**8D.6 MONSOONAL INFLUENCE ON THE TRACK CHANGE OF TYPHOON MORAKOT (2009)**

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## 1. INTRODUCTION

The monsoon activity in the South China Sea and western North Pacific includes prominent atmospheric variability ranging from the synoptic-scale tropical disturbance to the quasi-biweekly oscillation (QBW) to the Madden-Julian oscillation (MJO). The QBW and MJO are usually called tropical intraseasonal oscillations (ISOs). Studies revealed that TC tracks alternate between clusters of straight and recurving paths with an intraseasonal time scale (Harr and Elsberry 1991; Harr and Elsberry 1995; Chen et al. 2009). Ko and Hsu (2006, 2009) found that the ISO westerly phase was closely associated with recurving TC tracks in the vicinity of Taiwan. A pioneering study conducted by Carr and Elsberry (1995) provides a clue on how ISOs can alter the TC track and rainfall pattern.

Typhoon Morakot (2009) formed in the tropical western North Pacific on 3 August 2009 and made landfall over Taiwan late on 7 August 2009, leading to the worst flooding over the past 50 years in southern Taiwan. While previous studies emphasized the influence of southwesterly winds associated with intraseasonal oscillations and monsoon surges on moisture supply, the interaction between Morakot and low-frequency monsoon flows and the resulting influence on the slow movement and northward shift of the typhoon were examined through observational analysis and numerical simulation.

## 2. THE INFLUENCE OF ISO FLOWS ON TYPHOON MORAKOT

In order to examine the influence of flows associated with Morakot on various time scales, we use Lanczos filters in time at each grid point. A low-pass filter with a 20-day cut-off period is used to isolate the MJO-scale flow and the background state. A band-pass filter with a 10-20 day period is used for the QBW-scale flow. The synoptic-scale flow is the difference between the unfiltered flow and the flow from a 10-day low-pass filter.

Figure 1 shows the 700 hPa ISO wind fields prior to and during landfalling on Taiwan Island. This figure clearly shows the coalescence of the typhoon with the QBW and MJO gyres, respectively. On the QBW time scale (Figs. 1a-c), a cyclonic gyre can be seen just off the east coast of the Taiwan Island. Morakot was generally located to the east of the gyre center. When the typhoon made landfall over Taiwan, it was almost concentric with the QBW gyre. On the MJO time scale (Figs. 1d-f), a monsoon gyre can be seen off the west coast of Taiwan Island. Embedded in the monsoon gyre, Morakot also underwent a coalescence process with the MJO-scale cyclonic gyre. The typhoon was nearly concentric with the monsoon gyre when moved into the Taiwan Strait at 0600 UTC 8 August (Fig. 1f). In response to the two coalescence processes with the QBW and MJO gyres, Morakot turned northwestward when it made landfall on Taiwan and further northward when it moved into the Taiwan Strait, respectively.

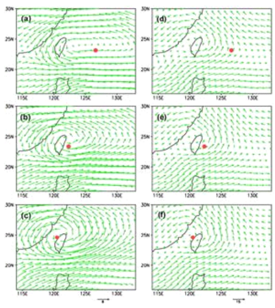

Figure 1 700 hPa winds (m s-1) on the QBW (left panels) and MJO (right panels) time scales at (a, d) 0600 UTC 6 August 2009, (b, e) 0600 UTC 7 August 2009, and (c, f) 0600 UTC 8 August 2009 with closed dots indicating the center of Morakot.

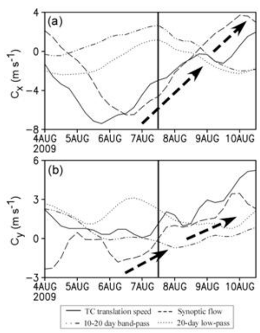


Figure 2 Time series of (a) the zonal component ($C_x$, m $s^{-1}$) and (b) the meridional component ($C_y$, m $s^{-1}$) of the translation speed (solid) of Morakot and the associated steering components. The vertical lines and arrows indicate the landfall time and the schematic trend of the synoptic-scale steering.

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TABLE 1 Description of experiments for Typhoon Morakot

| Experiment | Description |
|---|---|
| CTL | Control run with the realistic Taiwan topography and unfiltered initial fields within a bogus . |
| T100 | As in CTL, but the topography over Taiwan Island is set to 100 meters if the elevation is higher than the value. |
| OCEAN | As in CTL, but replace the Taiwan topography with ocean. |
| NO-QBW | As in CTL, but without QBW-scale flows in the model initial fields. |
| NO-SYN | As in CTL, but without the synoptic-scale flows in the model initial fields. |
| ONLY-MJO | As in CTL, but only MJO-scale flows (without QBW-scale and the synoptic-scale flows ) in the model initial fields. |

We calculated the contribution of different time-scale steering flows to the typhoon movement (Fig. 2). As the winds were enhanced on the southern side of the typhoon, the westward movement started to slow down before landfall. The synoptic-scale steering flow started to reduce the westward movement of Morakot late on 6 August and its contribution became eastward on 9 August. In the meridional direction, the contribution of the synoptic-scale steering flow first reduced the southward movement during 6-7 August and then enhanced the northward movement during 8-10 August. Thus the enhanced synoptic-scale flow was responsible for the northward track shift and slow movement of Morakot in the vicinity of Taiwan and the low-frequency gyres affect the track change of Morakot through the enhanced synoptic winds.

## 3. MODEL AND EXPERIMENT DESIGN

The numerical experiments in this study are conducted with the advanced research WRF (WRF-ARW) model. The model configuration is the same as used that in Ge et al. (2010). The numerical simulations include three two-way interactive domains with horizontal resolutions of 27 km, 9 km, and 3 km. The innermost domain is designed to move with the tropical cyclone (TC). The model has 28 levels in the vertical with a top of 50 hPa. Due to the relatively low resolution of the FNL analyses, a TC initialization scheme is used for the model initial fields, which was described in Ge et al. (2010).

The FNL-derived initial wind field associated with Morakot contains three components (Fig. 3). In this study, the Lanczos filter is used at each grid point to separate 20-day lowpass (hereafter MJO time scale) flows, 10-20 day bandpass (hereafter QBW time scale) flows and synoptic-scale flows that are the difference between the unfiltered flows and the flows from a 10-day lowpass filter. The filter is also used for separate other variables used in the initial and boundary conditions. An anticyclone on the synoptic time scale was located to the west of Morakot with strong northerly flows between the anticyclone and Morakot (Fig. 3b). A QBW-scale cyclonic gyre was located at 23°N, 130°E at 1200 UTC 5 August (Fig. 3c), which was embedded in a large MJO-scale monsoon gyre off the east coast of China with a trough extending southeast over the western North Pacific (Fig. 3d).

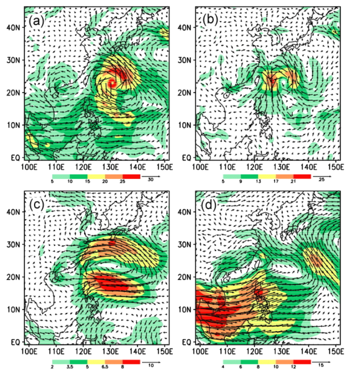


Figure 3 (a) the unfiltered initial wind field at 700 hPa at 1200 UTC 5 August 2009 and the corresponding components on the (b) synoptic scale, (c) QBW scale, and (d) MJO scale with the shading indicating wind speeds (m $s^{-1}$). A bogus vortex that is not shown here is inserted into the initial conditions in the simulations.

All of the numerical simulations cover a 108-hour period from 1200 UTC 5 August to 0000 UTC 10 August, 2009. Six numerical experiments are carried out in this study (Table 1).

## 4. THE SIMULATED MORAKOT IN THE CONTROL EXPERIMENT

The control experiment can well reproduce the intensity evolution, and track changes. In particular, the model can capture the northward deflections and slow-down when Morakot crosses the Taiwan Island and the Taiwan Strait (Figure 4).

The effect of Taiwan topography on Morakot is examined through the terrain sensitivity experiments including T100 and OCEAN. Figure 5 compares the simulated tracks and intensities in T100 and OCEAN with those in CTL during the period of 1200 UTC 5 August to 0000 UTC 10 August. In agreement with Ge et al. (2010), although the Taiwan Island affects the track, it is clear that the sudden northward deflection of Morakot is not directly a result of the influence of the island.

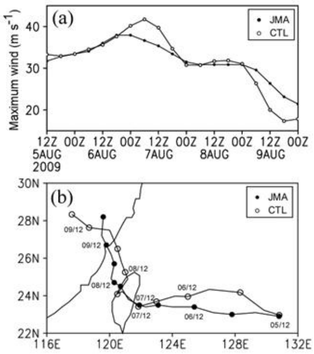


Figure 4 The observed and simulated (a) intensity and (b) track of Typhoon Morakot from 1200 UTC 5 August to 0000 UTC 10 August 2009. The marks are at 12-hour intervals.

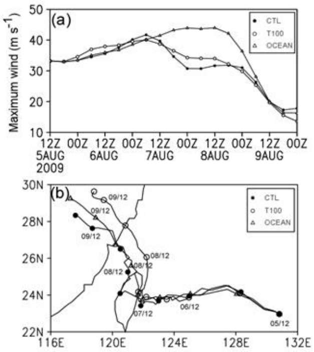


Figure 5 The simulated (a) intensity and (b) track of Typhoon Morakot from 1200 UTC 5 August to 0000 UTC 10 August 2009. The marks are at 12-hour intervals.

## 5. INFLUENCE OF MULTI-TIME SCALE MONSOON FLOWS

The influence of multi-time scale monsoon flows on Morakot's track is examined by comparing experiments NO-SYN, NO-QBW and ONLY-MJO with CTL.

Figure 6 displays the simulated intensity and track in these experiments from 1200 UTC 5 August to 0000 UTC 10 August, suggesting the significant influence of multi-time scale monsoon flows. In NO-SYN, the TC reaches its peak intensity around 0000 UTC 6 August (Fig. 6a), when it moves very slowly in low-frequency gyres. Under the influence of the steering flow associated with the low-frequency gyres, the TC first moves northeastward, suddenly turns northwestward at 0900 UTC 6 August, and then takes a northwestward track by 1200 UTC 7 August. During this period, the TC continues to weaken and maintains merely tropical storm intensity. An abrupt northward shift occurs around 1200 UTC 7 August, and the TC generally moves northward after the sudden turn. The simulated TC track is very similar to the cases discussed by Carr and Elsberry (1995). They found that sudden poleward track changes occur when a TC is embedded in a monsoon gyre. The NO-SYN experiment suggests that synoptic time-scale flows played an important role in the westward movement before Morakot made landfall over Taiwan.

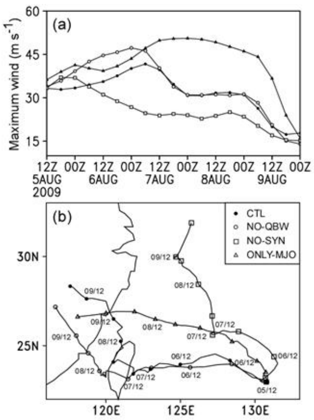


Figure 6 The simulated (a) intensity and (b) track of Typhoon Morakot in from 1200 UTC 5 August to 0000 UTC 10 August 2009. The marks are at 12-hour intervals.

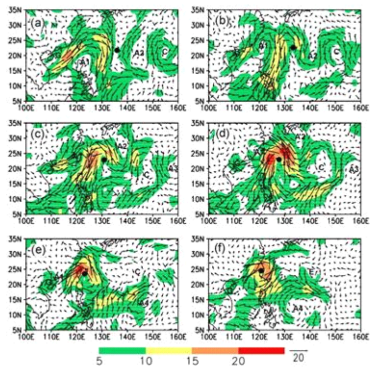

Figure 7 The 500 hPa 10-day highpass filtered winds (m s-1) at (a) 0000 UTC 4 August, (b) 0000 UTC 5 August, (c) 1200 UTC 5 August, (d) 0000 UTC 6 August, (e) 0000 UTC 7 August, (f) 0000 UTC 8 August 2009, respectively. The closed dot and letters G and E indicate the centers of Typhoon Morakot, Tropical Storm Goni, and Tropical Storm Etau, respectively.

It is found that prior to the landfall on Taiwan the westward movement is closely associated with a nearly zonal synoptic-scale wavetrain-like pattern, which consists of Goni over Guangdong Province, Morakot, and a cyclone over the northern West Pacific. The strong northerly winds between the anticyclone between Goni and Morakot reduced the northward steering component associated with the low-frequency gyres, leading to Morakot's westward movement directly towards Taiwan (Figure 7).

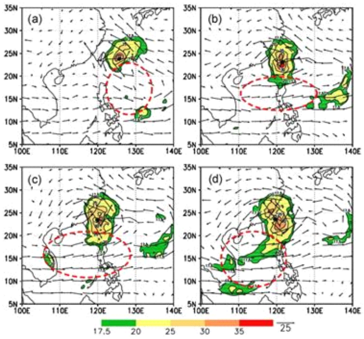

Figure 8 The simulated 700 hPa wind fields (m s-1) in the 27-km domain on 700 hPa NO-QBW at (a) 1200 UTC 6 August, (b) 1200 UTC 7 August, (c) 0000 UTC 8 August, and (d) 1200 UTC 8 August 2009.

The track change of Morakot in the vicinity of Taiwan is closely associated with its interaction with the low-frequency monsoonal flows (Figure 8). When Morakot approached to Taiwan, it coalesced with a QBW-scale gyre. As a result, the southwesterly winds were enhanced in the southern periphery of Morakot, reducing its westward movement and leading to the first northward deflection in the track of the typhoon. As Morakot moved into the Taiwan Strait, it merged with a large MJO-scale gyre and made the second northward shift in its track. The numerical experiments confirm that the coalescence of a TC with a monsoon gyre can lead to sudden changes in TC tracks, as suggested by Carr and Elsberry (1995). This study agrees with Ko and Hsu (2006, 2009) that the ISO flows are associated with recurving TC tracks.

Typhoon Morakot formed in a large-scale monsoon trough over the western North Pacific. Its cyclonic circulation contained significant components of monsoon flows on the MJO and QBW time scales when it merged with the low-frequency gyres. The numerical experiments confirm that the coalescence of Morakot with low-frequency monsoon gyres enhanced the synoptic-scale southwesterly winds on the southern side of Morakot and reduced its westward movement, leading to an unusually long residence time of the typhoon in the vicinity of Taiwan.

## 6. SUMMARY

Morakot generally moved westward prior to its landfall on Taiwan and underwent a coalescence process first with a cyclonic gyre on the quasi-biweekly oscillation (QBW) time scale and then with a cyclonic gyre on the Madden-Julian oscillation (MJO) time scale. The coalescence enhanced the synoptic-scale southwesterly winds of Morakot and thus decreased its westward movement and turned the track northward, leading to an unusually long residence time in the vicinity of Taiwan.

The numerical experiments were conducted to further confirm the influences of multi-time scale monsoonal flows on the track change of Morakot. The control simulation captured the slowing and northward deflections in the vicinity of the Taiwan Island, the highly asymmetric rainfall structure, and the associated rainfall pattern. The sensitivity experiments suggested that Morakot moved westward directly towards Taiwan due to a synoptic wavetrain-like pattern, which was consisted of Goni over mainland China, Morakot, and a cyclone over the western North Pacific with an anticyclone to the west of Morakot. Then the northward track shifts that occurred in the vicinity of the Taiwan Island were a result of the coalescences of Morakot with a QBW-scale gyre prior to the landfall on Taiwan and a MJO-scale gyre in the Taiwan Strait. In agreement with the previous study, the interaction between tropical cyclones and low-frequency monsoon gyres can cause sudden changes in tropical cyclone tracks.

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