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ABSTRACT
The effects of topography on the evolution of Typhoon Saomai (2006) are investigated by conducting a series of numerical simulations with the Weather Research and Forecasting (WRF) Model using 100%, 75%, 50%, and 25% of terrain heights of the Central Mountain Range (CMR) in Taiwan. Differences in the track and intensity of Typhoon Saomai between the experiments are strongly related to those of Tropical Storm Bopha, which passed Taiwan earlier than the typhoon. In the sensitivity experiments, the higher CMR drifts Bopha more southward, which results in the weakening of Bopha by prohibiting the interaction between the CMR and Bopha, and the flows induced by Bopha force Saomai to propagate along a more southerly track. The higher CMR weakens the easterly flow in the lower troposphere and suppresses the northerly flow in the upper troposphere to the west of Saomai. The resultant weak vertical wind shear keeps warm air near the typhoon center in the upper troposphere, which promotes the intensification of the typhoon. To examine the direct effects of topography on the track and intensity of Saomai, additional simulations involving the removal of Bopha from the initial condition with 100% and 50% of CMR are conducted. The results without Bopha showed that Saomai moves more southward at a slower speed and with greater intensity, due to the stronger northerly wind to the west of Saomai, which was not canceled out by the southerly wind to the east of Bopha, and there is no significant difference in the tracks or intensity with respect to the mountain heights.

1. Introduction
As a typhoon approaches a mountain range, its track, intensity, and precipitation distribution can be influenced by topography. The effects of topography on typhoons are observed on islands located in the path of typhoons, such as Taiwan and Luzon in the northwestern Pacific Ocean. The interaction between a typhoon circulation and terrain is highly complex; therefore, accurate prediction of typhoons under the influence of topography remains a challenge (Wu and Kuo 1999).

Previous numerical modeling studies based on idealized topography (e.g., Chang 1982; Yeh and Elsberry 1993a,b; Lin et al. 1999, 2005) have focused on the mechanisms of track deflection when typhoons pass over mountain ranges. Chang (1982) showed that the typhoon center moves cyclonically when passing over mountain ranges, due to the cyclonic circulation around the topography induced by the approaching typhoon. Yeh and Elsberry (1993a,b) demonstrated that the track deflections attributable to topography depend on the structure, intensity, and transition speed of typhoons and that track discontinuity is related to the formation of a secondary vortex on the lee side of mountains. Lin et al. (1999) explained the southward track deflection by topography in terms of the potential vorticity generation on the lee side of mountains, which results from the adiabatic warming associated with severe downslope windstorms. Lin et al. (2005) proposed six nondimensional parameters for diagnosing typhoon continuity and identified favorable conditions for track deflection. The influences of terrain on precipitation (e.g., Wu et al. 2002) and track deflection (e.g., Lin et al. 2006) have also been investigated using real-case simulations. Wu et al. (2002) showed that the strength of the lifting motion caused by the Central Mountain Range (CMR) in Taiwan is an important factor in determining the amount of precipitation associated with Typhoon Herb (1996). By comparing simulation results for Supertyphoon Bilis (2000) and Typhoon Toraji (2001), Lin et al. (2006) demonstrated that weaker and slower typhoons will...
tend to have a more discontinuous track when they cross the CMR.

If there is more than one storm near a mountain area, the effects of topography on the storms become much more complicated due to the interactions between the storms under differing topographical influences, which affect their movements. In several previous studies, pioneered by Fujiwhara (1921), concerning the interaction of two vortices, changes in the movements and intensities of two vortices have been investigated using idealized vortices under various circumstances (e.g., Chang 1983; Dritschel and Waugh 1992; Wang and Holland 1995; Shin et al. 2006). These studies mainly focused on the on the influence of the critical distance between two vortices in relation to the merger or mutual cyclonic circulation. Chang (1983) demonstrated the Fujiwhara effect using a three-dimensional tropical cyclone model without background wind. Dritschel and Waugh (1992) categorized the interaction regimes of two vortices with an identical vortex strength based on the nondimensional distance between the two vortices and the ratio of the two vortex radii. Wang and Holland (1995) found two critical separation distances—specifically, a mutual approach separation and a mutual merger separation—for storms simulated by a three-dimensional primitive equation model. Shin et al. (2006) demonstrated that the critical separation distance of binary vortices is slightly less than twice the radius at which the relative vorticity of one vortex becomes zero. In studies of real-storm cases, the observed movements of binary tropical cyclones (TCs) have been explained by their interactions (e.g., Carr et al. 1997; Kuo et al. 2000; Wu et al. 2003; C. C. Yang et al. 2008). Carr et al. (1997) proposed four conceptual models (direct, semidirect, indirect, and reverse-oriented monsoon trough formation) of track-altering binary tropical cyclones that occurred in the Pacific Ocean. Kuo et al. (2000) classified the interaction regimes between Typhoons Zeb and Alex (1998) based on Dritschel and Waugh’s (1992) theory. Wu et al. (2003) and C. C. Yang et al. (2008) used potential vorticity diagnosis to explain the motions of typhoons due to interaction of binary typhoons.

In 2006, 15 typhoons formed in the northwestern Pacific Ocean, and 5 of them developed into category-5 typhoons based on the Saffir–Simpson hurricane scale (Simpson 1974). Of the five strongest typhoons, Typhoon Saomai (2006) made the closest approach to Taiwan during its peak intensity. Investigations of Typhoon Saomai (2006) have been conducted by Zhao et al. (2008) and Kim and Chun (2010). Using a single Doppler radar observation, Zhao et al. (2008) investigated the change in the concentric eyewall of the typhoon near landfall. Kim and Chun (2010) examined the characteristics of the stratospheric gravity waves generated by the typhoon. In the present study, the orographic effects on the evolution of Typhoon Saomai are investigated by conducting a series of numerical experiments using a mesoscale model using 100%, 75%, 50%, and 25% of the terrain heights of Taiwan. In section 2, a brief overview of Typhoon Saomai is given. In section 3, the experimental design is described. In section 4, the results of the numerical simulations conducted with different mountain heights are discussed. Special emphasis is given to the influence of mountain height on Tropical Storm Bopha, which passed Taiwan prior to Typhoon Saomai, and its impact on the track and intensity of Typhoon Saomai. A summary and conclusions are presented in the final section.


The Joint Typhoon Warning Center (JTWC) first identified a tropical depression near the Caroline Islands in the western Pacific Ocean on 4 August 2006, and the Japan Meteorological Agency (JMA) designated it as a typhoon at 0600 UTC 7 August. Typhoon Saomai moved northwestward continuously without significant track deflection until its landfall on the southeastern coast of China on 10 August (Fig. 1a). The typhoon rapidly intensified and propagated, reaching its peak intensity at 1200 UTC 9 August with a minimum sea level pressure of 925 hPa and a maximum wind speed of 54 m s$^{-1}$ (Fig. 1b). Tropical Storm Bopha (2006) was located over Taiwan when Typhoon Saomai approached Taiwan. Bopha formed as a tropical depression on 5 August over the northwestern Pacific Ocean and propagated westward toward Taiwan. Bopha passed over the south of Taiwan from 1800 UTC 8 August–0000 UTC 9 August (Fig. 1a) with a minimum sea level pressure of 992 hPa and a maximum wind speed of 21 m s$^{-1}$ (Fig. 1b).

Figure 2 shows the observed features of Typhoon Saomai and Tropical Storm Bopha at 1800 UTC 8 August 2006. The infrared image over the northwestern Pacific Ocean is from the Multifunctional Transport Satellite-IR (MTSAT-IR; Fig. 2a), and the sea level pressure (Fig. 2b), horizontal wind vector at 850 hPa (Fig. 2c), and the geopotential height along with the horizontal wind vector at 500 hPa (Fig. 2d) are generated from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis data at a horizontal resolution of 0.25° latitude $\times$ 0.25° longitude (Figs. 2b–d). In the MTSAT-IR image (Fig. 2a), the larger convective system centered near 23°N, 130°E is Typhoon Saomai, and the smaller convective system centered near 23°N, 122°E is Tropical Storm Bopha. Typhoon Saomai strengthens from this time (1800 UTC 8 August), as shown in Fig. 1b, and Bopha has already made landfall in Taiwan. In the
ECMWF analysis data, Bopha is present in the southeastern part of Taiwan, approximately 730 km west of Saomai (Fig. 2b), and its secondary low is present to the west of the CMR. At 850 hPa (Fig. 2c), the strength of the flow between the two circulations becomes weak because the northerlies induced by Saomai are largely cancelled out by the southerlies induced by Bopha. The two lows associated with Saomai and Bopha are clearly shown up to 500 hPa (Fig. 2d) without significant vertical tilt. A short-wave trough between Saomai and Bopha is embedded in the prevailing easterlies. The strong southeasterlies in the northern part of Saomai flow toward the southeastern coast of China, and strong northerlies exist in the west of Taiwan.

As will be shown later, the influence of topography on Typhoon Saomai is strongly related to the influence of topography on Tropical Storm Bopha, given that the flows near Saomai when it approaches Taiwan are largely influenced by those associated with Bopha, which had already passed over Taiwan. This is a rather unique case that can be used to investigate the impact of topography on a typhoon by considering two vortices with different sizes and strengths that approached the same topography with a time lag.

3. Experimental design

The Weather Research and Forecasting (WRF) Model, version 2.2 (Skamarock et al. 2005), is used in the present study. The outmost domain (hereafter D1), centered at 20°N, 128.0°E, has 187 × 187 grid points with a horizontal grid spacing of 27 km. Two nested subdomains (hereafter D2 and D3) with a grid spacing of 9 and 3 km have 253 × 253 and 397 × 397 horizontal grid points, respectively. To investigate the structure of the typhoon in detail, the innermost domain is designed to follow the vortex center. The typhoon center, which is determined by the minimum geopotential height at 500 hPa, is always located at the center of D3; D2 also changes with time in accordance with the movement of D3. The topography and three
model domains are shown in Fig. 3. Note that the topography in the moving domains of D2 and D3 is interpolated from the D1-resolution topography in the current version of WRF, and as a result, the topography may be underestimated in D2 and D3. For example, the maximum height of the CMR in D3 is 1980 m in the current vortex-following simulations, whereas the maximum height of the CMR in a regular nonmoving domain with a 3-km horizontal resolution is 3194 m. The model includes 77 vertical layers from the surface to 5 hPa. The

FIG. 2. (a) The observed brightness temperature from the MTSAT-IR and (b) the sea level pressure, (c) horizontal wind vector at 850 hPa, and (d) geopotential height (contour) with the horizontal wind vector at 500 hPa at 1800 UTC 8 Aug from the analysis data of the ECMWF. The contour intervals in (b) and (d) are 2 hPa and 10 m, respectively.
vertical grid spacing increases with the height, about 200 m in the boundary layer below 2 km height and about 400 and 1000 m in the troposphere and lower stratosphere, respectively. A damping layer of 5 km is included at the uppermost part of the model domain. The numerical model is integrated for 60 h from 0600 UTC 8 August–1800 UTC 10 August 2006, in a two-way interactive nested grid system. The integration of D3 begins at 1200 UTC 8 August, 6 h after the integration in the outer domains is initiated.

For the initial and boundary conditions, we use the ECMWF analysis data with a horizontal resolution of 0.25° latitude × 0.25° longitude. A Geophysical Fluid Dynamics Laboratory (GFDL)-type typhoon initialization algorithm (Kwon et al. 2002) is employed to provide proper initial conditions. The maximum wind speed and radius of maximum wind used for the bogussing algorithm are 21.75 m s⁻¹ and 82.5 km, respectively. The subgrid-scale physical processes used in the present simulations include the WRF single-moment 6-class (WSM6) microphysics scheme (Hong and Lim 2006), the Mellor–Yamada–Janjic (MYJ) PBL scheme (Mellor and Yamada 1982; Janjic 2002), and the Kain–Fritsch cumulus parameterization scheme (Kain and Fritsch 1993). The cumulus parameterization scheme is applied only to D1 and D2. To examine the effects of the topography of the CMR on the track and intensity of Typhoon Saomai, four numerical simulations are conducted with 100%, 75%, 50%, and 25% of the terrain height of Taiwan; these simulations are referred to as CTL, H75, H50, and H25 simulations, respectively. All model parameters are identical to those used in the CTL simulation, except for the percent-adjusted terrain elevations.

### 4. Topographic effects on Tropical Storm Bopha and its influence on Typhoon Saomai

#### a. Effects of topography on the evolution of Tropical Storm Bopha

As shown in Fig. 2, Tropical Storm Bopha passed Taiwan before Typhoon Saomai passed north of Taiwan. That is, two vortices of different strengths and sizes coexisted side by side near Taiwan for a period of time and passed westward one after another. Therefore, to understand the influence of topography on Typhoon Saomai, it is essential to consider the influence of topography on Bopha. Near Taiwan, the environmental flow of Saomai could have been influenced strongly by the circulation associated with Bopha, which made landfall in Taiwan.

To examine the effects of the topography on the evolution of the two vortices, we show in Fig. 4 the sea level pressure at selected times from 1200 UTC 8 August to 0000 UTC 10 August. The main differences between the simulations shown in Fig. 4 are the location and intensity of Tropical Storm Bopha for whole period and those of the Typhoon Saomai after 0000 UTC 9 August. In the CTL simulation, Bopha is located to the southeast of Taiwan at 1200 UTC 8 August. Over time, the storm moves to the southwest of Taiwan without significant intensification because the blocking effect of the CMR is strong enough to deflect Bopha. Compared with the CTL simulation, the H75 simulation shows that the intensity of Bopha increases slightly but with almost no change in the location of the vortex center. Similar to the CTL simulation, the storm does not pass the CMR but moves along the southern coast of Taiwan. In the H50 simulation, Bopha is more intense as it passes directly over southern Taiwan and it is deflected southwestward after passing the CMR. The results of the H25 simulation are generally similar to those of the H50 simulation, except that the storm center is located over Taiwan, even at 0000 UTC 10 August, and the intensity of the storm is stronger. As a result, the CMR pushes out Bopha to the south, and Bopha has a better chance to interact with the topography with a decreased terrain height.

The southward-shifted tracks of Typhoon Saomai with higher elevations of the CMR are partly due to the southward shift of Bopha that occurs with higher elevations.
of the CMR. The southward shift of Bopha with higher elevations of the CMR can be explained in terms of the vortex Froude number (Fr) as a measure of the blocking effect of the topography when a tropical cyclone encounters a north–south-oriented topography, as suggested by Lin et al. (2005). The vortex Froude number is defined as $V_{\text{max}}/Nh$, where $V_{\text{max}}$, $N$, and $h$ are the maximum tangential wind, the Brunt–Väisälä frequency, and the mountain height, respectively. By organizing previous studies about the track deflection of tropical cyclones traversing the CMR, Lin et al. showed that tropical cyclones tend to have a discontinuous (continuous) track due to the increase (decrease) in the blocking effect when Fr is smaller (larger) than 1.5. The calculated Fr from the present CTL, H75, H50, and H25 simulations at 0900 UTC 8 August (not shown), when Bopha was located east of Taiwan but had not passed the CMR in all of the simulations, are 0.78, 1.12, 1.88, and 4.16, respectively. This demonstrates that the southward movements of Bopha in the CTL and H75 simulations (Fig. 4) stem from the increase in the blocking effect. The influence of development of Bopha on the track,
intensity, and structure of Saomai will be examined in detail in the following section. The left panel of each simulation in Fig. 5a is the moisture flux divergence \( \nabla \cdot \rho q_v V \); where \( \rho \) is air density, \( q_v \) is water vapor mixing ratio, and \( V \) is horizontal wind vector (shading) superimposed on the horizontal wind vector at 850 hPa near Taiwan at 1200 UTC 8 August, and right panel of each simulation in Fig. 5a is the vertical cross section of cloud property (cloud water mixing ratio plus ice mixing ratio) superimposed on the zonal wind (denoted by vector form) along the line shown in the left panel. At 1200 UTC 8 August, Bopha is located southeast of Taiwan in the CTL and H75 simulations and it makes a landfall in the H50 and H25 simulations. In the CTL simulation, the moisture flux converges in the upstream region of the CMR due to the easterlies from the circulation of Bopha and weak cyclonic circulation in the lee side of the CMR appears. In a cross section, dense cloud is developed between 700 and 500 hPa by the influence of the CMR. Results from the H75 simulation are generally similar to those from the CTL simulation, except that the cloud extends up to 200 hPa as Bopha approached CMR more closely than the CTL simulation. In the H50 and H25 simulations, stronger moisture flux convergence is formed as Bopha makes landfall in Taiwan. The cloud above the CMR extends up to 100 hPa due to the orographic uplift, and the strong outflow above 300 hPa expands to about 200 km horizontally. At 1200 UTC 9 August (Fig. 5b), Bopha is located south of Taiwan for all simulations, and strength of Bopha and associated convective activity near Taiwan are significantly different depending on the relative distance between CMR and Bopha. Similarly with the results at 1200 UTC 8 August, strong divergences at the upper troposphere with tall clouds are only presented in the H50 and H25 simulations at 1200 UTC 9 August as well. These strong divergences are related with the formation of anticyclonic circulation in the upper troposphere, which will be discussed in section 4b.

b. Changes in track, intensity, and structure of Saomai under the influence of Bopha

Figure 6 shows the tracks (Fig. 6a) and minimum sea level pressures (Fig. 6b) of Typhoon Saomai from the four simulations with different mountain heights along with the observed data from the JMA, as shown in Fig. 1. Compared with the JMA best track, the simulated tracks are generally slower, especially after 0000 UTC 9 August. The difference in the track between each simulation is noticeable after 1200 UTC 9 August when Typhoon Saomai approaches Taiwan and the tracks simulated with a higher topography shift southward for most of the simulation period as shown in Fig. 4. Unlike the track, the intensity of the typhoon increases monotonically with mountain height, even after 1200 UTC 10 August, when the typhoon has passed over Taiwan. Based on the minimum sea level pressure time series (Fig. 6b), the typhoon intensity in the CTL simulation is the best among the four simulations, especially in the rapidly developing and mature stages of typhoon evolution after 0600 UTC 9 August at which differences in the intensity in the four simulations become significant. As will be detailed later, the typhoon cannot develop fully in the reduced-topography simulations (H50 and H25) after 0600 UTC 9 August. This underdevelopment likely results from the circulations induced by Tropical Storm Bopha, which influence the development and movement of the typhoon. Although Saomai passed north of Taiwan rather than made landfall on Taiwan, there was likely a direct effect of topography on Saomai considering its passage that was very close to Taiwan. To examine this possibility, we performed additional numerical simulations with 100% and 50% mountain heights, identical to CTL and H50, respectively, except for removing Bopha from the simulations. This will be discussed in section 4c.

Figure 7 shows the temporal variation of the environmental steering flow near the typhoon center for the four simulations. Following M. J. Yang et al. (2008), the environmental steering flow is calculated by averaging the horizontal wind in a domain with a radius of 360 km from the typhoon center. In the CTL simulation, easterlies are dominant near the typhoon center from the lower troposphere to the lower stratosphere throughout the period shown in Fig. 4, and easterlies below 600 hPa increase to more than 9 m s\(^{-1}\) after 0600 UTC 9 August. The H75 simulation shows no significant difference from the CTL simulation before 1200 UTC 9 August. After that time, however, northerlies are created at 150 hPa, and the easterlies above 100 hPa become weaker until 0000 UTC 10 August in the H75 simulation. The temporal and vertical changes in the environmental steering flow in the H50 and H25 simulations are comparable to and generally greater than those in the CTL and H75 simulations. The northerlies between 300 and 150 hPa and the southeasterlies below 700 hPa after 1200 UTC 9 August are enhanced in the H50 and H25 simulations, with greater magnitudes being observed in the H25 simulation. The changes in environmental steering flow attributable to mountain height are strongly related to the development of Tropical Storm Bopha (as will be discussed in the explanation of Fig. 9).

Figure 8 shows a zonally oriented cross section of the simulated reflectivity through the typhoon center. In all simulations, the convection to the right of the typhoon center developed to 16 km and the convection to the left
Fig. 5. (left) Moisture flux divergence (shading) and horizontal wind vector at 850 hPa near Taiwan and (right) the vertical cross section of cloud property (cloud water mixing ratio plus ice mixing ratio) superimposed on the zonal wind vector along the line shown in the left panel at (a) 1200 UTC 8 Aug and (b) 1200 UTC 9 Aug for the (top left) CTL, (top right) H75, (bottom left) H50, and (bottom right) H25 simulations. The results are obtained from D1.
of the center is relatively low and weak. In the CTL simulation, a concentric eyewall is formed with a clear eye as its intensity increases after 0000 UTC 9 August. The typhoon structure in the H75 simulation is generally similar to that in the CTL simulation, except that the symmetry near the eyewall decreases slightly after 1800 UTC 9 August in the H75 simulation. The asymmetric structure is more pronounced in the reduced-topography simulations. In the H50 and 25 simulations, small-scale rainbands develop to the west of the typhoon center rather than strong convection in the eyewall region. Figure 8 clearly demonstrates that the eyewall symmetry increases with terrain height. This result differs somewhat from that of Ramsay and Leslie (2008), who showed that the topography increases eyewall asymmetry by strengthening the convection above the topography. In the present study, there is no evidence of convection strengthening above the topography for Saomai. For the Bopha case, however, the convection is strengthened over the topography, as shown in Fig. 5.

The influence of the mountain height on the circulation induced by Bopha can be seen clearly in Fig. 9, which shows the horizontal wind vector at 200 hPa from the four simulations at 1200 UTC 9 August when the typhoon is located in the northeastern part of Taiwan. The CTL simulation presents a cyclonic circulation...
induced by Saomai and an anticyclonic circulation induced by a convective system (not shown) in the southern part of Kyushu, Japan. The circulation induced by Bopha is presented only as weak anticyclonic circulation in the southwest of Taiwan. In the H75 simulation, the anticyclonic flow between Taiwan and China associated with Bopha becomes more visible compared to that presented in the CTL simulation. Because of the

FIG. 7. The vertical profiles of environmental steering flow in the vicinity of the typhoon center from 1200 UTC 8 Aug to 0600 UTC 10 Aug at intervals of 6 h from the (a) CTL, (b) H75, (c) H50, and (d) H25 simulations. The environmental steering flows are calculated by averaging the horizontal wind vectors within a radius of 360 km from the typhoon center. The results are obtained from D3.
enhanced anticyclonic circulation north of Taiwan, strong northeasterlies develop between Saomai and Taiwan due to the merging of flows from the anticyclonic circulation north of Taiwan and the cyclonic circulation west of Saomai. In the H50 and H25 simulations, the anticyclonic circulation in the northwest of Taiwan gains strength and strong northerlies develop in the west of Saomai. Owing to the strong northerlies in the west of Saomai, especially in the H25 simulation, the cyclonic circulation and associated convective system of the western portion of Saomai weaken significantly, as shown in Fig. 8.

To understand the strong anticyclonic circulation at 200 hPa shown in the H25 simulation of Fig. 9, we calculate and show in Fig. 10 the equivalent potential temperature and horizontal wind vector at 200 hPa (Figs. 10a,b) and at 300 hPa (Figs. 10c,d) for the CTL and H25 simulations at 1200 UTC 9 August. Compared to the CTL simulation, the strong divergence from the enhanced Bopha in the H25 simulation, as shown in Fig. 5b, moves warm air from the west of Taiwan to the eastern part of China by means of strong southeasterlies. The southeasterlies change to southwesterlies as they move farther north, and the warm southwesterlies and cold northwesterlies that blow from the north of China induce westerlies through the horizontal stretching deformation (Holton 1992). The strong northwesterlies consisting of the anticyclonic circulation shown in Fig. 10b can be explained by the thermal wind relationship using the equivalent potential temperature at 300 hPa. In the H25 simulation (Fig. 10d), warm regions expand into

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**Fig. 8.** Vertical cross sections of the radar reflectivity along the zonal distance passing the typhoon center from 1800 UTC 8 Aug to 0000 UTC 10 Aug at intervals of 6 h from the (a) CTL, (b) H75, (c) H50, and (d) H25 simulations. The results are obtained from D3.
a wide area including east of Taiwan in which cold air still remains in the CTL simulation. Therefore, strong negative temperature gradient in the zonal direction is formed in the west and northwest of Saomai. Through the thermal wind relationship, vertical shear of the meridional wind becomes negative in the regions of the negative temperature gradient, where strong northerlies form at 200 hPa as shown in Fig. 10b. In addition, these northerlies become stronger by combining with cyclonic circulation from Saomai. In summary, the formation of anticyclonic circulation in the H25 simulation shown in Fig. 9 is due to the expansion of warm air by stronger outflow associated with enhanced convective activity of Bopha.

The change in the horizontal wind with topography in the upper troposphere was discussed in the previous paragraphs, and this change eventually modifies vertical wind shear. The effect of the vertical wind shear on typhoon evolution has been emphasized in several previous studies (McBride and Zehr 1981; Merrill 1988;
FIG. 10. The equivalent potential temperature and horizontal wind vector at 200 hPa from the (a) CTL and (b) H25 simulations and at 300 hPa from (c) CTL and (d) H25 simulations at 1200 UTC 9 Aug. The results are obtained from D1.
DeMaria 1996; Frank and Ritchie 2001; Chambers and Li 2011). Among these studies, Frank and Ritchie (2001) suggested that larger vertical wind shear causes the development of a highly asymmetric eyewall structure and allows the ventilation of the TC eye, resulting in the disappearance of the warm core in the upper levels. These changes, in turn, increase the central pressure of the TC and therefore decrease its strength.

Figure 11 shows the time series of the deep-layer wind shear averaged over D3, which is calculated by the magnitude of the difference in the horizontal wind vector between 850 and 200 hPa. In the CTL and H75 simulations, the deep-layer wind shear decreases rapidly from 1800 UTC 8 August to 1200 UTC 9 August as the typhoon intensifies (Fig. 1b). The wind shear in the H75 simulation shows a generally similar trend to that in the CTL simulation (although with larger magnitude), except that its increase from 1200 UTC 9 August to 0000 UTC 10 August occurs more rapidly than in the CTL simulation. A similar decreasing trend is evident in the H50 and H25 simulations before 0000 UTC 9 August, but the wind shear increases continuously from 0000 UTC 9 August to 1800 UTC 9 August, at which the differences in sea level pressure between the simulations become larger (Fig. 6b). The increases in wind shear seen after 1200 UTC 9 August in the H50 and H25 simulations are due to the northerly flow near the typhoon center in the upper troposphere, as evidenced by the environmental steering flow (Fig. 7). The time series of wind shear (Fig. 11) and minimum sea level pressure (Fig. 6b) are well correlated, and the maximum correlation coefficients between the two variables are 0.76, 0.74, 0.18, and 0.72 at lags of +4, +6, +6, and +6 h for the CTL, H75, H50, and H25 simulations, respectively. Here, the positive lag means that the wind shear begins to decrease earlier than the sea level pressure. The extremely low correlation seen in the H50 simulation is probably due to the decrease in wind shear that begins after 1800 UTC 9 August and continues until 1800 UTC 10 August, although the sea level pressure increases continually throughout that period following decreases near 0600 UTC 10 August (Fig. 6b).

Figure 12 shows the equivalent potential temperature at 200 hPa and the magnitude of the deep layer (between 200 and 850 hPa) wind shear at 1800 UTC 9 August. In the CTL simulation, a strong warm region with a maximum equivalent potential temperature of 372 K is presented near the typhoon center, and the equivalent potential temperature decreases rapidly with increasing radial distance from the center. Relatively small and large magnitudes of the deep-layer wind shear are apparent in the eye and the eyewall, respectively, although with no regions exceeding 20 m s$^{-1}$. In the H75 simulation, the concentric shape of the equivalent potential temperature field near the typhoon center is slightly collapsed, and the maximum value of the equivalent potential temperature decreases slightly (371 K). In addition, the vertical wind shear in the northern part of the typhoon center is somewhat strengthened. In the H50 and H25 simulations, the concentric form of the equivalent potential temperature largely disappears, and the warm region near the typhoon center shrinks as the regions outside the center increase in temperature (see the thick contours of 368 and 358 K in Fig. 12). The magnitude of the vertical wind shear increases significantly, especially in the northern and southern parts of
the typhoon center. In summary, the simulations show that increasing the height of the CMR induces weaker vertical wind shear and enhances eyewall structure symmetry. These changes cause the warm air to be maintained near the typhoon center in the upper troposphere, resulting in increased typhoon intensity. The influence of topography on the development of the typhoon presented in the current study can be explained by the mechanism proposed by Frank and Ritchie (2001).
Moisture convergence upstream of the mountains can maintain the intensity of the typhoon (Bender et al. 1985; Chambers and Li 2011), and the changes in the moisture flux in the lower troposphere with respect to terrain height are examined from the present simulations (not shown). The results show that the moisture flux at 850 hPa is not significantly different from each simulation, except that a slight contraction of convergence is seen near Taiwan in the simulations with higher topography.

c. Interaction between Saomai and Bopha

Because Typhoon Saomai and Tropical Storm Bopha exist simultaneously in the western North Pacific region, as shown in Fig. 4, the interaction between the two vortices should be considered. Figure 13 shows the minimum sea level pressure of the two vortices at the four times shown in Fig. 4. First, the figure shows that the intensity of Saomai is significantly stronger than that of Bopha from 1200 UTC 8 August to 0000 UTC 10 August. However, the relative strength of the two vortices differs with time, depending on mountain height. At 1200 UTC 8 August, the intensity of Bopha increases significantly with decreasing mountain height, whereas there is no significant difference in the intensity of Saomai. At 0000 UTC 9 August, the intensity of Bopha increases in all simulations, whereas that of Saomai decreases. Between 0000 and 1200 UTC 9 August, Saomai intensifies for all simulations, and the degree of intensification is proportional to the mountain height. Between 1200 UTC 9 August and 0000 UTC 10 August, Bopha and Saomai are weakened rapidly in the H50 and H25 simulations, whereas the intensities of the two vortices in the CTL and H75 simulations do not change significantly.

Figure 14 shows the centroid-relative tracks from 1200 UTC 8 August to 0000 UTC 10 August at intervals of 6 h. Centroid-relative tracks denote the locations of two vortices relative to the geographical center of the two vortices. Note that the center location (0° in longitude and latitude), which denotes a geographical center between the two vortices, differs between the simulations and at the same time in each simulation. In the CTL and H75 simulations, mutual cyclonic circulations of the two vortices are evident without a significant change in the distance between them. Saomai moves more northward and Bopha moves more southward with respect to their geographical centers. In the H50 and H25 simulations, however, the zonal movements of the two vortices become dominant, especially after 1800 UTC 9 August, when the distance between the two vortices decreases continuously. The distances between the two vortices from 1200 UTC 8 August to 0000 UTC 10 August change from 1090 (1090) to 521 km (698 km) in the H25 (H50) simulation, whereas those in the H75 (CTL) simulation change from 862 (858) to 824 km (766 km). The distances between the two vortices at 1200 UTC 8 August in the CTL and H75 simulations are quite different from those in the H50 and H25 simulations, as the tracks of Bopha in the H50 and H25 simulations are significantly different from those in the CTL and H75 simulations during the first 6 h of the integration (0600–1200 UTC 8 August).

Most previous studies of the interaction between two vortices are based on ideal simulations, given certain assumptions, such as the same magnitudes of vorticity with different vortex sizes (e.g., Dritschel and Waugh 1992) or the same magnitudes of vorticity and size (e.g., Shin et al. 2006). Therefore, previously employed methods of categorizing interaction regimes cannot be easily applied to the present real-storm case. Nevertheless, we estimated the nondimensional distance (ND) between Saomai and Bopha and determined the ratio of the two vortex radii (VR), as suggested by Dritschel and Waugh (1992). The results are shown in Table 1 along with the interaction regimes selected. A total of 13 among 16 cases (4 times × 4 simulations shown in Fig. 13) belong in the “elastic interaction” category described by Dritschel and Waugh, a mutual cyclonic rotation of two vortices without significant changes in the strength of each vortex. Only three cases in the H25 (at 1200 UTC 9 August and 0000 UTC 10 August) and H50 (at 0000 UTC 10 August) simulations fall within the “complete merger” and “partial straining out” categories.

![Figure 13](image.png)

**Fig. 13.** The minimum sea level pressure of Saomai (PS_min) and Bopha (PB_min) from 1200 UTC 8 Aug to 0000 UTC 10 Aug at intervals of 12 h in the CTL (circle), H75 (square), H50 (triangle), and H25 (circle with dot) simulations.
respectively. This result is mainly due to the decreased nondimensional distance resulting from the increasing size of Bopha with decreasing mountain height. Although the degrees of interaction between the two vortices for these two interaction regimes are somewhat stronger (especially for the complete merger regime) than the real interactions between Saomai and Bopha shown in Figs. 4 and 14, Dritschel and Waugh’s (1992) interaction regimes are likely to be applicable to the present real-storm case simulations, at least in a qualitative sense.

Previous modeling results showed that the effects of topography on Typhoon Saomai’s track and intensity were strongly related to the effects of topography on Tropical Storm Bopha, which was probably more influenced by topography upon landfall in Taiwan before Saomai passed north of Taiwan. Thus, both the direct and indirect effects of Taiwan’s topography on Saomai through the changes in Bopha are included in the present simulations. Here, the direct effect refers to the influence of topography on Typhoon Saomai when Bopha does not exist, whereas the indirect effect denotes the influence of topography on Saomai through the changes in the strength of Bopha caused by the topography. To examine the direct and indirect effects of topography separately, two additional experiments are conducted by removing Bopha with 100% (NBH100 simulation) and

Fig. 14. The centroid-relative tracks from the (a) CTL, (b) H75, (c) H50, and (d) H25 simulations. Each symbol is marked at every 6 h from 1200 UTC 8 Aug, and the triangle in each panel denotes the geographical center between the two vortices. The results are obtained from D1.
Table 1. The nondimensional distance (ND), ratio of vortex radii (VR), and interaction regime according to Dritschel and Waugh (1992) calculated using the simulation results from 1200 UTC 8 Aug to 0000 UTC 10 Aug at intervals of 12 h. “EI,” “PS,” and “CM” denote “elastic interaction,” “complete merger,” and “partial straining out,” respectively.

<table>
<thead>
<tr>
<th>Hour and date</th>
<th>CTL</th>
<th>H75</th>
<th>H50</th>
<th>H25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 UTC 8 Aug</td>
<td>ND</td>
<td>2.82</td>
<td>2.81</td>
<td>3.66</td>
</tr>
<tr>
<td></td>
<td>VR</td>
<td>0.44</td>
<td>0.49</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Regime</td>
<td>EI</td>
<td>EI</td>
<td>EI</td>
</tr>
<tr>
<td>0000 UTC 9 Aug</td>
<td>ND</td>
<td>5.05</td>
<td>4.62</td>
<td>2.55</td>
</tr>
<tr>
<td></td>
<td>VR</td>
<td>0.48</td>
<td>0.97</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Regime</td>
<td>EI</td>
<td>EI</td>
<td>EI</td>
</tr>
<tr>
<td>1200 UTC 9 Aug</td>
<td>ND</td>
<td>4.34</td>
<td>3.23</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>VR</td>
<td>0.37</td>
<td>0.91</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>Regime</td>
<td>EI</td>
<td>EI</td>
<td>EI</td>
</tr>
<tr>
<td>0000 UTC 10 Aug</td>
<td>ND</td>
<td>4.32</td>
<td>3.43</td>
<td>1.01</td>
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<td></td>
<td>VR</td>
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<td>0.86</td>
<td>0.53</td>
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<tr>
<td></td>
<td>Regime</td>
<td>EI</td>
<td>EI</td>
<td>PS</td>
</tr>
</tbody>
</table>

50% (NBH50 simulation) topography heights. To remove Bopha from the initial condition, the vortex removal scheme used in WRF version 3.1 (Davis and Low-Nam 2001; Skamarock et al. 2008) is employed. First, nondivergent wind is removed by solving the Laplace equation based on the relationship between nondivergent wind and relative vorticity. Next, divergent wind and geopotential height anomalies are removed using the Laplace relationship between velocity potential and divergence and between geopotential and geostrophic vorticity, respectively. The temperature anomaly is also removed by using the hydrostatic relation. Finally, the water vapor mixing ratio is modified using a linear interpolation between the original mixing ratio and averaged mixing ratio surrounding the storm.

Figure 15a shows tracks of Typhoon Saomai from the CTL, H50, NBH100, and NBH50 simulations. Generally, the typhoon moves more southward at a slower speed when Bopha is removed. These results can be explained by the changes in the environmental steering flow (Fig. 16). In the NBH100 simulation (Fig. 16b), the southeasterly below 500 hPa becomes weaker than in the CTL simulation (Fig. 16a) after 0600 UTC 9 August, which is also true for the H50 (Fig. 16c) and NBH50 (Fig. 16d) simulations. The weakening of the environmental steering flows in the NBH100 and NBH50 simulations is associated with the changes in the flows between Bopha and Saomai. Figures 15b,c show the sea level pressure at 1200 UTC 9 August from the CTL and NBH100 simulations, respectively. In the NBH100 simulation, a closed low of 998 hPa representing Bopha, which appears in the southwest of Taiwan in the CTL simulation, disappears. As a result, the southerlies in the southwest of Saomai disappear; consequently, Saomai takes a more southern track. The intensity of the typhoon is generally stronger when Bopha is removed (not shown), probably because the northerly in the west of Saomai associated with the cyclonic circulation of the typhoon is maintained without Bopha. Consequently, the typhoon is stronger without Bopha, as shown in the surface pressure field (Fig. 15c). The stronger cyclonic circulation induces weaker southeasterlies in the low-level environmental steering flows, as shown in Fig. 16; consequently, Saomai moves at a slower speed without Bopha. The difference in the track between the NBH100 and NBH50 simulations is not significant and does not increase with time (Fig. 15a). The intensities of the typhoon in NBH100 and NBH50 are also similar, except that its decay after 0600 UTC 10 August is slightly slower in NBH100 than in NBH50. This result implies that the direct effects of topography on the track and intensity of Saomai are not significant when Bopha is removed and that the differences in the track and intensity of Saomai among the four simulations with respect to the mountain heights shown in Fig. 6 are largely due to the influence of topography on Bopha and the corresponding flow changes in the southwest of Saomai.

Figure 17 shows the horizontal wind vector at 200 hPa at 1200 UTC 9 August from the H50 and NBH50 simulations. In the NBH50 simulation (Fig. 17b), the anticyclonic circulation in the northwest of Taiwan is not presented. This result demonstrates that the strong anticyclonic circulations in the upper troposphere, as shown in the H50 and H25 simulations (Figs. 9c,d), are induced by the circulations associated primarily with Bopha. The horizontal wind field at 200 hPa from the NBH100 simulation is similar to that from NBH50 (not shown), implying no significant contribution of topography without Bopha. In summary, the results shown in Figs. 15–17 demonstrate that Taiwan’s topography influenced the track and intensity of Typhoon Saomai, which passed to the north of Taiwan, primarily through changes in Tropical Storm Bopha, which passed over Taiwan’s topography prior to Saomai, and due to the associated flow change between the two storms.

5. Summary and conclusions

The effects of topography on the evolution of Typhoon Saomai (2006) are investigated by conducting a series of numerical simulations using the WRF with 100%, 75%, 50%, and 25% of the terrain heights of Taiwan. In the CTL simulation with the actual topography (100%), the observed track and intensity of Typhoon Saomai are reproduced reasonably well. Differences in the track and intensity of Typhoon Saomai between the experiments with different mountain
Heights are strongly related to those of Tropical Storm Bopha, which passed Taiwan earlier than the typhoon. In the experiments employing reduced terrain height, Bopha strengthens near Taiwan. This is because higher topography prohibits the interaction between the topography and Bopha by shifting Bopha southward. In the simulations with relatively higher mountain heights (CTL and H75), the typhoon passes over the northern edge of Taiwan (relatively southward), whereas it moves much farther north of Taiwan (relatively northward) in the simulations with reduced topography (H50 and H25). This is because higher CMR weakens the easterly flow in the lower troposphere and suppresses the generation of the northerly wind component in the upper troposphere by restraining the expansion of warm air from Bopha. The resultant weaker vertical wind shear keeps warm air near the center of the typhoon in the upper troposphere, resulting in the intensification of the...
Typhoon. It is likely that the topography of Taiwan promoted the development of Typhoon Saomai by preventing the growth of Tropical Storm Bopha.

The influence of topography on the typhoon track can be explained by the interaction between the two vortices, which can be determined by their intensity and the distance between them. As mountain height increases, Bopha weakens and Saomai strengthens in all simulations, although the degree of change in the sea level pressure for the two vortices differs with time. Bopha is
located at nearly the same latitude and approximately 800–1000 km west of Saomai at the beginning of the simulation (1200 UTC 8 August); subsequently, the two storms rotate counterclockwise with time. In the higher-topography simulations, the two vortices rotate in a larger circle with respect to their geographical center, and Saomai and Bopha move more northward and southward, respectively. The interaction between Saomai and Bopha is investigated based on the nondimensional distance between the two vortices and the ratio of the two vortex sizes, as proposed by Dritschel and Waugh (1992). In most of the different mountain height simulations and over time within each simulation, the two vortices fall within the “elastic interaction” category of Dritschel and Waugh (1992), which is defined as the mutual cyclonic circulation of two vortices without significant changes in the strength of either vortex. Only one case in the H50 simulation and two cases in the H25 simulations are categorized as “partial straining out” and “complete merger,” respectively. The interaction regimes proposed by Dritschel and Waugh (1992) are based on ideal simulations of two vortices with uniform vorticity and different vortex sizes. Therefore, their criteria cannot be easily applied to real-storm cases. Nevertheless, in most cases of different mountain heights and storm evolution times, the interaction between Saomai and Bopha can be explained by Dritschel and Waugh’s (1992) regimes, at least in a qualitative sense.

To examine the direct effects of topography on the track and intensity of Saomai, two additional simulations are conducted that remove Bopha from the initial condition with 100% and 50% of Taiwan’s terrain heights. It is found that the typhoon moves more southward and at a slower speed when Bopha is removed because the southeasterly environmental steering flow weakens in response to the absence of cyclonic circulation from Bopha. Without Bopha, the influence of topography on the track and intensity of Saomai is not significant because Saomai passed north of Taiwan without directly contacting the mountains. This result demonstrates that topography influences the track and intensity of Saomai in the present case through the changes in the development of Bopha and associated circulations.

In this study, the effects of topography on Typhoon Saomai were examined by conducting four numerical simulations with different heights of the CMR in Taiwan. Although several aspects of topographic effects were investigated in this study, a secondary low on the lee side of the CMR was not considered. Although a variety of previous studies found that a secondary low can play an important role in deflecting a typhoon, the physical mechanism of the secondary low and its interaction with a primary low are not yet clearly understood. Therefore, the formation of a secondary low in the lee of the CMR and its influence on Tropical Storm Bopha and Typhoon Saomai are subjects that are worthy of future study.

FIG. 17. The horizontal wind vector at 200 hPa at 1200 UTC 9 Aug from the (a) H50 and (b) NBH50 simulations. The results are obtained from D1.
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