship between the location of the MLLJ at 850 hPa, as well as the SWLJ at 700 hPa and the falling area of the rainstorm is studied based on the horizontal evolution of the double LLJs. The different effect of double LLJs on moisture convergence is analyzed through specific humidity, relative humidity, moisture flux and moisture flux divergence. To determine the main moisture sources, their contributions to the rainstorm, and the changes of moisture transport paths, HYSPLIT version 4 is used.

The HYSPLIT model (Hybrid Single Particle Lagrangian Integrated Trajectory Model) (http://www.arl.noaa.gov./hysplit), based on Lagrangian methods, was developed by the NOAA Air Resources Laboratory, and is a mixed single-particle model and provides a way to analyze the trajectory, diffusion and sedimentation of air parcels. It is assumed that the trajectory of the air parcels moves along with the wind field. The trajectory is the integral of the particle in time and space. The vector velocity of the particle at its position is linearly interpolated in both time and space. The specific calculation method is as follows:

\[ P'(t + \Delta t) = P(t) + V(P, t)\Delta t \quad (1) \]

\[ P(t + \Delta t) = P(t) + 0.5 \times [V(P, t) + V(P', t + \Delta t)]\Delta t \quad (2) \]

In this equation, \( \Delta t \) is the time step, \( P \) is the initial position, and \( P' \) is the first guess position. The final position of the air parcels is calculated by using the average rate of the initial position and the first guess position. The terrain coordinates are used in the HYSPLIT model, and it is necessary
to interpolate the inputted meteorological data into the coordinate system for terrain tracking in the vertical direction. For more detailed information on model, please refer to the relevant literature [43,44].

Trajectory tracking step: Select two areas with a large value of accumulated precipitation in the two precipitation stages as the initial position for backward trajectory tracking, and the time with largest value of hourly accumulated precipitation as the initial time. The HYSPLIT model was run in the region (30° N–32° N, 106° E–107° E) at 0000 2 May UTC in the first stage, and (30° N–31° N, 106° E–108° E) at 2000 2 May UTC in the second stage. 850 hPa, 700 hPa and 600 hPa were selected as the initial heights of the simulation in the vertical direction. The simulation time was 7 days, and backtracking took place every 1 h. We obtained the physical attribute of the air parcels (specific humidity and temperature) at this position through interpolation [38].

Cluster analysis step: The location of the trajectory can be clearly seen for a single initial position based on the HYSPLIT model, while it is not easy to quantitatively describe the contributions of different moisture sources in the case of multiple levels and multiple initial positions. Therefore, the trajectories are classified by analyzing the changes of TSV (total spatial variance) based on a cluster analysis of the methods themselves [45]. Considering the resolution of the ERA interim data, the places (30.75° N, 106.5° E; 30.75° N, 107.25° E; 30.75° N,108° E; 31.5° N, 106.5° E) were selected as the initial positions. The initial time, from 2300 1 May to 0300 3 May, was 28 h. We obtain 348 trajectories by backward tracking 7 days in each process and re-simulating every one hour.

After clustering the trajectories, the contribution ratio of water vapor in each cluster to the total moisture transported to the target area was calculated as follows [38]:

$$Q_s = \frac{\sum_{i=1}^{m} q_{\text{last}}}{\sum_{i=1}^{n} q_{\text{last}}} \times 100\%,$$

whereby, $Q_s$ indicates moisture contribution rate of the path, $q_{\text{last}}$ indicates the specific humidity of the final position on the path, $m$ indicates the number of trajectories included in the path, $n$ indicates the total number of trajectories. In this paper, $q_{\text{last}}$ is the time 0 h (Figure 11).

2.3. Observed Precipitation

At 2300 UTC 1 May to 0100 UTC 3 May 2017, a sudden rainstorm occurred in the northeast Sichuan Basin of China. The sudden precipitation event was dominated by convective precipitation, and the precipitation was distributed in strips. Combined with the characteristics of the evolution of the hourly cumulative precipitation (Figure A1), it can be found that precipitation first appeared in Guangan in Sichuan Province and Tongnan in Chongqing City (Figure 2a). The precipitation continued for 4 h, and the maximum hourly rainfall was 40.7 mm, the maximum process (2300 UTC 1 May to 0300 UTC 2 May, the same below) rainfall was 63.7 mm. From 1700 UTC 2 May to 0100 UTC 3 May (Figure 2b), the maximum hourly rainfall (44.1 mm) and the maximum process rainfall (162.4 mm) occurred in Dazhou in Sichuan Province. It can be seen (Figures 1 and 2) that the precipitation process can be divided into two major periods of strong precipitation: in the first stage (2300 UTC 1 May to 0300 UTC 2 May, Figure 2a), the heavy precipitation area was zonal, and was located in Guangan and Nanchong in Sichuan Province; during the second stage (1700 UTC 2 May to 0100 UTC 3 May, Figure 2b), the distribution of the precipitation became a meridional belt, and the area with the greatest precipitation was located in Nanchong and Dazhou in Sichuan Province, and Wanzhou in Chongqing City. During the whole process (2300 UTC 1 May to 0100 UTC 3 May, Figure 2c), heavy rainfall of more than 50 mm occurred in Guangan, Nanchong, Dazhou, Bazhong, and Guangyuan in the northeast Sichuan Basin, with precipitation above 100 mm being concentrated in Nanchong, Guangan, and Dazhou in Sichuan Province.
During the two stages of precipitation, there are two enhanced LLJs over the rainstorm area; one is the large-scale SWLJ at 700 hPa, and the other is the meso-scale MLLJ at 850 hPa. The former is characterized by a strong southwesterly wind, and the latter by a strong southerly wind. In Figure 3,
the intensity and spatial evolution of the double LLJs during the first stage of precipitation are shown. It can be seen (Figure 3a,d) that at 1500 UTC 1 May, which is 8 h before the breaking out of the first stage of precipitation, the SWLJ at 700 hPa starts to strengthen, and a small-scale LLJ is formed in the southern part of Gansu Province. At the same time, the MLLJ at 850 hPa forms on the Yunnan-Guizhou Plateau in the northern part of the Dalou Mountains. Over the next 8 h (Figure 3b,c,e,f), the intensity of the double LLJs is strengthened and the range is expanded. In the first stage of the sudden rainstorm, the MLLJ reaches its strongest intensity, with a wind speed of 13.77 m s$^{-1}$, while the SWLJ reaches its strongest intensity at the next moment, with a wind speed of 14.25 m s$^{-1}$. The first stage of the rainstorm is located on the left front side of the SWLJ, the entrance region of the LLJ is in Gansu at 700 hPa, and the exit front region of the MLLJ is at 850 hPa.

Figure 4 shows the intensity and spatial evolution of the double LLJs during the second stage of precipitation. It can be seen (Figure 4a,d) that the SWLJ at 700 hPa starts to strengthen at 0600 UTC 2 May (Figure A2), and the MLLJ at 850 hPa is re-established at 0900 UTC 2 May. At the same time, there is a larger-scale southerly LLJ at 850 hPa in Guanxi-Guizhou (Figure 4d). Afterwards, the double LLJs maintain an increasing trend (range expands and wind speed increases), and the SWLJ moves towards the east. Unlike the first stage of the sudden rainstorm, when the heavy rains break out, in the second stage, the double LLJs do not reach their prime period, but rather remain in a development stage. The MLLJ at 850 hPa reaches a maximum intensity with wind speeds of 17.05 m s$^{-1}$ at 2100 UTC 2 May (Figure A3), and the SWLJ at 700 hPa reaches a maximum intensity with an average wind speed of 15.56 m s$^{-1}$ at the next moment, which may be the reason why the duration of the second stage heavy rain is longer than that of the first stage. The second stage of the sudden rainstorm is located on the left side of the SWLJ at 700 hPa and the exit zone of the MLLJ at 850 hPa. It is worth noting that the MLLJ is established 8 h before the rainstorm, during the two precipitation stages, which suggests that it could be an indication for rainstorm.

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**Figure 3.** Distributions of wind fields at 700 hPa (vectors, m·s$^{-1}$), LLJ (shading indicates wind speed over 12 m·s$^{-1}$) and distribution of wind fields at 850 hPa (vectors, m·s$^{-1}$), LLJ (shading indicates wind speed over 12 m·s$^{-1}$) at 1500 UTC 1 May (a,d), 1900 UTC 1 May (b,e), and 2300 UTC 1 May (c,f). F, G, and h represent the Guizhou province, Guangxi Province and Yunnan province, respectively.
3.2. Relationship between the LLJ and Water Vapor

To explore the influence of the establishment and development of the double LLJs on the water vapor content over the rainstorm area, area-averaged moisture flux divergence and relative humidity are used in this section. Figure 5a shows that the middle layer of the rainstorm area is a weak divergence zone of moisture flux during the day on the 1 May. From 1100 UTC 1 May, the water vapor transport and convergence in the rainstorm area are obviously enhanced. There is a center of water vapor convergence at both 850 hPa and 600 hPa. After 0400 UTC 2 May, although the convergence center weakens slightly weakened, there is always water vapor convergence below 700 hPa in the rainstorm area. At 0200 UTC 2 May, the water vapor convergence center is present only at a height below 700 hPa, and water vapor convergence below 700 hPa suddenly grows stronger after 0800 UTC 2 May. The water vapor convergence reaches a maximum at 1800 UTC 2 May, with an intensity of over $-12 \times 10^{-5}$ g s$^{-1}$·hPa$^{-1}$·cm$^{-2}$, and the largest water vapor convergence center is located at 850 hPa. It can be seen from the relative humidity profile (Figure 5b) that during the daytime, the upper and middle layers are the dry layer, and only the lower layer is the wet layer. At 1800 UTC 1 May, the relative humidity suddenly rises over the precipitation area, and both the middle-lower and upper layers become the wet layer. Relative humidity is maintained at a high value; over 90% from the surface to 300 hPa at 1800 UTC 2 May. The variation of moisture flux divergence and relative humidity in the rainstorm area has a strong correspondence with the occurrence and development of the double LLJs, and the establishment of LLJs causes the change of water vapor content in the rainstorm area. The relative humidity changes later than the moisture flux divergence, which indicates that the LLJs firstly transport water vapor for this sudden rainstorm, and then cause the change in relative humidity over the rainstorm area, triggering strong precipitation. Based on the analysis above, the double LLJs are particularly significant for the water vapor convergence during the heavy rain.
Figure 5. Height–time profile of (a) area-averaged moisture flux divergence, $10^{-5}\text{g s}^{-1}\text{hPa}^{-1}\text{cm}^{-2}$ and (b) relative humidity, %, over the rainstorm area (30.25° N–31.55° N, 106.05° E–108.05° E).

3.3. Analysis of Double LLJs on Water Vapor Convergence

The relationship between the area of moisture convergence, the moisture flux area with high value, and the LLJs in the rainstorm area is determined based on the moisture flux vector and moisture flux divergence at the time before the rainstorm (Figure 6). In the first stage of precipitation, the center of the largest water vapor convergence at 700 hPa is located in the Guangan area of the northeast Sichuan Basin, which is $-7.81 \times 10^{-5}\text{g s}^{-1}\text{hPa}^{-1}\text{cm}^{-2}$, and the minimum value of the moisture flux divergence at 850 hPa is located at the eastern edge of the northeast Sichuan Basin, with a value of $-21.95 \times 10^{-5}\text{g s}^{-1}\text{hPa}^{-1}\text{cm}^{-2}$. In the initial stage of the second stage of heavy precipitation, the center of the largest water vapor convergence of the 700 hPa is located in the eastern part of Guanyuan, with a value of $-28.96 \times 10^{-5}\text{g s}^{-1}\text{hPa}^{-1}\text{cm}^{-2}$. Corresponding to the SWLJ is a water vapor transport belt from the Iranian plateau through the Bay of Bengal to the Yunnan-Guizhou-Chongqing area. The area of the strongest water vapor convergence at 850 hPa is located in the rainstorm area in the northeast Sichuan Basin, with a central value of less than $-60 \times 10^{-5}\text{g s}^{-1}\text{hPa}^{-1}\text{cm}^{-2}$. There is a water vapor transport belt from the Indo-China Peninsula-South China Sea–Guangxi–Guizhou–Chongqing–northeast Sichuan Basin at 850 hPa. In the two precipitation stages, the divergence between the high value area of moisture flux and the low value area of moisture flux show a good correspondence with the rainstorm area at 850 hPa, and the area of strong moisture convergence is located at the exit regions of the MLLJ in both stages of precipitation. The maximum of the water vapor convergence at 850 hPa over the rainstorm area is almost three times that of 700 hPa. This therefore suggests that the double LLJs play a significant role in moisture convergence, and the LLJ at 850 hPa has a water vapor convergence capacity greater than that at 700 hPa. It can be found that the intensity of water vapor convergence for the second stage is higher than the first stage, and is three times that of the first stage at 850 hPa and almost four times that of the first stage at 700 hPa, which may be a result of the wind speed during the second stage being higher than during the first stage.

To better explain the relationship between LLJs and water vapor content over the rainstorm area and explore the effect of the double LLJs at different altitudes on water vapor convergence, Figure 7 shows the area-averaged specific humidity, the area-averaged moisture flux divergence, the intensity of the double LLJs, and the area-averaged hourly cumulative precipitation. It can be seen that the specific humidities at 700 hPa and 850 hPa increase significantly over the rainstorm area after 1500 UTC 1 May (Figure 7a). The first peak of specific humidity (8.85 g·kg$^{-1}$) at 700 hPa, which is 50% higher than that at 1500 UTC 1 May (4.21 g·kg$^{-1}$), appears at the end of the first stage of the sudden rainstorm, at 0200 UTC 2 May. The second peak of specific humidity at 700 hPa, which is higher than that of the first stage, with a value of 9.83 g·kg$^{-1}$, appears at 1900 UTC 2 May. At 850 hPa, the specific humidity maintains high values (over 10.5 g·kg$^{-1}$) from 1900 UTC 1 May to 2300 UTC 2 May, and exhibits the same situation, where the specific humidity is higher than that of the first stage. During the weakening
period of the double LLJs, which corresponds to the period of interruption of precipitation, the specific humidity at 700 hPa decreases, while the specific humidity at 850 hPa is higher than before. It is estimated that the increase in the specific humidity at 850 hPa is related to the evaporation of the precipitation on ground. By analyzing the temporal evolution of moisture flux divergence it is found that the change in moisture flux divergence has a highly correlated relation with the double LLJs (Figure 7a,b). With the arrival of the LLJ, the water vapor changes from a weak convergence zone to a strong convergence zone at 850 hPa, and from a weak divergence zone to a convergence zone at 700 hPa. Moisture flux divergence also increases during the weakening stage of the LLJs. The sudden increase in the specific humidity and the moisture convergence over the rainstorm area coincide with a change in the intensity of the double LLJs. The enhancement (reduction) of the double LLJs precedes an increase (decrease) in the precipitation. By calculating the correlation coefficient between the intensity of the double LLJs and the intensity of the precipitation over the rainstorm area, it is found that the correlation coefficient between the intensity of the MLLJ and the intensity of precipitation is 0.62, while that value is 0.55 between the SWLJ and the precipitation, indicating that the correlation between the LLJ and the intensity of precipitation at 850 hPa is higher than that at 700 hPa, and that moisture convergence plays a more significant role. During the second stage, the specific humidity peak is higher at both 700 hPa and 850 hPa than during the first stage, the moisture flux divergence is lower than during the first stage, and the intensity of the double LLJs is higher than during the first stage, which also suggests that the convergence of double LLJs plays a key role in enhancing moisture convergence and may be the reason that the cumulative precipitation in the second stage is higher than in the first stage. The moisture flux divergence at 850 hPa varies more than that at 700 hPa, and the specific humidity at 850 hPa is far higher than that at 700 hPa, both of which also suggest that the effect of LLJs at 850 hPa on moisture convergence is stronger than that at 700 hPa.

Figure 6. Distributions of moisture flux (vectors, g·s$^{-1}$·hPa$^{-1}$·cm$^{-2}$) and moisture flux divergence (b, 10$^{-5}$ g·s$^{-1}$·hPa$^{-1}$·cm$^{-2}$) at 2200 UTC 1 May (a,c) and 1600 UTC 2 May (b,d). Black rectangles represent the northeast of the Sichuan basin.
4. Analysis of Paths and Sources of Moisture

In order to study moisture sources over a wider area during this rainstorm, we introduce a Lagrangian method based on the HYSPLIT model. Previous research using the HYSPLIT model to track the sources of moisture in the Sichuan Basin has mostly been conducted with respect to regional and sustained rainstorms [46,47]. It was found that the high level of moisture during sustained rainstorms mainly comes from the western Tibetan Plateau, while moisture from the Bay of Bengal and the South China Sea contributes more to the middle and lower troposphere. At present, there is very little research on local and sudden rainstorms, and the influence of mountainous terrain on sudden rainstorms is also very important. Therefore, this section aims to explore the applicability of the HYSPLIT model in sudden rainstorms over mountainous terrain, and the main paths and sources of moisture for sudden rainstorms.

Because this mode requires its own specific format of meteorological data, and this mode does not support the temporary conversion of ERA5 data, we replace it with ERA-interim data. To prove that the ERA-interim data and the ERA5 data are capable of reproducing the same event, we firstly compare the height field and wind field of ERA-interim and ERA5 at 700 hPa. By comparing the flow field maps at 700 hPa (Figure 8), it can be found that ERA5 and ERA-interim are able to reflect the same event very well.

4.1. Characteristics of Moisture Transport

Zhou et al. [48], and Lei and Zhou [49] showed that there were some differences in the results of the characteristics of moisture transport calculated using different datasets. To increase the reliability
of the results, three types of dataset (ERA-interim data, GDAS data and NCEP/NCAR data) are used. Based on comparative analysis, it is found that change in height over time of the air parcel trajectory in the NCEP/NCAR data is smoother than that in the GDAS data and the ERA-interim data during the transport process. In the first stage of the sudden rainstorm, it can be seen from the trajectory diagram of the air parcels in the ERA-interim data (Figure 9a) that the air parcels at 600 hPa are mainly from the western part of the Iranian plateau, having passed the southern Tibetan Plateau and entering the Sichuan Basin after crossing through the Yunnan-Guizhou Plateau. The trajectories of air parcels at 700 hPa are divided into two paths, one is the relatively straight Tibetan Plateau path, starting from the Iranian Plateau and travelling eastward into the northeast Sichuan Basin, and the other originates in the Bay of Bengal. Most of the air parcels at 850 hPa originate from the East China Sea and the South China Sea, entering the Sichuan Basin after the uplift of the Yunnan-Guizhou Plateau. It can be seen that the trajectory results obtained using the GDAS data (Figure 9b) and the NCEP/NCAR data (Figure 9c) are in good agreement with those obtained using the ERA-interim data at heights of 850 hPa, 700 hPa and 600 hPa, with the outputs of ERA-interim data in the second stage of precipitation showing that there are four main passages of air parcel trajectory (Figure 9d). The operation trajectory of air parcels in 600 hPa, 700 hPa and 850 hPa is similar to that of the first stage: two western passages, one southwestern passage originating in the Bay of Bengal, and a fourth that is initially southward and then northeastward, originating in the East China Sea. The outputs of the GDAS data (Figure 9e) show that trajectories in the upper level and the lower level are highly consistent with the ERA-interim outputs. The outputs (Figure 9f) of the NCEP/NCAR data at 600 hPa and 700 hPa exhibit some differences compared with the ERA-interim data. Most of the operation paths of the air parcels are in the Arabian Sea path and the Bay of Bengal path. The outputs at 850 hPa are in good agreement with the ERA-interim outputs.

Figure 9. Moisture transportation paths during (a–c) the first stage; and (d–f) the second stage. The red lines, the blue lines and the green lines denote the transport trajectories of air parcels at 600 hPa, 700 hPa and 850 hPa, respectively.
Comparing the results of transport trajectories obtained using the three types of dataset, it is found that although there are some trajectories that are slightly different, the majority of the air parcel transport paths are the same. In summary, the output results of the three datasets are highly consistent, so the simulation results of this trajectory are highly reliable. So only the the ERA-interim output results are analyzed in Sections 4.2 and 4.3.

4.2. Moisture Source Regions and Quantification of Contribution

Figure 10 shows the spatial distribution of the air parcels on the third day (-3 d), 5th day (-5 d), 7th day (-7 d), 9th day (-9 d) before reaching the target area obtained using the ERA-interim data. At three days prior (Figure 10a), most air parcels can be tracked to the South China Sea area (i.e., the southern path), the eastern coastal area of China (i.e., the eastern path), the Myanmar area (i.e., the southwest path), and the Indian area (i.e., the western path). At five days prior (Figure 10b), the western path maintains its westward trajectory, and path 2 can be traced to the Iranian region. The southwestern path (path 3) advanced south to the Bay of Bengal. The southern path and the eastern path merge into the southeast path (path 4), reaching the the eastern coastal area of China. At seven days prior (Figure 10c), the western path maintains its westward trend. Path 1 can be traced to southern Iran, close to the Arabian Sea, and path 2 can be traced to Egypt, close to the Medeiterranean. The southwestern path (path 3) is still located in the Bay of Bengal, but further south, and the southeast path can be traced to the East China Sea. At nine days prior (Figure 10d), aside from the air parcels of path 1 and path 2, which continue slightly westward, the location of the air parcels in path 3 and path 4 is almost the same as at seven days prior. Comparing the position and height of the air parcels at 7 days prior and 9 days prior, it is found that the air parcels reached a steady state at 7 days prior. Therefore, we believe that the air parcels have been traced to their nearby source area at -7 d. Furthermore, the contribution percentage of air parcel at -7 d is used to analyze the moisture contribution percentage of the source. We can find that there are roughly four moisture sources in this process, based on the positions of the air parcels at 5 days prior, 7 days prior and 9 days prior.

To further distinguish the contribution rates of moisture transported from the different source areas, the sources of the moisture during the sudden rainstorm are divided into four parts (Figure 11a): the Arabian Sea–Indian Peninsula (Source 1), the Middle East (Source 2), the Bay of Bengal (Source 3) and the South China Sea–East China Sea (Source 4). Figure 11b shows the contribution rate of the air parcels and moisture carried from each source. During the sudden rainstorm, the South China Sea–East China Sea has the maximum contribution, with the air parcels being transported to the Sichuan Basin accounting for 29% of the total transport; the moisture carried by the air parcels contributes about 38% to the moisture transport during the rainstorm in the Sichuan Basin. The Arabian Sea–Indian Peninsula has the second largest contribution to transportation, with 40% of the air parcels coming from the area near the Arabian Sea, and a moisture contribution of 34%. This is followed by the southwestern path of the Bay of Bengal, which accounts for 16% of air parcel transport and 17% of moisture transport. Although the air parcels from the Middle East contribute 15% of the total transport, they only account for 11% of moisture transport because of their dryness and coldness.

Combined with the moisture flux divergence and relative humidity (Figure 5), the moisture acting on this rainstorm is primarily at 850 hPa, and originates mainly from the East China Sea, the South China Sea, and the Bay of Bengal, which together account for more than 55% of the total. At 700 hPa, moisture from the Arabian Sea–Indian Peninsula also contributes a lot to the rainstorm, with the value of 34%. Although there is moisture convergence at 600 hPa, the moisture contribution is very weak compared with the middle-lower troposphere.
Atmosphere 2019, 10, x FOR PEER REVIEW 13 of 19

Figure 10. The average trajectory (bold lines) and the corresponding percentage (a) on the third day (-3 days), (b) 5th day (-5 days), (c) 7th day (-7 days), and (d) 9th day (-9 days) before reaching the target area. The percentages inside the brackets indicate the fractions of the trajectory number in each path (i.e., the air parcel’s contribution to the target area) in all trajectories. The numbers 1, 2, 3, 4 represent path 1, path 2, path 3 and path 4, respectively.

Figure 11. Moisture source distribution division (a) and the contribution percentages (units: %) of moisture and air parcels transport from sources (b).

4.3. Physical Attribute Changes along the Trajectories

Actually, the moisture carried by the air parcels is always changing throughout the process of transportation, due to surface evaporation and condensation/precipitation. Therefore, combined with the tracking analysis method of the air parcels, the group-averaged physical attributes (temperature and specific humidity) of the air parcels are analyzed up to 7 days prior.
It can be seen from the evolution of height, temperature and specific humidity during moisture transport from the different sources and paths (Figure 12a–c) that the air parcels of path 2, the Middle East area, mainly consist of dry and cold air parcels at 500 hPa in the upper troposphere (with a temperature of 254 K and a specific humidity of 0.8 g/kg). These trajectories experience slight moisture increases from -168 h to -60 h, moisture decreases from -60 h to -20 h, and notable moisture increases from -20 to approximately -5 h. When the air parcels arrive in the Sichuan Basin, the moisture is limited due to their always being at a high level. The air parcels of path 1, from the Arabian Sea–Indian Peninsula area, are mainly found in the middle layer of the troposphere at 700 hPa. Path 1 trajectories have the same trend as in path 2. The initial specific humidity of the air parcels is low. During transportation toward the east, the temperature increases slightly, and the humidity increases obviously. The air parcels of path 3, from the Bay of Bengal area, are mainly found in the level below 900 hPa, at low latitudes. The air parcels carry more moisture due to the evaporation of the tropical oceans. The temperature and specific humidity of the air parcels exhibit no significant changes when they are over the ocean, while the height of the air parcels increases sharply at around -60 h. The specific humidity and temperature of the air parcels decrease significantly due to the changing topography of the underlying surface throughout the landing process. The temperature and humidity of the air parcels in path 3 continue to decrease until -30 h during the transportation process, and these air parcels are still warm and wet when the moisture enters the Sichuan Basin, as a result of the high initial values of temperature and humidity. The air parcels in path 4, from the South China Sea–East China Sea area, are mainly found in the level below the 950 hPa in the middle latitudes. The evaporation of the mid-latitude ocean is not as strong as that of the tropical ocean, so the moisture that is carried by the air parcels in path 4 is less than that carried by those in path 3. Although the initial temperature and humidity of the air parcels are not the highest, the air parcels have been in the state of gaining moisture from -168 h to -40 h, with specific humidity increasing from 7.3 g/kg to approximately 15 g/kg, which can be attributed to the high humidity of eastern coastal cities, which is a result of evaporation over the East China Sea and the Western Pacific. Therefore, the temperature and humidity are at their highest entering the Sichuan Basin.

Figure 12. Changes in moisture paths with respect to height (a), temperature (b) and specific humidity (c).
It is not surprising that the trajectories of paths 1, 2, and 3 experience moisture loss at approximately -60 h, most likely due to topographical lifting. At approximately -60 h, the trajectories of path 1 and path 2 arrive at the region near the Indian Peninsula, and path 3 arrives at the north of the Indochina Peninsula. As a result, the air parcels in these paths lose moisture rapidly. They enter the target area with an obvious increase in specific humidity from -20 h to -5 h. The trajectories of Path 4 gain moisture from the East China Sea to the South China Sea, while they lose moisture while crossing through the mountains when entering the Sichuan Basin from its southern border. The moisture changes in the transport trajectories are greatly affected by topography. The main terrains affecting path 1 and path 2 are the Indian Peninsula and the Yunnan-Guizhou Plateau; for path 3, they are the Indochina Peninsula and the Yunnan-Guizhou Plateau.

5. Conclusions and Discussion

In this study, we analyzed the effect of double LLJs on moisture convergence during a sudden rainstorm in the northeast Sichuan Basin of China on 2–3 May 2017. Based on the understanding of the background of moisture transport on a large scale, the paths and sources of moisture are quantitatively analyzed throughout this rainstorm process by using the Lagrangian method (HYSPLIT model) to simulate the backward trajectory of air parcels in order to deepen our understanding of the characteristics of moisture transport during a sudden rainstorm in mountainous terrain and provide a reference for further study of sudden rainstorms in mountainous terrain. Our major findings can be summarized by the following points:

1. The sudden rainstorm in the mountainous terrain occurred on the left side (or the left front side) of the large-scale SWLJ at 700 hPa, and the exit regions (or in front of the exit regions) of the meso-scale MLLJ were at 850 hPa. The MLLJ was established 8 h before the sudden rainstorm and maintained an increasing trend, providing a good indication of the subsequent rainstorm.

2. The double LLJs had a significant effect on moisture convergence during this heavy precipitation. The moisture convergence capacity of the LLJ at 850 hPa was better than that at 700 hPa for the rainstorm. In particular, when the MLLJ and southerly LLJ were concurrent at 850 hPa, the effect on moisture convergence was more significant.

3. The enhancement (weakening) of the double LLJs was earlier than the increase (decrease) in the rainstorm, and the change in water vapor content over the rainstorm area was consistent with the change in the intensity of the LLJ.

4. The HYSPLIT backward trajectory model can find favorable application for sudden rainstorms in mountainous terrain. There were 4 moisture sources, the largest contribution of which was from the East China Sea–South China Sea region, accounting for 38% of the moisture of the sudden rainstorm, followed by the Arabian Sea–Indian Peninsula area (34%). The Bay of Bengal had the third largest contribution, at 17%, and the Middle East area (11%) contributed the least. Among of them, the moisture transport from the East China Sea–South China and the Bay of Bengal mainly occurred in the lower troposphere, and the transport from the Arabian Sea–Indian Peninsula and the Middle East mainly occurred the middle and upper troposphere.

5. The moisture changes in the transport trajectories were greatly affected by topography, especially the high terrain around the Sichuan Basin. The air parcels from the Bay of Bengal lost moisture, while the other three gained moisture, during transportation from the source to the target area, and the air parcels from the East China Sea gained the most moisture among the three paths that gained moisture.

This paper analyzes the free-atmospheric LLJ in detail for a sudden rainstorm in mountainous terrain. The relationship between both the location, the establishment time of the MLLJ at 850 hPa, the falling area of the rainstorm, and the eruption time provides some references for the further study of sudden rainstorms in the mountainous terrain. Therefore, the analysis of MLLJ with respect to moisture convergence is meaningful. We expect to collect more examples of sudden rainstorms in the mountainous terrain to verify whether the establishment time and location of the MLLJ at 850 hPa can
be used as indicators to forecast sudden rainstorms. In this paper, the HYSPLIT model is applied for the first time in order to explore a sudden rainstorm. It is found that the applicability of this model is credible, and could provide a simple and feasible method for exploring the moisture sources of sudden rainstorms in the future. However, since only one individual case is studied in this paper, and the characteristics of moisture transport at 600 hPa, 700 hPa and 850 hPa are only analyzed in the vertical direction, the characteristics of moisture transport obtained from the simulation results may have a certain deviation from the real situation. In the future, we can select further cases of sudden rainstorms that exhibit the same circulation background, and more in-depth research should be conducted to determine moisture paths that have continuous stability in sudden rainstorms. The input data of the HYSPLIT model has consisted of NCEP/NCAR data [37–39,46] and GDAS data [47] in previous studies. Although this article improved the spatial resolution (0.75° × 0.75°) of the input data (ERA-interim), if ERA5 data could be used to simulate the trajectory of the air parcels in future work, more accurate transport characteristics will be undoubtedly obtained. Due to space limitations, we do not discuss the differences between the three types of datasets with respect to the contribution rate of air parcels and moisture. This would be meaningful work in terms of clarifying what abnormal paths would look like.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**Appendix A**

![Figure A1. Hourly cumulative precipitation (2300 UTC 1 May to 0000 UTC 2 May).](Image)
Figure A2. Distributions of wind fields at 700 hPa (vectors, m·s\(^{-1}\)) LLJ (shading indicates wind speed over 12 m·s\(^{-1}\)) at 0600 UTC 2 May.

Figure A3. Distributions of wind fields at 850 hPa (vectors, m·s\(^{-1}\)) LLJ (shading indicates wind speed over 12 m·s\(^{-1}\)) at 2100 UTC 2 May.

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