Influence of Mesoscale Topography on Tropical Cyclone Tracks: 
Further Examination of the Channeling Effect

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Abstract

Observations have documented typhoons experiencing pronounced track deflection before making landfall in Taiwan. In this study, idealized full-physics model experiments are conducted to assess the orographic influence on tropical cyclone (TC) track. An intense and westward-moving TC is simulated to approach a bell-shaped terrain imitating the Taiwan topography. Sensitivity numerical experiments are carried out to evaluate the topographic effect under different flow regimes and parameters, such as TC intensity, terrain height, and incident angle of the TC movement toward the topography. All the presented simulated storms experience southward track deflection prior to landfall. Different from the mechanism related to the channeling-effect-induced low-level northerly jet as suggested in previous studies, this study indicates the leading role of the northerly asymmetric flow in the mid-troposphere in causing the southward deflection of the simulated TC tracks. The mid-tropospheric northerly asymmetric flow forms due to the wind speeds restrained east to the storm center and winds enhanced/maintained west to the storm center. In all, the study highlights a new mechanism that contributes to the terrain-induced southward TC deflection in addition to the traditional channeling effect.
The landfall of tropical cyclones (TCs) is often accompanied by heavy rain, strong winds and destructive floods, which makes accurate prediction of TC intensity, structure and track an urgent and important issue. Taiwan, under frequent TC threats, is a mountainous island where the summit of the Central Mountain Range (CMR) exceeds 3000 m and complicated topography covers a horizontal scale of 150 km in width and 400 km in length. The highly complicated orographic influence on typhoon tracks, circulation, and the precipitating systems in Taiwan has always been an active research topic (Wu and Kuo 1999; Wu 2013).

Both observational and numerical studies have shown that a TC would occasionally experience significant track deflection when passing over a mesoscale mountain range. Observational studies (Brand and Blelloch 1974; Wang 1980; Yeh and Elsberry 1993; Hsu et al. 2013) have assessed the statistical behavior of TC movement near Taiwan and the concurrent changes in the TC intensity and structure. For instance, Yeh and Elsberry (1993), examining 103 westward-moving typhoons near Taiwan between 1947 and 1990, found that weaker and slower TCs tend to experience greater track deflection probably due to larger influence and longer impact time of the Taiwan terrain. However, analyses in the observational studies were less informative.
regarding the relative importance of synoptic scale systems and the terrain in the
identified TC track deflection.

Numerical simulation studies on the terrain-induced TC track deflection, a useful
approach if with proper design, can be classified into studies of real cases (e.g., Wu
2001; Jian and Wu 2008; Huang et al. 2011) and idealized experiments (Chang 1982;
Bender et al. 1987; Yeh and Elsberry 1993; Lin et al. 1999; Wu and Kuo 1999; Kuo et al.
and Chan 2013). Numerical simulations with idealized settings, deployed in many
previous studies, have provided insights into the terrain-induced changes in TC
movement under different flow and parameter regimes. An idealized numerical
simulation with 60-km horizontal resolution and 7 vertical layers was carried out to
understand the terrain-induced track deflection of a westward-moving TC in Chang
(1982). It was suggested that a TC would make a northward turn in its path following
the additional cyclonic circulation which is induced by the cumulus heating near the
terrain. Adopting the model resolution to 45 km, Yeh and Elsberry (1993) also
conducted an idealized simulation to examine the effects of topography on TCs with
different initial positions, background flow speed and storm intensity. The numerical
results were consistent with their observational analysis.
A dry and frictionless model and a family of non-dimensional parameters were utilized to identify the flow regimes under which the terrain-induced discontinuity or deflection of TC tracks occurs (Lin et al. 2005). It was found that TC tracks tend to be discontinuous and more deflected with small values of Froude numbers ($Fr; U/Nh$ for basic flow, $V_{max}/Nh$ for the vortex), Rossby number ($Ro; U/fL_x$ for basic flow, $V_{max}/fR$ for the vortex) and ratio of the vortex scale to the mountain range in a direction perpendicular to basic flow ($R/L_y$), and/or a large value of steepness of the prescribed mountain ($h/L_x)^1$. This parameter regime was suggested being useful in measuring the orographic blocking, which was presented as a major explanation for track deflection in Lin et al. 2005 (their Fig. 12) and Lin 2007 (their Fig. 5.36). The southward track deflection occurs when aforementioned parameters corresponds to conditions in which a vortex experiences topographic influence, and when $R/L_y$ is particularly small. Such southward track deflection was explained by a pronounced orographic blocking effect on basic flow, a stretching/shrinking air column in the windward/leeward side of the terrain (Fig. 5.36a of Lin 2007), and vorticity advection due to the channeling effect in

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$^1U$ stands for the basic flow speed, $N$ for the Brunt–Väisälä frequency, $h$ for the mountain height, $f$ for the Coriolis parameter, $L_x$ for the topography width, $V_{max}$ for the maximum tangential wind, $R$ for the radius of the maximum wind, and $L_y$ for the topography length.
Using a sophisticated full-physics model, Jian and Wu (2008) investigated the looping motion of Supertyphoon Haitang (2005) prior to its landfall in Taiwan. It was demonstrated that Haitang’s southward deflection could be attributed to the channeling effect, which is characterized by low-level wind acceleration over the confined region between the storm center and the terrain where air parcels of the swirling wind are forced to converge. These accelerated low-level winds between the storm center and the terrain thus contribute to the formation of the northerly steering flow near the inner core of the TC and push the TC southward. The investigation on the southward track deflection of Typhoon Krosa (2007) in Huang et al. (2011) showed results generally consistent with findings of Jian and Wu (2008). Huang et al. (2011) conducted a series of idealized simulations with sophisticated physical processes at 3-km horizontal resolution to identify the key mechanisms leading to the terrain-induced track deflection for vortices approaching different locations of the topography. Results demonstrated the important role of the channeling effect in advecting an intense typhoon to the south, generally in good agreement with findings of Jian and Wu (2008).

The southward track deflection that some intense typhoons experienced when getting close to the Taiwan topography has been noted and investigated in a number of
recent studies (e.g., Jian and Wu 2008; Huang et al. 2011; Hsu et al. 2013). It has been shown that although a TC would deflect to the north under the influence of topography during the earlier period, it would start to deflect to the south just before landfall. It is noteworthy that the southward TC track deflection documented in observations or captured in the numerical simulations is mostly for more intense TCs, suggesting that tracks of intense TCs could also be profoundly affected by the presence of mesoscale topography, such as the terrain of Taiwan.

As a follow-up study of Huang et al. (2011), this work attempts to further assess the orographic influence on TC track deflection, in particular to re-examine robustness of the channeling effect. A full-physics model with fine grid spacing is utilized to understand the role of topography in TC track deflection. While Huang et al. (2011) only examined the sensitivity to the initial latitudinal position of the vortex, this study investigates sensitivities to more parameters and flow regimes, such as the terrain height, incident angle of TC movement toward the terrain, TC intensity and translation speed. A series of idealized simulations are conducted to investigate how the terrain impacts TC motion under different configurations of mountain range, height and shape, vortex intensity and structure, the incident angle of a moving vortex toward the mountain, initial latitudinal position of the vortex center, and storm translation speed. Model
description and experiment design are described in section 2. In sections 3 and 4, the
result of the control experiment and sensitivity experiments are presented respectively.
The impact of the channeling effect is discussed and a new mechanism responsible for
the terrain-induced TC track deflection is presented. The role of the channeling effect
is discussed in section 5. Key findings are summarized in section 6.

2. **Model description and experimental design**

The fifth-generation Penn State University-National Center for Atmospheric
Research (NCAR) Mesoscale Model (MM5, version 3.7.3; Anthes and Warner 1978;
Anthes et al. 1987; Grell et al. 1994) is employed to conduct a set of numerical
simulations with sophisticated physical processes and non-hydrostatic dynamics. The
numerical settings are the same as those in Huang et al. (2011), except for the design of
grids points and vertical layers. The horizontal grid spacing of the three nest domains
is 27, 9, and 3 km respectively, with 337×427, 223×259, and 241×460 grid points, and
the corresponding resolution of the terrain and land-use data is 19, 9, and 4 km. The
large outermost domain is used to minimize the effects of fluctuations and disturbances
at the lateral boundary on the simulated vortex. Twenty-three vertical layers are
applied to the numerical simulations from the surface to 10 hPa in the terrain-following
σ coordinate ($\sigma = 0.995, 0.985, 0.97, 0.945, 0.91, 0.875, 0.825, 0.775, 0.725, 0.675,$
$0.625, 0.575, 0.525, 0.475, 0.425, 0.375, 0.325, 0.275, 0.225, 0.175, 0.125, 0.075,$
$0.025$). To exclude the impact of the beta-effect on the typhoon track, all of the
numerical experiments are simulated on f-plane located at 15 degrees north latitude.
The simple ice scheme of Dudhia (1989) is utilized in the two inner meshes, with the
Grell cumulus parameterization (Grell et al. 1994) employed in the outer most mesh.
The simple long-wave radiation cooling scheme and the high-resolution Blackadar
planetary boundary layer (PBL) scheme (Blackadar 1976, 1979; Zhang and Anthes
1982) are applied to all meshes. Based on the above numerical setting, each
simulation is run for 168 h to assess how a typhoon-like vortex responses when
impeded by a mesoscale high topography under different flow regimes and topographic
properties. First, the control and ocean control experiments are conducted with
moderate background flow. The idealized Taiwan-like topography is placed in the
control experiment, while terrain is excluded and the ocean surface property is used for
the ocean control experiment. Second, a set of sensitivity experiments with different
flow and/or topographic parameters are performed.

(a) Control experiment

Uniform easterly flow at 5 m s$^{-1}$ is used as the basic flow in the control (CTL) and
ocean control (OC-CTL) experiments. An idealized vortex structure (DeMaria and Chan 1984) is adopted for the initial vortex structure, prescribed as

$$V' = V_{\text{max}} \left( \frac{r}{r_{\text{max}}} \right)^{1} e^{b[1-(r/r_{\text{max}})^{b}]} , \quad (1)$$

where \(V_{\text{max}}\) is the maximum tangential wind speed, \(r_{\text{max}}\) is the radius of maximum wind (RMW), and \(b\) is a factor that determines the exponential decay rate of the tangential wind beyond \(r_{\text{max}}\). \(V_{\text{max}} = 35 \text{ m s}^{-1}\), \(r_{\text{max}} = 50 \text{ km}\), and \(b = 0.5\) are specified (same as in the idealized setting of Huang et al. 2011) to construct a vortex representing an intense tropical cyclone with a pertinent structure. The mass field and wind field are balanced following the nonlinear balance equation (Charney 1955). The mean West Indies sounding data from July to October presented in Jordan (1958, their Table 5) are utilized as the reference state for the initial fields, including pressure, height, temperature and relative humidity.

The idealized bell-shaped topography described in Lin et al. (1999) is used in this study:

$$h(x,y) = \frac{h_{\text{max}}}{\left[ \left( \frac{x}{a} \right)^{2} + \left( \frac{y}{b} \right)^{2} + 1 \right]^{3/2}} , \quad (2)$$

where \(h\) is the mountain height, \(h_{\text{max}}\) is the peak value of the mountain height, and \(a\) and \(b\) indicate the half width and half length of the mountain, respectively. To make the
edge of the topography zero, as well as to set the terrain center to (longitude, latitude) =

\[(x_c, y_c)\], we rewrite equation (2) as

\[
h(x, y) = \frac{h_{\text{max}}'}{\left[\left(\frac{x - x_c}{a}\right)^2 + \left(\frac{y - y_c}{b}\right)^2 + 1\right]^{3/2}} - h', \tag{3}
\]

where \(h' = \frac{h_{\text{max}}'}{2^{3/2}}\). \(h_{\text{max}}'\) is determined by the maximum terrain height, defined as

\[
h_{\text{max}}' = h_{\text{max}} \left(1 + \frac{1}{2^{3/2}}\right).
\]

A family of parameters \((h_{\text{max}} = 3 \text{ km}, a = 75 \text{ km}, b = 200 \text{ km}, x_c = 24.0^\circ \text{ N}, y_c = 121.1^\circ \text{ E})\) are used to construct an idealized terrain that mimics the properties of the Taiwan topography. Mixed forest is used to represent the land properties of the mountain topography.

By comparing results between CTL (with the aforementioned bell-shaped terrain) and OC-CTL (solely with the ocean surface), this study examines how a westward-moving vortex responds when approaching the topography. To obtain an initial condition with adjusted model physics, a number of pre-runs are carried out. First, a simulation is run to spin up the vortex in a quiescent background environment. After 7-day integration, the vortex in this pre-run reaches a quasi-steady state, with its maximum wind speed at 0.7 km height and around 70 m s\(^{-1}\), the radius of maximum wind around 60 km, the minimum central sea level pressure at 933 hPa, and the gale-force wind radius around 300 km. Second, two types of pre-runs are performed
for the basic flow (vortex excluded), one embedded with topography and the other with solely the ocean surface. The average flow speed of basic flows in the pre-runs, either with or without topography, has a steady and moderate magnitude of 3 to 4 m s$^{-1}$. In the pre-run with basic flow and topography, the basic flow is deflected and split by the terrain. In addition, a clear lee-side vortex is present in this simulation (not shown), in general consistent with the results of previous studies. (e.g., Smith and Smith 1995; Smolarkiewicz and Rotunno 1989)

After the above pre-runs are conducted, the spun-up vortex is embedded in the background flow to construct the idealized simulations. The vortex is placed 800 km east of the terrain. The geographic center of the topography is implanted at 24° N, collocated with the latitudinal position of the vortex center in OC-CTL after the initial adjustment.

(b) Sensitivity experiments

A set of experiments are carried out to investigate the sensitivity of TC motion to the height, shape, and range of terrain, the intensity, structure, and latitudinal position of the initial vortex, vortex translation speed, and the angle at which the vortex approaches the topography. Details of the idealized experimental design are provided in Table 1.
To demonstrate the sensitivity of TC track to mountain height, experiments with $h_{\text{max}} = 5$ km and $h_{\text{max}} = 1$ km are carried out (H50 and H10 in Table 1). Simulations with the narrower and wider topography are performed with $2a = 75$ km and $2a = 300$ km respectively in Eq. 3, referred as to A75 and A300 (Table 1). Sensitivity simulations with respect to the topography length ($2b = 200$ and 600 km for B200 and B600, respectively) are also conducted. Vortex intensity and structure are also altered by using different $V_{\text{max}}$ and $r_{\text{max}}$ in Eq. (1) for the vortex pre-runs. A weaker storm is used to assess the sensitivity to a small deviation in the maximum wind for an intense TC (T27 in Table 1). The response of a TC with a smaller or larger RMW to the topography is examined as well (SML and LGE in Table 1). By rotating the terrain and changing the mountain’s center position, experiments with varying TC incident angle (I+15 and I-15 in Table 1) and initial position are conducted (H2N and H2S in Table 1). Different magnitudes of initial easterly background flow are also adopted in the sensitivity experiments to understand how the TC responds to the topography when traveling at different translation speeds (SLW, MED and FST in Table 1). The position of the topography center is implanted at different latitude, collocated with the latitudinal position of the vortex center in each corresponding ocean experiment after the initial adjustment.
3. The control experiment

Figure 1 shows the track of the control (CTL) and ocean-control (OC-CTL) experiments. During the initial 24 h of the simulation, the storms in both CTL and OC-CTL follow similar west-northwestward tracks, demonstrating that the terrain has little impact on the track of CTL in which the vortex center is more than 600 km upstream of the topography. After 24 h, OC-CTL persistently travels westwards, primarily steered by the background easterly flow, until the end of the integration. Meanwhile, the difference of the vortex movement between OC-CTL and CTL appears and becomes distinct after 40 h. From 40 h to 60 h, a period when the vortex center is about 200 to 600 km upstream of the topography (denoted as Region A in Fig. 1), CTL is deflected to the north under the influence of the topography. During the later hours, sometime between 62 h and 71 h, a period just before and also during the storm center’s passage through the mountain, the TC movement in CTL experiences a sudden change from west-northwestward to southwestward. The spatial interval where the southward deflection of CTL occurs is denoted as Region B (Fig. 1). The southward deflection of CTL is about 100 km, which is measured from the northernmost extent to the southernmost extent of the TC track in Region B. When the vortex center of CTL is about to leave the topography (t = 72 h), CTL storm makes a pronounced northward
The region in which CTL moves northward after 72 h is denoted as Region C. The corresponding mechanisms of track deflections in CTL in Regions A, B and C are investigated in this section.

The representativeness of using steering flow for the vortex motion (Chan and Gray 1982; Wu and Emanuel 1995a, b) is examined. The deep layer areal ($\sigma = 0.825$) mean asymmetric flow in an area of $1^\circ \times 1^\circ$ around the storm center is calculated as the steering flow for TC movement in this study. It is found that the direction indicated by the evaluated steering flow vector mostly aligns with the TC motion vector in both Regions A and B (cf. Figs. 1 and 2), despite some deviations in magnitude and direction found prior to landfall (with one exception of large discrepancy at 66h; Fig. 2b). In Region C, the storm is much weaker and less organized after passing over the mountain, and thus is farther away from being a rigid or stiff vortex. This may cause the vortex to deviate from the steering flow (Fig. 2). In Huang et al. (2011; their Fig. 13), it was shown that the northwestward movement of the storm can be explained by the steering flow concept regards the tropical cyclone as a rigid vortex (or simply a point vortex) advected by the mean environmental flow crossing the storm center. The calculation within a small area with high spatial resolution data can well represent the steering flow (Roux and Marks 1991; Wu and Emanuel 1995a, b).
channeling winds between the topography and the east side of the storm as well. Wind enhancement in the channel is also found in this study (figures not shown) as the storm is leaving the topography. The concurrently-induced northward component of the deep-layer-mean flow may thus serve as a possible explanation for the northwestward movement during this time period. However, uncertainties over locating a weaker and loose circulation may grow, causing higher uncertainties in obtaining storm motion vectors and steering flow in Region C. Therefore, this study intends to focus the discussion on changes in TC track prior to landfall, when the storm center can be well defined.

According to the alignment of TC motion vectors and the obtained asymmetric flow, one may infer that understanding the dynamical process causing the asymmetric flow is very likely to provide valuable insights into the mechanism(s) responsible for changes in the storm’s movement in Regions A and B. The northward (southward) deflection in Region A (Region B) corresponds to the northward (southward) deflection of the evaluated steering flow, consistent with results of Lin and Savage (2011) and Jian and Wu (2008). While the northward steering flow in Region A is found closely connected to the terrain-induced deflection of the basic easterly flow (i.e., the topographic effect on the large-scale flow, and thus on the TC movement), the identified
steering flow in Region B is different from the terrain-deflected basic flow (figures not shown). The northerly steering flow such as that obtained in Region B was shown to be related to the channeling effect (the terrain-induced effect on the vortex structure) in Jian and Wu (2008) and Huang et al. (2011). In these two previous studies, enhanced northerly low-level jet was found to the west of the storm center, and was attributed to the enhancement of the low-level cyclonic TC circulation in the narrow region between the storm center and the high topography. The role of the channeling effect on the southward deflection in Region B in CTL is thus investigated in this study.

As in the previous studies (e.g., Jian and Wu 2008; Huang et al. 2011), the backward trajectory analysis of air parcels is used to examine the occurrence of the channeling effect during the storm’s southward deflection. Unlike the parallel trajectories obtained in OC-CTL, the air parcels in CTL become slightly confluent when passing through the channel between the topography and the storm center (Fig. 3). Nevertheless, the identified small confluence does not produce a distinct northerly low-level jet (cf. Figs. 4 and 5) as pointed out in Jian and Wu (2008) and Huang et al. (2011). The absence of the low-level northerly jet west to the TC center demonstrates that channeling effect is not the mechanism causing the southward deflection of the storm in CTL. Instead, Fig. 4 shows changes in the mid-tropospheric winds (roughly
between 700 and 300 hPa). Before 60 h, the mid-tropospheric winds on eastern and western sides of the TC have similar strength. A transient vertically upward extension of the wind maximum in the eastern eyewall occurs at 61 and 62 h, and enhances mid-tropospheric winds east to the storm center. After 62 h, when the storm in CTL starts to make a southward turn, the enhancement or maintenance of winds on the western side of the storm, together with a continual decrease in wind speeds east to the TC center, generating asymmetry of mid-tropospheric winds. This asymmetry of mid-troposphere wind speeds around the storm center grows as the storm moves toward the terrain, in agreement with the increasing southward deflection of the TC track (cf. Figs. 1 and 4g-l). The elevations where the northerly asymmetric flow occurs are apparently different from those shown in Jian and Wu (2008) and Huang et al. (2011). The result of CTL suggests a different dynamical pathway of the terrain-induced southward TC track deflection.

The difference in the areal mean asymmetric flow vector between CTL and OC-CTL (Fig. 6) further demonstrates that the northerly steering flow at the middle level (σ = 0.7 to 0.3, around 2.7 to 7 km) between 65 and 70 h (corresponding to Region B in Figs. 1 and 2.) reflects the steering flow for the southward moving storm in CTL. It is the combined effect of the terrain-induced strengthening wind on the west side of
the TC, that either enhances or maintains the winds, and the terrain-induced reduction in
wind speeds on the east side of the TC in the mid-troposphere that contributes to the
northerly deep-layer-mean steering flow, and resulting in the southward deflection of
the TC in Region B. (cf. Figs 1, 2, 4, and 6).

4. Sensitivity experiments

Sensitivity experiments are performed with different parameters describing the
structure of the idealized vortex and topography. Simulations showing greater
variability are discussed in this section, including those with different mountain height
($h$), TC incident angle, initial position, intensity ($V_{max}$), and translation speed ($U$) (see
Tables 1 and 2).

(a) Influence of mountain height

In addition to CTL, which has the terrain maximum height at 3000 m, two
experiments with the maximum mountain heights of 5000 m (H50) and 1000 m (H10)
are conducted to understand the impact of mountain height on TC movement.
Compared with the magnitude of the track deflection in CTL, H50 shows similar
southward deflection to CTL, while in H10 the deflection is apparently reduced (Fig. 7).
Although CTL and H10 show that the terrain-induced track deflection is larger for an intense TC encountering a higher mountain, CTL and H50 demonstrate the convergence behavior of the southward deflection. These results are not inconsistent with the findings of Lin et al. (2005), which showed that the smaller $Fr$, the larger the TC deflection could be.

Changes in the vortex structure of H10 and H50 are also analyzed to examine the close connection between the TC’s southward track deflection and asymmetric winds as demonstrated by the result of CTL. Similar to CTL, during the storm’s southward turn in H10, enhanced winds at low levels (the product of the channeling effect) on the west side of the TC are absent (cf. Figs. 4 and 8), and the azimuthal asymmetry of tangential winds at middle levels is evident (Figs. 8f-j). This result further supports the mechanism proposed based on CTL. Since the difference in wind speeds between the west and east sides at the mid-level is smaller than that in CTL, the consequential deep-layer-mean northerly steering flows is smaller (Fig. 9), and thus the magnitude of the TC’s southward deflection is nearly absent in H10 (Fig. 7).

Same as in CTL and H10, the signal of low-level northerly jet induced by the channeling effect is unclear on the west side of the TC in H50. Only limited enhancement of wind speed in the channel is found between 59 h and 60 h (Figs. 10a, b)
and between 66 h and 67 h (Figs. 10h, i). During 60 h to 66 h, wind speeds on the west side of the TC remain unchanged when the storm is approaching the topography. The asymmetric flow further demonstrates that even though the channeling effect may contribute to the maintenance or slight increase in wind speeds, its impact is apparently insufficient to generate low-level northerly asymmetric flow to drift the TC southward (Fig. 11). In contrast, the asymmetric wind at the mid-troposphere (Fig. 11), which is used to explain the storm’s southward track deflection for CTL and H10, is also present in H50. Comparisons among the results of CTL, H10 and H50 indicate the robust role of the mid-tropospheric northerly asymmetric flow in the storm’s southward deflection. Results of CTL and H10 imply that the strength of such asymmetric flow is highly related to the terrain height— a higher terrain induces more pronounced asymmetric flow (cf. Figs 6 and 9), while steering flows in CTL and H50 (cf. Figs. 6 and 11) share much similarity.

(b) Sensitivity to TC incident angle and TC initial position

By horizontally rotating the idealized terrain, another group of sensitivity experiments are conducted to investigate the impact of the storm’s incident angles (Figs. 12a, b). Compared with CTL (also shown in Fig. 12c; 100 km southward if it is measured from the northernmost point to the southernmost point), both I+15 (rotating
the terrain clockwise by 15 degrees) and I-15 (rotating the terrain counterclockwise by 15 degrees) shows less significant southward deflection (60 km and 50 km southward deflection, respectively) prior to landfall. Before making this southward turn, however, the direction of the TC motion in I+15 does not undergo a distinct northward turn as found in other simulations (e.g., CTL, H10, H50, and I-15). The different tracks in these two experiments demonstrate that the TC sensitivity to incident angle would affect the TC track deflection, especially in Region A.

Furthermore, experiments H2N and H2S are performed to understand how the vortex responds when approaching different portions of the topography. The initial vortex in H2N (H2S) is embedded in the basic flow at 1 degree latitude north (south) to the CTL vortex. Compared with CTL (with 100 km southward in Region B), southward deflection of the TC track is slightly greater in H2N (at 110 km southward), but much less in H2S (roughly 30 km) (Fig. 12c). This finding demonstrates that as the storm moves toward the northern portion of the topography, it may undergo slightly more pronounced southward TC deflection, consistent with findings of Huang et al. (2011). Stronger wind speed at low levels (the product of the channeling effect) on the west side of the TC is identified in H2N during the early stage of the storm’s southward turn (61 h – 64 h; Figs. 13f-i). Figure 14 shows that corresponding southward
asymmetric flow starts to appear at low levels (below $\sigma = 0.85$) around 60 h and weakens after 64 h. The asymmetric flow is also present at higher levels after 63 h, suggesting the occurrence of low-level and mid-tropospheric northerly jets together contribute to drift the TC southward in H2N.

(c) Sensitivity to TC intensity and TC translation speed

Sensitivities to TC intensity and TC translation speed are examined in this section. In an experiment with a weaker vortex ($V_{\text{max}}$ is 8 m s$^{-1}$ weaker than CTL; see T27 in Tables 1 and 2 for details), the storm experiences similar southward deflection (100 km) near the topography (Fig. 15a) to that in CTL. This suggests that the terrain-induced southward deflection is not sensitive to such a deviation in $V_{\text{max}}$ of intense TCs embedded in the moderate basic flow. The impacts of topography on TC tracks at different TC translation speed are obtained by embedding the vortex in basic flow with different speed (Figs. 15b-d). The TC translation speed in SLW (slower basic flow; Fig. 15b), MED (medium basic flow; Fig. 15c) and FST (faster basic flow; Fig. 15d) are 2.5 m s$^{-1}$, 3.3 m s$^{-1}$ and 4.9 m s$^{-1}$, respectively. Among these three simulations, the slower a TC moves (i.e., a smaller $Fr$ of the basic flow), the more southward deflection it undergoes near the topography. This is consistent with results of Lin et al. (2005) and other previous studies, although this study mainly focuses on the flow regimes for
According to the results of CTL and a series of sensitivity experiments, the acceleration of low-level winds is not the universal feature for TCs experiencing southward track deflection near the topography. Our new findings suggest that the conventional channeling effect is not a robust flow characteristic, and thus cannot serve as the dominant dynamical pathway leading to the southward TC movement near topography. Low-level winds enhanced to the west of the storm are solely found in H2N (a vortex approaching the northern portion of topography) during the first few hours of the TC’s southward turn, suggesting a supporting impact of channeling effect on the TC’s southward movement. The backward trajectory analysis shows that air parcels in H2N are obviously affected by the terrain and become confluent when passing the channel between the storm center and topography, while those in CTL start to converge at the northwest side of the storm (Fig. 16). It is speculated that the broader space to the north of the storm may allow more air parcels to enter the channel between the storm center and topography, and thus may contribute to the stronger confluent flow and channeling winds at lower levels. In conclusion, the channeling
effect that results in the low-level northerly jet seems to occur for an intense TC
approaching the northern topography while being absent or unclear in the remainder of
the simulations. In addition, channeling-effect-induced low-level wind acceleration
plays a supporting role in leading to the southward turn of the storm in H2N.

6. Concluding remarks and issues to be further addressed

While the northward track deflection has been documented in some earlier studies
(brand and Blelloch 1974; Wang 1980; Chang 1982; Bender et al. 1987; Yeh and
Elsberry 1993; Wu 2001) for TCs approaching Taiwan topography from the east, a
number of recent studies (Jian and Wu 2008; Huang et al. 2011) have pointed out that an
intense typhoon may occasionally make a sudden southward turn just prior to and
during the landfall. As a follow-up study of Huang et al. (2011), this work investigates
more flow and parameter regimes to further understand the impact of mesoscale
topography on TC movement and the role of channeling effect in the sudden southward
turn of a TC vortex. An important finding of this work is that the robust flow
characteristic identified during the southward turn of a TC is the azimuthal asymmetry
of tangential winds at middle levels, not the asymmetry caused by channeling winds at
lower levels. To examine whether the vertical resolution would affect the result, we
carry out an additional experiment with 32 vertical levels, the same as in Huang et al. (2011). The result of this experiment well agrees with the findings presented in this study, supporting the finding of a different mechanism for the terrain-induced southward track deflection as compared to Huang et al. (2011). The mid-level winds that weaken to the east and strengthen/remain unchanged to the west of the TC center in the vortex’s inner core are considered responsible for enhancing the northerly steering flow that advects the TC southward near the topography. Moreover, the azimuthal changes in the winds speeds appear to be connected to the changes in the vertical velocity, suggesting the importance in further examining the relationship between the terrain-induced changes in both primary and secondary circulations. The momentum budget analysis is yet to be carried out to fully understand the dynamical processes leading to the weakening (enhancement/maintenance) of winds east (west) to the TC center during the storm’s southward deflection. Meanwhile, the asymmetry of water vapor mixing ratio and potential stability is examined. A region of a drier and relatively stable air column is found east to the storm center at low and middle levels (figures not shown). This implies that terrain-induced azimuthal changes in the thermodynamic structure of a TC (e.g., changes in diabatic heating and the atmospheric static stability) and its connection to the asymmetry of mid-level tangential winds need to be further explored, as the thermodynamic structure is closely related to the changes
of the overturning circulation and thus to the TC’s primary circulation.

In the sensitivity experiments, examinations are conducted with respect to different parameters describing the idealized vortex and mountain, including the mountain height, width, and length, as well as the TC incident angle, initial position, intensity, the radius of the maximum wind, and translation speed. The result demonstrates that the southward track deflection prior to landfall is a common phenomenon among intense TCs under various flow regimes. Findings further point out that intense TCs experience greater southward deflection prior to landfall when the mountain is higher, when the vortex approaches the northern and middle portion of the terrain, or when the storm moves slower. In addition to the results presented in section 4, limited variability is found among sensitivity experiments to the mountain width (narrower: A75; wider: A300) and length (shorter: B300; longer: B600), as well as the storm’s RMW (SML: smaller; LGE: larger) under the flow regimes of an intense TC and moderate basic flow (Fig. 17 and Tables. 1-3). The $R/L_y$ values adopted in this study are relatively small (from 0.09 to 0.15) and in the regime where vortices were anticipated to make a southward turn near topography in Lin et al. (2005). According to findings in Lin et al. (2005), one might expect that a TC with a realistic RMW [10 to 150 km (Willoughby and Rahn 2004; Kossin et al. 2007)], corresponding to the small
value of $R/L_y$, would experience southward track deflection when approaching a terrain
similar to that of Taiwan. Although the coherent southward deflection of TC motion in
this study (e.g., Figs. 17e, f) shows supporting evidence, it should be noted that other
factors may also need to be evaluated. First, microphysics and surface processes,
which are not included in the numerical experiments of Lin et al. (2005) but are
important in the evolution of a TC in the real world, are likely to impact interactions
amid the terrain, environmental flow, and TC, and thus can influence the terrain-induced
changes in TC structure and motion. Second, it is still unclear how a TC at moderate
or weak intensity responds to terrain in different flow regimes since only intense TCs
are investigated in the current study. These issues require further examination. In all,
the study highlights the robust asymmetric flow in the mid-troposphere as a new
mechanism other than the traditional channeling effect that contributes to the
terrain-induced southward TC deflection.

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101-2111-M-002-008-MY3.
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**Figure Captions:**

Fig. 1. Simulated TC tracks (green for CTL, and red for OC-CTL) are overlaid on the terrain height contours (black; at intervals of 500 m) employed in CTL. The TC center position is marked every hour, and highlighted by a larger closed circle every 6 hours. The ordinate and abscissa show the latitudinal and longitudinal distance from the terrain’s geographical center (Unit: km), respectively. Regions A, B, C are referred to as the regions where the storm in CTL is deflected toward the north in the upstream of the topography, toward the south prior to and after the landfall, and toward the north again after leaving the topography, respectively.

Fig. 2. (a) The red closed circles are the hourly positions of the TC center in CTL, superposed with the deep layer \((\sigma = 0.825 - 0.325)\) areal mean asymmetric flow (black lines) that is calculated within 100-km radius around the storm center. The black lines in (b) are same as those in (a), additionally overlaid with the TC motion vectors (green lines). It focuses on the time period when the storm makes a southward turn (indicated by the box in (a) as well). The blue circles in (b) indicate the magnitude of 3 m s\(^{-1}\).

Fig. 3. Backward trajectories retrieved by the RIP4 are overlaid on the simulated 850-hPa wind speed (shaded). Air parcels are released between the TC center and terrain at 800 hPa at 66 h, when the storm is in Region B, and calculated backward for 1 h.

Fig. 4. The vertical cross sections of the meridional wind (shading; m s\(^{-1}\)) and the vertical velocity (contour; m s\(^{-1}\)) in CTL. The values are averaged from 10 km to the south to 10 km to the north of the TC center (the southward deflection in CTL is from...
623 62 h to 71 h). The white area on the left is terrain, and the smaller white area on the right is TC center (no data at several lowest levels due to the TC’s lower surface pressure).

626 Fig. 5. Same as in Fig. 4, but for OC-CTL.

627 Fig. 6. Difference of the area-mean asymmetric flow (magnitude as shown in the bottom color bar) between CTL and OC-CTL. The difference is obtained by subtracting the results of OC-CTL from CTL. The area-mean value is calculated within the area of a 50-km radius around the TC center. The y-axis shows the σ coordinate, and the x-axis presents the integration time (Unit: h).

630 Fig. 7. Same as in Fig. 1, but for H50 (black) and H10 (blue).

632 Fig. 8. Same as in Fig. 4, but for H10 (the southward deflection in H10 is identified from 62 h to 71 h).

634 Fig. 9. Same as in Fig. 6, but for H10. The difference is obtained by subtracting the results of OC-CTL from H10.

636 Fig. 10. Same as in Fig. 4, but for H50 (the southward deflection in H50 is identified from 66 h to 71 h).

638 Fig. 11. Same as in Fig. 6, but for H50. The difference is obtained by subtracting the results of OC-CTL from H50.

640 Fig. 12. Same as in Fig. 1, but for (a) I+15 (blue), (b) I-15 (black) and (c) H2N (black),
and H2S (blue). Results of the corresponding ocean control experiments are in red.

Fig. 13. Same as in Fig. 4, but this is for H2N (the southward deflection in H2N is identified from 61 h to 74 h).

Fig. 14. Same as in Fig. 6, but for H2N. The difference is obtained by subtracting the results of H2N from H50.

Fig. 15. Similar to Fig. 1, but showing the TC track of (a) T27, (b) MED and (c) FST. Results of the corresponding ocean control experiments are in red. TC centers are marked by either a closed circle or a typhoon symbol every 3 hours.

Fig. 16. Same as in Fig. 3, but (a) CTL (66 h), and (b) H2N (66 h),

Fig. 17. Same as in Fig. 15, but for (a) A75, (b) A300, (c) B200, (d) B600, (e) SML, and LGE.

653

654
Table 1. A summary of the conducted MM5 idealized experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Terrain</th>
<th>Tropical Cyclone</th>
<th>Sensitivity to</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>Idealized bell-shape, 3000 m in height</td>
<td>Idealized TC</td>
<td>presence of topography</td>
</tr>
<tr>
<td>OC-CTL</td>
<td>Ocean, no terrain</td>
<td>Same as CTL</td>
<td></td>
</tr>
<tr>
<td>H10</td>
<td>Same as CTL, but has a height of 1000 m</td>
<td>Same as CTL</td>
<td>topography height</td>
</tr>
<tr>
<td>H50</td>
<td>Same as CTL, but has a height of 5000 m</td>
<td>Same as CTL</td>
<td></td>
</tr>
<tr>
<td>A75</td>
<td>Same as CTL, but has a 50 % width</td>
<td>Same as CTL</td>
<td>topography width (a in Eq. 3)</td>
</tr>
<tr>
<td>A300</td>
<td>Same as CTL, but has a doubled width</td>
<td>Same as CTL</td>
<td></td>
</tr>
<tr>
<td>B200</td>
<td>Same as CTL, but has a 50 % length</td>
<td>Same as CTL</td>
<td>topography length (b in Eq. 3)</td>
</tr>
<tr>
<td>B600</td>
<td>Same as CTL, but has a 150 % length</td>
<td>Same as CTL</td>
<td></td>
</tr>
<tr>
<td>I+15</td>
<td>Same as CTL, but is rotated 15 degree counterclockwise</td>
<td>Same as CTL</td>
<td>incident angle at which the vortex approaches topography</td>
</tr>
<tr>
<td>I-15</td>
<td>Same as CTL, but is rotated 345 degree counterclockwise</td>
<td>Same as CTL</td>
<td></td>
</tr>
<tr>
<td>H2N</td>
<td>Same as CTL, but is 1 latitude to the south</td>
<td>Same as CTL</td>
<td>initial latitudinal position of the vortex center</td>
</tr>
<tr>
<td>H2S</td>
<td>Same as CTL, but is 1 latitude to the north</td>
<td>Same as CTL</td>
<td></td>
</tr>
<tr>
<td>T27</td>
<td>Same as CTL</td>
<td>Weaker TC</td>
<td>TC intensity (still an intense TC)</td>
</tr>
<tr>
<td>T27-OC</td>
<td>Same as OC-CTL</td>
<td>Weaker TC</td>
<td></td>
</tr>
<tr>
<td>SML</td>
<td>Same as CTL</td>
<td>Smaller RMW TC</td>
<td>radius of maximum wind (RMW)</td>
</tr>
<tr>
<td>SML-OC</td>
<td>Same as OC-CTL</td>
<td>Smaller RMW TC</td>
<td></td>
</tr>
<tr>
<td>LGE</td>
<td>Same as CTL</td>
<td>Larger RMW TC</td>
<td></td>
</tr>
<tr>
<td>LGE-OC</td>
<td>Same as OC-CTL</td>
<td>Larger RMW TC</td>
<td></td>
</tr>
<tr>
<td>SLW</td>
<td>Same as CTL</td>
<td>Slow moving TC</td>
<td>vortex translation speed</td>
</tr>
<tr>
<td>SLW-OC</td>
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<td>Slow moving TC</td>
<td></td>
</tr>
<tr>
<td>MED</td>
<td>Same as CTL</td>
<td>Medium moving TC</td>
<td></td>
</tr>
<tr>
<td>MED-OC</td>
<td>Same as OC-CTL</td>
<td>Medium moving TC</td>
<td></td>
</tr>
<tr>
<td>FST</td>
<td>Same as CTL</td>
<td>Fast moving TC</td>
<td></td>
</tr>
<tr>
<td>FST-OC</td>
<td>Same as OC-CTL</td>
<td>Fast moving TC</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Flow and terrain parameters in each experiment.

\[ f = 3.76 \times 10^{-5} \text{ (s}^{-1}) \text{, } N = 0.01 \text{ (s}^{-1}) \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( V_{\text{max}} ) (m s(^{-1}))(^3 )</th>
<th>( U ) (m s(^{-1}))</th>
<th>( R ) (km)</th>
<th>( h ) (m)</th>
<th>( L_x ) (km)</th>
<th>( L_y ) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>H10</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>1000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>H50</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>5000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>A75</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>75</td>
<td>400</td>
</tr>
<tr>
<td>A300</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>B200</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>B600</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>600</td>
</tr>
<tr>
<td>I+15</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>I-15</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>H2N</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>H2S</td>
<td>78</td>
<td>3.6</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>T27</td>
<td>70</td>
<td>3.6</td>
<td>32</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>SML</td>
<td>78</td>
<td>3.6</td>
<td>20</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>LGE</td>
<td>78</td>
<td>3.6</td>
<td>50</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>SLW</td>
<td>78</td>
<td>2.5</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>MED</td>
<td>78</td>
<td>3.3</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>FST</td>
<td>78</td>
<td>4.8</td>
<td>36</td>
<td>3000</td>
<td>150</td>
<td>400</td>
</tr>
</tbody>
</table>

\(^3\) The \( V_{\text{max}} \) denotes the maximum wind, which could be located at slightly different altitudes in different experiments.
Table 3. The non-dimensional parameters in each experiment.

\[ f = 3.76 \times 10^{-5} \text{ (s}^{-1}) , \ N = 0.01 \text{ (s}^{-1}) \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \frac{V_{\text{max}}}{N_h} )</th>
<th>( \frac{U}{N_h} )</th>
<th>( \frac{R}{L_x} )</th>
<th>( \frac{U}{fL_x} )</th>
<th>( \frac{V_{\text{max}}}{fR} )</th>
<th>( \frac{h}{L_x} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>2.6</td>
<td>0.12</td>
<td>0.09</td>
<td>0.62</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>H10</td>
<td>7.8</td>
<td>0.35</td>
<td>0.09</td>
<td>0.62</td>
<td>59.3</td>
<td>0.0067</td>
</tr>
<tr>
<td>H50</td>
<td>1.56</td>
<td>0.07</td>
<td>0.09</td>
<td>0.62</td>
<td>59.3</td>
<td>0.033</td>
</tr>
<tr>
<td>A75</td>
<td>2.6</td>
<td>0.12</td>
<td>0.09</td>
<td>1.24</td>
<td>59.3</td>
<td>0.04</td>
</tr>
<tr>
<td>A300</td>
<td>2.6</td>
<td>0.12</td>
<td>0.09</td>
<td>0.31</td>
<td>59.3</td>
<td>0.01</td>
</tr>
<tr>
<td>B200</td>
<td>2.6</td>
<td>0.12</td>
<td>0.15</td>
<td>0.62</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>B600</td>
<td>2.6</td>
<td>0.12</td>
<td>0.05</td>
<td>0.62</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>I+15</td>
<td>2.6</td>
<td>0.12</td>
<td>0.09</td>
<td>0.62</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>I-15</td>
<td>2.6</td>
<td>0.12</td>
<td>0.09</td>
<td>0.62</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>H2N</td>
<td>2.6</td>
<td>0.12</td>
<td>0.09</td>
<td>0.62</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>H2S</td>
<td>2.6</td>
<td>0.12</td>
<td>0.09</td>
<td>0.62</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>T27</td>
<td>2.33</td>
<td>0.12</td>
<td>0.08</td>
<td>0.62</td>
<td>58.1</td>
<td>0.02</td>
</tr>
<tr>
<td>SML</td>
<td>2.26</td>
<td>0.12</td>
<td>0.05</td>
<td>0.62</td>
<td>90.4</td>
<td>0.02</td>
</tr>
<tr>
<td>LGE</td>
<td>2.26</td>
<td>0.12</td>
<td>0.125</td>
<td>0.62</td>
<td>36.1</td>
<td>0.02</td>
</tr>
<tr>
<td>SLW</td>
<td>2.6</td>
<td>0.083</td>
<td>0.09</td>
<td>0.44</td>
<td>59.3</td>
<td>0.02</td>
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<tr>
<td>MED</td>
<td>2.6</td>
<td>0.11</td>
<td>0.09</td>
<td>0.59</td>
<td>59.3</td>
<td>0.02</td>
</tr>
<tr>
<td>FST</td>
<td>2.6</td>
<td>0.16</td>
<td>0.09</td>
<td>0.69</td>
<td>59.3</td>
<td>0.02</td>
</tr>
</tbody>
</table>
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Fig. 4. (Continued)
Fig. 5. Same as in Fig. 4, but for OC-CTL.
Fig. 5. (Continued).
Fig. 6. Difference of the area-mean asymmetric flow (magnitude as shown in the bottom color bar) between CTL and OC-CTL. The difference is obtained by subtracting the results of OC-CTL from CTL. The area-mean value is calculated within the area of a 50-km radius around the TC center. The y-axis shows the σ coordinate, and the x-axis presents the integration time (Unit: h).
Fig. 7. Same as in Fig. 1, but for H50 (black) and H10 (blue)..
Fig. 8. Same as in Fig. 4, but for H10 (the southward deflection in H10 is identified from 62 h to 71 h).
Fig. 8. (Continued).
Fig. 9. Same as in Fig. 6, but for H10. The difference is obtained by subtracting the results of OC-CTL from H10.
Fig. 10. Same as in Fig. 4, but for H50 (the southward deflection in H50 is identified from 66 h to 71 h).
Fig. 10. (Continued).
Fig. 11. Same as in Fig. 6, but for H50. The difference is obtained by subtracting the results of OC-CTL from H50.
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Fig. 13. Same as in Fig. 4, but this is for H2N (the southward deflection in H2N is identified from 61 h to 74 h).
Fig. 13. (Continued)
Fig. 14. Same as in Fig. 6, but for H2N. The difference is obtained by subtracting the results of H2N from H50.
Fig. 15. Similar to Fig. 1, but showing the TC track of (a) T27, (b) SLW, (c) MED and (d) FST. Results of the corresponding ocean control experiments are in red. TC centers are marked by either a closed circle or a typhoon symbol every 3 hours.
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Fig. 17. Same as in Fig. 15, but for (a) A75, (b) A300, (c) B200, (d) B600, (e) SML, and (f) LGE.