Comparative analysis of two hazard rainstorm processes in Hunan affected by the Southwest China vortex

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Abstract. Based on surface rain-gauge data, Doppler radar products, the National Center for Environmental Prediction (NCEP) reanalysis data and other multi-source datasets, two regional rainstorm processes caused by the Southwest China vortex (SCV) in June, 2015 are diagnosed and analyzed from the aspects of water vapor condition, dynamic and thermodynamic mechanisms, and the causes of the regional rainstorms are discussed. The results show that the two processes belong to the SCV rainstorm, and there is the southwest jet in the middle and lower levels. The high-value area of water vapor flux and the water vapor convergence center can well indicate the rainstorm area. In the first process, two water-vapor-flux transport bands from the Bay of Bengal and the South China Sea converge. In the second process, the water vapor mainly comes from the Bay of Bengal. The extreme values of dynamic and thermodynamic factors all appear near 850 hPa in the rainstorm development stage, and the latitudes of the extreme values are close to the severe rainfall area. The first process has a typical rainstorm vorticity configuration with negative vorticity at upper layer and positive vorticity at lower layer. The second process is mainly driven by the strong positive vorticity at the lower layer. There are strong energy frontal zones near the ground, and the rainstorm area is consistent with the convergence region of cold and warm air. The characteristics of radar echo show that there are mid-level and low-level jet streams in the two rainstorm processes. The first process is dominated by the cumulus precipitation, and the adverse wind region promotes the development of the rainstorm. The second process is dominated by cumuliform-stratiform-mixed cloud precipitation, and the train effect is the main cause of the regional rainstorm.

1. Introduction
Hunan Province is located in the subtropical monsoon region where warm and humid southerly wind prevails in summer, with abundant water vapor. The interannual change of precipitation is large, and the average annual precipitation can reach 1200–1700 mm [1]. Regional extreme rainstorms often occur here, which bring a great threat to people's lives and property. There are many mountains, hills, rivers and a lake in Hunan, the distribution of rainfall center is similar to that of terrain. According to the statistics of extreme precipitation in Hunan from 1951 to 2009, the northeastern Hunan and northwestern Hunan are both the centers of extreme precipitation [2]. The statistical results from 1961 to 2016 have shown that the occurrence frequency of persistent rainstorm in June is the highest, and the regional rainstorm in the western and northern Hunan is the most, showing an increasing trend.
year by year [3]. Other studies have shown that the rainstorm in the Yangtze River Basin is closely related to the southwest jet [4–5], and the large wind speed zone near the exit of the low-level jet is consistent with the rainstorm area in the Yangtze River Basin [6]. Many scholars have also carried out the cause analysis of the regional rainstorm process. It is found that the convective energy is triggered by the mid-level and low-level shear lines in the initial stage of regional rainstorm [7–8], and the warm shear is one of the main formation mechanisms. During the occurrence and maintenance of rainstorms, the wind shear line has a single direction and the low-level jet often appears in the middle and lower levels [9]. In addition, the surface convergence line is also very easy to lead to mesoscale convective regional rainstorm [10], which is an important factor triggering short-time severe precipitation [11].

In June 2015, there were four regional rainstorm processes in Hunan, and the severe rainfall areas were almost overlapped, mainly concentrated in the central and northern Hunan, resulting in many casualties and huge economic losses and inducing some geological disasters such as serious landslides. The accumulated rainfall was more than twice of the normal years. In process I, the affected population reaches 1.774 million, nine people died or missed due to the disaster, and the direct economic loss reaches 2.29 billion Yuan. In this study, the most severely two regional rainstorms (from June 1 to June 4 and from June 6 to June 8 in 2015) are selected, and the thermodynamic and dynamic mechanisms of the two rainstorms are diagnosed, to provide technical reference for the hazard rainstorm forecasting in the future.

2. Materials and methods
The four kinds of data in this study includes surface rain-gauge data and the Hunan Doppler radar products provided by the China Meteorological Data Network, the spatial resolution of the reanalysis data 1°×1°, the reanalysis data which is provided by the National Center for Environmental Prediction (NCEP), the Global Data Assimilation System (GDAS) data from the National Oceanic and Atmospheric Administration (NOAA), the temporal resolution is 6h, spatial resolution is 1°×1°.

Using the HYSPLIT4 model from the National Oceanic and Atmospheric Administration (NOAA), the backward trajectory is calculated by Lagrangian method. The model is used to track the 7-day trajectory of the rainstorm center in the two regions, determine the source and transport trajectory of water vapor, and quantitatively calculate the contribution rate of different water vapor channels to the rainstorm area by clustering method. The simulation area selected that is 27 – 31°N, 108 – 114°E, and the initial vertical simulation heights are 1000 m, 1500 m, and 3000 m.

3. Characteristics of the two regional rainstorm processes
From June 1 to June 4 in 2015, there was a regional rainstorm process in the north of central Hunan (hereinafter referred to as process I, Figure 1a), with characteristic of strong locality, long duration and strong rainfall intensity. The severe rainfall began from the night of June 1 and moved from north to south. Specifically, the rainfall was the severest from the night of June 1 to June 3, and the severe rainfall was mainly concentrated in the north of central Hunan. The rainfall significantly weakened and moved southward rapidly on June 4. From June 6 to June 8 in 2015, there was another regional rainstorm process in central and northern Hunan (hereinafter referred to as Process II, Figure 1b). The rainfall began from the west of Hunan on June 6, and there was a large area of severe rainfall on the north of central Hunan on July 7. On June 8, the main rain band moved slightly to the south and steadily maintained in the central part of Hunan.

The statistical analysis (Table 1) shows that the average rainfall of process I is 53.0 mm in the whole province. The accumulated rainfall exceeds 100 mm in 653 townships, of which the accumulated rainfall in 84 townships exceeds 200 mm, and the maximum hourly rainfall is 97.1 mm. The average rainfall of process II is 45.5 mm in the whole province. The accumulated rainfall exceeds 100 mm in 189 townships, of which the accumulated rainfall in three townships exceeds 200 mm and the maximum hourly rainfall is 65.9 mm. The comparison shows that in process I, the rainstorm area is wider, the maximum rainfall and hourly rainfall intensity are stronger and the disaster-causing ability
is stronger than that of the process II. In the two processes, there are geological disasters such as debris flow caused by landslide, and the disaster degree of process I is more serious than that of process II.

![Figure 1](image1.png)

**Figure 1.** Accumulated rainfall in Hunan (a) from 08:00 BJT (Beijing time, the same below) on June 1 to 08:00 on June 5 and (b) from 08:00 on June 6 to 08:00 on June 9 in 2015 (unit: mm).

| Table 1. Rainfall and damage situation from 08:00 on June 1 to 08:00 on June 5 and from 08:00 on June 6 to 08:00 on June 9 in 2015. |
|---------------------------------------------------------------|
| **Comparison of rainfall and damage situation between the two regional rainstorm processes** |
| Process I | Process II |
| Rainstorm stations (station) | 653 | 1038 |
| Average rainfall (mm) | 53 | 45.5 |
| Daily maximum rainfall (mm) | 163.8 (Linxiang County, Yueyang City) | 113.8 (Taoyuan County, Changde City) |
| Maximum hourly rainfall intensity (mm·h⁻¹) | 97.1 | 65.9 |
| Duration (d) | 4 | 3 |
| Affected population (thousand) | 1774 | 1471 |
| Affected crop area (hectare) | 106.2 | 74.5 |

4. The difference of large-scale circulations
The 500hPa upper-level charts in the strongest rainfall periods of the two processes were presented in Figures 2a and 2b. In Process I, the western Pacific subtropical high was distributed in blocks. The west ridge point of 588dagpm was 104° E, which was more than 20 longitudes westward than that in the same period of the normal year. The northern boundary was 22°N, and the maximum positive anomaly of geopotential height reached 80–100 dagpm. The circulation was a trough-ridge type in mid-high latitude, the upper-level trough moved eastward from Sichuan Basin to the boundaries between Hunan and Hubei. Hunan was located on the northwest edge of the subtropical high and in the warm and humid unstable airflow in the front of the upper-level trough. In Process II, the circulation meridional is large in middle and high latitudes, which is two troughs and one ridge. The central intensity of the northeast cold vortex reached 555dagpm, and the maximum positive distance of the cold vortex reached 80-100dagpm, which was powerful. The northerly airflow behind the cold vortex was conducive to the southward movement of cold air to affect Hunan. The western Pacific subtropical high was distributed in zonal from east to west. The west ridge point of 588dagpm was 95° E, which was 24 longitudes westward than that in the same period of the normal year. The northern boundary was 26°N. the maximum positive anomaly of geopotential height reached 80–100 dagpm, and the intensity was strong. The southwest flow of the trough drove the vortex to the north of Hunan, and the low-level jet transported water vapor to the rainstorm area. The two processes were both influenced by the SCV or the eastern section of the herringbone shear in the middle and low levels,
which were the main dynamic driving factors. In Process I, the SCV lasted longer in Hunan, and the intensity of SCV was strengthened under the influence of the upper-level forward-tilted trough, which lasted more than 60 hours from 20:00 BJT (Beijing time, the same below) on June 1 to 08:00 on June 4. Some scholars have found that the SCV is the main cause of rainstorms in the Yangtze River Basin, and it often causes rainstorms in spring and summer in Hunan Province [12].

There are significant differences in circulation background between the two processes. In Process I, the west ridge point of subtropical high is more easterly, the northern boundary is more southerly, which is beneficial for the long wave trough to drive the vortex eastward. Addition to, the strength of the western north pacific subtropical high is more stronger, which hinders the vortex eastward, slows down the eastward movement of the trough, and causes the stagnation of the southwest vortex to be longer. It is also one of the main reasons for a large range of heavy rainfall in the process. In Process II, it is mainly affected by the high-altitude shortwave trough and the southward cold air behind the cold vortex.

![Figure 2](image)

**Figure 2.** 500-hPa mean geopotential height (black isoline, unit: dagpm) and the anomaly (color spot area, unit: dagpm) at (a) 20:00 on June 1 and (b) 20:00 on June 7. The red isolines represent the climatological mean (unit: dagpm).

5. Difference of water vapor
The summer rainstorm area often distributes around the high-energy tongue and the high specific humidity tongue. The physical diagnostic analysis of water vapor conditions, dynamic and thermodynamic factors is helpful to find out the causes and predictability indexes of disaster-causing rainstorms.

5.1. Water vapor conditions
The water vapor flux vector is a physical quantity that measures the intensity of water vapor transport, and the water vapor flux divergence is a physical quantity that quantitatively analyzes the inflow and outflow of water vapor in the rainstorm area. According to the vertical profile of the water vapor flux in June on average from 1948 to 2020 in Hunan (Figure 3), the water vapor from the ground to 850hPa is growing rapidly, reaching the maximum at 850hPa (12*10^{-7}g·cm^{-1}·hPa^{-1}·s^{-1}). As the height increases, the water vapor flux decreases. The lower layer is the main transport layer of rainfall in Hunan.

Before the occurrence of rainstorm in Process I (Figure 4a), 850-hPa water vapor mainly originated from the Bay of Bengal, and there was a significant transport band of water vapor flux from the southern coast of Guangxi to the western Hunan. When the rainstorm 4 developed (Figure 4b), the transport passages from the Bay of Bengal and the transport band from the South China Sea converged over Hunan, maintaining a long time. The strong southwesterly airflow transported water vapor and momentum to the territory of Hunan and Jiangxi, and the water vapor band lasted for more than 36 hours. At 08:00 on June 3, there was a strong northeasterly inflow, which intersected with the southwesterly airflow in the west and north of Hunan. At the weakening stage (Figure 4c), the transport band of water vapor flux gradually moved southward and weakened, and the main transport pathway was from the Bay of Bengal. From the divergence of water vapor flux(Figure 4a), the strong...
water vapor sink was located in the southern Chongqing at 08:00 on June 1, with the center of maximum negative value of water vapor flux divergence, and there was a weak water vapor convergence zone in northern Hunan. At 08:00 on June 2(Figure 4b), the cold air from the north moved southward and converged with the strong water vapor band moving northward from the South China Sea. There was an obvious water vapor convergence band on the north of central and western Hunan. At 08:00 on June 3(Figure 4c), the water vapor convergence band moved from northern Hunan to central Hunan. There was a high-value area of water vapor flux divergence in both the northwestern and northeastern Hunan, with the maximum value of $-8 \times 10^{-7}$ g·cm$^{-2}$·hPa$^{-1}$·s$^{-1}$. On June 4, the water vapor flux significantly weakened, and then the water vapor convergence weakened in Hunan. The precipitation gradually weakened from the north to south in Hunan.

In Process II, the water vapor mainly came from the Bay Bengal. Before the rainstorm occurrence (Figure 4d), the strong water vapor flux band distributed northeast-southwestward and was located in central Hunan. In the rainstorm development stage (Figure 4e), there was a weak southward water vapor flux vector in northern Hunan and a significant water vapor flux transport band in central and southern Hunan. The intersection of the two water vapor flux transport bands produced strong water vapor convergence. By 02:00 on June 9 (Figure 4f), the water vapor flux decreased rapidly, and the high-value area retreated to the north of Guangdong and Guangxi. From the analysis of water vapor flux divergence (Figure 4d–f), a water vapor convergence center was formed in Xiangxi Prefecture and Yueyang City at 02:00 on June 8, with the maximum value of $-10 \times 10^{-7}$ g·cm$^{-2}$·hPa$^{-1}$·s$^{-1}$. Until 20:00 on 8 June, the high-value area of water vapor flux divergence stably remained in the central Hunan and its northern area for 18 continuous hours, which was consistent with the heavy rainfall area. After 20:00, the high-value area of water vapor flux and the water vapor convergence center rapidly weakened and moved southward.

The comparative analysis shows that there were the convergence of two water vapor transport bands in the two processes, which resulted in the intersection of cold and warm air and the occurrence of the two regional rainstorm processes. The difference was that the transport band of water vapor flux in Process I maintained longer, and the northerly airflow was also stronger. In Process I, the two water vapor flux transport bands from the Bay of Bengal and the South China Sea converged, which provided sufficient water vapor source for the large-scale rainstorm and resulted in greater accumulated rainfall and hourly rainfall intensity. While in Process II the water vapor mainly came from the Bay of Bengal. In summary, the transport band of water vapor flux vector and the water vapor convergence center can well indicate the rainstorms area. The establishment of water vapor channel in the lower troposphere and the large concentration of water vapor can provide favorable water vapor and unstable conditions for the development of convective systems.

Figure 3. Vertical profile of multi-year average water vapor flux from 1948 to 2020.
Figure 4. Distributions of water vapor flux and water vapor flux divergence at 850 hPa. The color spot area represents the negative large value of water vapor flux divergence (unit: 10^{-7} g·cm^{-2}·hPa^{-1}·s^{-1}). The arrow is the water vapor flux vector (unit: g·cm^{-1}·hPa^{-1}·s^{-1}). at (a) 08:00 on June 1, (b) 08:00 on June 2, (c) 08:00 on June 4, (d) 02:00 on June 7, (e) 02:00 on June 8, (f) 02:00 on June 9.

5.2. Source and contribution rate of water vapor

The HYSPLIT model is used to track the backward trajectory of the air block in the center of the maximum rainstorm in the two processes (111.0°E, 28.2°N) (111.1°E, 27.8°N). It is selected as the starting point, and the simulation starting time is 08:00 on June 3rd and 20:00 on June 9th. According to the water vapor transport of multi-year average at 925hPa, 850hPa, 700hPa level, which are corresponding to the altitude of 1000m, 1500m, 3000m, and the backward 168h water vapor trajectory is tracked. The number of cluster water vapor channels was determined by TVS, and the contribution rate of water vapor was analyzed.

Through the backward trajectory tracking comparison (Figure 5), the water vapor of the two processes at 700hPa (3000m) is from the Bay of Bengal. In Process I, the southwest airflow is transported across the central and southern peninsula to the South China Sea, and the southerly airflow is transported northward through the Guangdong and Guangxi. The warm and humid airflow after the Vietnam Ridge Mountains is uplifted and transmitted to the rainstorm center. In Process II, the water vapor is transported through the Yunnan-Guizhou Plateau by the southwest airflow, and the mountains promote the forced uplift of the airflow to the westward airflow to the rainstorm area. During the two processes, the 850hPa vapor mass originated from the rainstorm area in the Yangtze River Basin, and the short-range transmission was the main path. In Process I, the height of the vapor mass fluctuated greatly. In the near-surface process one, there is a water vapor from the East China Sea to the easterly flow through the Yangtze River Basin to the rainstorm center of Hunan. The height of the water vapor mass changes little, the air block is below 500m in the early stage, and rises slightly near the rainstorm area. In Process II, the source and transport trajectory of water vapor are consistent with 850hPa.
Figure 5. The 168-h back tracking of the air parcel at (a) 08:00 3 June, at (b) 20:00 9 June 2015. (Heights of the air parcel are represented by different colors lines, red line:1000, blue line: 1500, green line: 3000, unit: m)

Figure 6. Water vapor transportation paths at (a) 850hPa in Process I, the first water vapor channel in Process I (b), water vapor transportation paths at (c) 850hPa in Process II, the first water vapor channel in Process(d).

Based on the characteristics of 850hPa rainfall in Hunan, the contribution rate of different water vapor transport paths at 850hPa, we analyzed the air mass of the two rainstorm centers. Simulation time of water vapor backward paths is 168h, interval step 12h. The HYSPLIT4 model was clustered to obtain the spatial variance change rate of the two processes (Figure omitted). The TSV all changed abruptly when they were clustered to the four trajectory. The fourth trajectory increased sharply in Process I, and decreased rapidly at the second trajectory. Therefore, four cluster vapor trajectories were selected to analyze the contribution to the rainstorm area.

In Process I (Figure 6a, b), there are four water vapor transport paths at 850hPa with 97 trajectories, which originate from the Viet Nam Peninsula in the Bay of Bengal, and the contribution rate is 51% from the South China Sea. The transportation trajectory from the middle and lower reaches of the
Yangtze River to the rainstorm area reaches 37%, and the two air streams are superimposed to provide abundant water vapor. There are 73 trajectories for the process II(Figure 6c, d), and the southward trajectory from the Yellow Sea through Jiangsu, Anhui, and Hunan to the center of the rainstorm has a contribution rate of 47%. It is the main water vapor transport channel, which may be the northeast cold vortex. The water vapor from the southwest vortex in the eastern part of Sichuan accounted for 42% of the water vapor brought by the northeast airflow from the back rotating southward through the Yellow Sea, and the water vapor transmitted from the South China Sea through the Guangdong and Guangxi regions accounted for 8%. In summary, in Process I, the main water vapor transport sources are the Bay of Bengal and the western Pacific, while in process II, it is mainly from the confluence of the warm and humid airflow in front of the southwest vortex and the northerly airflow.

6. Comparison of dynamic and thermodynamic conditions

6.1. Dynamic conditions
Dynamic uplift is the triggering condition for the rainstorm, and the systematic ascending motion is conducive to the occurrence and maintenance of rainstorm [5]. The cross-sections along 112°E of 850-hPa vorticity in Process I and process II are given in Figure 7a and Figure 7b, respectively. In the initiation and development stages of Process I (Figure 7a), there were two positive vorticity centers in 27°N and 30°N at 20:00 on June 2 and 08:00 on June 3, and the locations and time were corresponded to those of the severe rainfall centers in western and northeastern Hunan. The maximum value of positive vorticity center was $10 \times 10^{-5}$ s$^{-1}$. There was stably weak positive vorticity before 20:00 on June 7 in Process II (Figure 7b). After that time the vorticity increased significantly in Hunan, reaching a maximum value of $12 \times 10^{-5}$ s$^{-1}$ at 14:00 on June 8, and then decreased. Compared with the inappropriate express, the stage of maximum vorticity corresponded to the intense development of precipitation in central Hunan. The analysis shows that the strong positive vorticity appeared at low levels in both processes.

In order to better understand the coordination between the upper-level and low-level vorticities and the relevance with rainstorms, the vertical cross-sections of vorticity are made along 112°E when rainfall was intensively in the two processes (Figure 8). In the two processes the positive vorticity centers both appeared below 500 hPa, and the maximum positive vorticity center in process II was $8 \times 10^{-5}$ s$^{-1}$, which was stronger than that in Process I. The large positive vorticity zone in Process II extended from 850 hPa to 600 hPa, which presented a “Bull’s eye” situation with double centers and the thickness was larger than that in Process I. The negative vorticity intensity in the upper troposphere of process II was obviously weaker than that of Process I. The configuration of negative vorticity at upper levels and the positive vorticity at low levels was a typical upper-level and low-level vorticity situation that is conducive to the occurrence and development of severe rainfall. Process II was mainly driven by strong positive vorticity at low levels.
6.2. Thermodynamic conditions

Thermodynamic condition is one of the main factors affecting the formation of convective rainstorms, and regional rainstorms often have convective properties. The vertical distribution characteristics of pseudo-equivalent potential temperature \( \theta_{se} \) can characterize the temperature-humidity distribution and vertical stability of the atmosphere. The spatial distribution can reflect the frontal activity, and the vertical velocity is corresponding to the intensity of ascending motion. Therefore, the vertical cross-sections of pseudo-equivalent potential temperature and vertical velocity along 110°E in the two processes are given in Figure 9, so as to analyze the similarities and differences of thermodynamic conditions in the two processes.

From Figure 9, the 350-K high-energy center appeared at 700hPa (25°N–27°N) in the north of central Hunan during the whole precipitation period of Process I. In the rainstorm initiation stage (at 08:00 on June 1), the high-energy tongue above 346 K bulged upwards, extending to 600hPa, and the atmosphere had a convective unstable stratification. The isolines of \( \theta_{se} \) below 900hPa were dense in the rainstorm development stage (at 08:00 on June 2), and the near-surface \( \theta_{se} \) reached the maximum of above 360 K, indicating the \( \theta_{se} \) dense zone for frontal zone, instead of maximum area of \( \theta_{se} \). The extension height of the high energy tongue above 350K reached 600 hPa, and the convective instability conditions significantly strengthened. By 08:00 on June 4, the cold air moved southward, and the northern region of central Hunan (25–27°N) was in the rainstorm formation stage (at 20:00 on June 6) in process II (Figure 8). The 346 K isolines of \( \theta_{se} \) bulged upward, and the expansion height of high-energy tongue reached 500hPa. The atmospheric convection instability was greater than that in Process I. The maximum pseudo-equivalent potential temperature in the near surface was above 366 K in the rainstorm development stage. The density of \( \theta_{se} \) strengthened, and the energy frontal zone in the near surface was stronger than that in process I.

From the perspective of vertical velocity (Figure 9-10), there were large areas of negative vertical velocity in the rainstorm initiation and development stages on the north of central Hunan (25°N–27°N) during the two processes. The vertical extension height was above 300hPa, and the ascending motion was intense. At the same time, the center of maximum negative value was located at 850hPa. The negative value center in Process I was \(-2 \text{ pa·s}^{-1}\) near 26°N, and the high-value area of negative vertical velocity in Process II had two regional centers, with \(-1.7 \text{ pa·s}^{-1}\) and \(-1.4 \text{ pa·s}^{-1}\) in 26°N and 28°N, respectively. Therefore, the ascending motion in the middle and lower troposphere of Process I was stronger than that of Process II. In the rainfall weakening stage, the vertical velocity of Process I began to weaken and the vertical velocity center of Process II rose to 700hPa, and the velocity remained at a large value, which indicated the rainstorm development in Process II was mainly affected by the strong ascending motion at low levels.
7. Conclusions

Through the comparative analysis of two disaster-causing regional rainstorm processes under the influence of SCV in 2015, the following conclusions are drawn.

Both of the two heavy rainstorm were caused by SCV. The eastward movement of upper-level trough drives the SCV to move eastward and affects Hunan. The unstable warm-humid airflow on the edge of the subtropical high transports water vapor and unstable energy to the rainstorm area.

In the two processes, there is a convergence of two transport bands of water vapor flux, resulting in the intersection of cold and warm air. The intensity of water vapor convergence was enhanced, and caused the regional rainstorm processes. The transport band of water vapor flux in Process I maintains longer, and the northerly airflow is also stronger, resulting in the greater accumulated rainfall and hourly rainfall intensity in Process I. The main water vapor transport sources are the Bay of Bengal and the western Pacific, while in process II, it is mainly from the confluence of the warm and humid airflow in front of the southwest vortex and the northerly airflow.

In the two processes, the maximum values of dynamic and thermodynamic factors all appear near 850hPa in the rainstorm development stage, and the latitude of the extreme value is close to the severe rainfall area. The distribution characteristics of low-level convergence and upper-level divergence appear in both processes. Process I has a typical rainstorm vorticity configuration of negative at upper layer and positive at lower layer. Process II is mainly driven by the strong positive vorticity at low levels.

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