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Numerical simulation and analysis of the Yangtze River Delta Rainstorm on 8 October 2013 caused by binary typhoons

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ABSTRACT

Torrential rainfall associated with the 23rd Typhoon Fitow in 2013 hit the Yangtze River Delta (YRD) region of China, resulting from mutual effects of residual low pressure cyclonic circulation of Fitow and the 24th Typhoon Danas, which imposed great challenge to forecasters. In this study, the Weather Research and Forecasting (WRF) model was used to simulate the rainstorm under the background of binary typhoons of Fitow and Danas. Three sensitivity experiments of typhoon intensity changes of binary typhoons were carried out. It was found that the Typhoon Danas was the main factor in this torrential rain event, in which its accompanied strong eastward low-level jet was the major moisture conveyor belt through which the warm and moist air was brought into the heavy rainfall zone and the static instability was maintained and enhanced over the YRD. The convergence line formed by periphery easterly flow of Typhoon Danas and southward cold air, together with the local frontogenesis mainly due to convergence, was an important trigger factor of this rainstorm. The large scale forcing was the major uplift mechanism, and the underlying frontal uplift played a secondary role for rainstorm in the north YRD, while uplift mechanism for rainstorm in the southern YRD is mainly local underlying frontal uplift induced large CAPE release resulting in local strong buoyancy uplift that led to strong upward motion. Not only did the convergence of twin typhoons directly provide dynamic conditions for the rainstorm, but also the dynamic lifting was enhanced by binary typhoons through strengthening the coupling of upper-level and low-level jet. The sensitivity tests revealed that the rainstorm in YRD was sensitive to both typhoons' intensity, and the rainfall in the south YRD was more sensitive than that in the north. A conceptual model of YRD rainstorm under binary typhoon situation was proposed based on the above-mentioned factors.

1. Introduction

The heavy rainfall associated with landfall of typhoons causes major floods that lead to tremendous economic losses and many fatalities along the coast over eastern and southern China during summer times. Therefore typhoon-induced heavy rainfall is an important topic for the typhoon research community (Chen et al., 2010). In the past decades, torrential rainfall induced by the tropical cyclones (TCs) has been intensively studied (e.g., Chen and Ding, 1979; Rodgers and Adler, 1981; Elsberry, 2002; Chien et al., 2008; Wang et al., 2009a, 2009b; Wu et al., 2009; Wang et al., 2010; Chien and Kuo, 2011; Yue and Shou, 2011; Li et al., 2013a, 2013b). Better understanding of physical mechanisms leading to TC heavy rainfall may help improve operational forecast of severe weather events. Most TCs weaken quickly after landfall because the surface fraction consumes the kinetic energy input significantly and cuts off inflows; the rainfall will decrease correspondingly because the moisture conditions at the underlying surface become poorer after the TC landfall (Dong et al., 2010). However, sometimes, the weakening TC remnant circulation can produce even heavier rainfall and cause more serious losses than it did at landfall under the interaction of mid-latitude weather systems, favorable moisture transportation from ocean, favorable cold air, topography, mesoscale convective systems and underlying surface (Li et al., 2010; Dong et al., 2010; Zhou et al., 2013; Wei and Li, 2013). Typhoon Fitow (1323) is a case in point. It is the strongest typhoon land falling Chinese mainland in October since 1949, and brought severe rainstorms, which renewed historical rainfall records in many regions of YRD during making landfall. The typhoon weakened and its precipitation gradually stopped at about 10 h after landfall. But 20 h later, this rare extraordinary rainstorm hits the YRD region resulting from the remnant of Typhoon Fitow with its interaction of Typhoon Danas (1324), which is about 1000 km away from Fitow. Typhoon Fitow's total rainfall was responsible for the total loss of $10.2 billion in YRD region, the most serious one in the past 10 years. Compared with regular typhoon and remnant rainstorms, this scenario was much more difficult to forecast and has always been a challenge to forecasters. So, it is very meaningful to study it.

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Early in the 1920s, Fujiwhara(1921, 1923) found from experiments and observations that two nearby cyclones tend to contrarotate mutually and approach each other, which was later named "Fujiwhara Effect". In the past few decades, scholars have investigated the interaction between binary typhoons through synoptic experiments, statistics, laboratory simulation, and numerical simulation. The interaction between binary typhoons is an essential cause of complex tropical cyclone tracks. Statistical analyses (Brand, 1970; Chen and Ding, 1979; Dong and Neumann, 1983) indicate that only binary tropical cyclones that are less than 6 to 7 latitudes apart have obvious inter-attraction; the attraction becomes subtle when the spacing is larger than 6 to 7 latitudes. Many previous studies (Chang, 1983; Lander and Holland, 1993; Lander, 1995; Ziv and Alpert, 1995; Carr and Elsberry, 1998; Kuo et al., 2000; Wu et al., 2003; Yang et al., 2008) focused on the effect of the interaction of tropical cyclones on the anomalous change in the tropical cyclone track, structure, and intensity. However, only a few studies have focused on the effect of the above-mentioned interaction on TC rainstorms. After surveying the severe damage caused by Typhoon Morakot (the 8th typhoon in 2009) to multiple China provinces and cities, it was found that the abundant moisture, energy, and vorticity conveyed by Typhoon Koni (the 7th typhoon in 2009) in the west benefited the development and long-term maintenance of Typhoon Morakot to its east and significantly contributed to an extraordinary rainstorm event in Taiwan (Xu et al., 2011; Wu et al., 2012). Xu et al. (2011)suggested that the exceptional rainfall over Taiwan is not directly related to Typhoon Koni. After a careful synoptic-scale diagnosis analysis on the causes of a heavy rainfall event in Shanghai under a situation of twin typhoons Lionrock (the 6th typhoon in 2010) and Kompasu (the 7th typhoon in 2010), Qi and Cao (2013) suggested that the location of this event is different from the so-called three traditional rainfall locations for this type of situation, namely the typhoon core area, typhoon inversed-trough area and area combined with cold air. And it is extremely difficult to forecast this type of heavy rainfall because any deviation from the twin typhoons' location, intensity and structure predicted by NWP would result in inaccurate forecast of rainstorm locations.

The Yangtze River Delta Rainstorm on 8 October 2013 is different from both traditional typhoon heavy rainfalls as proposed in the literature and those that occurred in the vicinity of a typhoon remnant and was directly induced by it. It is also distinguished from those caused by one typhoon under the background of twin typhoons. The physical mechanisms for this rainstorm, the trigger factors of the mesoscale convective systems (MCSs) internal to the system, and the uplift mechanisms for such heavy rainfall events to occur in so short a period of time have yet to be fully discussed. Hence, the purpose of the study is to explore the questions including how such long-distance binary typhoons influence the occurrence of the rainstorm, what the trigger and uplift mechanisms are, and how to help the forecasters.

This study is structured as follows. Section 2 analyzes the characteristics of this rainstorm and its large-scale circulation background based on US National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) data and precipitation observational data with a brief overview of the binary typhoon activity. Section 3 describes the basic features of the WRF model and the experimental design, including methodologies to enhance or weaken the initial typhoon vortex in the initial conditions. Results from the control simulation are verified in Section 4. The effects of Typhoon Fitow's remnant and its interaction with Typhoon Danas on heavy rainfall in YRD and the physical mechanisms involved are discussed in Section 5. Major findings are summarized in Section 6.

2. Binary typhoon activity and synoptic circulation of atmosphere

2.1. An overview of binary typhoons

Based on the best track data provided by China Meteorological Administration (CMA), the tracks of Typhoons Fitow and Danas are shown in Fig. 1. Typhoon Fitow (the 23rd typhoon in 2013) developed from a tropical depression on the eastern ocean surface of the Philippines at 12:00 on September 30, 2013 (universal time, similar hereafter) and moved northwestward with increasing intensity. It intensified into a severe typhoon by 9:00 on October 4 and began to move northwestward by west on October 5. It landed in Shacheng Town of Fuding City in Fujian Province at 17:15 on October 6. With the intensity of severe typhoon upon landfall, the maximum surface wind reached 42 m/s, and the central pressure reached 955 hPa. The typhoon moved southwestward after landing and then quickly weakened to a tropical depression by 1:00 on October 7 within the borders of Jian'ou Town of Fujian Province. Typhoon Danas (the 24th typhoon in 2013) developed from a tropical depression near the northern Marianas at 6:00 on October 4 and then moved northwestward by west and intensified into a severe typhoon by 0:00 on October 7. The center of this super typhoon was approximately 540 km northeast by east of Zhoushan at 12:00 on October 7. With decreasing intensity afterward, it began to move northward gradually and degraded into a typhoon at 3:00 on October 8. It then began to move northwestward to the Sea of Japan and then quickly weakened to a tropical depression before dissipating completely several hours later. It was closest to the YRD between 15:00 of October 7 and 0:00 of October 8. It then moved northward gradually, and the circulation center of the remnant of Fitow remained almost stationary near southern Fujian and eastern Guangdong at approximately 1100 km away from Typhoon Danas.

2.2. The rainstorm character

The distribution of cumulative precipitation (Fig. 2a) between 12:00 of October 7 and 12:00 of October 8, 2013, showed that precipitation covered the YRD, including the entire Shanghai, eastern and northern regions of Zhejiang Province, and southern and eastern regions of Jiangsu Province. The Y-type north–south rain band had obvious mesoscale characteristics. Heavy precipitation mainly concentrated at the right-hand side of the Y band, along an arch-shaped multiple rainstorm center line. The precipitation in Songshan Station near the extreme rainfall point of Shanghai reached 222.1 mm. The precipitation in Haining Station near the extreme rainfall point of Zhejiang Jiaxing reached 249 mm. The precipitation in Cixi Station near the extreme rainfall point of Ningbo reached 154.9 mm. The precipitation in Yuyao Station, which was the worst-hit area in the earlier stage, reached 112.2 mm. The precipitation in Taizhou Daxi Station in the southernmost rainstorm center reached 241.9 mm. Fig. 2b showed that the precipitation in Shanghai and southeastern Jiangsu in this 24-hour phase accounted for 60% to 70% of the total precipitation of Typhoon Fitow. Several rainstorm centers in eastern and northern Zhejiang also received 40% to 50% precipitation. The hourly precipitation variation (not shown) observed by the meteorological station near the precipitation core showed that the concentration time of precipitation was between 16:00 and 21:00 on October 7.

2.3. Synoptic background

NCEP FNL grid data at 6 h intervals were used to analyze the evolution of weather situation and stream fields. At 12:00 on October 7, 2013, the square-shaped center of subtropical high pressure (SH) at 500 hPa was above the northwestern Pacific Ocean south of Honshu Island, and the westward ridge point of SH stretched to the southern Korean Peninsula. Typhoon Danas was at the southwest side of SH, whereas the remnant of Typhoon Fitow on the continent covering the regions near the junction of Guangdong, Jiangxi, and Fujian Provinces. The low trough was at the Hetao in North China. The southwestward low-level jet at 850 hPa originated from southwest of the subtropical high and north side of Typhoon Danas, extended from east to west to the mouth of the Yangtze River, passed the north side of Typhoon Fitow's remnant until up to central Vietnam. A powerful upper-level westerly