Topographic Influence on the Motion of Tropical Cyclones Landfalling on the Coast of China

XIAOYU CHEN

Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/Pacific Typhoon Research Center, Nanjing University of Information Science and Technology, Nanjing, China

LIGUANG WU

Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/Pacific Typhoon Research Center, Nanjing University of Information Science and Technology, Nanjing, and State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China

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ABSTRACT

A few recent numerical studies investigated the influence of a continent, which is much larger in size than islands, on the track of a landfalling tropical cyclone. It has been found that land surface roughness and temperature tend to make a tropical cyclone move toward the continent. In this study, the effect of the elevated terrain on the western part of mainland China on landfall tracks is examined through idealized numerical experiments, in which an initially axisymmetric vortex is embedded into a monsoon trough and takes a landfall track across China’s mainland. It is found that the effect of the elevated terrain on the western part of mainland China can enhance the southerly environmental flows in the low and midtroposphere, leading to an additional landward component of tropical cyclone motion, suggesting that forecasts for tropical cyclone tracks over land should take into consideration the change in thermal condition over the continent. The study suggests that the increased duration of tropical cyclone overland tracks observed in China may be associated with the reduction of the thermal forcing over the Tibetan Plateau.

1. Introduction

Economic damage and casualties associated with tropical cyclones (TCs) occur mostly during and after landfall (Zhang et al. 2009, 2010) and thus it is very important to predict the timing and location of landfall in operational TC forecasts. While many studies have focused on the influence of islands on TC activity (e.g., Chang 1982; Bender et al. 1987; Yeh and Elsberry 1993a, b; Lin et al. 2005; Jian and Wu 2008; Yang et al. 2008; Huang et al. 2011; Wang et al. 2012; Xie and Zhang 2012), attention has been paid recently to the effects of continents that are much larger than the TC circulation on the horizontal scale. It has been found that land surface roughness and temperature can affect landfalling TC motion (Wong and Chan 2006, 2007; Au-Yeung and Chan 2010; Szeto and Chan 2010; Li et al. 2014; Xu et al. 2013). So far, few studies have examined the influence of continental terrain on landfalling TC motion.

Early studies paid much attention to TC track changes associated with topography. Idealized numerical and real case studies suggest that island topography like that of Taiwan can significantly affect environmental flows and TC tracks during landfall, leading to track deflection or looping tracks (Chang 1982; Yeh and Elsberry 1993a,b; Wu 2001; Jian and Wu 2008; Wang et al. 2012; Xie and Zhang 2012). For instance, it is suggested that the unusual tracks of Typhoons Nari (2001) and Krosa (2007) were closely related to the terrain height of the island of Taiwan (Yang et al. 2008; Huang et al. 2011). Additionally, the slowdown of Typhoon Morakot (2009) when crossing Taiwan was mainly attributed to the asymmetric latent heating induced by the
topography and monsoonal flows (Liang et al. 2011; Wu et al. 2011; Wang et al. 2012). It is indicated that the island topographic effect can affect lower-level flows and induce significant asymmetric diabatic heating that will result in TC track changes (Yeh and Elsberry 1993a,b; Wang et al. 2012).

A few numerical studies found that TC asymmetric flows induced by land surface roughness can lead to a landward component of TC motion during landfall in a resting environment (Wong and Chan 2006, 2007; Au-Yeung and Chan 2010; Szeto and Chan 2010; Li et al. 2014). Wong and Chan (2006) for the first time performed idealized numerical experiments that investigated the effects of land surface roughness and moisture flux on TC motion. They found that the TC can drift toward the continent at a speed of about 1 m s\(^{-1}\) in a resting environment on an \(f\) plane as a result of the induced TC asymmetric flows at lower levels; this process is now called land drift. Land drift was further demonstrated in the idealized numerical experiments with a triangle-shaped coastal delta on the \(f\) plane and the numerical experiments on the \(\beta\) plane (Au-Yeung and Chan 2010; Szeto and Chan 2010). Uniform environmental flows were added in numerical experiments and the land drift was also found by Li et al. (2014). However, we notice that the surface roughness length was set to be 0.5 m in these land drift experiments, which is much larger than those for common land surface conditions of eastern China when using the Advanced Research version of the Weather Research and Forecasting (WRF) Model (ARW). However, the influences of environmental flows and continental topography have not been fully investigated in previous studies.

Xu et al. (2013) conducted a 60-yr (1950–2009) survey on TCs that made landfall on China’s mainland and suggested that supertyphoons (maximum sustained 1-min surface winds above 65 m s\(^{-1}\)) tend to take a track toward the warmer part of the mainland. Based on their observational analysis, Xu et al. (2013) further performed a set of numerical experiments to show the influence of land surface temperature on landfalling TC tracks. In their experiments, they modified the land surface temperature and found that the simulated typhoon gravitates to the region with higher land surface temperature. They proposed that the warmer land surface, with intense moisture supply from the summer Asian monsoon, is conducive to deep convection that attracts supertyphoons.

In this study, we also examine the influence of the continent on the landfalling TC motion through idealized numerical experiments. The investigation of changes in the motion of TCs making landfall is closely associated with TC track and damage prediction. Our work differs from the previous numerical studies in the following aspects. First, we use a surface roughness length that is much smaller than the land drift experiments; this approach is more realistic for eastern mainland China. Second, we use a relatively realistic environmental flow including the typical monsoon trough and subtropical high over the western North Pacific for the embedded TC, which was derived from the low-frequency fields of Typhoon Matsa (2005). Finally, the influence of the continental-scale terrain is included.

2. Experiment design

The numerical experiments conducted in this study include five two-way interactive domains using the WRF Model (version 2.2). The horizontal resolutions are 27, 9, 3, 1, and \(\frac{3}{2}\) km, respectively, with 40 levels in the vertical and a top of 50 hPa. The fifth domain, with subkilometer resolution, is used for better simulation of the inner-core structure during TC landfall (Moon and Nolan 2015). In fact, a sensitivity experiment was conducted without the subkilometer domain. While the simulated tracks are very similar, the intensity evolution is different as a result of the different horizontal resolutions. Two eyewall replacement processes occur in the subkilometer run. Topography data with a resolution of 30 s (about 1 km) are used in the study. The center of the outermost domain is located at 30.0°N, 132.5°E, and the three innermost domains move with the TC (Fig. 1).

Fig. 1. Domains for the numerical experiments and the initial background flow (m s\(^{-1}\)) at 850 hPa. The terrain height (m) is shaded and the TC track in OCN is plotted.
The physics parameterization schemes are adopted as follows. The WRF single-moment 3-class scheme and the Kain–Fritsch scheme (Kain and Fritsch 1993) are used in the outmost domain for microphysics and cumulus parameterization schemes, respectively, while the WRF single-moment 6-class microphysics scheme (Hong and Lim 2006) and no cumulus parameterization scheme are used in the four inner domains. The other physics options include the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme (Mlawer et al. 1997), the Dudhia shortwave radiation scheme (Dudhia 1989), the Yonsei University scheme for planetary boundary layer parameterization (Noh et al. 2003), and the Noah land surface model.

The National Centers for Environmental Prediction (NCEP) Final (FNL) operational global analysis dataset with a resolution of 1.0° × 1.0° at every 6 h is used to initialize the simulation. The FNL data are first filtered with the Lanczos method to obtain the 20-day low-pass components (Duchon 1979). The low-frequency fields of Typhoon Matsa from 0000 UTC 5 August to 0000 UTC 9 August 2005 are selected as the background of our experiments. At 0000 UTC 5 August, Typhoon Matsa was located to the northeast of Taiwan with maximum surface winds of 45 m s⁻¹. During the following 3 days, Typhoon Matsa moved northwestward and then made landfall on China’s mainland at 1940 UTC 5 August. The low-frequency environmental flows represent the typical large-scale circulation pattern for TC activity over the western North Pacific (Fig. 1), including a monsoon trough and a subtropical high in the lower troposphere.

A warm-core vortex with the radial profile of tangential wind used in Wang (2007) is put into the low-frequency background. It is initially axisymmetric with maximum surface winds of 30 m s⁻¹. After 12 h of spinup on an f plane, the vortex shows a structure typical of mature TCs. The minimum sea level pressure is 965 hPa and the maximum surface wind is 40 m s⁻¹. The storm is placed to the northeast of Taiwan (25.4°N, 123.0°E), moving along the southeasterly steering flows between the monsoon trough and the subtropical high and then making landfall along the southeastern coastal areas of mainland China (Fig. 1). The TC tracks in our experiments are very similar to that of Typhoon Matsa.

Two sets of numerical experiments are discussed in this study and each one consists of three runs (Table 1). Both the sea surface temperature and the land surface temperature are set to 29°C to eliminate the possible influences of the initial temperature contrast between land and sea. The uniform land use is set to exclude possible influences of different types of land use, as the typical type of land use in the eastern plain of mainland China is the irrigated cropland and pasture and a crop-land/grassland mosaic. Therefore, we retain the uniform roughness length of 0.07 m in our designed landfall experiments (FLT, TOP, FLTB, and TOPB), as prescribed for these types of land use in Chen and Dudhia (2001), which is about one order smaller than the length (0.5 m) used in Wong and Chan (2006), but is reasonable for the type of land use in the eastern plain of mainland China. As described in Table 1, the three experiments in the first set are conducted with different lower boundary conditions. While the first experiment is run without land [the ocean experiment (OCN)], the other two runs include the flat terrain experiment (FLT) and the elevated topography experiment (TOP). FLT is designed to examine the land drift induced by land surface roughness, and TOP investigates the effect of continental topography on the landfalling TC motion. In the second set, the experiments are the same as the corresponding experiments in the first set, but they are initiated only with the background environment (without inserting the TC vortex) to demonstrate the influences of land and terrain on the environmental flows (OCNB, FLTB, and TOPB, respectively). The background experiments designed in the second set are used to examine the evolution of the environmental flows.

### Table 1. Summary of the numerical experiments.

<table>
<thead>
<tr>
<th>Expt</th>
<th>Terrain</th>
<th>Land use</th>
<th>Roughness length (m)</th>
<th>TC vortex inserting</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCN</td>
<td>No</td>
<td>Water</td>
<td>Smooth</td>
<td>Yes</td>
</tr>
<tr>
<td>OCNB</td>
<td>No</td>
<td>Water</td>
<td>Smooth</td>
<td>No</td>
</tr>
<tr>
<td>FLT</td>
<td>Flat terrain</td>
<td>Irrigated cropland and pasture</td>
<td>0.07</td>
<td>Yes</td>
</tr>
<tr>
<td>FLTB</td>
<td>Flat terrain</td>
<td>Irrigated cropland and pasture</td>
<td>0.07</td>
<td>No</td>
</tr>
<tr>
<td>TOP</td>
<td>Topography</td>
<td>Irrigated cropland and pasture</td>
<td>0.07</td>
<td>Yes</td>
</tr>
<tr>
<td>TOPB</td>
<td>Topography</td>
<td>Irrigated cropland and pasture</td>
<td>0.07</td>
<td>No</td>
</tr>
</tbody>
</table>

3. Tracks and intensity of the simulated TCs

The simulated TC tracks with at least tropical storm intensity are shown in Fig. 2a. The TC centers in this study are determined at 1-h intervals. A variational approach is used to locate the TC center until the maximum azimuthal mean tangential wind speed is
found (Wu et al. 2006). The TC centers at 700 hPa are used to avoid the influence of topography on low-level circulation in this figure. The simulated TCs generally move in a similar direction (Fig. 2a). The storms make landfall at 39 and 24 h in the FLT and TOP runs, respectively. The storm in OCN reaches the coastline in FLT and TOP at 41 h. Figure 2a indicates that the TCs in TOP move much faster than those in OCN and FLT, suggesting the topographic influence on the landfalling TC motion over China’s mainland.

In OCN, the vortex intensifies during the first 12 h and then remains around 40 m s\(^{-1}\) (Fig. 2b). The storms in FLT and TOP start to weaken about 3 h before their landfall. When the TCs in FLT and TOP make landfall, the maximum wind speeds are 31.0 and 31.3 m s\(^{-1}\), respectively, and then drop to 21.9 and 19.5 m s\(^{-1}\) about 6 h after landfall. The TCs in FLT and TOP weaken rapidly after landfall and the maximum wind speeds fall below tropical storm intensity at 13 and 10 h after landfall, respectively.

4. The difference in environmental steering

To estimate the influence of environmental steering, the TC motion speed in this study is averaged between 850 and 300 hPa in all experiments. We focus mainly on the period from 24 h before to 12 h after making landfall in the experiments. During the 36-h period, the TC in OCN moves at a mean speed of 2.67 m s\(^{-1}\) while the mean speeds are 3.13 and 4.62 m s\(^{-1}\) in FLT and TOP, respectively (Fig. 3a). The TC accelerates at about 10 h before landfall in FLT and then moves faster than that in OCN. It seems that the presence of land and the topography really leads to a landward component, compared to OCN. In TOP, the landward component (1.95 m s\(^{-1}\)) accounts for an increase of 73% in the TC motion speed.

Previous studies have suggested that environmental steering is dominant in TC motion (e.g., Chan and Gray 1982; Wang and Holland 1996; Wu and Wang 2000). Our further analysis indicates that the difference in the translation speed results mainly from the different influences of steering in the three TC experiments. The steering is calculated within a radius of 400 km from the TC center and is then vertically averaged (Fig. 3b). We examined the different average sizes for calculating the steering and found that the 400-km radius can minimize the root-mean-square error (RMSE) between the TC translation speeds and environmental steering. The mean steerings in OCN, FLT, and TOP are 2.51, 2.71, and 4.23 m s\(^{-1}\), respectively. The RMSEs between the TC translation speed and the environmental steerings are 0.27, 0.56, and 0.67 m s\(^{-1}\) in OCN, FLT, and TOP, respectively. Although the deviation of the TC motion from the steering increases with the complication of the lower boundary, we can see that the steering can generally account for the differences in the TC translation speed during the 36-h period.

To examine the influence of the land surface roughness on TC motion, we also calculated the environmental steering in the corresponding background experiments without TCs embedded (Fig. 3c). The TC center positions are used from the three TC experiments. The average background steering in OCNB is 1.41 m s\(^{-1}\) during the 36-h period. In the background experiments with flat land (FLTB) and terrain (TOPB), the mean steerings are 1.63 and 3.40 m s\(^{-1}\) during the same period. After removing the background steering (Fig. 3d), the translation speeds are 1.26, 1.50, and 1.11 m s\(^{-1}\) in OCN, FLT, and TOP, respectively. Based on Wong and Chan (2006), the land
drift is the difference in the remaining translation speeds between OCN and FLT. It is only 0.24 m s\(^{-1}\), which is smaller than those in the previous land drift experiments. Moreover, the remaining speed in TOP is slower than that in OCN. Two possible reasons are responsible for the results. One is that the roughness length in our experiments is much smaller than that in the previous land drift experiments. The other is that this component includes the beta drift and the asymmetric flows resulted from the interaction between the TC and environmental flows. Based on our above analysis, we conclude that the different translation speeds in OCN, FLT, and TOP are mainly due to the differences in the environmental steering (Fig. 3c).

5. The topographic effect

What causes the enhanced landward steering in the presence of the topography? Figure 4 shows the simulated 850-hPa wind fields in the three background experiments during the first 12 h of integration. We can see that the evolution of the 850-hPa wind is very similar in OCNB and FLTB, suggesting that the flat terrain has little influence on the environmental flows. The westerly monsoon flows that are dominant south of 20\(^\circ\)N come from the Indochina peninsula and meet the trade winds over the western North Pacific. In the midlatitudes (30\(^\circ\)–40\(^\circ\)N), a branch of westerly flow comes into the domain from the western lateral boundary in OCNB and FLTB. The midlatitude westerly flows form two branches over China’s mainland: one moving eastward and the other turning southward. On the other hand, the midlatitude westerly flows are absent in TOPB because of the blocking of the topography in the northwest of the domain. The westerly monsoon flows from the Indochina peninsula turn northward over the South China Sea and extend northward over China’s mainland. Figure 4 clearly indicates that the blocking of the elevated terrain leads to a very different flow pattern over China’s mainland, which enhances the landward motion of the TC in TOP.

As shown in Fig. 1, the model domain actually covers part of the Tibetan Plateau. In summer the Tibetan Plateau receives strong solar radiation at the surface, while the rest of Asia is in the relatively cold midtroposphere. It has been demonstrated that the Tibetan Plateau acts as an elevated heat source with strong sensible heating (Yeh et al. 1957; Flohn 1957; Wu et al. 2007). In TOP, the thermal effect of the elevated terrain is represented by the high land surface temperature, which is initially set to be the same as in the eastern plain. In other words, the land surface temperature in the mountainous western areas is initially the same as that in the eastern plain. In TOP and TOPB, the thermal effect can lead to intensification of southerly winds in the eastern plain. The mechanism is similar to the thermal effect of the Tibetan Plateau on the enhancement of the summertime East Asian monsoon (Chou 2003; Wu et al. 2007; Wu et al. 2012). We think this mechanism may also work in TOP and TOPB.

Figure 5 shows the wind difference between TOPB and OCNB during the 24-h period of TC landfall. The
FIG. 4. The 850-hPa winds (m s\(^{-1}\)) at (left) 6 and (right) 12 h in (a) OCNB, (b) FLTB, and (c) TOPB.
enhanced southerly winds at 850 and 500 hPa in TOPB are very clear in the eastern plain, extending from the South China Sea to a latitude of about 40°N. The enhanced southerly winds make the TC move northward faster in TOP. We also examine the wind difference between TOPB and FLTB, and the wind difference pattern is very similar to that shown in Fig. 5. Note that the southerly winds can be well developed in TOPB during the first several hours of integration (Fig. 4).

6. Conclusions and discussion

The continent, which is much larger in size than islands, can affect the landfalling TC motion. While it has been revealed that land surface roughness and temperature tend to make a TC move toward the continent (Wong and Chan 2006, 2007; Au-Yeung and Chan 2010; Szeto and Chan 2010; Li et al. 2014; Xu et al. 2013), the topographic effects of the elevated terrain on the western part of mainland China on the motion of landfalling TCs is examined in this study through idealized numerical experiments, in which an initially axisymmetric vortex is embedded into a monsoon trough and takes a landfall track toward China’s mainland. It is found that the effects of the elevated terrain on the western part of mainland China can enhance the southerly environmental flows, leading to a landward component of TC motion. We suggest that the effect of the elevated terrain in our experiments is similar to that of the Tibetan Plateau on the enhancement of the summertime East Asian monsoon (Chou 2003; Wu et al. 2007; Wu et al. 2012). Both the mechanic and thermal effects play a role in enhancing the southerly flow over mainland China.

The numerical results from this study may have implications for interpreting the observed TC track changes on an interdecadal time scale (Wu et al. 2005; Chen et al. 2011). Chen et al. (2011) found that the annual average duration of TCs over China’s mainland increased significantly during the period 1975–2009. The increasing overland duration resulted from both the decreasing translation speed on the interdecadal scale and the decreasing vertical wind shear. Duan and Wu (2008) demonstrated that the sensible heat (SH) flux over the Tibetan Plateau has exhibited a significant decreasing trend since the mid-1980s, mainly because of decreases in the surface wind speed. The weakening trend in the thermal forcing of the Tibetan Plateau is associated with global warming (Duan and Wu 2008; Liu et al. 2012). Our numerical experiments suggest that the reduced thermal forcing can decrease the northward motion of TCs over mainland China by reducing southerly winds in the eastern plain.

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