A possible mechanism responsible for exceptional rainfall over Taiwan from Typhoon Morakot

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Abstract

During 6–9 August 2009, Typhoon Morakot hit Taiwan with exceptional rainfall and caused severe flooding and landslides, which resulted in a large number of human loss of life and significant property damage. The rainfall intensity broke the 50-year record and was largely under-forecasted. In this study, we have identified a possible mechanism responsible for this unusually heavy rainfall. It is found that the presence of the tropical storm Goni upstream of Morakot may be an important factor for the maintenance and intensification of Morakot. Goni transported a large amount of moisture and energy to Morakot. Numerical simulations indicate that the interaction of Goni and Morakot accounts for about 30% more rainfall than if Goni was not presented. This study may explain the unusual amount of rainfall for Morakot and thus provide additional considerations for future forecasts of similar situations.

Keywords: Typhoon Morakot; tropical cyclone precipitation; binary typhoon vortices (BTV)

1. Introduction

Typhoon Morakot made landfall on Taiwan in the morning of 7 August 2009 and brought about historically and exceptionally severe disasters over the island. The storm caused more than 650 people to perish and $3.3 billion in property damage (Wikipedia, 2009). Figure 1 shows Morakot’s path and the distribution of total accumulated rainfall during this event (from 6 August to 10 August), analyzed from raingage data (EPA, 2010). The southern portion of Taiwan underwent the heaviest torrential rain event in the past 50 years. The event rainfall reached 500–1500 mm over most parts of the island, 1500–2500 mm in many cities and counties in the central and southern Taiwan and even more than 3000 mm at some local sites in the Alishan region. The torrential rain resulted in floods and mud-rock flows in central and southern Taiwan. Morakot also hit Fujian, Zhejiang, and other provinces in the eastern coastal areas of mainland China after passing through Taiwan, and caused severe damage to many cities and counties in the coastal areas of mainland China as well. The accumulative rainfall reached 500 mm in northeast Fujian and southeast Zhejiang, and over 1200 mm at Jiufeng town in Taisuen County of the Zhejiang Province. During this event, the water level of Taihu Lake broke historical records for this century.

Every year, Taiwan and the southeast coast of mainland China experience several hits of landfalling typhoons, and these typhoons can cause various degree of damage to these regions. However, the amount of rainfall brought by Morakot is quite rare in the recent high-impact weather history. Besides the interaction of landfalling Morakot and surface topography of Taiwan, what other factor contributed to this record rainfall event? In this study, we have identified the interaction of Typhoon Morakot and tropical storm Goni, and analyzed the rainfall and energy reinforcement of Morakot by Goni.

2. Satellite observations of interaction between Typhoon Morakot and Goni

Figure 2 is a set of pictures of blackbody temperature (TBB) at (a) 0000 UTC 6 August 2009, (b) 1200 UTC 7 August 2009, (c) 0600 UTC 8 August 2009, and (d) 1200 UTC 9 August 2009, from Chinese satellite Fengyun 2c, in the region of western Pacific and the coast of China. On 6 August (Figure 2(a)), Typhoon Morakot approached the east coast of Taiwan. The central vortex of Morakot moved westward, with three large rainbands trailing behind. Meanwhile, new spiral rainbands were developed around Morakot, which coincided in time with the intensification of Goni. Notice that at this time, the two typhoon centers are almost lined up west–east. As Morakot made landfall on Taiwan on 7 August (Figure 2(b)), the large rainbands began to detach from the central vortex core and were left behind in the Pacific. Meanwhile, new spiral rainbands were developed around Morakot, which coincided in time with the intensification of Goni. Notice that at this time...
time, the two typhoon vortex cores gradually aligned in the southwest to northeast direction. The spiral rainbands of Morakot clearly connected to the rain area of Goni. The two systems continued to interact with each other as they further aligned with the southwesterly Monsoonal flow (discussed in the next section), and the rainbands from the two systems were trailed south-westward (Figure 2(c)). Finally, on 9 August (Figure 2(d)), tropical storm Goni began to dissipate, Morakot made landfall over mainland China. It is noted that when Morakot dumped the largest amount of rain on 8 and 9 August, Goni gradually weakened and dissipated. Could this timing be coincidental? How could Morakot have retained such a large amount of water vapor since there was a relatively dry condition in the Taiwan area during this time (Hsu, 2010)? Could Goni have played an important role in reinforcing Morakot by providing additional moisture and energy? From these observations, we hypothesize that the interaction between Typhoon Morakot and Goni may have contributed to the unusual rainfall of Morakot over Taiwan Island. In the following sections, we will analyze how these two systems interacted.

3. Data analyses

As early as the 1920s, Japanese scientists began to note the binary typhoon vortices (BTV) phenomenon (Fujiwhara, 1921, 1923). Later, Brand (1970) studied 22 cases of BTV over the North Pacific. He found that an interaction can exist between two tropical cyclones when their central distance is less than 700 nautical miles (approximately 1300 km). The distance between Morakot and Goni is about 400 km.

We first calculated the column water vapor flux, the two components of which are defined as follows:

\[ Q_u = \frac{1}{g} \int_{P_1}^{P_s} u q \, dp \]
\[ Q_v = \frac{1}{g} \int_{P_1}^{P_s} v q \, dp \]

where \( P_t \) and \( P_s \) are the top and surface pressure, \((u, v)\) a horizontal velocity vector, and \( q \) the water vapor mixing ratio. At any point in space and time, the column water vapor flux is the vector sum of \( Q_u \) and \( Q_v \).

Figure 3 shows the evolution of column water vapor flux in the domain consistent with that of the satellite observations in Figure 2, using US National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay, 1996). It can be seen from Figure 3(a) that at 0000 UTC 7 August, there was a distinctive water vapor channel from Goni to Morakot, and the high value areas of the vertical integrated moisture fluxes in their peripheral areas both displayed a ring-shaped pattern. The strongest rainbands for both systems tend to occur on the south-east side of the vortex core, lining up along the southwesterly moist flows. After 18 h (Figure 3(b)), the ring-shaped rainfall pattern around Goni dissolved, but ring-shaped rainbands...
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Figure 2. Blackbody temperatures (TBB) observed from both visible and infrared spin scan radiometer of Chinese Fengyun 2c during (a) 0000 UTC 06 August, (b) 1200 UTC 07 August, (c) 0600 UTC 08 August, and (d) 1200 UTC 09 August 2009. The red marks indicate storm centers for Goni and Morakot.

around Morakot intensified. The spiral rainbands of Morakot trailed south-westward and connected to the rainbands of Goni. The moisture transfer between the two typhoon vortices appeared as a continuous flow pattern. During the period from 0000 UTC 8 August (Figure 3(c)) to 0000 UTC 9 August (Figure 3(d)), Goni continued weakening and its moisture transferred to Morakot by the environmental flow field. Eventually, all residual rainbands from Goni were drawn into the spiral rainbands of Morakot and unified into a single system. This analysis indicates that the appearance of Goni upstream of Morakot may be an important factor for Morakot’s maintenance and intensification. In the configuration of both Goni and Morakot lining up along the southwesterly monsoon flow, a large amount of moisture and energy were transferred from Goni to Morakot during the interaction of the two typhoon systems.

4. Modeling and sensitivity studies

The results of the above analysis of the interaction process of Goni and Morakot suggest that Goni’s energy and moisture transfer during its weakening process makes important contribution to the intensification and development of Morakot. To confirm this moisture transfer, the coupled FLEXPART-WRF model was used to trace the motion trajectories of a cluster of air particles that are uniformly released from Goni. The Weather Research and Forecasting (WRF) model is jointly developed by NOAA and NCAR (Skamarock et al., 2005). The WRF model is fully compressible and nonhydrostatic, and has a full set of physical parameterization schemes. The FLEXPART model is a Lagrangian Particle Dispersion Model developed in the Department of Atmospheric and Climate Research, Norwegian Institute for Air Research (Stohl et al., 2005). In this study, we couple WRF and FLEXPART to analyze particle transport. The WRF-controlled run (discussed later in this section) is used to drive the FLEXPART model.

Figure 4 plots the trace of the particle cluster released in Goni for every 6 h from 1800 UTC 7 August to 0000 UTC 9 August 2009. These particles advanced along the forward trajectories, then were ingested into Morakot. One can see that at initial time (Figure 4(a) and (b)), particles are transported nearly horizontally by the zonal flow. As Morakot moves westward, the two typhoon systems line up along the southwesterly monsoonal flow, and particles are transported out of the Goni vortex and drawn into the Morakot vortex (Figure 4(c) and (d)). Eventually, Goni dies out and the particle transport tracer becomes...
Figure 3. Vertically integrated moisture flux (vectors) with their magnitudes greater than 8000 kg m$^{-1}$ s$^{-1}$ (color-shaded) at (a) 0000 UTC 7, (b) 1800 UTC 7, (c) 0000 UTC 8, and (d) 0000 UTC 9 August 2009, calculated from the NCEP/NCAR1 degree reanalysis data.

A part of Morakot’s spiral bands. We want to emphasize that these trajectories are three-dimensional (3D) fields, but Figure 4 is a plane view of these projected 3D fields.

To further demonstrate the impact of Goni on the Morakot rainfall intensity, we conduct a weather research and forecasting (WRFv2.2) model simulation. The simulation period is from 0000 UTC 7 August to 0000 UTC 9 August, and the NCEP-NCAR 1$^\circ$ × 1$^\circ$ reanalysis data are used for the initial fields and the lateral boundary conditions. Outer and nested integration domains centered at 25$^\circ$N, 125$^\circ$E are set up. The grid spacing for the coarse and fine grid domain is 30 and 10 km, resulting in 133 × 94 and 160 × 127 grid points, respectively, for each domain. The model is divided vertically into 29 levels with the top at 50 hPa. The time step is 180 s. Lin’s scheme is used for microphysical processes, the RRTM scheme for long wave radiation, Dudhia’s scheme for short wave radiation, and Kain and Fritsch’s scheme is used for cumulus convection.

Controlled and sensitive experiments were performed. In the control experiment, the NCEP-NCAR reanalysis data are directly used in the initial fields, while in the sensitive experiment, the Goni vortex in the reanalysis data is removed. The method to remove a vortex in the analysis field is as follows. First, within a 400-km domain-surrounded Goni, we define the storm center as the location where the maximum positive vorticity is found. Then, a streamfunction ($\psi$) and velocity potential ($\chi$) are calculated in the circular domain centered with this maximum vorticity (with a radius of 300 km), by solving the Laplace equations for both vorticity, $\nabla^2 \psi = \zeta$ and divergence $\nabla^2 \chi = D$. Next, the flow fields for Goni are constructed by adding together the velocities associated with the streamfunction, $v_\psi = k \times \nabla \psi$ and velocity potential $v_\chi = \nabla \chi$. The geopotential field associated with Goni is obtained from knowing the geostrophic vorticity: $\nabla^2 \phi = \zeta - f$, where $f$ is the Coriolis parameter. The perturbation temperature and moisture fields can also be calculated. To remove Goni, one
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Figure 4. Six-hour dynamic evolution of the forward trajectories of the cluster of particles released at 0000 UTC 7 August in Goni in the coupled FLEXPART-WRF model to simulate the process in which the moisture in Goni (A) was transferred into Morakot (B) during their interaction in the period of (a) 1800 UTC 7 August, (b) 0000 UTC 8 August, (c) 0600 UTC 8 August, (d) 1200 UTC 8 August, (e) 1800 UTC 8 August, and (f) 0000 UTC 9 August 2009.

Figure 5(a) and (b) shows the initial 850 hPa wind fields for the control and sensitive experiment, respectively. In the initial field of the control experiment, Goni and Morakot’s typhoon vortex structures can be seen from these initial fields (Figure 5(a)), but only Morakot’s vortex in the sensitive experiment (Figure 5(b)).

The corresponding simulated rainfall distribution and 48-h accumulated rainfall are shown in Figure 5(c) and (d), respectively, for the experiments with (Figure 5(c)) and without (Figure 5(d)) the presence of Goni. It is seen from the figures that the Morakot rainfall in the control experiment is obviously higher than that in the sensitive experiment. Without the presence of Goni, there is more than a 30% reduction in the amount of rainfall by Typhoon Morakot over Taiwan Island. The rainfall is distributed more in the south of Taiwan when Goni is not present. When Goni is located upstream of Morakot, the rainfall is concentrated on south-central Taiwan, which is consistent with the observations.

5. Conclusions
In this study, we explored a possible mechanism responsible for unusual heavy rainfall over Taiwan by Typhoon Morakot. Satellite observations showed that
prior to and during the period of Typhoon Morakot making landfall over Taiwan, there presented another tropical storm, Goni, upstream of Morakot in the South China Sea. The observations indicated some interactions between the two typhoon systems.

By analyzing reanalysis data, we found that the maintenance and intensification of Morakot was indeed due to moisture transport from Goni to Morakot. The numerical experiment with a particle transport model verified this hypothesis. We further conducted modeling and sensitivity studies. The WRF model simulations suggested that without the presence of Goni upstream of Morakot, there would be a 30% reduction in the amount of rainfall over Taiwan Island than in reality and a slightly different storm track that may also contribute to different rainfall amounts. This study may have addressed the discrepancy of under-forecasted rainfall by the forecasters during the event (Yeh, 2010).

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References


