Observational characteristics and causes of extreme heavy rainfall in typhoon ‘Duksuri’ (2305)

Liuming Wang

Reading Academy, Nanjing University of Information Science and Technology, Nanjing, China

202183110003@nuist.edu.cn

Abstract. Super Typhoon ‘Duksuri’ (2305), made landfall in Fujian Province, causing significant impacts from July 27th to July 31st. The typhoon resulted in heavy to torrential rainfall in multiple provinces, particularly in southern Taiwan, eastern Fujian, and the Beijing-Tianjin-Hebei region. Daily accumulated precipitation reached a maximum of 200 to 220 millimeters. Using ERA5 reanalysis data and NCEP Climate Forecast System Version 2 reanalysis data, this article conducted an observational analysis of ‘Duksuri’. The results indicate that the interaction between subtropical high-pressure systems, typhoons, and the strong southeast and east winds created favorable conditions for the prolonged duration of ‘Duksuri’ and extreme precipitation. The extreme rainfall in southern Taiwan and eastern Fujian was primarily caused by the abundant moisture associated with the typhoon itself. In contrast, the extreme rainfall in the Beijing-Tianjin-Hebei region was primarily due to the northward movement of the remnants of the typhoon, hindered by the high-pressure systems, resulting in longer and concentrated precipitation. Additionally, both regions are located on the windward slopes of mountainous areas, which significantly enhance the rainfall due to orographic lifting.

Keywords: Super Typhoon ‘Duksuri’ (2305), Extreme Heavy Rainfall, Southeast Jet Stream, Topographic Water Augmentation.

1. Introduction

A tropical cyclone is a non-frontal weather system, that originates over tropical or subtropical oceanic regions, exhibiting organized convection and a closed low-level circulation. When the maximum winds reach or exceed 32.7 meters per second, the World Meteorological Organization designates it as a typhoon or hurricane. Typhoons, with their strong winds, heavy rainfall, giant waves, and storm surges, can cause significant damage and loss to human beings.

Tropical cyclones generally occur during the summer and autumn seasons. Their most common distribution feature is their formation in tropical oceans, moving with the activity of monsoon winds. Tropical cyclones primarily occur in tropical oceans near the equator, such as the hurricane belt in the Atlantic Ocean, the typhoon belt in the Pacific Ocean, and the monsoon low-pressure system in the Indian Ocean. These tropical weather systems are typically accompanied by massive storms and precipitation, causing significant impacts on coastal areas.

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Research on typhoons is beneficial for mitigating the extensive damages they inflict upon human society. Additionally, studying typhoons has significant implications for understanding their physical mechanisms, exploring numerical forecasting models related to typhoons, and assessing the influence of climate change on typhoon trends in the context of global warming. Extreme rainfall records are closely linked to typhoon activity [1]. Adequate water vapor and its transport are fundamental requirements for the occurrence of heavy rainfall. [2-5]. In addition, the influence of topography [6]. also plays an important role in enhancing rainfall associated with landfalling typhoons.

In light of the recent occurrence of the super typhoon 'Duksuri', it is essential to conduct research on various aspects of the storm, including its wind field, pressure field and precipitation patterns. Analyzing these factors will provide valuable insights into the characteristics and impacts of this powerful typhoon. In this report, it is divided into the following sections: Section 1 focuses on the data sources and the selection of the research area. Section 2 presents observational characteristics of Typhoon 'Duksuri'. Section 3 depicts the causes of extreme heavy rainfall in 'Duksuri'. The final section provides a summary and discussion.

2. Data

In this study, total precipitation data, water vapor flux and water vapor flux divergence were obtained from ERA5 hourly data on single levels from 1940 to the present. The 850hPa U-component of wind and 850hPa V-component of wind data were obtained from ERA5 hourly data on pressure levels from 1940 to the present, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Data for the 10 meters U-component of wind above ground, 10 meters V-component of wind above ground, and pressure reduced to mean sea level (MSL) were obtained from the NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Product (ds094.1) produced by the National Center for Atmospheric Research (NCAR). The typhoon path data were obtained from Japan Meteorological Agency. The study area is defined as the marine and terrestrial areas ranging from 100°E to 135°E in longitude and 9°N to 10°N in latitude. The study period was selected from July 21st to July 31st, 2023. The spatial resolution of the ERA5 data is 0.25° × 0.25°, the spatial resolution of pressure reduced to MSL is 0.5° × 0.5°, and the spatial resolution of the 10 meters U-component of wind above ground and 10 meters V-component of wind is 0.205° × 0.205°.

3. Result

3.1. Observational Characteristics of Typhoon

From 1949 to 2019, a total of 1,918 typhoons occurred in the Northwest Pacific and South China Sea, averaging 27 typhoons per year. Among them, 425 were classified as super typhoons, with maximum sustained wind speeds near the surface reaching 51 meters per second. The rainfall associated with typhoons can be divided into two categories: rainfall within the typhoon circulation itself (including eyewall rainfall, concentric rainbands, rain within the typhoon's shear line, and rain along the prefrontal squall line) and rainfall in the typhoon's distant area of influence [7]. Generally, typhoon rainfall can be symmetric or asymmetric [8]. In the study of asymmetric rainfall, it has been found that when the typhoon has made landfall or is about to make landfall, there is typically a noticeable increase in terrain elevation on the right front of the typhoon, and the maximum rainfall often occurs in the right-front quadrant or the front part of the typhoon. Research has shown that after the typhoon makes landfall, the rainfall distribution generated by the typhoon's circulation is significantly asymmetric, with the maximum rainfall center mainly located northeast of the landfall point. This is influenced by factors such as the typhoon's structure, moisture conditions, and topography [9]. After making landfall, the typhoon rapidly weakens and the rainfall decreases. However, under the influence of terrain uplift and surface traction effects, the rainfall can temporarily intensify. Furthermore, the interaction between the typhoon and the terrain can also give rise to the development of mesoscale systems, which can influence the intensity and distribution of rainfall [10].

3.2. Case Study of Duksuri

3.2.1. Typhoon path and Intensity. Typhoon 'Duksuri' formed on the surface of the northwest Pacific Ocean on the morning of July 21st, 2023. It gradually developed and strengthened, reaching a super typhoon intensity of level 17 or above as determined by the Central Meteorological Observatory (China) on July 25th. It made landfall on Fuga Island in the Philippines in the early morning of July 26th. It was upgraded to a super typhoon again on the evening of July 27th. On July 28th, at 9:55 am, it made landfall in Jinjiang City, Fujian Province, with a strong typhoon intensity (level 14, 40 meters/second, 955 hPa). It eventually weakened into a tropical depression in Anhui Province on the morning of July 29th.

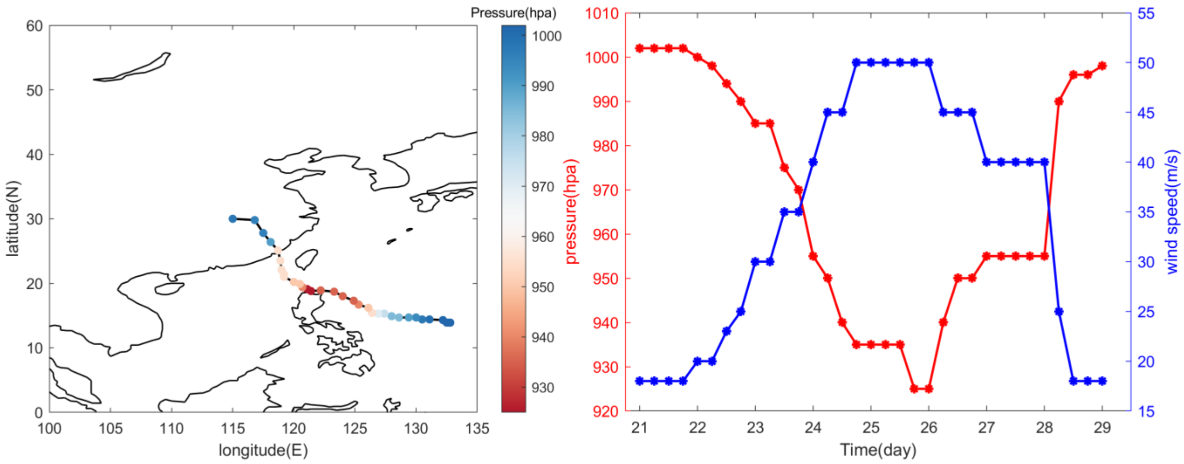

Figure 1. The track of typhoon 'Duksuri' (the dot-line) and central pressure and maximum wind speed from July 21st to July 29th.

3.2.2. Sea Surface Temperature (SST). SST is one of the essential conditions for the occurrence and development of typhoons [11]. Warmer sea temperatures (above 26 °C) have higher evaporation rates, and the main energy for the occurrence and development of typhoons comes from the ocean's sensible heat and latent heat release [12]. Fig. 2 shows the sea surface temperatures at 08:00 Beijing time three days before the landfall of Typhoon 'Duksuri'. It can be observed that the sea temperatures are notably higher in the South China Sea and the East China Sea. The sea temperatures along the path of 'Duksuri' are all above 28 °C, indicating that the warmer sea waters are favorable for its development. Additionally, there is a slight decrease in sea temperatures in the areas where 'Duksuri' passes through, indicating that the typhoon has obtained a significant amount of moisture and energy from the ocean.

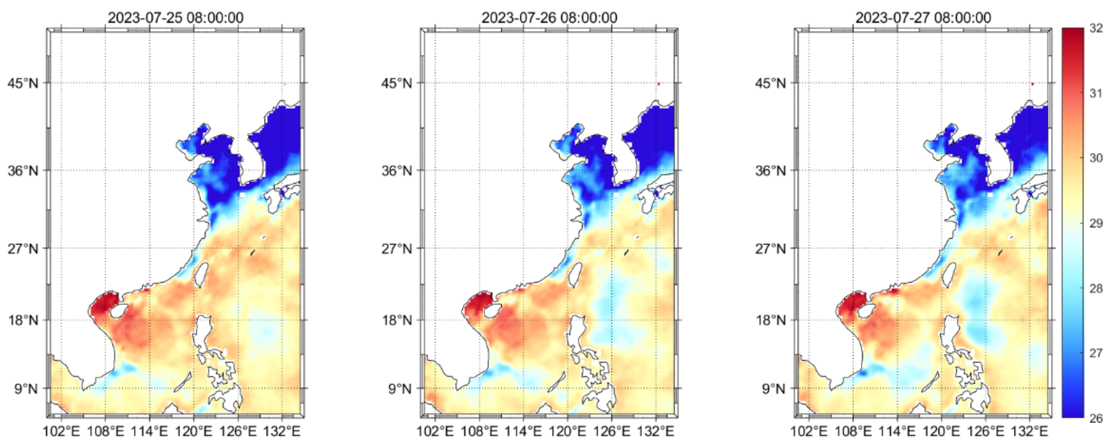

Figure 2. The SST at 0800BT July 25th, 0800 July 26th, 0800BT July 26th.

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3.2.3. Precipitation during Typhoon Landing. Due to the impact of Typhoon 'Duksuri', heavy rain occurred in Taiwan, Zhejiang, and Fujian from July 28th to July 29th. The southern part of Taiwan and the eastern part of Fujian experienced extreme heavy rainfall, with a maximum single-day rainfall of 200-220 millimeters (Fig. 2).

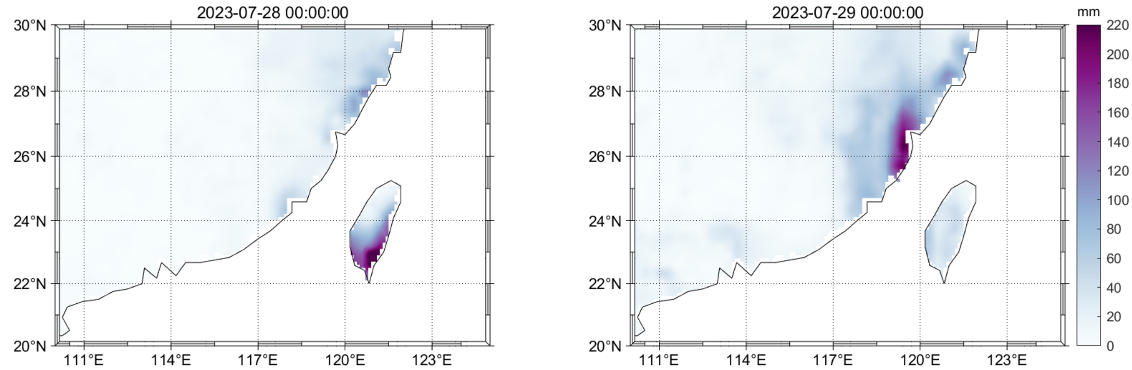

Figure 3. The cumulative rainfall from 0000BT 27 July to 0000 BT 28 July and 0000BT 28 July to 0000 BT 29 July in 2023.

The extreme heavy rainfall zone in Taiwan was located in the southern part and had a circular distribution. In Fujian, the extreme heavy rainfall zone was close to the eastern coastal area, located on the eastern side of the Mindong Mountains, and had a north-south belt-like distribution.

3.2.4. Precipitation during the Northward Movement of Residual Circulation. After Typhoon 'Duksuri' made landfall, under the guidance of the south wind airflow on the western side of the subtropical high-pressure belt, some residual circulation moved northwards, bringing characteristics such as prolonged stays, intense rain and wind, and wide-ranging impacts to most parts of East China and North China.

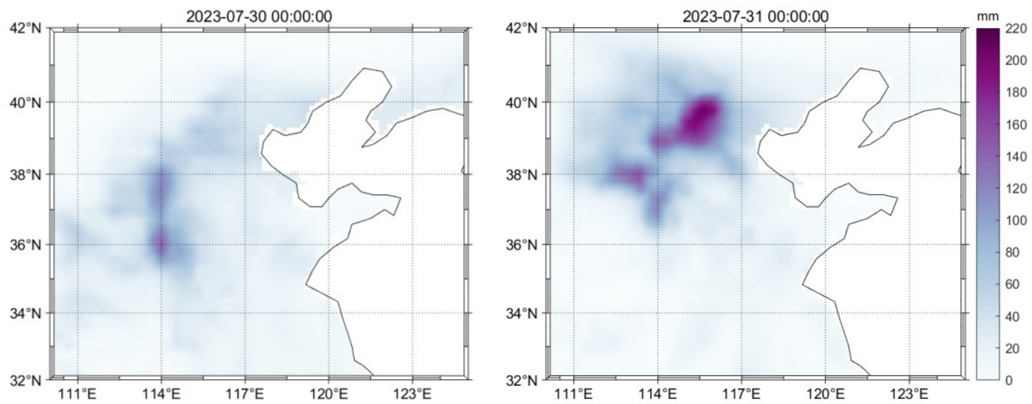

Figure 4. The cumulative rainfall from 0000BT 29 July to 0000 BT 30 July and 0000BT 30 July to 0000 BT 31 July in 2023.

The Beijing-Tianjin-Hebei region was affected by extreme precipitation, and the cumulative maximum precipitation for the whole day on the 31st is expected to be around 200-220 millimeters (Fig 3). The precipitation area is distributed in block shapes, mainly in Beijing and the northeastern part of Hebei Province.

3.2.5. Changes in Typhoon 'Duksuri' Circulation Background. Based on the distribution of the 500 hPa geopotential height field and 850 hPa wind field (Fig 5), it can be observed that during the northward landfall of Typhoon 'Duksuri', the northwest Pacific subtropical high on the northeast side of the typhoon is dominant. It continuously interacts with the typhoon circulation, providing favorable background conditions for Duksuri's northward movement and allowing it to sustain for a long time. At the same time, a strong southeast low-level jet supplies continuous heat and moisture on the northeast side of the typhoon, providing ample thermal and dynamic conditions to support the structural evolution of the typhoon and the occurrence of extreme heavy rainfall.

On July 27, 2023, at 20:00, the center of Typhoon 'Duksuri' was located along the eastern coast of Fujian. It was under the influence of the subtropical high on its northeast side and guided by southwesterly winds on the western side of the 588 hPa ridge. The typhoon was gradually moving northward along a northwest direction. The wind field near the center of the typhoon had a well-organized structure, and the centers of the 500 hPa geopotential height field and the wind field were basically aligned. Prevailing southeast winds were observed on the northern side of the typhoon, which facilitated the transport of moisture and heat over the eastern ocean surface.

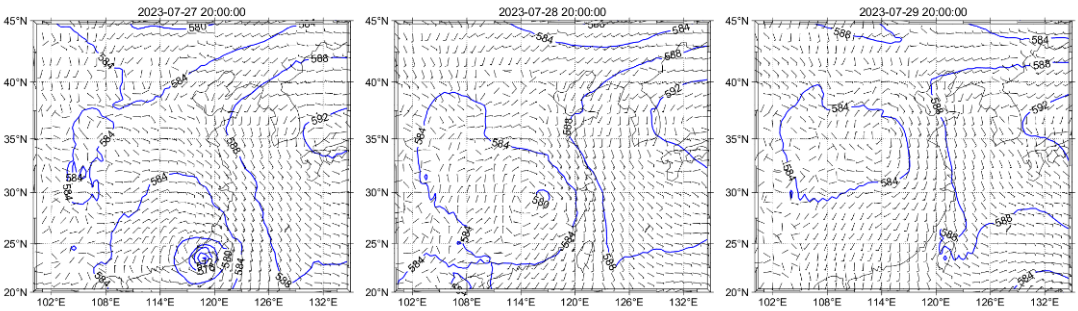

Figure 5. On July 27, 2023 at 20:00, on July 28 at 20:00, and on July 29 at 20:00, the 500 hPa geopotential height (contour line, unit: dagpm) and 850 hPa wind field (wind plume).

On July 28, 2023, at 20:00, the center of Typhoon 'Duksuri' was located at the border between Jiangxi province and Fujian province. Based on the analysis of the 850 hPa wind field, it was observed that the wind speed at the center of the typhoon significantly decreased, indicating a weakening of its intensity. In addition, there was a noticeable hollowing effect observed in the structure of the typhoon. Simultaneously, the center of the 500 hPa geopotential height field was found to be shifted eastward compared to the center of the 850 hPa wind field. This indicates that the structure of the typhoon has been disrupted or damaged.

On July 29, 2023, at 20:00, Typhoon 'Duksuri' was located within the territory of Anhui Province. By this time, the typhoon had been downgraded to a tropical depression. Under the influence of southerly winds on its eastern side, the residual circulation continued to move northward, impacting the northern regions of China.

From above, it can be observed that the interaction between the subtropical high-pressure system and the typhoon system provided favorable environmental conditions for the prolonged northward movement of Typhoon 'Duksuri' and the occurrence of extreme heavy rainfall during and after its landfall. Additionally, there are differences in the nature of rainfall between Fujian and the Beijing-Tianjin-Hebei region. Extreme heavy rainfall in Fujian is mainly caused by the intense rainfall from the deep typhoon system itself. On the other hand, in the Beijing-Tianjin-Hebei region, extreme heavy rainfall is primarily generated during the northward movement of typhoons. Apart from the abundant moisture carried by the typhoon, it is continuously supplemented by easterly and southeasterly winds, resulting in precipitation.

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4. Causes of Extreme Heavy Rainfall

4.1. Causes of Extreme Precipitation in Taiwan and Fujian

The phenomenon of extreme heavy rainfall in Taiwan and Fujian is primarily induced by the powerful core of a deep typhoon. As depicted in Fig. 4, it showcases the water vapor flux and its divergence at different time intervals during the occurrence of Typhoon 'Duksuri'. Notably, there is a conspicuous presence of robust water vapor transport surrounding the core of the typhoon, serving as a continuous supply that facilitates the maintenance of the ‘Duksuri‘ circulation and creates favorable conditions for the onset of extreme rainfall. Specifically, during the period from the 27th to the 28th, as the typhoon advances in a northerly trajectory, a pronounced convergence of water vapor flux becomes evident in the coastal regions of Taiwan and Fujian. Consequently, it is within these areas exhibiting heightened convergence of water vapor that the intense precipitation is primarily concentrated.

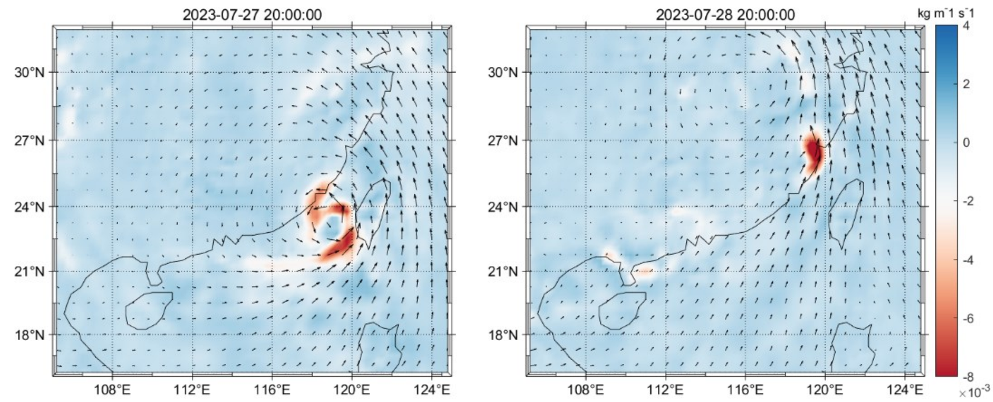

Figure 6. Water vapor flux (arrow) and water vapor flux divergence (filling) of Typhoon 'Duksuri' at 2000BT 27th, July and 28th, July.

4.2. Causes of Extreme Precipitation in Beijing-Tianjin-Hebei Region

The extreme heavy rainfall in the Beijing-Tianjin-Hebei region can be attributed to the northward movement of the residual circulation of Typhoon ‘Duksuri’. According to Fig.7, the eastern offshore subtropical high pressure gradually extended westward, while the western onshore high pressure ridge shifted eastward. On the evening of the 29th, these two systems merged, forming a high-pressure belt in northern China that hindered the northward progress of Typhoon ‘Duksuri’, causing it to linger over northern China for an extended period.

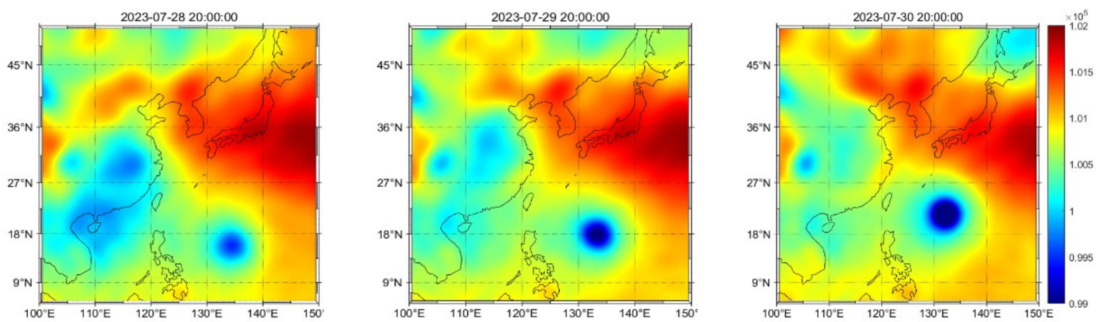

Figure 7. Pressure filed (reduce to MSL) of typhoon ‘Duksuri’ at 2000BT 28th, 29th, 30th, July.

Additionally, due to the significant pressure gradient between ‘Duksuri’ and the eastern high-pressure system, the easterly and southeasterly winds strengthened, continuously transporting and

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supplying moisture. Moreover, as Typhoon ‘Khanun’ in the northwest Pacific matured, the strong southeasterly winds transported abundant moisture from the vicinity of ‘Khanun’ to northern China. Consequently, this precipitation event reached significant magnitudes.

4.3. Topographic Water Augmentation

The coastal areas of Fujian Province are characterized by the presence of hilly terrain with relatively fluctuating elevations of around 600 meters. Prior to the landfall of a typhoon, the coastal region of Fujian Province is situated on the northern side of the typhoon, where the prevailing easterly airflow intersects perpendicularly with the northeast-southwest mountain ranges along the coast. As a result of this topographical configuration, the warm and humid airflow brought by the typhoon is forcefully uplifted due to the barrier of the mountains. This uplift leads to condensation of water vapor and the release of latent heat, consequently causing an increase in precipitation.

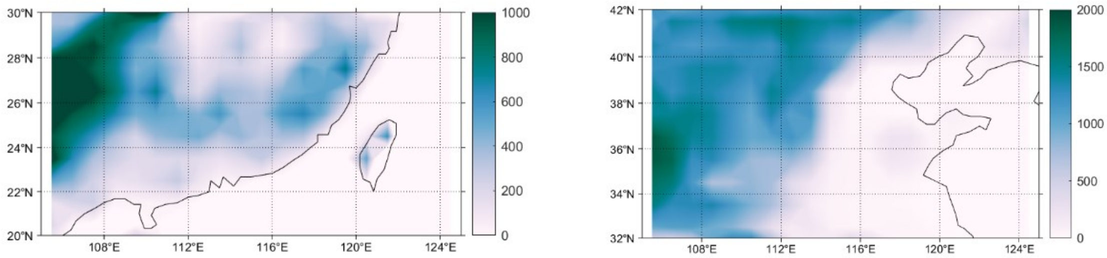

Figure 8. Land elevation map of Fujian and Beijing-Tianjin-Hebei region.

In the western part of the Beijing-Tianjin-Hebei region, the Taihang Mountain range intersects with the eastward and southeasterly winds carrying water vapor. Similarly, the Yanshan Mountain range to the north also intersects with the moisture-laden airflow. As a result of the topographical barriers, the water vapor is forced to ascend, leading to the concentration of moisture in front of the mountains and the formation of extreme precipitation events.

5. Conclusion

In conclusion, the super typhoon 'Duksuri' exhibited characteristics such as a wide range of impact, intense and prolonged extreme precipitation, resulting in significant economic losses and casualties in East China and North China. This study analyzed various features including precipitation, background circulation changes, water vapor flux, water vapor flux divergence, and sea-level pressure fields associated with 'Duksuri'. The analysis indicated that the southeast jet stream continuously supplied energy and moisture to the typhoon, enabling its sustained existence. The causes of extreme precipitation in Fujian Province and southern Taiwan differed from those in the Beijing-Tianjin-Hebei region. In the eastern part of Fujian and southern Taiwan, extreme precipitation was primarily caused by the deep core of the typhoon itself, while in the Beijing-Tianjin-Hebei region, it was attributed to the northward movement of the residual circulation. The influence of terrain-induced water enhancement should also not be overlooked.

This study has several limitations that should be considered. Firstly, it primarily focuses on features such as precipitation, background circulation, and water vapor flux, while not fully considering the influence of other environmental factors, such as temperature, humidity. Secondly, the study only analyzes the characteristics of precipitation and does not delve deeply into precipitation patterns. Additionally, since the analysis is conducted on a single typhoon, the generalizability of the results may be limited.

In future research, it would be beneficial to comprehensively consider more environmental factors, such as temperature, humidity, and analyze their relationships with typhoon formation and development. Multivariate analysis and integrated models can be employed to gain a more comprehensive understanding of typhoon characteristics and impacts. Additionally, a deeper analysis

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of precipitation patterns can be conducted, including the formation of precipitation bands, their movement paths, and intensity changes. Precipitation models and statistical methods can be utilized to improve the accuracy of precipitation predictions and descriptions, providing more effective support for disaster management and warnings.

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