11A.6 THE EFFECTS OF COMPLEX TERRAIN ON TROPICAL CYCLONE TRACK, INTENSITY, AND RAINFALL DURING TCS-08

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1. INTRODUCTION

The island of Taiwan is located in an especially active area of tropical cyclone activity. On average, three or four typhoons strike the island annually (Wu and Kuo 1999) with a maximum of eight occurring in 1914. Wu and Kuo (1999) identify the top three priorities for typhoon forecasts in Taiwan as track, intensity, and wind/precipitation forecasts. They also identify the effects of topography on each of these forecasts as an important research topic. In the succeeding ten years, there have been a been a number of new landfalling typhoons on Taiwan, some of them resulting in extreme rainfall amounts and high wind gusts. There are two such examples from the THORPEX-Pacific Asian Regional Campaign/Tropical Cyclone Structure - 2008 (T-PARC/TCS08) field experiment, which covered much of the northwestern Pacific Ocean. On 13-15 September 2008, Typhoon Sinlaku moved across the island producing rainfall amounts of up to 1611 mm (63.4 in). Two weeks later, on 28-29 September, Typhoon Jangmi crossed much of the same area with a maximum rainfall accumulation of 1124.5 mm (44.3 in). In this study, the Naval Research Laboratory's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®) will be used in an attempt to isolate the terrain effect on the track, structure, and precipitation distribution for Typhoon Sinlaku. The later effect is likely a combination of direct upslope forcing and changes in the larger-scale convective pattern through changes in the storm track and structure. Preliminary results for Typhoon Jangmi will also be presented.

2. MODEL SETUP

This study utilizes the tropical cyclone version of the COAMPS model (COAMPS-TC, Reynolds et al. 2010). The initial first guess fields are provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS) and 3D-Var data assimilation is performed by the Navy Advanced Data Assimilation System (NAVDAS). Since both storms had deep centers ($<$ 950 mb) as they approached Taiwan, the simulations were initialized by blending available observations (including a set of synthetic observations based on the JTWC warning messages) with a 12-hour forecast from a previous COAMPS-TC run. The tropical cyclone circulation from this analysis is then relocated to that in the Joint Typhoon Warning Center warning message. Lateral boundary conditions during the simulation are provided by the operational NOGAPS forecasts.

Each simulation contains a fixed, 45-km resolution outer domain, which covers most of the western Pacific and two nested moving domains of 15- and 5-km resolution, which follow the center of mass of an identified tropical cyclone. The innermost domain is approximately 900 km on each side. Cumulus parameterization is used in the two outer domains while explicit moist physics is used in the innermost domain. COAMPS-TC also includes sea spray processes and dissipative heating near the ocean surface. Following a series of 12-hour update cycles, the control simulations were 72-hours in length, the same as in the real-time TCS08 runs.

To examine the effect that the complex topography of Taiwan has on the precipitation distribution, a series of sensitivity experiments were performed similar to Jian and Wu (2008) and Yang et al. (2008). At the beginning of the 72-hour simulation, the elevations of the land surface of the island were reduced to 75%, 50%, and 0% of their actual value. Additionally, to distinguish between the effects of elevated terrain and the land surface, an additional run was performed where the island of Taiwan was replaced with ocean. No attempt was made to modify the initial atmospheric or oceanic conditions to compensate for the terrain modifications. This initially results in an artificial high pressure area over Taiwan, which rapidly disappears over the first few hours of the simulations.

3. TYPHOON SINLAKU

3.1 *Control Simulation*

During the first ninety-six hours after Sinlaku's formation, the storm moved in either a north-northwest or northerly direction until 0000 UTC 12 September. Around this time, the typhoon made a sharp west-northwest turn begin to move toward the island of Taiwan. This portion of the track was not captured by the real-timel COAMPS-TC runs, so the control simulation for this study begins at 1200 UTC 12 September. The JTWC best track and COAMPS-TC forecast track are shown in Fig. 1a. Sinlaku continued to move in a west-northwest direction until making landfall on the northeast coast of the island. After landfall, the typhoon made a tight cyclonic loop before continuing to move across the northern end of the island. After the storm had finished crossing over the island, it

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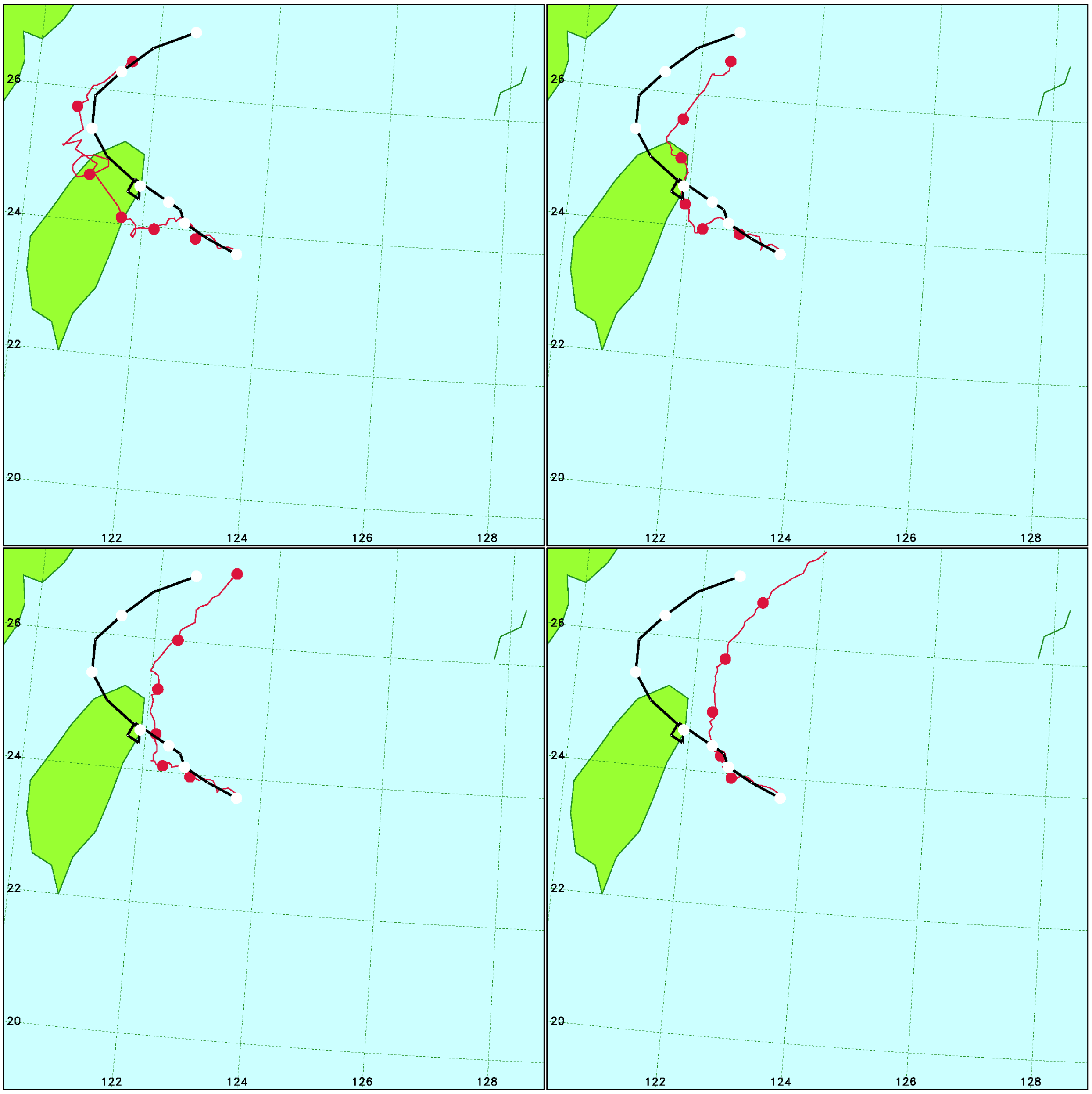

FIG. 1: JTWC best track (black) and COAMPS forecast tracks (red) from 1200 UTC 12 Sep - 1200 UTC 15 Sep 2008 for control (ul), 75% (ur), 50% (bl), and 0% (br) terrain simulations.

immediately began to recurve to the northeast.

The COAMPS-TC track simulates the general features of Sinlaku's track well. The initial motion is to the west-northwest, the storm undergoes a cyclonic loop upwind of Taiwan, and the track begins to recurve immediately upon leaving the island. (The COAMPS-TC tracker software uses the center of the wind circulation, so the large loop prior to leaving Taiwan's west coast may be more a result of local terrain effects than a representation of the actual track of the typhoon.) The most significant difference between the two tracks is the southward deflection in the model track prior to the upstream loop. The error in latitude at the bottom of the two loops is approximately 65 km (≈35 nm). While this would be considered better than the average track error for a 30-36 hour forecast, it has dramatic consequences on the simulated precipitation distribution.

Figure 2 shows the difference between the COAMPS-TC 72-hour accumulated precipitation forecast and an objective analysis based on Taiwan Central Weather Bureau rain gauge data for the same period. The largest errors, both positive and negative, occur in the area which lies between the observed and simulated typhoon tracks. The area of large overprediction ($>$ 1000 mm) on the east coast experiences upslope forcing north of the typhoon in the simulation, but in reality was located in a downslope area south of the typhoon. Similarly, the most significant area of underprediction (≈ -800 mm) on the western slopes of the Central Mountain Range would be characterized by upslope forcing south of Sinlaku in reality, but was simulated to receive downslope motion to the north of the storm in the model. The excessive southern deviation in the model also results in an area of overprediction on the west slopes of the southern tip of the mountain range. On the other hand, COAMPS does capture the rain shadow (with individual observations as low as 9 mm) on the southeastern coast that is to the south of both the observed and simulated tracks.

COAMPS-TC uses synthetic wind observations based on the JTWC warning message, so the initial model maximum wind agrees with the JTWC best track. However, the intensity of the simulated typhoon decreases rapidly after only one hour of model integration (Fig. 3). The simulated storm remains 10-15 m s^{-1} weaker than the best track maximum winds, both on the approach toward the Taiwan coast and after landfall when both the observed and simulated storms are significantly weaker. Lin et al. (2005) showed that weaker storms tend to experience larger track deflections than more intense ones. Since the COAMPS-TC simulation of Typhoon Sinlaku is weaker than the actual storm as it approaches the Taiwanese coast, this could partially explain why the simulated storm experiences a larger track deflection than that observed in reality.

When a previous COAMPS-TC forecast is available for initialization, improvements have been seen in track errors for weaker storms as a result of removing the synthetic observations from the analysis. This was attempted for the control simulation analysis for Typhoon Sinlaku and an improvement in the intensity forecast was observed. However, the modified wind structure in the absence of synthetic observations (not shown) appears to have had a more significant detrimental impact on the forecast. The resulting track contains no westward movement of the system and quickly moves to the NNE. Additional methods to improve the control run track forecast and the initial intensity and structure are being pursued.

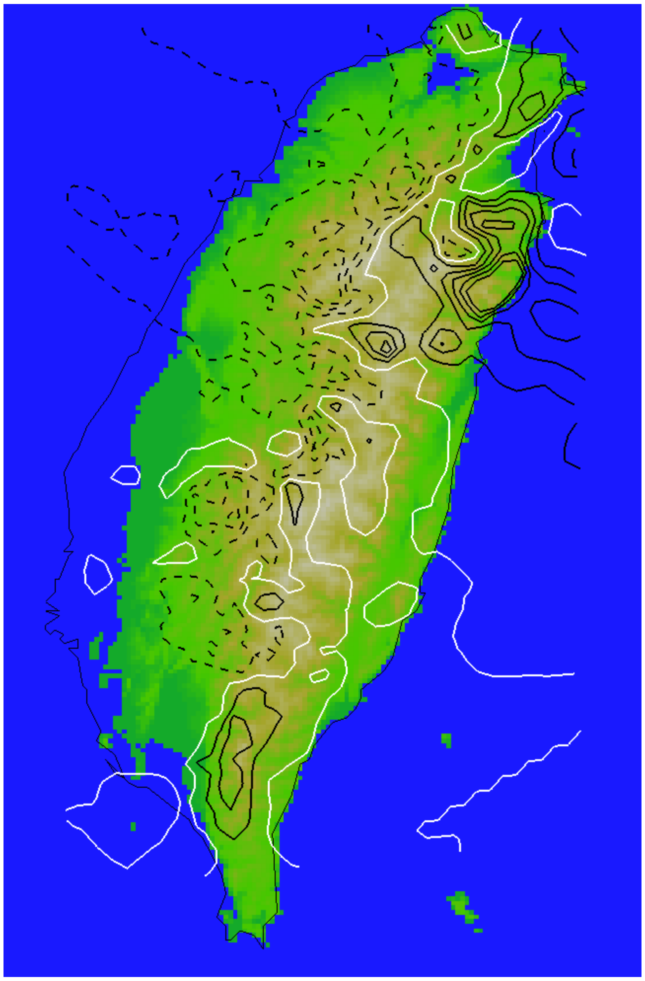

FIG. 2: Topography (shaded) and difference between simulated and observed total accumulated rainfall (contour interval 200 mm; 0 mm in white) from 1200 UTC 12 Sep - 1200 UTC 15 Sep 2008.

3.2 *Sensitivity Experiments*

Figure 1b-d show the forecast track from the reduced terrain sensitivity experiments. When the terrain is 75% of its actual value (Fig. 1b), the southern deflection upstream is reduced relative to the control simulation. This results in a landfall point which is close to the best track, although the incident angle is significantly different and the forecast track obtains a right of track bias after this point. The precipitation distribution from the 75% ter-

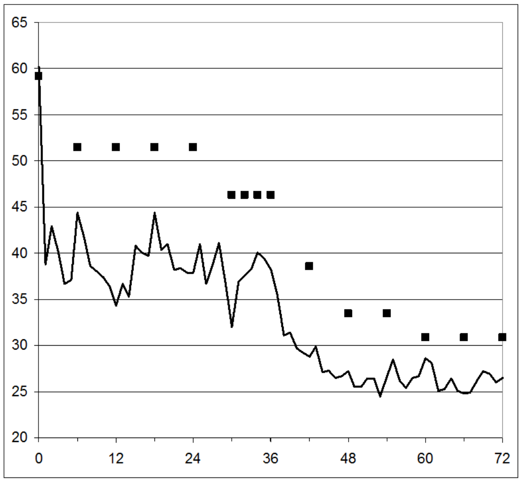

FIG. 3: 10-m maximum wind speed (m/s) for JTWC best track (squares) and COAMPS forecast (line) for Sinlaku from 1200 UTC 12 Sep - 1200 UTC 15 Sep 2008.

rain simulation (not shown) is much improved on the east coast of the island, though underprediction is still prevalent on the western mountain slopes. When the terrain elevation is further reduced to 50% of its actual value (Fig. 1c), the southern deflection is even further reduced to a very small deviation from the initial west-northwest movement. In this case, the storm actually begins recurvature before making landfall on Taiwan and simply moves northward along the island's eastern coast. This modified terrain also results a significant reduction of the rain shadow on the islands southeastern coast, with the forecast precipitation beginning to become much higher ($\approx$ 750 mm) than observed.

When Taiwan has been completely replaced by flat land, there is no southward deflection at all (Fig. 1d). This is consistent with previous studies by Lin et al. (2005) and Jian and Wu (2008) who attribute the southward deflection to a jet of strong northerly flow forming between the typhoon and the elevated terrain of Taiwan. However, it should be emphasized that the terrain is only removed for the last 72 hour simulation. When the terrain is removed for the previous two 12 hour update cycles, the track is more similar to the 50% terrain simulation. Regardless of when the terrain is removed, the storm does not make landfall on the island, as was the case for the 50% terrain simulation. The rainfall totals over Taiwan are dramatically lower in this case with amounts $>\approx$ 125 mm only occurring over the far northeast corner of the island. This reduction in accumulated precipitation is due to both the absence of upslope forcing over the flat terrain and the change in the storms track, which results in the heaviest convection to the right of the storm track moving away from the island. The simulations in which Taiwan is replaced by ocean (not shown) is very similar to the simulation with flat terrain, indicating that the effects of elevated terrain are more significant than the effects of a drier, rougher surface boundary.

Due to the significant track differences between the simulations with and without higher terrain, the storms in the former case make landfall and move across the island, while in the later case the storms remain over the ocean for the entire simulation period. This alone would be expected to result in differences in intensity between the two sets of simulation, independent of a direct topography-intensity interaction. More insight could be gained in an idealized modeling framework where a constant mean flow can produce relatively straight tracks. This is the subject of a companion paper (Billings and Doyle 2010, P2.104) which also explores the resulting surface wind field over the island.

4. TYPHOON JANGMI

Typhoon Jangmi passed over Taiwan two weeks after Sinlaku. Though there are significant differences between the JTWC and JMA best tracks as Jangmi moved over land, both tracks show a west-northwest movement from formation until it approached Taiwan, a landfall point between the central and northern portion of Taiwan's east coast, and immediate recurvature after the typhoon moves offshore. While Jangmi did produce extreme rainfall totals at individual points, amounts of these magnitude were not as widespread as in Sinlaku, likely due to Sinlaku's longer residence time on or near the island ($\approx$3.5 days for Sinlaku versus $\approx$2 days for Jangmi).

The setup for the COAMPS-TC control simulation for Jangmi was identical to the simulation for Sinlaku, with the exception of a new starting time at 1200 UTC 27 September. The JMA best track and COAMPS-TC forecast track are shown in Fig. 4a. While the tracks are not far apart as they cross over Taiwan, there is significant divergence both upstream and downstream of the island. Upstream, the forecast track continues to move along the initial heading after the best track begins to turn slightly northward and then makes a much sharper turn to the north several hours later. These problems with the track may be related to the starting time of the simulation, since this is approximately when Jangmi was interacting with the cool SST left in the wake of Sinlaku (Black et al. 2009). These track errors result in a dipole in the precipitation error (not shown) between the two tracks similar to that seen for Sinlaku. There is also a continued underprediction of precipitation for the western slopes of the Central Mountain Range.

A no terrain simulation was also performed for Jangmi with flat land in the place of Taiwan. The differences in the tracks with and without (Fig. 4b) terrain is less significant than in the case of Sinlaku. The northward deflection of the forecast track is more gradual and does not occur as far upstream. Also, after exiting the island, the storm maintains a westerly component to its motion and makes a faster landfall on the Chinese mainland. Both of these simulations contain very large track errors at the end of the 72-hour integration time, which underscores the importance in understanding the terrain effect on tropical cyclone motion.

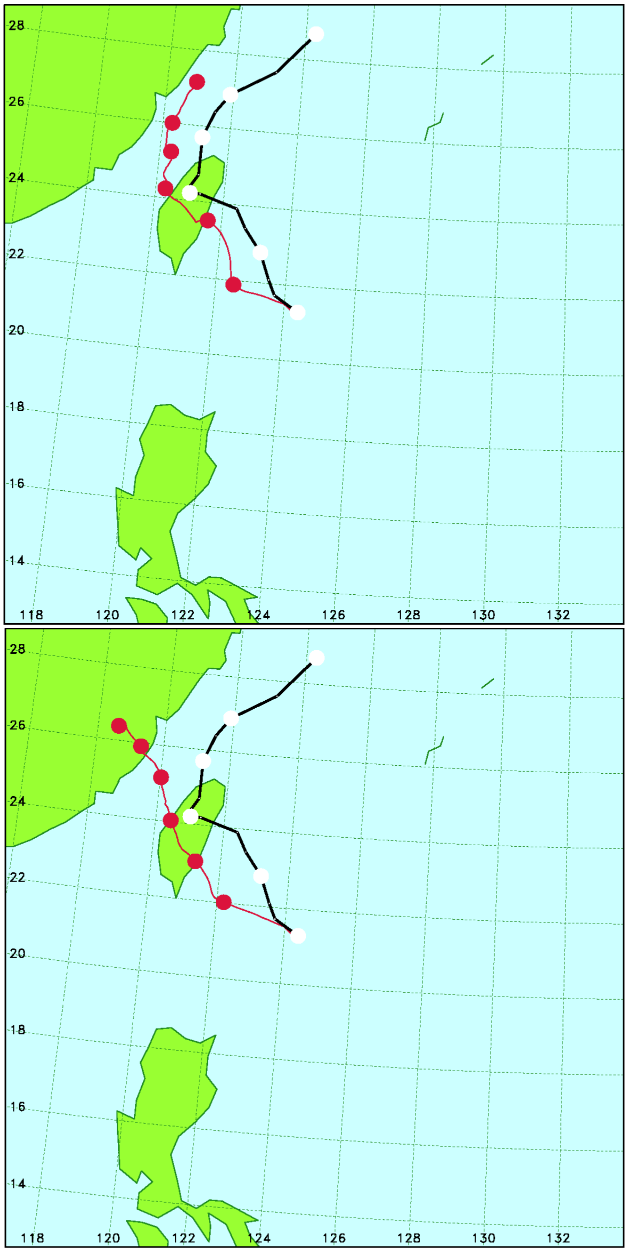

FIG. 4: JMA best track (black) and COAMPS forecast tracks (red) from 1200 UTC 27 Sep - 0000 UTC 30 Sep 2009 (1200 UTC for forecast) for Typhoon Jangmi control (top) and no terrain (bottom) simulations.

5. SUMMARY AND FUTURE WORK

Numerical simuations using COAMPS-TC demonstrate the large impact the steep topography of Taiwan had on both the track of Typhoon Sinlaku and on the rainfall distribution associated with this storm. During the period of interest, the typhoon was about to begin a recurving process, which would have moved it away from the island and kept the heaviest convective precipitation offshore. However, due to the presence of the Central Mountain Range, the storm is deflected southward, undergoes a cyclonic loop, and makes landfall on the northeastern coast of the island. Heavy rainfall is produced by both upslope forcing on the western mountain slopes and by the pre-existing convective precipitation accompanying the typhoon which is able to pass over the northern part of Taiwan. It can be seen that relatively small track errors can result in very large errors in the forecast of accumulated precipitation and subsequent flood forecasts. The terrain effect in initial simulations of Typhoon Jangmi appears to be less significant, but these results are still preliminary.

In addition to investigating avenues for further improving the COAMPS-TC control simulations and examining additional storms (such as the record breaking Typhoon Morakot), there are still more advanced diagnostics to be examined. This work has not examined the effect of the coupled ocean-atmosphere system to storm evolution, although this is likely an important process particularly for Typhoon Jangmi. Since the primary adverse effect of heavy rainfall is flooding of basins and urban areas, these rainfall distributions should be evaluated through the use of a hydrological model such as the simple empirical relationship used by Smith et al. (2009) or an independent numerical model. The sensitivity of forecast precipitation errors to forecast track errors can be examined more elegantly through the use of analytical models or using special modeling systems such as ensemble or adjoint models. Finally, the results from idealized numerical simulations of the effect of terrain on tropical cyclone track and intensity should provide further insight into the features observed in these and other real data simulations.

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