2D.6 EFFECTOF TOPOGRAPHY ON TROPICAL CYCLONE MOVEMENT

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1. Introduction

Tropical cyclone (TC) brings severe wind and heavy rain and thus causing threats to both economy and life during landfall. We recognize that the strong wind and heavy rainfall, which cause the most damage, of a TC is mainly confined to the core of the TC. If the forecast of the track of a TC is not accurate enough, the most dangerous area of TC would devastate other places in which the citizens did not take any precautions and even larger properties and human resources would be lost. Therefore, forecasting the track of TC accurately is a central part of research focusing on TC. In recent decades, our understanding of TC motion over the sea is well documented. Previous studies demonstrated that a TC is an area of positive relative vorticity, Chan (1984) found that the factors and processes change the relative vorticity and, thus, the TC motion. This concept was improved by regarding the TC as an area of positive potential vorticity (PV) rather than relative vorticity because of the contribution from the diabatic heating (Wu and Wang 2000).

However, when a TC approaches land, significant track deflection would occur, which leads to a larger forecasting problem. Possible mechanisms leading to track changes due to topographic effects have recently been studied by Kuo et al. (2001). When a TC gets closer to a coast, the bottom levels, the boundary layer, winds over land are weaker than those over the sea. The surface heat flux, moisture flux and also the convergence and divergence patterns are changed. Wong and Chan (2005) showed that the convergent (divergent) flow to the south (north) associated with the friction induced divergence (convergence) at the south (north) within the boundary layer drifts the TC southwestward to a meridional orientated rough flat land. Moreover, track deflection caused by land with topography, especially the Taiwan terrain was studied (e.g. Yeh and Elsberry 1993; Kuo et al. 2000). However, they mainly focused on the track change of a TC under different background flow strength and barotropic vortex with a huge radius of maximum wind and their explanations for the track deflections were not comprehensive.

The objectives of this paper are therefore to have a clearer explanation of the track deflection under no background flow by using the potential vorticity tendency dialogic approach and also comparing the track deflection when TCs move toward Taiwan with those move toward Philippines. Numerical experiments with real topography are performed with Weather Research and Forecast (WRF) model.

2. Model and Experimental Design

The Weather Research and Forecasting (WRF) model was employed in this study. Two sets of Triply-nested domain with 45-, 15-, and 5-km grid size and 33 vertical layers were used. The centers of each set of domains were co-located. One set of domains focuses on Taiwan with covering an area of 33^o lon x 40^o lat, 25^o lon x 30^o lat, and 15^o lon x 22^o lat from the outermost to innermost domain. The other set of domains focuses on Philippines covering an area of 33^o lon x 32^o lat, 22^o lon x 25^o lat and 18^o lon x 18^o lat from the outermost to innermost domain. The vertical layers were in eta levels, which is defined as $\eta = \frac{P-P_t}{P_s-P_t}$, where P is the pressure at certain

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level, P_t and P_s are the environmental pressure along the top level and surface level respectively. In this study, Pt and Ps were set to be 5hPa and 1010hPa respectively. The Coriolis parameter (*f*) was set to vary with the latitude, which means all experiments were conducted on beta plane.

The initial conditions of the specified bogus vortex in all experiments were the same as those used by *Wong and Chan [2004]* except some parameters of the vortex which were changed in different cases (will be covered in late part of this section). Real topography was used in this study. Different parts of topography were set either present or absent in different experiments. Moisture structure and temperature profile were set vary with terrain height. There was no background flow in the whole domain of all experiments, so that the movement of the Tropical Cyclone (TC) was not affected by the background flow. Moreover, the sea surface temperature was kept constant at 28.5^{o}C over the sea in the domains.

There were two main sets of experiments. Experiments in set 1 were to investigate the effect of Taiwan topography (central mountain range) on the track of the TC. In control experiment (CTRL1), all topography was removed from the domains but rough flat lands were left. Some initial parameters of the TC were explicitly defined. The radius of maximum wind, the radius of 15ms^{-1} wind and radius of TC were set to be 70, 300 and 1000km respectively, and the maximum tangential wind was set to 35ms^{-1}. For the landfall experiment, only Taiwan topography was present in the only Taiwan case (OnlyTW1). The initial characteristics of the TC in OnlyTW1 case were the same as that in the CTRL1.

Experiments in set 2 were to study the effect of Philippines topography especially the Luzon terrain on the track of the TC. The radius of 15 ms^{-1} wind of TC was enlarged to 450km. "-L", meaning Large, was added at the end of the symbol as indicant. In control experiment (CTRL2-L), all topography was removed from the domains but rough flat lands were left. On the other hand, all topography was present in the domains in the all-terrain case (AllTerr2-L). One additional experiment which was categorized in this set of experiments was only Luzon terrain case (Luzon2-L) in order to investigate the effect of the sharp terrain on Luzon only. All initial parameters of the TC in this experiment were the same as that in CRTL2-L but only Luzon terrain was present in the experiment. A summary of all experiments is shown in the Table 1.

Potential Votrticity Tendency (PVT) approach was employed to investigate the change in the TCs tracks. Moreover, the center of the TC in each experiment was defined by averaging all the pressure minimum center at each level within 0.85 and 0.55 eta levels since the TC at lower and middle levels tend to move to the region with maximum wavenumber one PVT. Bicubic interpolation is used to determine the pressure minimum center at each level.

As the topography effect is overpowered by the beta effect, the wavenumber one pattern of PVT and horizontal flow pattern of the control experiment were subtracted from that of the corresponding experiment. As the horizontal advection is the dominant term in the PVT equation in the most of the time of the simulation, only horizontal advection was studied in this paper.

Table 1. Summary of all experiments

<table>
<tr><th colspan="2">Experiments</th><th>Terrain presented</th><th>Maximum tangential wind(ms^{-1})</th><th>Radius of Maximum wind (km)</th><th>Radius of 15ms^{-1} wind (km)</th><th>Radius of TC (km)</th></tr>
<tr><td rowspan="2">Set1 (Taiwan)</td><td>CTRL1</td><td>None</td><td rowspan="5">35</td><td rowspan="5">70</td><td rowspan="2">300</td><td rowspan="5">1000</td></tr>
<tr><td>OnlyTW1</td><td>Only Taiwan</td></tr>
<tr><td rowspan="3">Set 2 (Philippines)</td><td>CTRL2-L</td><td>None</td><td rowspan="3">450</td></tr>
<tr><td>AllTerr2-L</td><td>All</td></tr>
<tr><td>Luzon2-L</td><td>Only Luzon</td></tr>
</table>

3. Set 1 - Experiments (Taiwan)

The TC center is defined by averaging all the pressure minimum center at each level within 0.85 and 0.55 eta levels. Bicubic interpolation is used to determine the pressure minimum center at each level. Figure 1 shows the track of TCs in set 1 experiments. The TC in the CTRL1 case (black lines in Fig. 1) moves toward northwest all the way and make landfall in the central part of Taiwan at 88 hour after the simulation started. The TC in the OnlyTW1 case moves toward northwest with similar track with that in the CTRL1 at the early stage of the simulation. When TC gets closer to Taiwan, it deflects toward the right compared with the CTRL1. The TC, then, bends toward the land when it is about to make landfall and deflects toward southwest during moving over Taiwan terrain. The TC have northwestward track again after it got into Taiwan Strait.

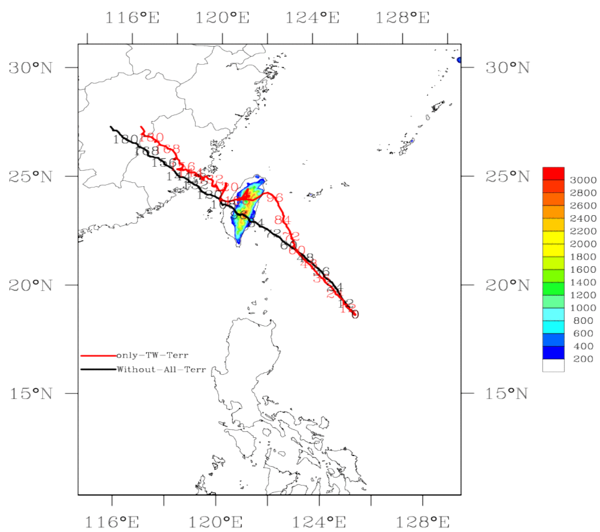

Figure 1. Track of the TC in CTRL1 (black line) and OnlyTW1 (red line). the labeled number denote 12-hourly TC positions.

As the HA term in PVT equation is the dominant term in the most of the time of the simulation, this paper, thus, focuses on the HA term. In order to investigate the HA term, horizontal flow pattern is studied. In this study, the asymmetric flow is obtained by subtracting the symmetric wind field from the total wind field. 12 hourly average is then applied to the hourly output of the asymmetric flow pattern because the oscillatory motion is avoided. In the early stage of the simulation, 24 to 36 time period, terrain induced gyre pair is found in the asymmetric flow difference between OnlyTW1 and CTRL1 (Fig.2). At this time period, the westerly wind at the outermost radius of TC encounters the northeastern part of Taiwan terrain and be forced to raise along the Central Mountain Range (CMR) of Taiwan. Convergence at Taiwan is thus induced. After passing over the CMR, the wind descents at the southwestern part of the mountain and thus induces a divergence at that region. However, the ventilation flow between this gyre pair does not yet affect the TC center. Therefore, the track deviation of OnlyTW1 and CTRL1 is small at the early stage of the simulation.

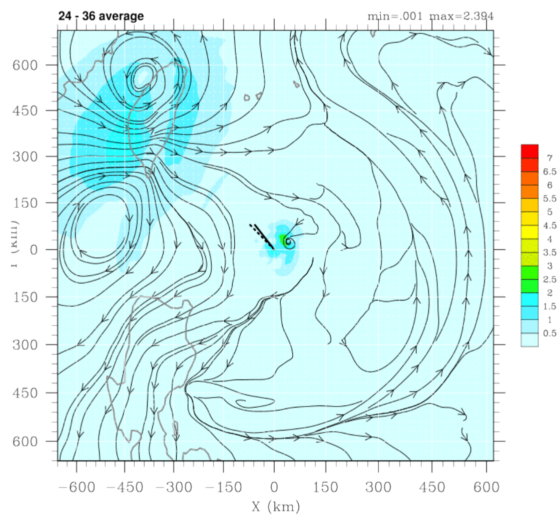

Figure 2. Asymmetric flow difference between OnlyTW1 and CTRL1 in 24-36 time period (lines with arrows represent the streamlines and the colors show the wind speed difference, in m/s, between two cases) (solid straight line represent the overall direction of the TC in OnluTW1 within this time period and dotted line represent TC in CTRL1)

As the TC moves toward Taiwan, the terrain induced gyre pair rotates cyclonically around the TC center. The southwesterly ventilation flow between the gyres starts to affect the TC center and to "push" the TC center toward northeast (Figures 3a-b). Therefore, there is a rightward deflection of the TC track in onlyTW1.

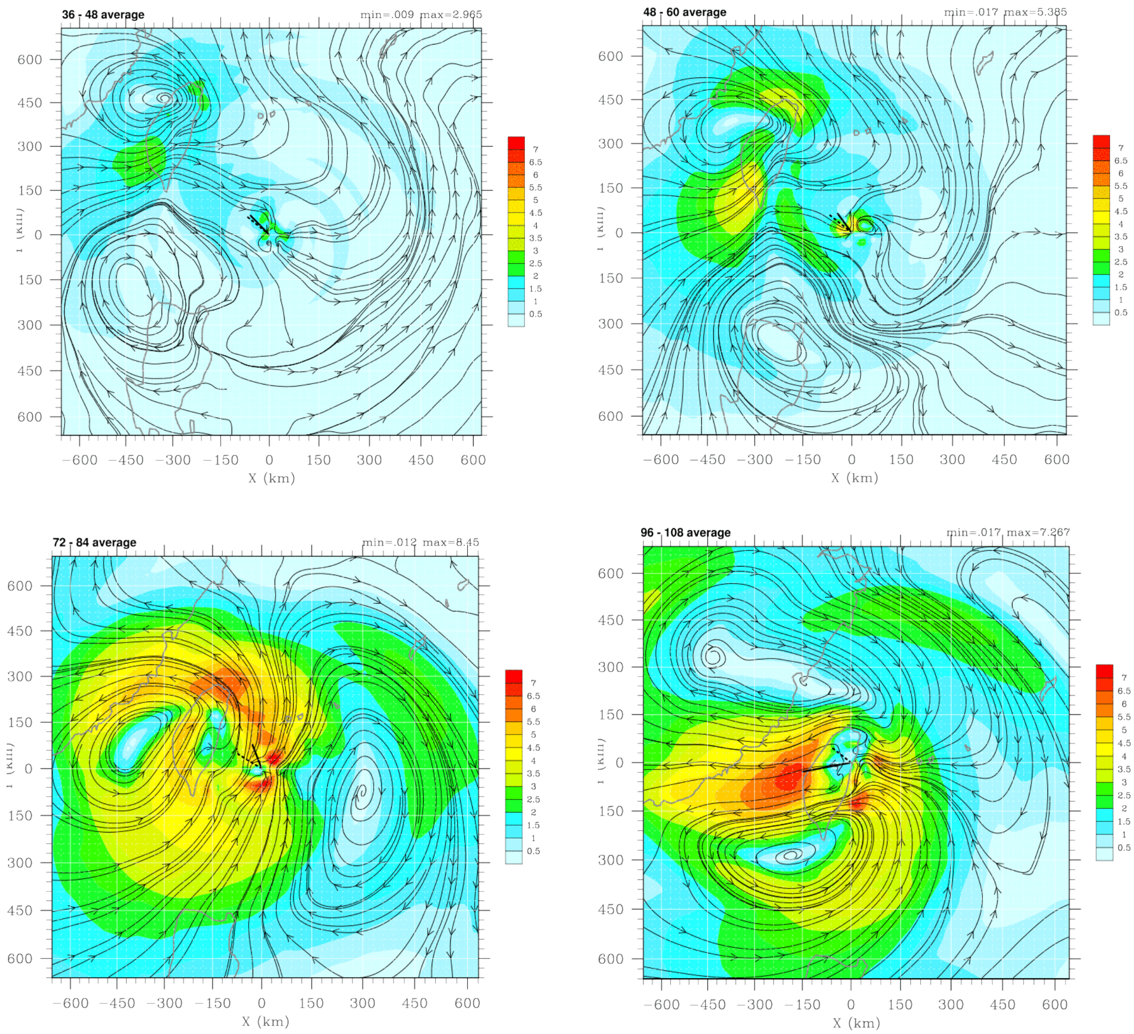

Figure 3. Asymmetric flow difference between OnlyTW1 and CTRL1 at the period of (a) 36-48 hour, (b) 48-60 hour (c) 72 -84 hour and (d) 96-108 hour

Figure 3c shows that the ventilation flow is almost perpendicular to the direction of the TC motion in CTRL1. Therefore, there is the largest track direction deviation between two cases. When the TC is about to landfall on Taiwan, the terrain induced gyre pair is now in the north-south orientated and the ventilation flow is from the east to the west (Figure 3d). However, the track deviation between two cases is in southwest direction. The ventilation flow between the gyre pair contributes the westward component of the track deviation. The southern component of the track deviation is contributed by the diabatic heating (DH). Figure 4 shows that DH term becomes comparable to HA term. However, DH term is out of scope of the paper, it will not be covered in this paper. When the TC gets into Taiwan Strait, the ventilation flow is in the opposite direction to the TC motion (Figure 5). Therefore, the speed of TC in OnlyTW1 is decelerated.

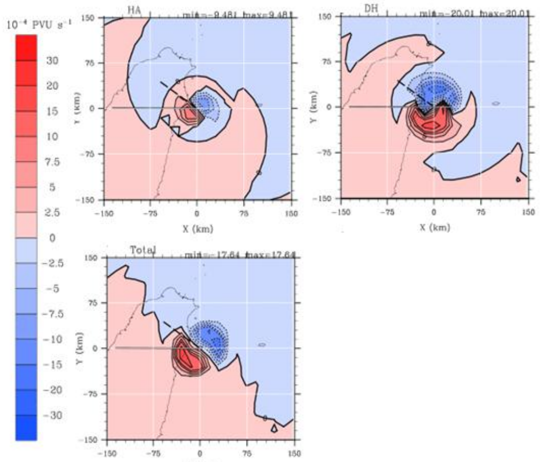

Fig.4 azimuthal WN1 component of PVT at 96-108 time period: (top left) horizontal advection term, (topright) diabatic heating term, and (bottom left) the total potential vorticity tendency. unit: 10^{-4} $PVUs^{-1}$

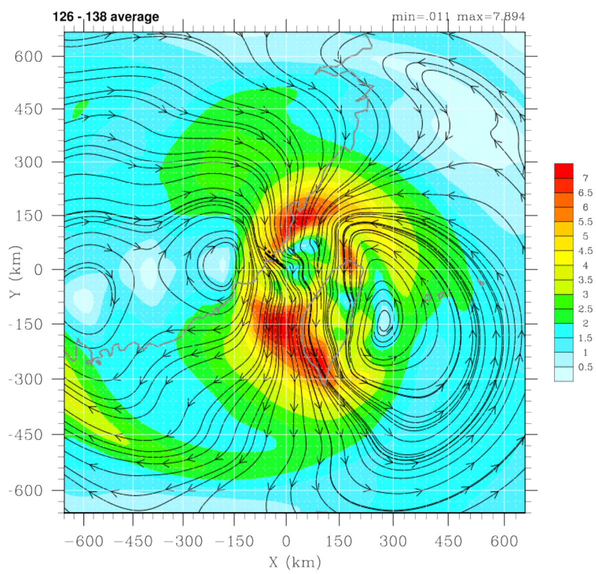

Fig. 5 asymmetric flow difference between OnlyTW1 and CTRL in 126-138 time period

4. Set 2 - Experiment (Philippines)

Figure 6 shows the Track of TCs in set 2 experiments. The TC in the CTRL2-L case (black line in Fig.6) moves northwest-ward all the way and landfall at Luzon at 44 hour after the simulation started. The TC in the Luzon2-L case moves northwest-ward with rightward deflection prior to landfall and band toward to the land when the TC is above to landfall. The rightward deflection of the TC in AllTerr2-L case is less than that of the TC in Luzon2-L case. However, it moves more westward after leaving Luzon than the other two cases.

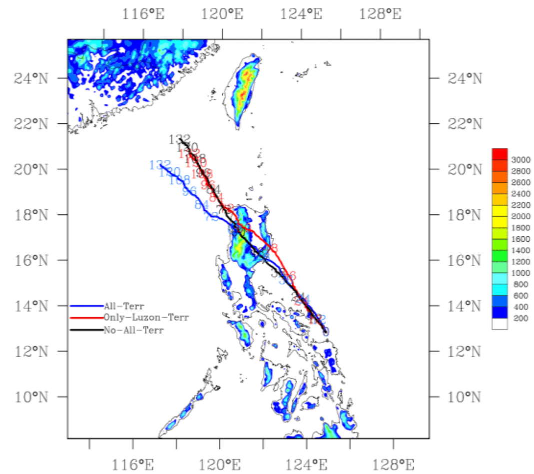

Figure 6. Track of the TC in CTRL2-L (black line), Luzon2-L (red line) and AllTerr2-L (blue line). the labeled number denote 12-hourly TC positions. Contours represent the terrain height.

As the HA term in the PVT equation also dominates in this set of experiment, we mainly focus on HA term.

a) Luzon2-L case

Figure 7 shows the terrain induced gyre pair is also found. The formation of the terrain induced gyre pair has the similar mechanism as that in the set 1 experiment (the Taiwan's experiments). It tends to rotate cyclonically around the TC center as the TC moves toward to the mountain on Luzon. The westerly ventilation flow between the gyres "pushes" the TC center eastward. However, the strength of the ventilation flow is not that strong as that in Taiwan experiments (not shown), so the rightward deflection is not that large as that in Taiwan experiments.

When the TC make landfall at Luzon, the DH term becomes comparable to HA term in the PVT equation. After the TC enters the South China Sea, HA term becomes the dominant term again. However, the ventilation flow is in the southwest direction (Figure 8). It, thus, "pushes" the TC toward southwest compared with the CTRL2-L and decelerates the speed of TC in South China Sea.

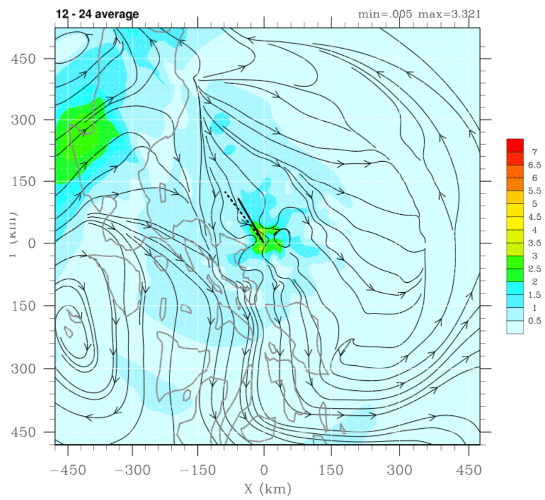

Figure 7. asymmetric flow difference between Luzon2-L and CTRL2 in 12-24 time period. (solid straight line represent the overall direction of the TC in Luzon2-L within this time period and dotted line represent TC in CTRL2)

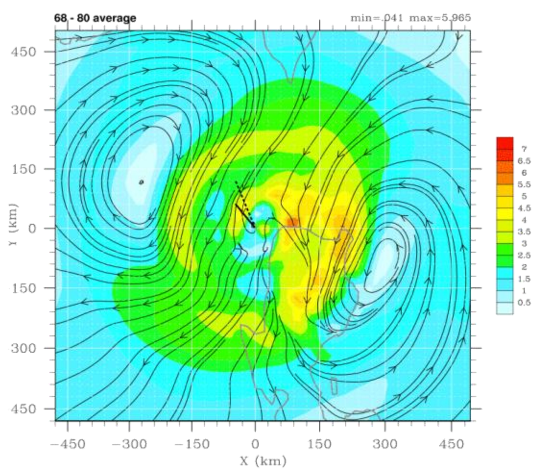

Figure 8. asymmetric flow difference between Luzon2-L and CTRL2 in 68-80 time period.

b) AllTerr-L case

In order to investigate the whole Philippines terrain effect on TC track, all terrains are present in this AllTerr-L case. Terrain induced gyre pair is also found in this case (Figure 9). However, the eastward extension of the anticyclonic gyre is suppressed because of the convergence over the Philippines island chain. This convergence weaken the anticyclonic gyre when it rotates over the island chain. As a result, the ventilation flow between the gyre pair is weakened. The rightward deflection of the TC is much smaller when compared with that in Luzon2-L case.

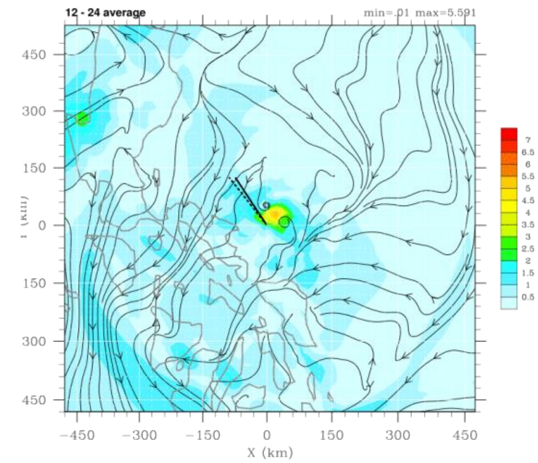

Figure 9. asymmetric flow difference between AllTerr2-L and CTRL2 in 12-24 time period. (solid straight line represent the overall direction of the TC in AllTer2-L within this time period and dotted line represent TC in CTRL2)

Figure 10 shows that when the TC enter South China Sea, the terrain induced gyre pair is in northwest-southeast orientation. The convergence over the island chain enhances the anticyclonic gyre and, thus, the stronger ventilation flow "pushes" TC more southwest-ward compared with the CTRL2-L case.

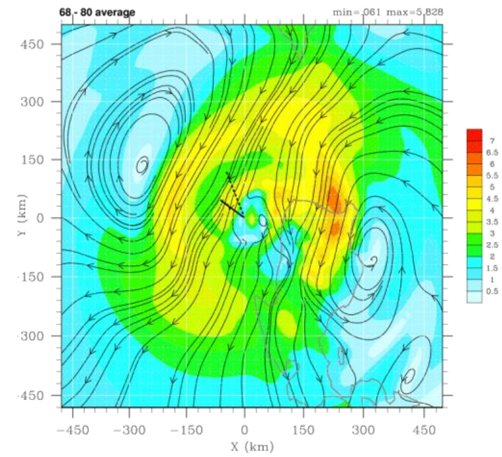

Figure 10. asymmetric flow difference between AllTerr2-L and CTRL2 in 68-80 time period.

5. Conclusion and Future work

Numerical experiments are conducted in Weather Research and Forecast (WRF) model in order to study the effects of Taiwan and Philippines terrain on the tropical cyclone movement. On beta plane, the TCs are initially placed far away from the sharp mountain, like central mountain ranges in Taiwan and Luzon, in an atmosphere at rest. It is found that terrain induced gyre pair induced near to the terrain due to the sharp mountain. The ventilation flow of the gyre pair does not yet affect the TC center at the early stage of the simulation. The gyre pair is advected to rotate cyclonically around the TC center and its ventilation flow starts to push the TC toward the east. The rightward deflection is, thus, obtained. TC in all experiments except the CTRL1 and CTRL2-L case are accelerate (decelerate) when the ventilation flow is align with (opposite direction to) the direction of the movement of TC respectively. Diabatic heating becomes comparable to horizontal advection term during the landfall of TCs.

Similar rotation of the terrain induced gyre pair is found in Philippines terrain case. But the ventilation flows in two Philippines terrain experiments are weaker than that in the TW terrain case since the mountains in Luzon are lower than the central mountain range in Taiwan and thus the weaker terrain induced gyre pair. Therefore, the rightward deflections of the Tracks in two Philippines terrain cases are less than that in Taiwan terrain case. One more point worth mentioning is the effect of the Philippines island chain on the strength of the terrain induced gyre pair. The convergence over the Philippines island chain weakens the anticyclonic gyre of the gyre pair, which is associated with a divergent region. Therefore, the ventilation flow is only attributed by the cyclonic gyre and thus a weaker ventilation flow and even smaller rightward deflection is found for the AllTerr2-L case. On the other hand, the convergence over Philippines island chain enhances the cyclonic gyre of the gyre pair, which is associated with a convergent region, when it rotates to pass over the Philippines island chain. Therefore, the TC in AllTerr2-L move more southwestward than that in OnlyLuzon2-L when the TCs get into the South China Sea.

As the DH term becomes one of the major term in the PVT equation when the TC is above to and during landfall, DH term will be investigated in the coming future. It would be useful to understand the changes in tracks during landfall due to the topography effect.

6. Acknowledgment.

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7. References

Andie Y. M. Au-Yeung, Johnny C. L. Chan, 2010: The Effect of a River Delta and Coastal Roughness Variation on a Landfalling Tropical Cyclone. Journal of Geophysical Research 115:D19, doi:10.1029/2009JD013631,2010

Chan. J. C. L., 1984: An observation study of the physical process responsible for tropical cyclone motion. J.Atmos. sci., **41,** 1036-1048.

Elsberry, R. L., 1995: *Global Perspective of Tropical Cyclones. World Meteorological Organization WMO-TD-No. 693, Rep. TCP-38*, 289pp.

K. C. Szeto, Johnny C. L. Chan, 2010: Structural changes of a tropical cyclone during landfall: β-plane simulations. Advances in Atmospheric Sciences. 27:5, 1143-1150

Kuo, H. **C**., R. T. Williams, J. H. Chen, and Y. **L**. Chen, 2001: Topographic effects on barotropic vortex motion: No mean flow. *J. Atmos. Sci.*, **58,** 1310–1327

Wong, M. L. M., and J.C.L. Chan, 2006: Tropical cyclone motion in response to land surface friction. *J. Atmos. Sci.*, **63,** 1324-1337

Wu, L., and B. Wang, 2000: A potential voracity tendency diagnostic approach for tropical cyclone motion. Mon. Wea. Rev., **128,** 1899-1911.

Yeh T-C, Elsberry RL,1993: Interaction of typhoons with the Taiwan orography. Part I: Upstream track deflections. Mon Wea Rev **121:** 3193–3212