9.4 Influence of topography on the track and intensity of tropical cyclones

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1. INTRODUCTION

Tropical cyclones derive their energy as latent heat from surface evaporation of warm ocean water, and, as a result, tend to diminish over land. Mountainous terrain changes the circulation, and alters the deep convection that releases the latent energy, changing the intensity and track of the tropical cyclone. Some examples of these effects can be found in the recent literature. Geerts, et al. (2000) documents the changes in Hurricane George as it moved over the mountainous island of Hispaniola. May et al. (2008) used weather radar to gather detailed observations of Tropical Cyclone Ingrid as the storm passed parallel to and close to the coastline near Darwin, Australia. They noted significant changes to the tangential wind field as the storm passed over a narrow region of open ocean. Chan and Liang (2003) used the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) to simulate landfall of a hypothetical vortex. They found that while the main effect on the storm came from the modification of the surface latent heat flux, lack of moisture changed where the convection appeared in the storm, by modifying the moist static stability of the atmosphere. Farfán and Cortez (2005) used the MM5 to investigate Hurricane Marty as the storm moved over the Baja Peninsula and into the Gulf of California. Flattening of the mountains in one model run allowed Marty to not be deflected into the Gulf, suggesting that the mountains acted as a physical barrier to the storm movement. Ramsay and Leslie (2008) used the MM5 to investigate the influence of mountains on Hurricane Larry as the storm made landfall. They did two model runs, one with real topography, and one with topography set to zero. The mountains played a significant role in the modification of the wind field and in the track as Larry moved inland.

Several storms that passed near land or over land occurred in the hurricane season of 2010. Hurricanes Alex, Karl, and Richard all passed over the Yucatan Peninsula without dissipating. Tropical Storm Nicole moved right over Cuba before dissipating south of Florida. Hurricane Paula grazed the coast of Nicaragua, curved by the Yucatan Peninsula, and then moved along the north coast of Cuba, ending near the same point Nicole ended at, just south of Florida. Finally, Hurricane Tomas, after moving westward for nearly a week, recurved south of Haiti, and moved through the narrow strait (the Windward Passage) between Haiti and Cuba, then continuing on to the northeast.

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2. Hurricane Tomas

Hurricane Tomas, the last storm of the 2010 season, is the focus for the work discussed here. Tomas caused 44 deaths and more than $340 million in damages. Figure 1 shows the National Hurricane Center Best Track. Figure 2 shows the central sea-level pressure from the Best Track data. There were three periods of intensification and weakening. The first period occurred on October 31, 2010, soon after the storm formed. The sea-level pressure hit its lowest point, and the maximum surface wind in Tomas reached 85 knots, the highest in its lifetime. Tomas weakened for the next three days as the storm moved westward along the north coast of South America. As Tomas turned to the north, it began to strengthen, reaching its second peak in strength on November 5, 2010, with a sea-level pressure of 970 mb. Tomas was now hemmed in by the islands of Jamaica to the southwest, Hispaniola to the east, and Cuba to the northwest. Tomas lost strength from this time until the next day, as it passed through the Windward Passage between Cuba and Hispaniola. Once north of the Passage, Tomas underwent its third period of intensification, followed soon afterwards by a final weakening and eventual dissipation.

3. Research Questions and Model Setup

The track of Tomas threaded the narrow Windward Passage presenting an excellent opportunity to test the effect of the land on the movement and structure of Tomas. Did Tomas move eastward into the Passage because the southeastern end of Cuba presented a barrier? Did the storm weaken during the period it moved through the Windward Passage because the presence of land reduced the surface latent heat fluxes, and thus reduced the available energy for the storm? How did the location and amount of precipitation change as a result of the interaction with the land?

To answer these questions, the NCAR Advanced Research Hurricane WRF (AHW) model was used to simulate Hurricane Tomas, using two domains. The outer domain is shown in Fig. 3, with the inner domain outlined in red. The outer domain had 186x132 grid points at 30 km grid spacing, while the inner, two-way interactive nest had 151x145 grid points at 10 km grid spacing. The physics packages used with the model were the same in both domains, and followed the recommended setup for

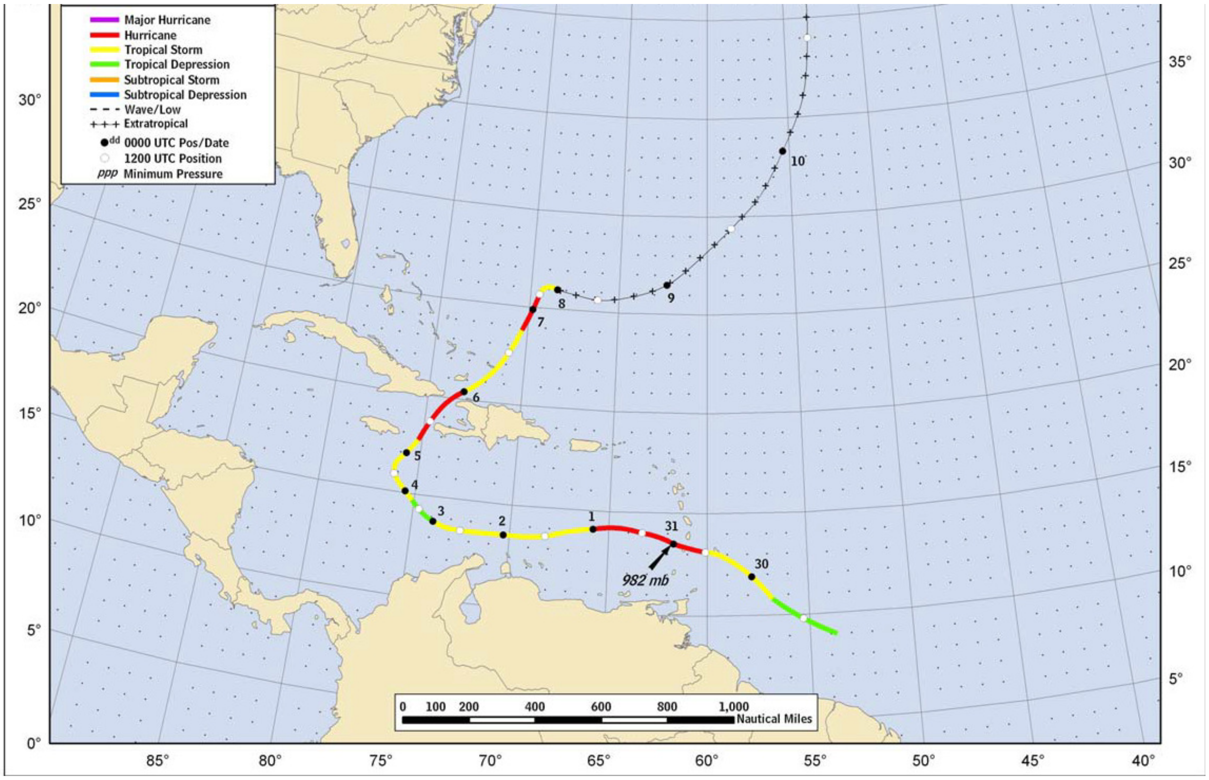

Figure 1. National Hurricane Center Best Track for Hurricane Tomas.

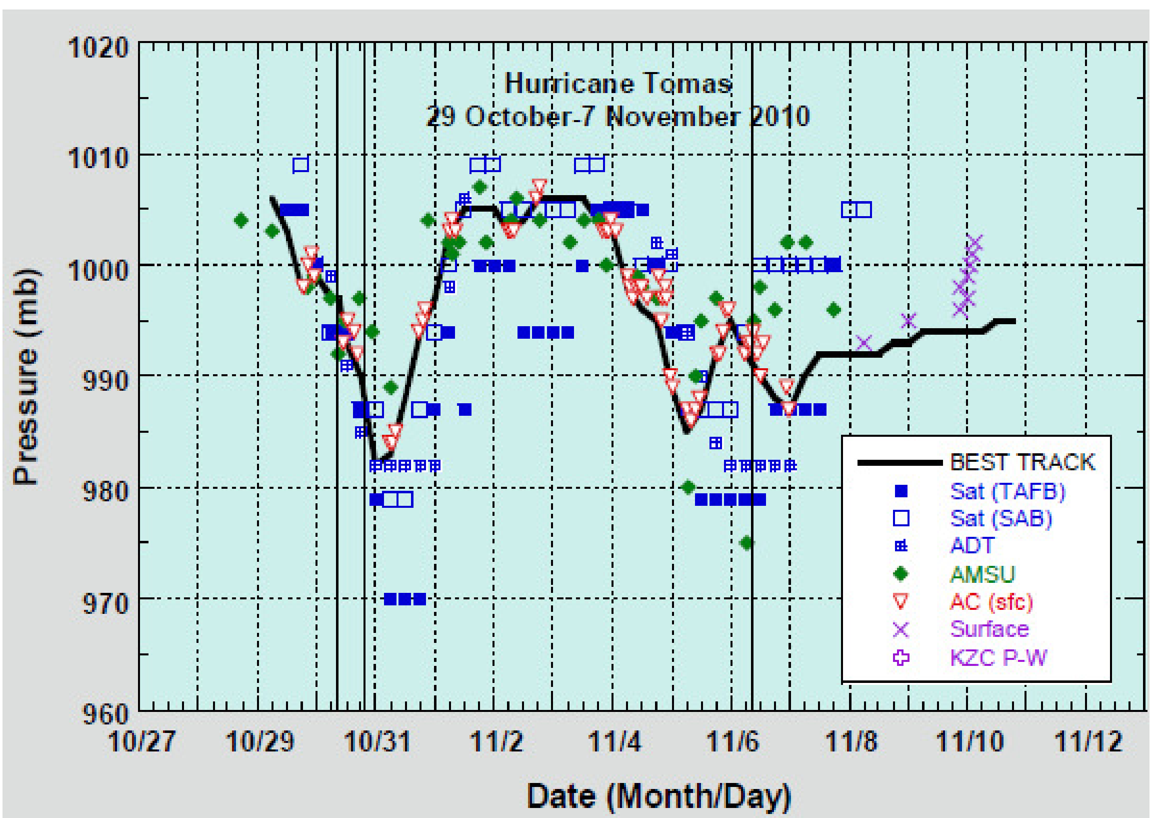

Figure 2. National Hurricane Center Best Track central sea-level pressure data.

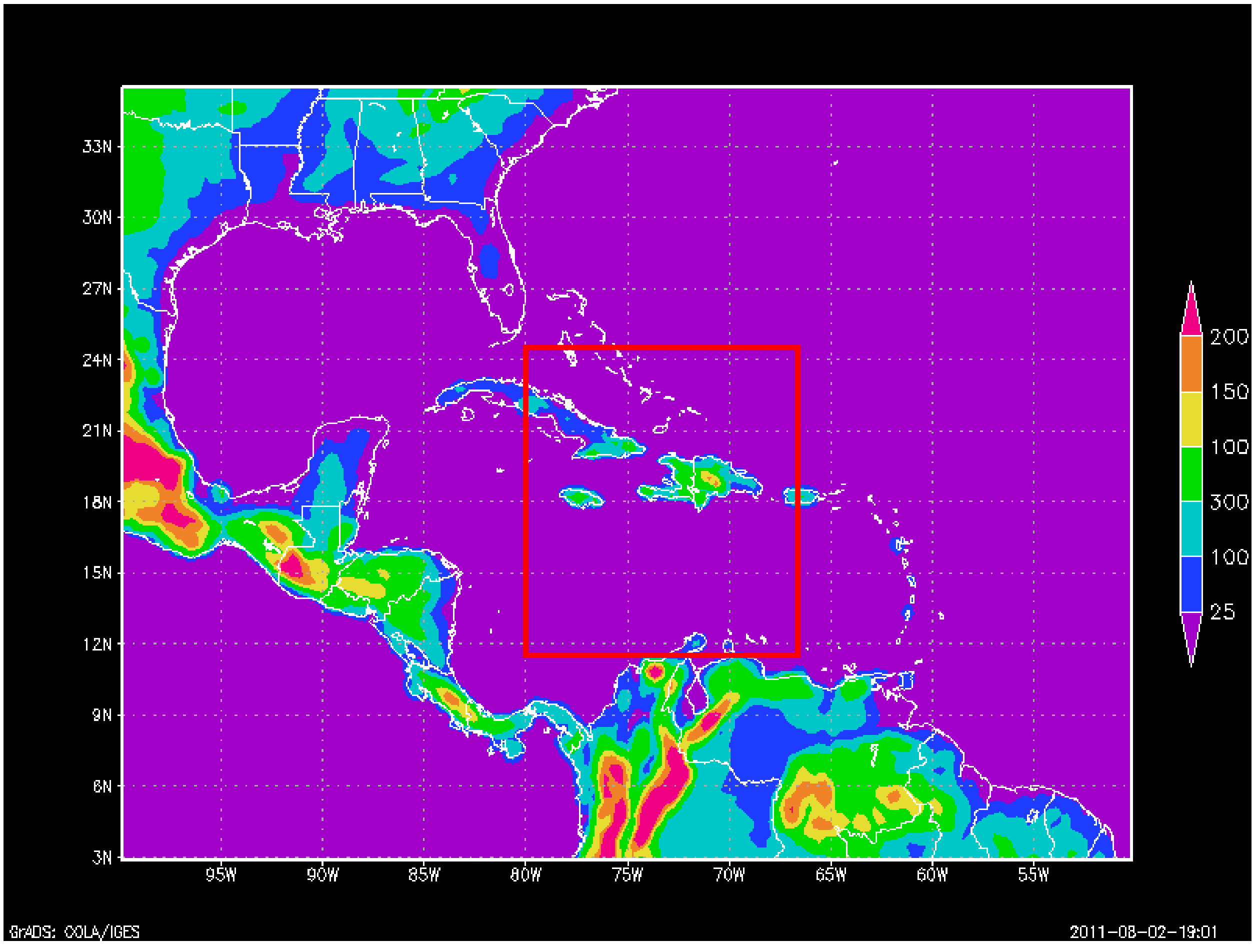

Figure 3. Model outer domain, with elevation in m. Location of inner domain shown with red box.

the AHW model according to the WRF ARW website (UCAR, 2011).

Four model runs were made starting at 00 UTC, November 5, 2010: Control, in which the operational terrain available in the model software was used, Flat, in which the terrain elevation was reduced to sea level in the inner nest, Sea, in which the terrain elevation in the inner nest was reduced to sea level and the land surface was turned into ocean, and Water Mountain (designated WMtn), in which the terrain elevation was left as in Control, but the land surface was changed to water. Although this last configuration is physically impossible, it allowed the effect of the raised surface to be tested more carefully.

4. Model Results

The suite of model runs show, to the extent that the model is able to simulate the real world correctly, that the presence of land weakened Tomas and reduced the amount of precipitation. The mountains on the eastern side of the island of Cuba deflected Tomas to the east, reduced the total amount of precipitation, and changed where the intense precipitation fell. Most of these results were caused by the change in the size and location of the surface latent heat fluxes which provide the energy for the storm. The details of these changes follow.

4.1 Weakening

Figure 4 shows the central sea-level pressure from the four model runs. The two model runs that have no land in them, the Sea run and the WMtn run, both show an almost linear strengthening as the storm passes through the Windward Passage. The Control run shows a weakening as the storm moves into the Passage after 18 UTC, November 5, followed by a period of no change, until the storm is north of the Passage after 22 UTC. The Flat run is almost the same as the Control run, although there is only a period of no change from 18 UTC through 22 UTC. After the simulated storms emerge from the Passage, both the Control and Flat runs show intensification. The presence of land is what separates these pairs of runs. Whether there are mountains or not is secondary, and the WMtn run ends up being the strongest storm of all the runs.

4.2 Amount and Location of Precipitation

Figure 5 shows the accumulated precipitation ending 00

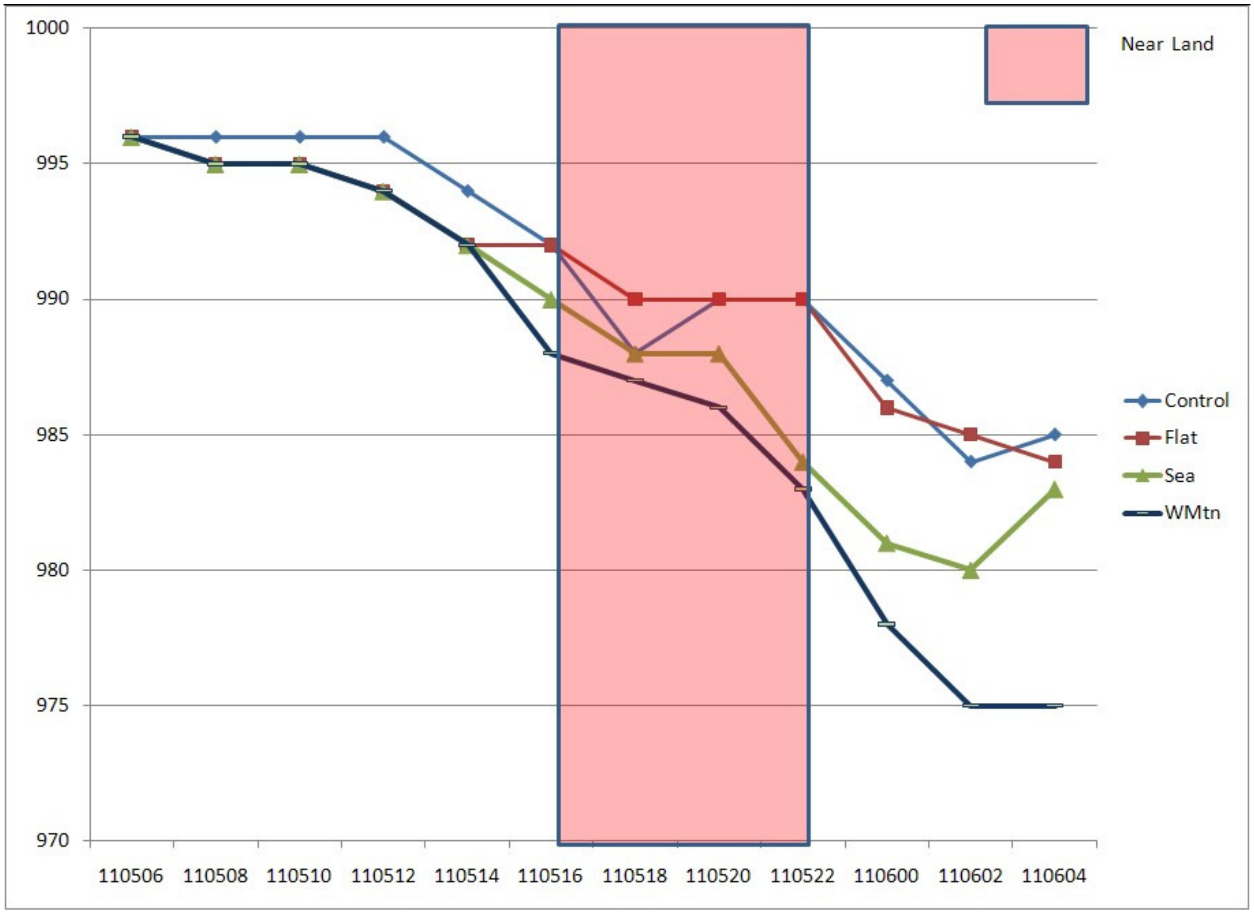

Figure 4. Central sea-level pressure in mb from the four model runs. Pink shading shows time period when storm was close to land.

UTC, November 6, from the Control run while Fig. 6 shows the same field from the Sea run. The peak intensity in the Control run is more than 350 mm, while that in the Sea run is less than 300 mm. The area covered by the precipitation in the Sea run is spread over the eastern part of the island of Cuba, while the precipitation in the Control run all fell just east of the mountains on the eastern tip of Cuba. To the south, along the peninsula from Hispaniola, the effect is similar with higher intensity of precipitation in the Control run. Despite the more intense accumulations in the Control run, however, the average precipitation in the red box is 80.7 mm for the Sea run, and only 67.8 mm in the Control run, a difference of 19%. The greater amount of precipitation in the Sea run is more evenly spread out in the area where the terrain was in the Control run. Figure 7 shows the difference in accumulated precipitation between the Control and Sea runs, as of 00 UTC, November 6. The heightened intensity along the eastern edge of the island of Cuba shows up clearly here. Figure 8 shows the precipitation difference between the Control and Flat runs. The pattern shows a small area of greater intensity right along the eastern edge of the island of Cuba, but very little difference over the land. The difference between the Control and Flat runs is driven entirely by the mountainous terrain, and the difference reflects the orographic uplift. The WMtn run reflects the influences of both the water surface and the raised surface. Figure 9 shows the difference between the Control run and the WMtn run, and the pattern resembles that in Fig. 7 for the Control and Sea runs. The WMtn run has more precipitation than any of the runs, but the pattern of precipitation is more like the Sea run than the Control run. The influence of the water surface is more important to the pattern of precipitation than the orographic uplift that the elevated surface provides.

4.3 Eastward Deflection

The streamlines for the Control and Flat model runs at

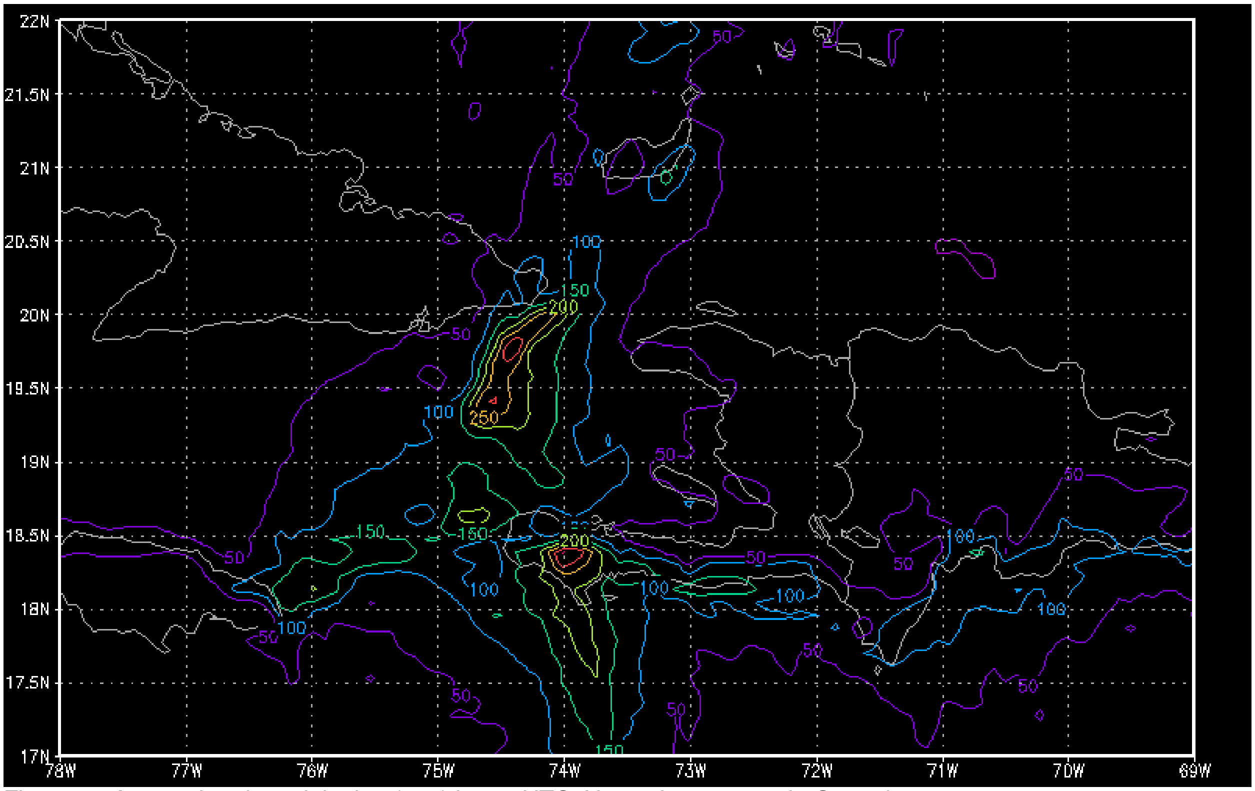

Figure 5. Accumulated precipitation (mm) by 18 UTC, November 5, 2010 in Control run.

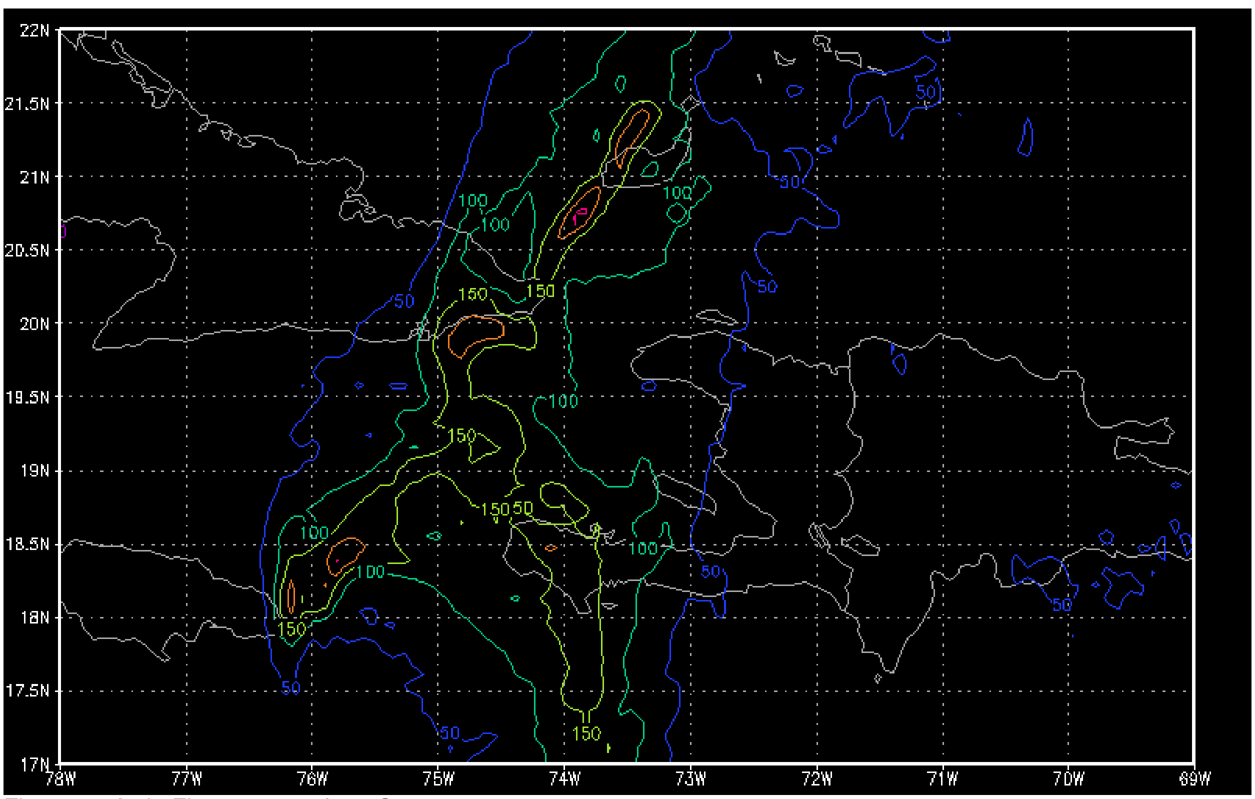

Figure 6. As in Fig. 5, except from Sea run.

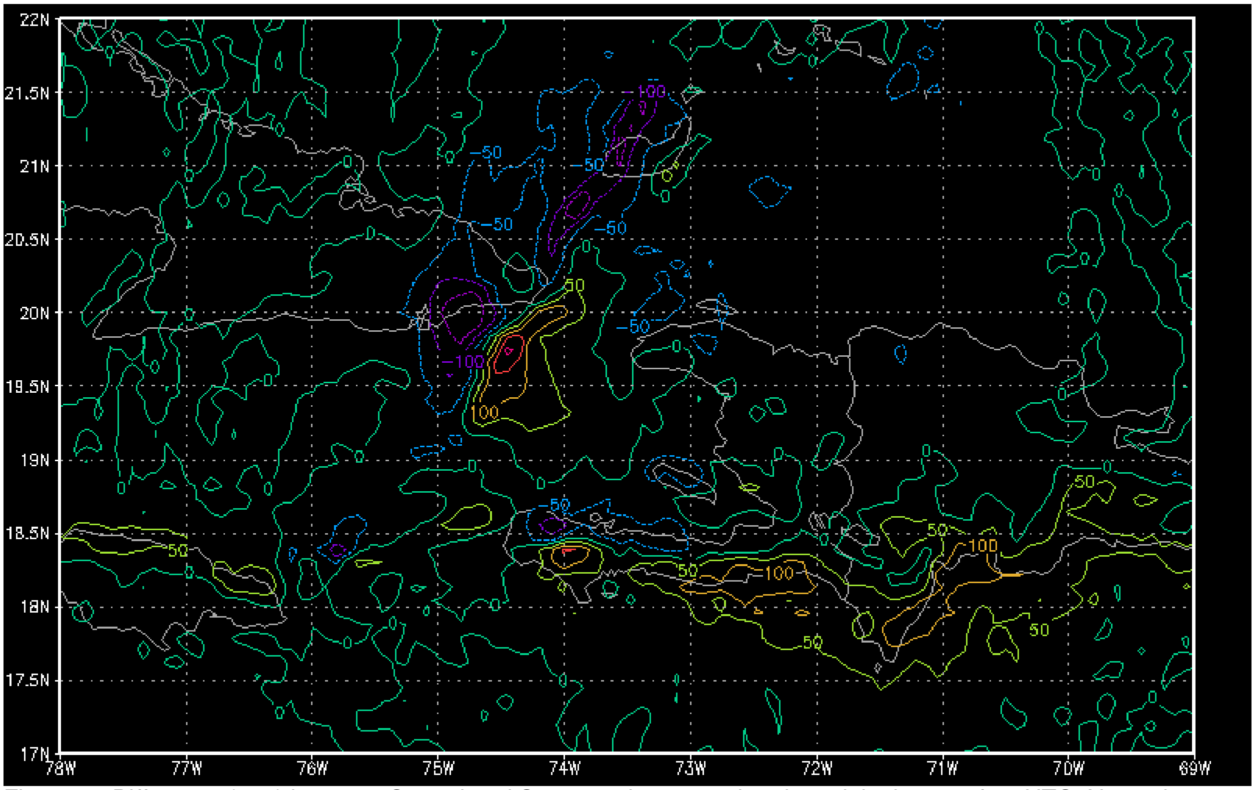

Figure 7. Difference (mm) between Control and Sea runs, in accumulated precipitation as of 00 UTC, November 6, 2010.

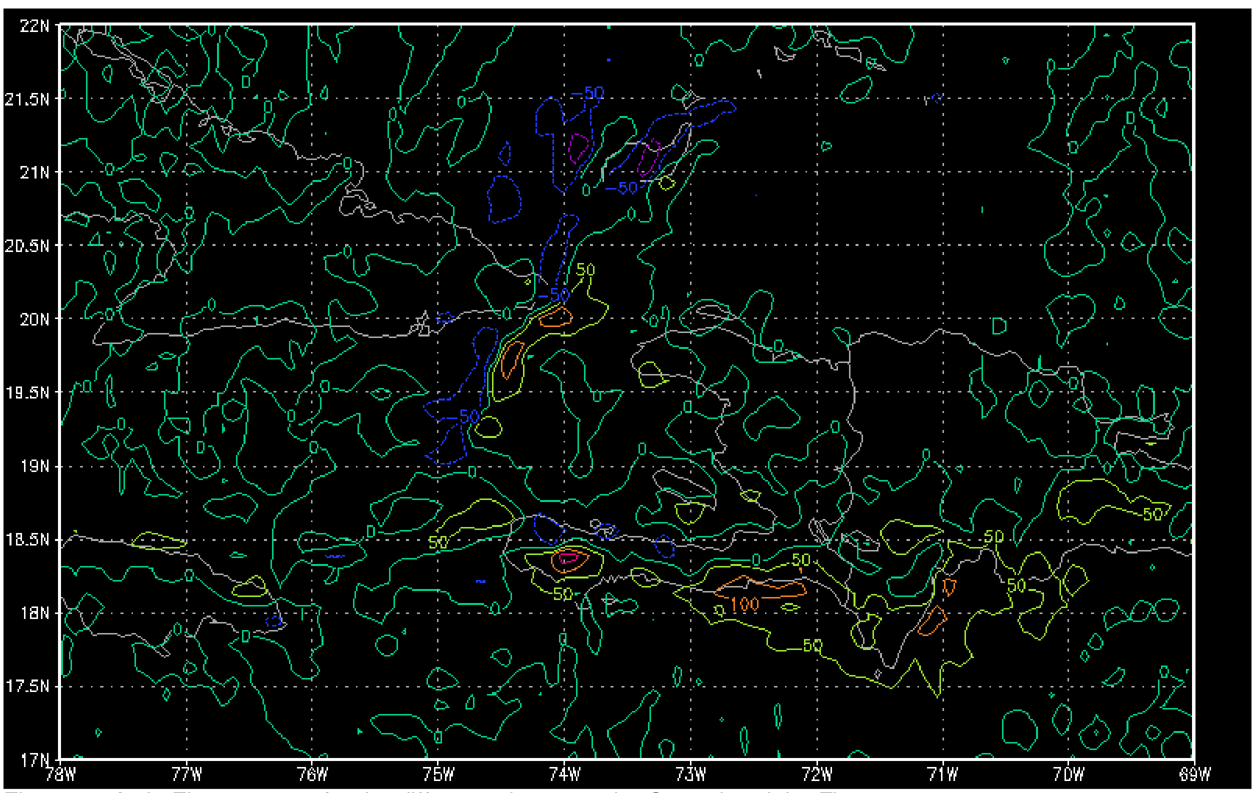

Figure 8. As in Fig. 7, except for the difference between the Control and the Flat runs.

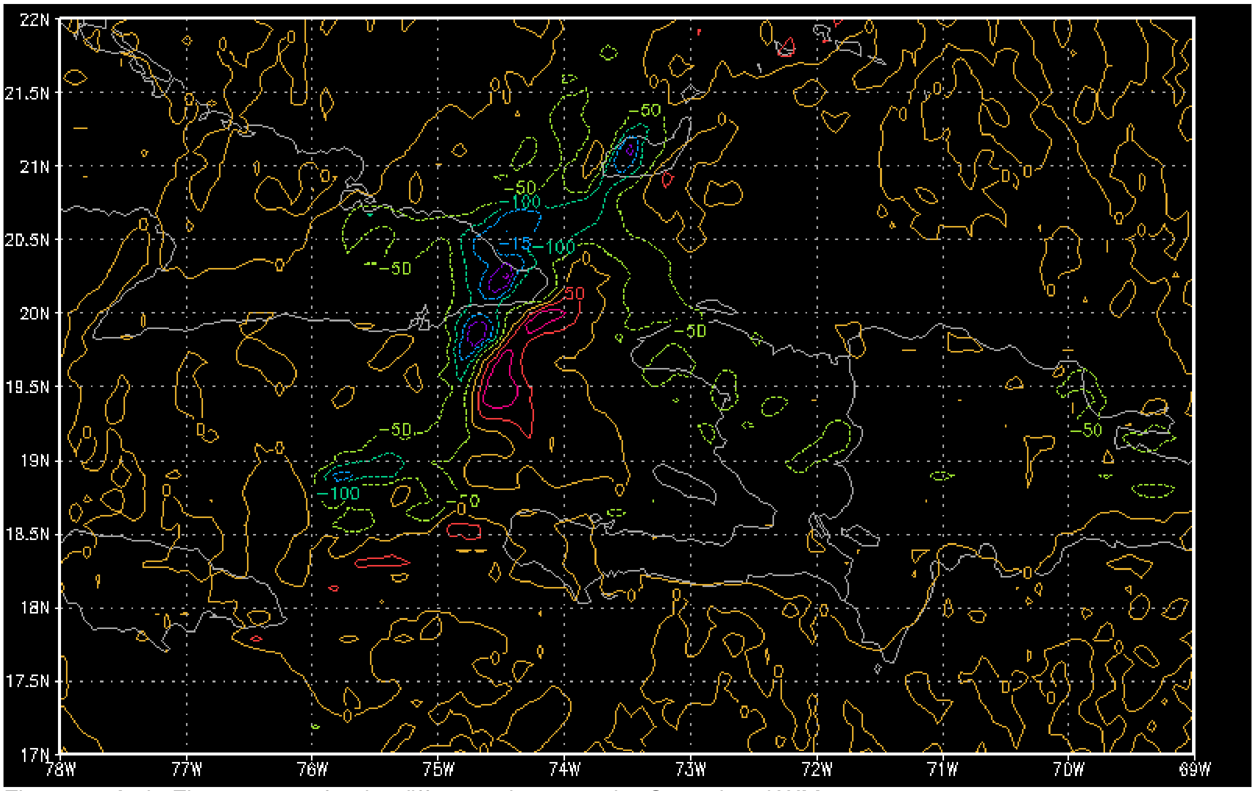

Figure 9. As in Fig. 7, except for the difference between the Control and WMtn runs.

16 UTC and 22 UTC, November 5, are shown in Fig. 10. Before this time, the centers of circulation for each run were in nearly the same locations. Beginning at 16 UTC, the Control run shows an eastward deflection compared with the Flat run, and this deflection persists as Tomas passes through the Windward Passage, through 22 UTC. Comparing the Sea run and the Flat run (Fig. 11) shows no deflection, only a speed difference, suggesting that the presence of the mountains deflects the circulation and that the elevated terrain in the Control run caused the deflection of the circulation. Figure 12 shows that the circulations in the WMtn and Sea runs are virtually the same. The elevated terrain by itself is not enough to cause the deflection. The presence of the land surface and the land surface being elevated together causes the deflection.

4.4 Surface Latent Heat Fluxes

Many of the differences in the model runs can be related to the location and size of the surface latent heat fluxes, since these fluxes provide the energy that sustains the storm. The latent heat fluxes are large over water surfaces, and increase with higher wind speeds. The model runs without any land surface have larger latent heat fluxes, and the differences are largest where the land surface is converted to water. Figure 13 shows the difference in accumulated surface latent heat fluxes between the Control and Sea runs. Within the red box, the difference represents more than a 25% increase for the Sea run over the Control run. This difference in energy input explains the differences in storm strength discussed in section 4.1 above. More energy input allows the storm in the Sea run to be stronger. The greater input of latent heat also explains the greater amount of precipitation in the Sea run, since the latent heat flux is also a water vapor source, and the latent heat is only released as the water vapor is condensed into liquid drops. The Flat run has only a slightly larger accumulated surface latent heat flux. Figure 14 shows the difference between the Control run and the Flat run. Within the red box, the difference represents a 7% increase for the Flat run over the Control run, similar to the difference in precipitation amount already discussed above.

5. Summary

The presence of the islands of Cuba and Hispaniola, despite having relatively modest terrain along the sides of the Windward Passage, had a significant influence on the track and the strength of Hurricane Tomas. The surface latent heat fluxes were reduced as much as 25% from what they might have been over an equivalent ocean surface, causing the storm to weaken. The amount of precipitation was reduced by the land surface, and the location of the precipitation changed as well. The storm was deflected to the east by 60 km by the presence of the mountains.

The model runs discussed here show that most of the changes were due to the presence of land, and that the elevation of the terrain exerted a smaller influence. The storm in the Flat run was weakened by the islands just as much as the storm in the Control run was. The accumulated surface latent heat fluxes and the total

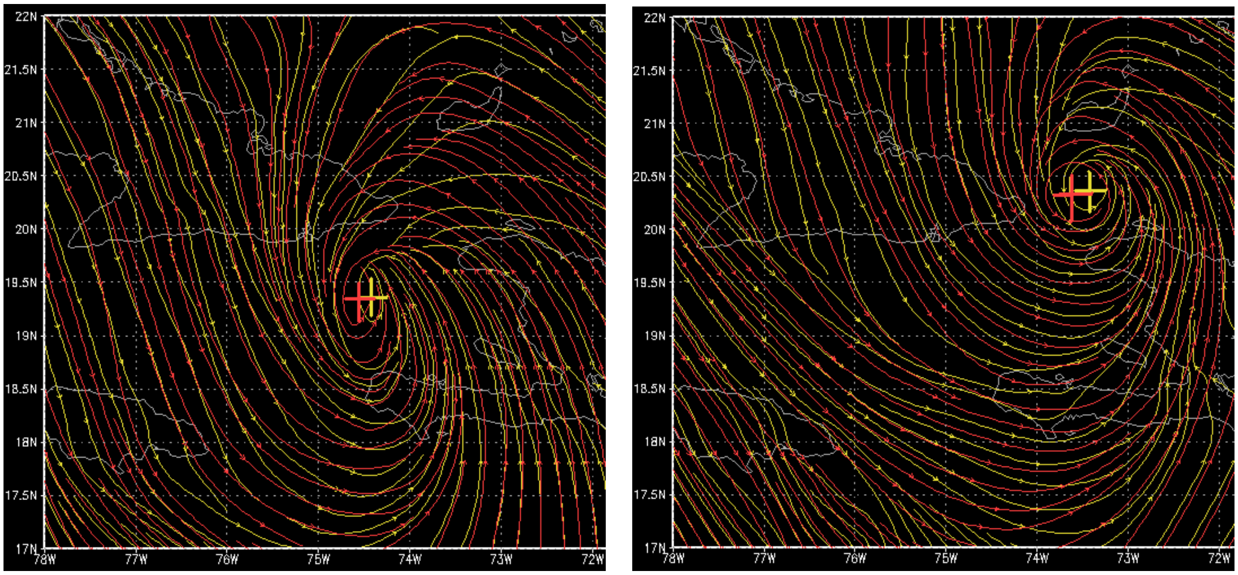

Figure 10. Streamlines showing 10 m wind from Control (yellow) and Flat (red) model runs, valid at 16 UTC (left) and 22 UTC (right) on November 5. Centers of circulation are shown with large crosses.

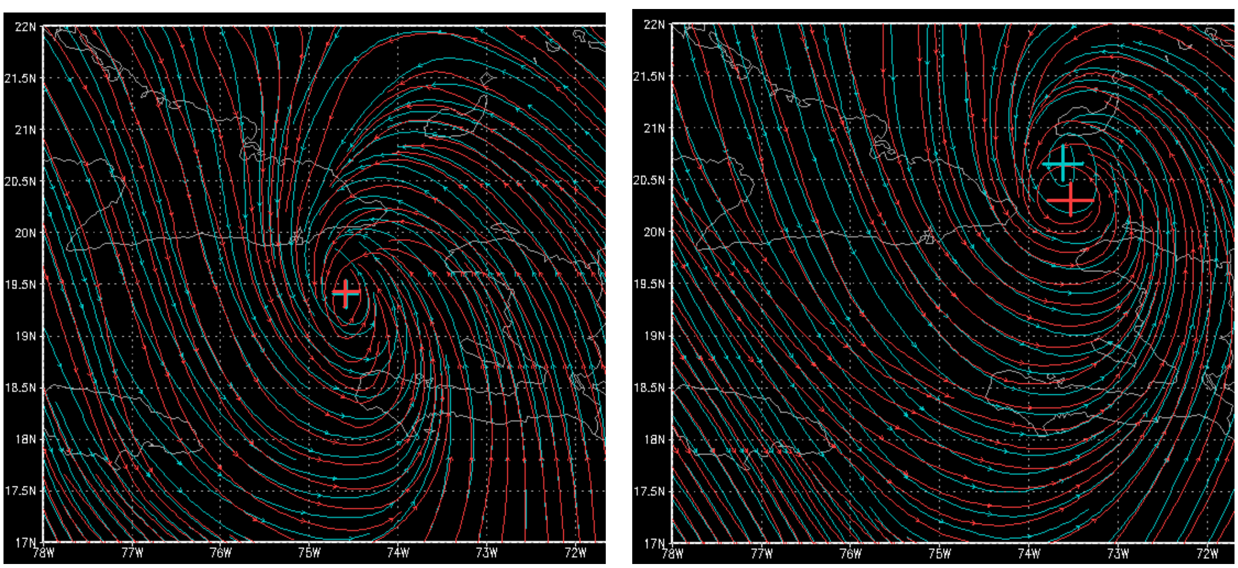

Figure 11. Streamlines showing 10 m wind from Sea (cyan) and Flat (red) model runs, valid at 16 UTC (left) and 22 UTC (right) on November 5. Centers of circulation are shown with large crosses.

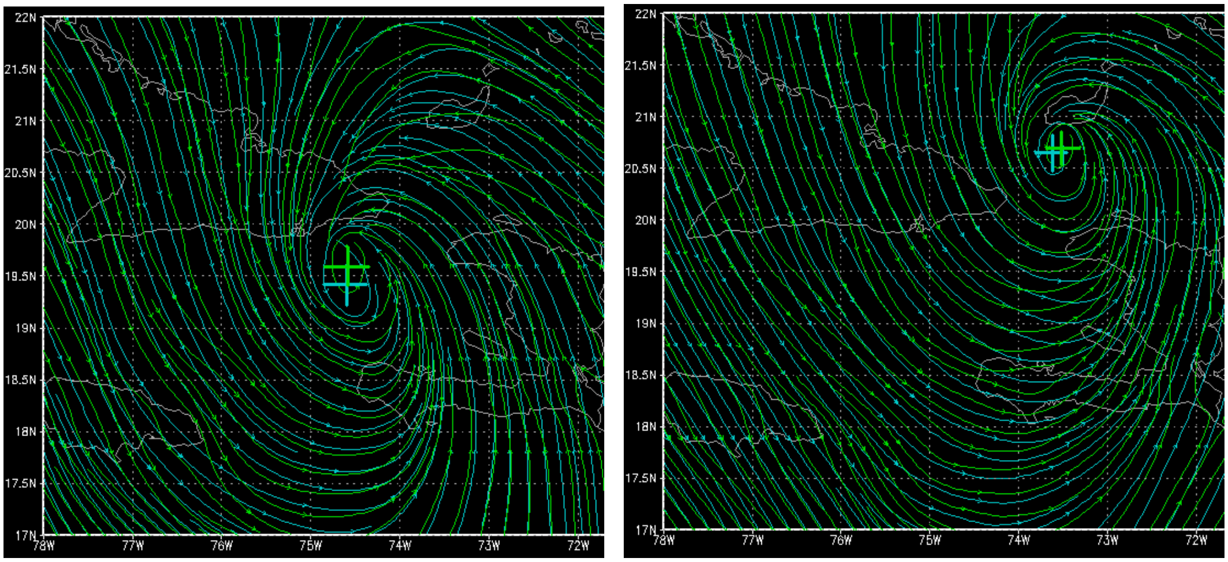

Figure 12. Streamlines showing 10 m wind from Sea (cyan) and WMtn (green) model runs, valid at 16 UTC (left) and 22 UTC (right) on November 5. Centers of circulation are shown with large crosses.

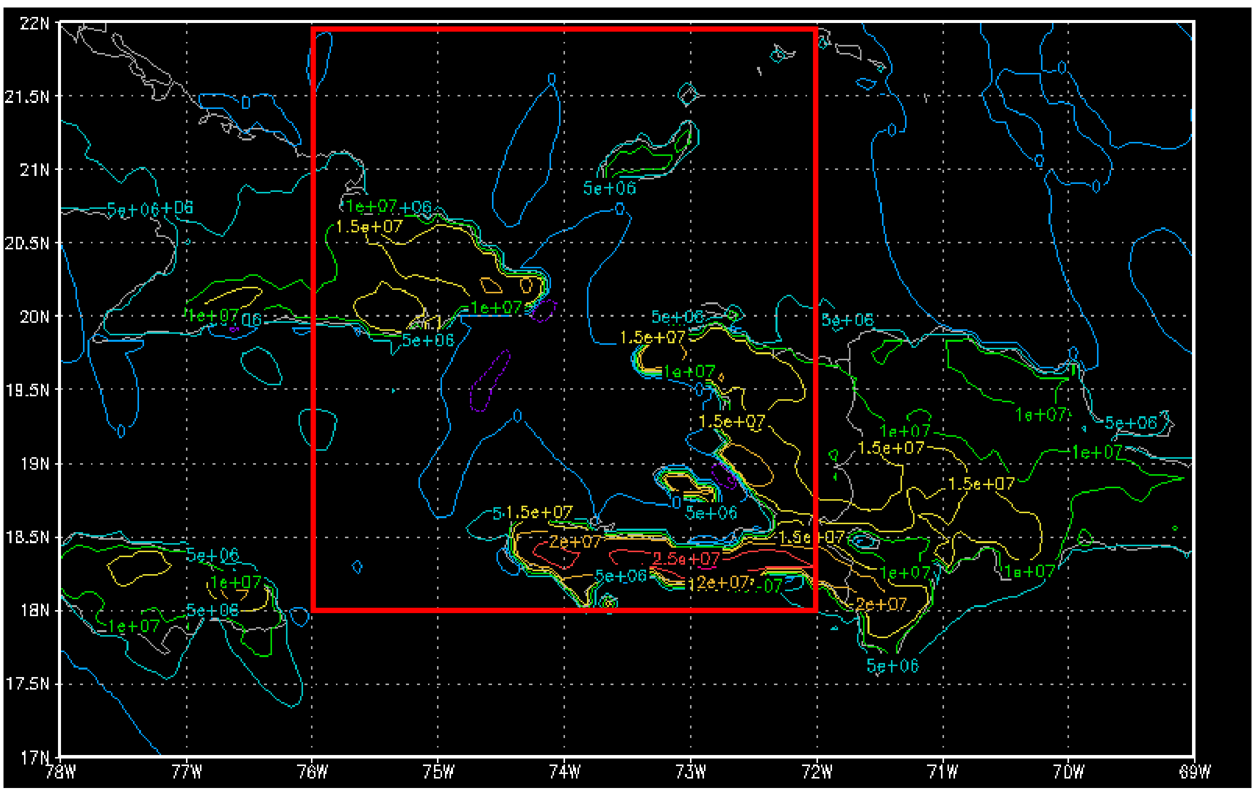

Figure 13. Difference in total accumulated surface latent heat fluxes (joules m^{-2}) between Sea and Control runs as of 00 UTC, November 6. Sea run has 26% higher average accumulated flux than the Control run within the red box.

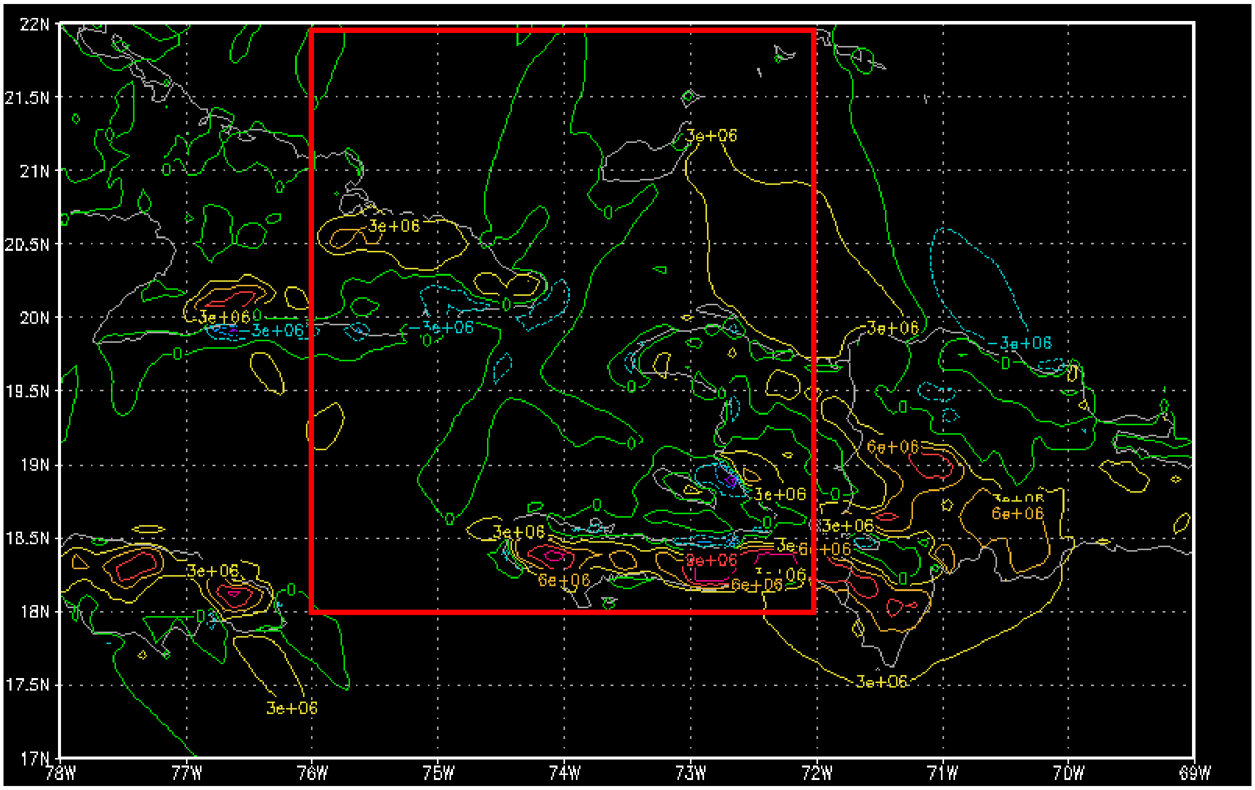

Figure 14. Difference in total accumulated surface latent heat fluxes (joules m^{-2}) between Flat and Control runs as of 00 UTC, November 6. Flat run has 7% higher average accumulated flux than the Control run within the red box.

amount of precipitation were only slightly higher in the Flat run. The only effect which depended strongly on the elevation of the terrain was the storm track. It was the combined effects of land surface and elevation that caused the eastward deflection of the storm as it passed through the Windward Passage.

5. REFERENCES

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