Landfall tropical cyclone rainstorms on the north slope of the Dabie Mountains

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Abstract. The formation and development mechanism of landfall cyclone rainstorms that occur on the north slope of the Dabie Mountains were investigated by the determination of typical occurrences. Interaction between the tropical cyclone and the westerly trough was characterized by the favorable circulation backgrounds of landfall tropical cyclone rainstorms on the north slope of the Dabie Mountains. A conveyor belt was created between the easterly jet flow of the tropical cyclone and the subtropical high pressure of the western equatorial Pacific Ocean and the southerly jet flow of the westerly trough front, creating a huge amount of energy and vapor from the landfall tropical cyclone in the rainstorm area and destabilizing the stratification. These conditions were advantageous to the frontogenesis of a warm front and the development of Mesoscale convective systems (MCS) in the westerly cold air that met the inverted trough located at the northern portion of the tropical cyclone. The existence and development of the mesoscale front area in the ground provide a trigger mechanism for the rainstorm. The MCS occurred and developed in the equivalent potential temperature $\theta_e$ frontal zone, which is located between the low pressure area of the typhoon and the cold air, which is located at the rear of the westerly trough. The terrain block slowed or stopped the motion of the low pressure system formed by the landfall tropical cyclone, which was conducive to the enhancement of the rainstorm.

1. Introduction

The area on the north slope of the Dabie Mountains primarily includes the upper and middle reaches of the HuaiHe River, which is one of multiple rainstorm areas in China [1]. The track movement of Tropical Cyclones after landfall are of three types: towards the west, towards the north, and towards the northwest. When the tropical cyclone moves toward the northwest, it is prone to the enhancement of rainstorms on the north slope of the Dabie Mountains, which can
produce extreme precipitation [1]. For example, the extreme Henan "75.8" rainstorm was enhanced by the interaction between a tropical cyclone and a mid-altitude weather system after the cyclone landed, resulting in extreme precipitation values that reached 189.5mm within one hour and 680mm within six hours, and resulted in a total precipitation of 1631mm [1, 2].

This type of rainstorm occurs outside of tropical cyclone circulation; however, a physical connection with the tropical cyclone is inherent to this event [3, 4]. The characteristics of these rainstorms include a sudden, strong, relatively concentrated precipitation period, local precipitation intensity and an obvious mesoscale system with prominent mesoscale features [3, 4, 5]. The interaction between weather systems of different scales and at different latitudes provides a favorable large-scale circulation background for the occurrence and development of the MCS of the landfall cyclone rainstorm. When southwest monsoons and tropical cyclones interact, the abundant water vapor induced by the southwest monsoon contributes significantly to the formation and development of MCS, which results in the occurrence of rainstorms [6, 7].

The occurrence and development of tropical cyclone circulation potential vorticity, water vapor and energy transport provide favorable conditions for the development of the MCS. As a powerful source of disturbance, in a suitable atmospheric node, the effect of a tropical cyclone on the environment is characterized by nonlinear dynamics similar to a Rossby disturbance wave form, which stimulates the occurrence and development of MCS. A large amount of potential energy is converted into kinetic energy, which causes the MCS and promotes the occurrence of heavy rain [8, 9, 10].

Based on special rainstorm occurrences, there are obvious geographical characteristics and limitations that affect the formation mechanisms of rainstorms caused by tropical cyclones, which must be investigated in greater depth. This study investigates the mechanism of tropical rainstorm cyclones in the northern Dabie Mountains, including the background characteristics of large-scale circulation, water vapor sources and transport processes, as well as MCS triggering mechanisms [11, 12, 13, 14, 15].

2. Date and methodology
A total of 57 stations within the 113-117°E and 33-38°N region were identified. A rainstorm occurrence was defined as an event that affected no fewer than five stations and resulted in precipitation exceeding 50mm over 24h of constant rain. From 1996 to 2015, there were a total of seven documented tropical cyclone rainstorms that occurred on the northern slope of the Dabie Mountains.

Precipitation data was obtained from the Atmospheric Detection Center of China Meteorological Administration. The diagnosis analysis data was the NCEP final analysis data.

3. Results and discussion

3.1. Circulation Characteristics
On July 19, 2005 (UTC), the "Haitang" typhoon reached land in Lianjiang County of Fujian Province. After touching land, the storm system moved northwest on July 20th (UTC) and was reduced to a low pressure system. On July 22, a wide area of heavy rainfall occurred on the northern slope of the Dabie Mountains, delivering more than 50mm of precipitation at 38 rainfall stations, more than 100mm of precipitation at 13 stations, and a maximum recorded precipitation of 295mm.
As shown in Figure 1, prior to the rainstorm on July 21, at 12:00 (UTC), in 500hPa, the low-pressure center of the "HaiTang" typhoon was located in the Poyang Lake area, and the trough of "HaiTang" stretched northward to the north slope of the Dabie Mountains. The sub-tropical high pressure area in eastern and northern China created a trough that moved eastward into the Hetao area. Additionally, a tropical storm was forming to the east of the Philippines, as shown in Figure 1(c). As shown in Figures 1(a) and (b), respectively, in the Huaihe area at 700hPa and 850hPa, there was a low level of easterly jet flow, with the greatest wind speed reaching 18m/s. The atmospheric circulation evolved from 00:00 to 12:00 on July 22 in the "HaiTang" low-pressure center, positioned in the Poyand Lake region, though the subtropical intensity and scope did not change significantly. However, the low trough in the Hetao area moved toward the northern Dabie Mountains and began to weaken and contract in the north. On July 12, at 21:00 (UTC), the weak cold air located at the surface accumulated in the Hetao area, and as of 22:18 (UTC), it began to approach the north slope of the Dabie Mountains, as shown in Figure 1(d). The rainstorm on the north slope of the Dabie Mountains in the 500hPa trough then moved to the trough located to the north of the "HaiTang" typhoon. This occurred as a result of the interactions between the tropical storm, the subtropical high, the westerly trough, the low-level jet and the cold air at the surface.

4. Water vapor transport and convergence
Adequate water vapor supply is one of the basic criteria for the formation of heavy rainfall. Tropical cyclones travel over the warm ocean and thus serve as heat engines, and they transfer water vapor and energy to the area of heavy rainfall. On July 22, 2005 at 12:00 (UTC), before...
the heavy rain began, abundant moisture had gathered in the troposphere of the Dabie Mountains, nearly saturating the atmosphere with a large amount of convective available potential energy (CAPE). As shown in figure 2, when "HaiTang" travelled to the northwest, the southwest monsoon from the Indian Ocean advanced, and the monsoon and the “HaiTang” typhoon merged to form a southerly jet in eastern China. Additionally, the easy flow of the subtropical high combined with the southerly airflow of the eastern portion of "HaiTang" to form a southeastern low-level jet in the region of eastern China, as shown in figure 2. Finally, J-1 and J-2 combined to form a strong partial low-level easterly jet flow in the HuaiHe area, as shown in figure 2. This transported water vapor and energy to the Dabie Mountains area and led to the strong water vapor convergence in the area. Additionally, the southerly airflow on the western side led to water vapor convergence on the north slope of the Dabie Mountains. As a result, the low-level jet flow stream on the eastern side of the "HaiTang" monsoon provided a link through which the middle latitude and low latitude weather systems could interact.

![Figure 2. 850hPa water vapor flux divergence and wind vector at 12:00 (UTC) on 21 July 2005. Water vapor flux divergence (color-filled, g•hPa⁻¹•cm⁻²•s⁻¹) and wind vector (black arrows, m•s⁻¹).](image)

According to the water vapor transport data provided in figure 3, the transport of water vapor occurred primarily in the 700 hPa layer, while the transport of water vapor was very low at 500 hPa and above. The 850 hPa layer and the 950 hPa layer included two vapor transport belts. One belt was consistent with the direction of the southwest monsoon, which transported water vapor from the Indian Ocean and the South China Sea to the area of heavy rainfall. The other belt was located to the southwest of the eastern portion of the "HaiTang" typhoon and the subtropical high, and transported water vapor from the East China Sea to the area of heavy rainfall. These two conveyor belts were in contact with J-2 and J-1, respectively, and finally merged in the Huaihe area. In addition, the terrain of the Dabie Mountains blocked the easterly jet, forcing the jet to climb in altitude, which was therefore conducive to the further development of upward movement.
Figure 3. Water vapor flux and wind vector at 12:00 (UTC) on 21 July 2005. Water vapor flux (color-filled, g•hPa•cm•s⁻¹) and wind vector (black arrows, m•s⁻¹).

5. Unstable features and dry intrusion

As shown in figure 1, the rainstorm on the north slope of the Dabie Mountains occurred in the westerly "HaiTang" trough on the northern front, as a result of the interaction between the cold and warm air on the north slope of the Dabie Mountains. Figure 3 depicts the evolution of θse. As the westerly trough moved eastward and "HaiTang" moved to the northwest, a θse frontal zone formed between the cold air from the westerly trough and the warm air from the "HaiTang" typhoon. From 950 hPa to 500 hPa, the θse frontal zone tilted toward the west. The mesoscale clouds developed a pattern in the 850-700 hPa θse frontal zone, resulting in heavy rainfall. Additionally, the θse face steeped, easily leading to the development of moist slantwise vorticity that was conducive to the enhancement of ascending motion.
Figure 4. The distribution of θse (contour, °C) at 12:00 (UTC) on 21 July 2005.

Figure 4 depicts the low level dry cold air invasion process of tropical cyclone troughs. The intersection between the westerly flow and the easterly flow occurred on the west side of the storm zone. In the 925hPa layer, cold air extended into the heavy rain area, and in the 850-700 hPa layer, the partial easterly jet at the bottom of the cold air began an upward climb. The cold air from the 700-500 hPa layers were divided into two portions, as depicted in figure 5: the invasive air in the trough of “HaiTang” was forced over the storm and to the western side of the rainstorm zone. This indicates that the cold air in the middle and lower layers was continuously increasing as a result of the westerly trough. The middle level of the cold air intrusion under the "HaiTang" trough consisted of warm moist air flow at the bottom, which forced the cold air to climb. These circulation conditions were very conducive to the development of MCSs. Additionally, the storm area was located to the upper right front of the exit area of the upper air jet stream and the left front of the low-level wind jet. The coupling between the upper level westerly jet and the low-level jet strengthened the low level convergence and the upper level divergence in order to promote and maintain the vertical movement of the developed storm.
Figure 5. Zonal section of the rainstorm center (shown) along 36°N at 12:00 (UTC) on 21 July 2005. θse (contour, °C), wind vector (black arrows, m•s⁻¹).

5.1. Upward movement mechanism
As shown in figure 6, the 850hPa layer demonstrated strong convergence over the area of heavy rainfall, the 500-400hPa layers demonstrated strong radial scattering, and the 200hPa layer demonstrated strong radial scattering. The convergence of the 850hPa layer was caused by the easterly flow. The divergence of the 500-400hPa layers was a result of the cold advection of the westerly trough. The convergence of the 200hPa layer was caused by the upper level jet stream. As demonstrated by the vertical distribution of the vertical velocity, a rising movement occurred from the boundary layer to the middle troposphere in the rainstorm area. These results clearly indicate that the high-level divergence and low-level convergence of the atmospheric circulation conditions were conducive to the development of upward movement. In addition, the vertical velocity of the zonal profile (figure 6a) demonstrates that both sides of the storm, to the east and west, exhibited sinking movement. The sinking movement on the edges and the rising area were induced by secondary circulation rings. The two secondary circulation rings were located to the east and west of the rainstorm area, which served to maintain the rainstorm.
Figure 6. Zonal section of the rainstorm center (shown) along 36°N. (a) Meridional cross-section of the rainstorm center along 115°E (b) at 12:00 (UTC) on 21 July 2005. Vertical velocity (color-filled, Pa·s⁻¹), wind vector (black contour, m·s⁻¹).
Figure 7. Meridional cross-section of the rainstorm center (shown) along 115°E at 12:00 (UTC) on 21 July 2005. Moist potential vorticity (contour line, 10^{-5} s^{-1}).

Under moist potential vorticity conservation conditions, the increase in the vertical shear of the horizontal wind or the wet compression of the horizontal wind would lead to significant development of the vertical vorticity as well as enhancement of the upward movement. The rainstorm area was located in the center of the negative center of the 850hPa moist potential vorticity and in the center of the 500hPa moist potential vorticity (figure 7). The vertical distribution of the moist potential vorticity strengthened and maintained the rainstorm.

6. Conclusions

Based on the NECP reanalysis data, the occurrence and development mechanisms of the tropical cyclone rainstorm that occurred on the north slope of Dabie Mountains were investigated. The study suggests the following conclusions.

- As the tropical cyclone moved toward the northwest, the subtropical high was strengthened and extended westward. A low level easterly jet was formed between the two systems in the east, and warm, wet air flow was transported to the north by the easterly jet. Induced by the movement of the middle-latitude westerly trough, cold air moved to the south and the cold and warm air on the northern slope of the Dabie Mountains experienced confluence, resulting in torrential rain.

- A southerly low-level jet was formed between the east side of the tropical cyclone, the west side of the subtropical high and the front of the westerly trough, which conveyed steam and energy to the rainstorm area. Between the jet and the jet stream, positive feedback made the circumstances conducive to the enhancement of low level convergence and the development of vertical motion.

- The cold air at the surface was the trigger mechanism for the development of MCSs. Among the low level dry air intrusion of the low pressure trough to the north, the
atmospheric stratification became extremely unstable. Mesoscale convective clouds developed in the θse frontal zone, which led to an increase in the heavy rainfall.

Acknowledgements
This work was supported by the Public welfare industry special (meteorological) funds (grant GYHY201306012) and Research and Operation Project for IHR (IHRKYYW201604).

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