The Change in Rainfall from Tropical Cyclones Due to Orographic Effect of the Sierra Madre Mountain Range in Luzon, Philippines

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This paper discusses the Sierra Madre Mountain Range of the Philippines and its associated influence on the intensity and distribution of rainfall during tropical cyclones. Based on Weather and Research Forecasting model simulations, a shift in rainfall was observed in different portions of the country, due to the reduction of the topography of the mountain. Besides increasing the rainfall along the mountain range, a shift in precipitation was observed during Tropical Storm Ondoy, Typhoon Labuyo, and Tropical Storm Mario. It was also observed that the presence of the Sierra Madre Mountain Range slows down the movement of a tropical cyclones, and as such allowing more time for precipitation to form over the country. Wind profiles also suggest that the windward and leeward sides of mountain ranges during Tropical Cyclones changes depending on the storm path. It has been suggested that in predicting the distribution of rainfall, the direction of movement of a tropical cyclones as well as its adjacent areas be taken into great consideration. While the study shows high amounts of variation in the characteristics of different tropical cyclones with respect of the Sierra Madre Mountain Range, the results of this study can provide insights to pre-disaster operations before tropical cyclones approaches land. The decrease in tropical cyclones speed introduced by the Sierra Madre Mountain Range can be used to identify the possible areas that can experience prolonged rains due to the mountain range. Disaster management authorities can also prepare in advance by identifying which locations can experience or ographic enhanced precipitation. However, due to the lack of available data and resources, further studies are recommended due to the study presenting limited cases.

Key words: geomorphology, numerical weather prediction, orographic effect, precipitation, tropical cyclones, weather and research forecasting modelling

INTRODUCTION

The Philippines is in constant exposure to tropical cyclones (TCs) that originate from the West Pacific Ocean (WPO). Out of all storms that form in the WPO,

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an average of 30.3% of these TCs make landfall in the Philippines (David et al. 2013). Correspondingly, every year as much as 19.4 TCs enter the Philippine Area of Responsibility, with 9 of these TCs actually making landfall (Cinco et al. 2016). Packing both strong winds and bringing extreme rainfall, most of these cause direct and indirect effects to the country, resulting to loss of lives and large damage to property. While the Intergovernmental Panel on Climate Change (IPCC) projects a decrease in the number of TCs over the West Philippine Sea (a part of the WPO) in the future, it conversely projects an increase in activity near subtropical Asia (Kirtman et al. 2013; Wang et al. 2011). Similarly, a significant increase in number of Category 4-5 TCs is expected between the years 2000 to 2050 in the neighboring southwest Pacific Ocean Basin (Leslie et al. 2007).

In the recent decade, the Philippines has experienced a number of intense and devastating TCs afflicting the country. In 2009, Tropical Storm Ondoy (international name: Ketsana) flooded the country's capital, Metro Manila in the Luzon region by bringing a month's worth of rain which surpasses the country's forty-year record for rain over one day (Abon et al. 2011). This was followed by similarly devastating storms such as Typhoon Pepeng (Parma) in 2009; Typhoon Juan (Megi) in 2010; Tropical Storm Sendong (Washi) in 2011, Super Typhoon Pablo (Bopha) in 2012; Typhoon Labuyo (Utor) and Super Typhoon Yolanda (Haiyan) in 2013, and Tropical Storm Mario (Fung-Wong) in 2014.

Tropical Storm (TS) Ondoy, Typhoon (TY) Labuyo, TY Glenda, and TS Mario have made landfall in Luzon, the northernmost and largest island among the Philippine Island Groups. With a population of 48.5 million (National Statistics Office 2010), Luzon is also home to the country's capital Metro Manila which has been severely affected by the mentioned storms.

Storms coming from the Pacific Ocean moving towards the east of Luzon traverse the Sierra Madre Mountain Range (SMMR) before reaching Metro Manila (Figure 1). With a length of 600km and a maximum elevation of more than 1.5km, the SMMR borders the entire eastern portion of Luzon (Rantucci 1994). Due to its high elevation, it acts as a barrier between the larger central portion of Luzon and its eastern coastal region. As most TCs form towards the east of the Philippines (Terry and Feng 2010), the SMMR acts as an obstruction for TCs moving from east to west along Luzon. Known data on TC and Philippine landmass interactions, specifically along SMMR, are either outdated or largely anecdotal in nature. As the SMMR is higher than 1.5km in height, a height and scale in which orographic precipitation is expected to occur (Roe 2005), knowing how the orographic effect associated with these land features affect extreme weather events in terms of both extent and magnitude will have great implications on geohazard mapping and land use planning. Hazards such as floods and landslides are largely rainfall-induced, and identifying how the dynamics of extreme rainfall events such as TCs are affected by different land features such as mountains and coasts in the Philippines can help identify possible hazard hotspots. It has been previously established that the western side of SMMR is drier as the mountain range prevents the intrusion of the northeast monsoon (Juanico and Agno 1987). Unfortunately, no study has been conducted regarding the effect of the SMMR on the precipitation of TCs which have different dynamics compared to monsoons.

Similarly, with precipitation measurements over the area not readily available, few studies have been previously conducted relating the SMMR and extreme weather events. While there have been recent efforts to address the measurement of rainfall in the Philippines using weather radars (Crisologo et al. 2014), weather radar observations over mountainous areas leave much to be desired due to the interactions between the radar measurements and the topography causing precipitation measurements to be degraded (Germann et al. 2006).

As such, researchers turn to numerical weather prediction models. Related studies by Yang et al. (2008) used a non-hydrostatic version of the PSU-NCAR MM5 model to see the effects of topography on Typhoon Nari (2001) in Taiwan. They observed that torrential rainfall is determined by large-scale flows enhanced by the local topography due to the interaction of the typhoon and the topography. Similarly, Minamide and Yoshimura (2014) examined the orographic effect in Mindanao Island on Typhoon Washi using a Regional Spectral Model, in which they concluded mountainous terrain causes more rainfall in Mindanao Island in the Philippines. Finally, using the Weather Research and Forecasting (WRF) model, Lagmay et al. (2015) observed that certain volcanos in the Philippines enhance rainfall from the combined effects of the Southwest Monsoon, TCs, and the orographic effect.

In this study, downscaling of the NCEP FNL Operational Global analysis data using the WRF model was conducted to analyze the effects of the SMMR during the passing of TCs by running models with reduced mountain range heights.

Weather Research And Forecasting (WRF) Model

The Weather Research and Forecasting Model or WRF model is a numerical weather prediction model that allows researchers and operational forecasters to simulate real (observational and reanalyzed) and ideal data to reconstruct or forecast atmospheric conditions (Skamarock et al. 2005). One of the key features of WRF is nesting: downscaling of simulated data from larger to smaller domains. Through nesting, coarser grid resolutions from gathered data are downscaled to higher grid resolutions. This allows the researcher to capture finer details of simulated weather events such as TCs.



Figure 1. Extent of the Sierra Madre Mountain Range outlined in red with selected weather stations labelled.

The WRF model uses two sets of data to simulate weather models: meteorological data and geographic terrestrial data. One of the meteorological datasets that can be used for WRF is the National Center for Environment Prediction Final (NCEP FNL) Global Tropospheric Analyses. The NCEP FNL data uses the Global Forecast System (GFS) model, a weather forecasting model that covers the entire Earth. Besides utilizing GFS, NCEP FNL also takes into account various observational data from different meteorological agencies. On the other hand, the terrestrial data used by WRF include parameters such as topography (in meters above sea level in 30 second grids), land use, albedo, soil type, and soil temperature, all of which are derived from Moderate Resolution Imaging Spectroradiometer (MODIS) and Shuttle Radar Topography Mission (SRTM) data. Both the Global NCEP FNL data and terrestrial data are preprocessed using the WRF Preprocessing System (WPS) where it defines the domains and interpolates the static terrestrial data and meteorological fields before they can be used in the WRF model. WRF also allows the researcher to fine tune simulations by selecting physical components such as the cumulus parametrization scheme and microphysics scheme. The cumulus parametrization scheme simulates convective processes such as large-cale thunderstorms or TCs for the model (Kain 2004). On the other hand the microphysics scheme parametrizes cloud particles and precipitation drops (Hong and Lim 2006). For the purposes of this study, the Kain-Fritsch cumulus parametrization scheme and the WRF single-moment six class microphysics (WSM6) scheme will be used as this combination of physics components produce the best WRF TC simulation results over Southeast Asia (Raktham et al. 2015). The Yonsei Planetary Boundary Layer scheme was used as well for all the simulations. These were all chosen as these are the same parameters that are used by the state weather bureau, the Philippine Atmospheric, Geophysical and Astronomical Services Administration.

Modification of Topography

To determine whether the topography of SMMR does have a significant effect on weather events two sets of geographic terrestrial data were used as separate inputs for WRF simulations: original (ORIG) and modified (MODI) geographic data shown in Figures 2a and 2b. In modifying the geographic data, the SMMR towards the east was reduced to 50 meters above sea level to approximate the heights of adjacent flatter slopes. In doing so, it simulates the effect of reducing the height of SMMR but not totally eliminating topography down to sea level. The Global NCEP FNL weather data, on the other hand remained unmodified to simulate the effects of the same weather event on modified geographic data.

WRF Simulation of Tropical Cyclones

Four test cases were used in this study, namely TS Ondoy (international name Typhoon Ketsana), TY Labuyo (international name Typhoon Utor), TY Glenda (international name Typhoon Rammasun) and TS Mario (international name Severe Tropical Storm Fung-wong). A summary of the aforementioned TCs can be found in Table 1 with their storm tracks plotted in Figure 3. These four cases have been selected due to having caused significant destruction in Luzon.

To observe the effects of the topography on the selected TCs, the 1 x 1 degree or approximately 111.32 x 111.32 km Global NCEP FNL data was downscaled using a 3-nested domain scheme with resolutions of 36km, 12km, and 4km centered on Luzon (Figure 4). For this study, two sets of simulations were conducted: ORIG, where

Table 1. Test cases included in the study.

Local Name	International Name	Simulation Dates	
TS Ondoy	Typhoon Ketsana	18-30 September 2009	
TY Labuyo	Typhoon Utor	03-18 August 2013	
TY Glenda	Typhoon Rammasun	09-20 July 2014	
TS Mario	Severe Tropical Storm Fung Wong	11-25 September 2014	



Figure 2. (a) Original (ORIG) and (b) modified terrestrial input data for WRF (MODI)



Figure 3. Tracks of TS Ondoy, TY Labuyo, TY Glenda and TS Mario adapted from NOAA-IBTRaCS (Knapp 2010).



Figure 4. WRF model domains used for this study. The model downscaling goes from the black outline (36 km), towards blue (12 km), and finally towards the red outline (4 km) as the model output becomes finer.

the topography remains untouched, and MODI where the height of the SMMR was reduced. This was done to simulate the effects of reducing the mountain range on TCs with the MODI simulation. To verify the accuracy of the forecasts, the model generated TC tracks will be compared to the National Oceanic and Atmospheric Administration's International Best Track Archive or NOAA-IBTrACS (Knapp 2010).

RESULTS

Validation of WRF with CMORPH, IBTraCS, and Weather Stations

To verify the validity of the simulations, the results for ORIG were compared to the National Oceanic and Atmospheric Administration's Climate Prediction Center MORPHing technique (CMORPH), a technique which provides global precipitation estimates using microwave data from satellites such as the Tropical Rainfall Measuring Mission (TRMM) and infrared data from geostationary satellites (Joyce et al. 2004). Figures 5, 6, 7, and 8 show the total accumulated precipitation for the (a) CMORPH- derived total accumulated precipitation estimate and the (b) ORIG simulation total accumulated precipitation for TS Ondoy, TY Labuyo, TY Glenda, and TS Mario, respectively. Although the model precipitation estimates do not exactly match in terms of amount as they overestimate and exceed the CMORPH measurements, the model precipitation captures the general areas of high precipitation as estimated by CMORPH. However, for the cases of TS Ondoy and Labuyo, the WRF model results have precipitation shifted towards the north. This is due to the lower accuracy of the CMORPH estimates over mountainous areas. While Jamandre and Narisma (2013) note that CMORPH tends to perform well during high rainfall events such as TCs, Zhang et al. (2013) on the other hand notes that CMORPH estimates perform poorly over complex terrain such as mountains. Towards the northern regions of the Philippines are both the SMMR and the Cordillera Mountain Range, and as such, CMORPH estimates tend to be low towards those regions.



Figure 5. (a) CMORPH-derived total accumulated precipitation for and (b) WRF total accumulated precipitation TS Ondoy.



Figure 6. (a) CMORPH-derived total accumulated precipitation for and (b) WRF total accumulated precipitation TY Labuyo.



Figure 7. (a) CMORPH-derived total accumulated precipitation for and (b) WRF total accumulated precipitation TY Glenda.



Figure 8. (a) CMORPH-derived total accumulated precipitation for and (b) WRF total accumulated precipitation TS Mario.

A simple algorithm was also used to locate the center of the simulated TCs to be able to generate a TC track for comparison with the IBTrACS data. For every time step, two locations in the TC's region are considered for locating the center of the TC: the location of the minimum pressure, and the location of the minimum wind speed. After taking the location of the minimum pressure and minimum wind speed, the midpoint of these locations are taken to be the TC center. Figure 9 shows both the IBTrACS observed TC tracks and the WRF model generated TC tracks for the selected cases, in which the general direction of the storm tracks are well in agreement between the observed and the model.

Results from simulations were also cross-verified with available weather station data plotted in Figure 1. Comparing the ORIG simulation results with the available weather station data in Luzon, the ORIG simulations for the three TC cases overestimate rainfall over nine stations from 10.24% to 49.29%. However, as results are comparable with both CMORPH estimates and weather station records to some extent, the WRF simulations are deemed acceptable for the purposes of this study.

Comparison of Simulations with Original Topography and Modified Topography

Graphical Comparison

Figure 10 shows the normalized difference between the ORIG and MODI simulations to show the redistribution of precipitation after the SMMR is reduced for (a) TS Ondoy, (b) TY Labuyo, (c) TY Glenda, and (d) TS Mario.



Figure 9. 6-hourly IBTrACS TC tracks (in red), 1-hourly WRF ORIG tracks (in green), 1-hourly WRF MODI tracks (in blue) for (a) TS Ondoy, (b) TY Labuyo, (c) TY Glenda, and (d) TS Mario.



Figure 10. Difference in Precipitation Between Original and Modified Topography for (a) TS Ondoy, (b) TY Labuyo, (c) TY Glenda, and (d) TS Mario. The color red denotes the increase in precipitation due to the mountain range, while the color blue denotes the decreased precipitation for the selected TCs.

100.00%

The areas in red denote the increase in precipitation when the mountain range is present, while the blue areas on the other hand denote the decrease in precipitation. In general, for the TS Ondoy, TY Labuyo, and TS Mario cases, the precipitation shifted towards the north. The TS Ondoy case (Figure 10a) shows that as expected, the rainfall is increased along the mountain range itself. However, it can be seen at the southwest portion well beyond the mountain range that the rainfall significantly increased due to the presence of the mountain range. While quite similar in track but deflecting more towards the north, the same case is not observed for TY Labuyo (Figure 10b), in which the mountain range in fact does reduce rainfall towards the west as highlighted in blue. Conversely, with movement leaning more towards the south, the case for TY Glenda (Figure 10c) shows that due to the SMMR, rainfall is mostly decreased towards the west of the mountain range. Finally with a more extreme northern track in the Philippines, the TS Mario case shows that there are no significant changes in precipitation near the mountain range. However, due to the absence of the SMMR in the simulations, rainfall was instead redistributed to the Cordillera Mountains to the northwest.

In general, based on the simulations the presence of the SMMR caused a significant increase of precipitation along the SMMR itself. An increase in precipitation was also found along the southern portion of the storm track and west side of the mountain range when the storm direction is directly perpendicular with the mountain range, as in the case of TS Ondoy. Finally, when the TC approaches the northern locations of the country as in the case of TS Mario, the presence of the SMMR increases rainfall towards the northern Cordillera Mountains due to the interaction of the TC with the mountain range.

Quantitative Comparison

Data at different weather stations (Figure 1) were extracted to compare the effect of the reduction of the mountain range on the change in precipitation for key locations in Luzon Island. Simulation results for MODI were subtracted from the simulation results from ORIG to extract the change of precipitation when the mountain range is removed. Afterwards, the difference is divided by ORIG results to get the percent change. Based on the results, precipitation for different stations did not just increase nor decrease as a whole, with different locations experiencing different changes in precipitation upon reduction of the mountain range. For TS Ondoy (Figure 11), there was a general increase in precipitation for all stations with SMMR removed. However, for TY Labuyo (Figure 12), there was an increase in precipitation for 5 stations while there was a decrease in 3. For TY Glenda (Figure 13), decrease in precipitation was only observed in 2 stations. Finally, for TS Mario (Figure 14)

Modifying Topography for TS Ondoy





Change in Precipitation after Modifying Topography for TY Labuyo



Figure 12. Percent change in precipitation after removing SMMR for selected stations during TY Labuyo.

Change in Precipitation after Modifying Topography for TY Glenda



Figure 13. Percent change in precipitation after removing SMMR for selected stations during TY Glenda.

Change in Precipitation after Modifying Topography for TS Mario



Figure 14. Percent change in precipitation after removing SMMR for selected stations during TS Mario.

a decrease of precipitation as much as twice the original was observed for the Casiguran Station. However, while general increase in precipitation was observed for TS Ondoy, these selected stations are not representative of the change in precipitation as a whole. Going back to the graphical comparison in the previous section, it can be observed that the changes in precipitation cannot be quantified by single stations as the spatial extent of the changes is too large.

It was also observed that while TY Labuyo (Figure 9b) had a similar track with TS Ondoy (Figure 9a), the precipitation of TY Labuyo is not as high as TS Ondoy as seen in the CMORPH estimates in Figures 6a and 5a respectively. As such, not as much change in precipitation was observed in TY Labuyo over land besides the general increase in precipitation west of the SMMR.

Change in TC Movement Speed due to SMMR

Based on the hourly TC location generated from the model, the TC movement speed was derived by getting the distances between the track points of the TCs for every time step and then getting the average movement speed for the whole duration of the storm (Table 2). It is expected that TC movements slow down over land (Brand & Blelloch 1970). As such, upon removal of the SMMR, TC movement speeds generally increased for TS Ondoy, TY Glenda and TS Mario, with TS Mario speeding up by as much as 17.84%. When the SMMR then slows down the TC, it is understood that the TC stays over the Philippine landmass at a longer duration, and as such, causing more precipitation.

Table 2. Increase in TC movement speed for the four cases.

	ORIG (kph)	MODI (kph)	% Change
TS Ondoy	34.90	36.44	4.22%
TY Labuyo	24.22	23.23	-4.24%
TY Glenda	24.54	25.72	4.60%
TS Mario	21.21	25.81	17.84%

TY Labuyo, however, deviates from this behavior as its movement speed actually decreased upon removal of the SMMR. It is assumed that this is because in the absence of the SMMR, TY Labuyo went straight to the Cordillera Mountain Range, a region of similar high topography that can similarly cause the slowing down of the Tropical Cyclone.

DISCUSSION

The Orographic Effect of the SMMR on Tropical Cyclones

It can be seen from the change in precipitation when the mountain range is reduced (Figure 10) how the orographic effect greatly influences precipitation during TC events. While precipitation is generally concentrated towards the southern portion of the storm upon interaction with the mountain range, the TC experiences an upslope ascent, wherein due to the flow of wind across the mountain range, there is a forced mechanical lifting of the air which results into condensation and precipitation along the windward flank (Roe 2005). Besides reduction of precipitation along the mountain range, shifts in precipitation patterns are observed in the four different storms as most evident in the TS Ondoy and TS Mario case (Figures 10a and 10d), where there the evident rain bands in the West Philippine Sea moved north. It is presumed that these shifts in precipitation patterns are due to the altering of the movement of the storm when the storms do not experience friction due to the SMMR. An increase in precipitation was similarly observed along higher relief areas towards the west of the SMMR as in the case of TS Mario (Figure 10d), in which precipitation that should have been distributed by the orographic effect along the SMMR have shifted towards the succeeding mountain ranges, particularly the Cordillera Mountain Range in the northwest.

The Interaction Between Wind Circulation and the Mountain Range

While the increase in precipitation along the windward side of mountain ranges is a well-studied phenomenon for the midlatitudes (Roe 2005) with winds moving in a straightforward manner as in the cases of monsoons, there are few studies assessing the precipitation increase along different portions of mountain ranges due to wind circulation during TCs. Note that depending on where the TC passes, the windward and leeward side of the mountain range are different along portions of the mountain range due to the circular movement of wind in a TC. In the case of a TC moving from east to west the wind direction towards the north of the TC moves east to west as well. On the other hand however, towards the south of the TC, the wind direction moves from east to west, opposite the direction of movement of the TC system. As seen in the direction of the wind as a TC intersects with the SMMR (Figure 15), depending on the location of the intersection, the windward and leeward side of a mountain range are not simply on each side of the mountain range. Taking the cases of TS Ondoy and TY Glenda, both storms traversed the mountain range in different tracks: TS Ondoy moved from east to west at higher latitudes compared to TY Glenda. As such, the windward and leeward side for the



Figure 15. Wind maps at 10 meters height of (a) TS Ondoy and (b) TY Labuyo, (c) TY Glenda, and (d) TS Mario upon landfall. Depending on the intersection of the center of the TC and the mountain range, the windward and leeward portions of the mountain range is different.



Figure 16. Schematic diagram of windward and leeward side depending on storm direction for (a) TS Ondoy and (b) TY Glenda.

same portions of SMMR were different for the two cases, in which for TS Ondoy (Figure 15a) the southwestern portion of the SMMR range is the windward side, whereas the same area is the leeward side for TY Glenda (Figure 15c). As such, at the precise moment a TC intersects with a mountain range, the northeastern and southwestern portions of the intersection between the mountain range and TC become the windward side, while the southeastern and northwestern portion becomes the leeward side. Figure 16 further shows this phenomenon in a simplified schematic diagram for TS Ondoy and TY Glenda. During TS Ondoy (Figure 16a) due to the cyclonic nature of winds, Metro Manila was in the windward side of the mountain during the storm. On the other hand, during TY Glenda (Figure 16b), Metro Manila was on the leeward side of the mountain of which not as much precipitation was experienced over the area. This phenomenon has been similarly observed over the Central Mountain Range in Taiwan, wherein during Typhoon Morakot, in which precipitation spread is topographically enhanced when storm circulations are favorably positioned with respect to the topography of Taiwan especially towards the southwestern portion of the storm and the mountain range (Fang et al. 2011).

In terms of precipitation for TS Ondoy, Figure 10a shows that there is an increase of precipitation of more than 500mm towards the south of the storm and west of SMMR mountain range (windward side) when the mountain range is present. On the other hand, the increase in precipitation is less evident in the TY Glenda case (Figure 10c) for the same location as it has become the leeward side for TY Glenda, in which a rain shadow occurs. Therefore, at least on the southern segment of the intersection between the center of the TC and the mountain range, the western part receives more precipitation because of the circulation that occurs when the storm moves through northern latitudes. It is to be noted as well that due to the absence of the SMMR in the MODI cases, rainfall is topographically enhanced over the Cordillera Mountains to the west of the SMMR as precipitation that was supposed to be generated by the SMMR was transferred to the Cordillera Mountains.

This can also be seen by comparing the ORIG and MODI simulation results for different stations for TS Ondoy and TY Glenda. The Science Garden and Sangley Point stations experienced a west-to-east wind movement during TS Ondoy, hence these stations were located in the windward side of the mountain and experienced an increase in rainfall. On the other hand, the aforementioned stations experienced an east-to-west wind movement during TY Glenda, and as such were located in the leeward side of the mountain. These stations experienced an increase in precipitation when the SMMR was present during TS Ondoy (Figure 11). During TY Glenda, on the other hand (Figure 13), while the presence of the SMMR increased precipitation for the selected stations, the reduction was not as pronounced as with TS Ondoy. Based on these results, it is important to take into consideration the track of a TC as it traverses the SMMR as the windward and leeward side of a mountain range changes based on the path of the TC.

Finally, while the wind circulation patterns for TS Ondoy and TY Labuyo are similar (Figures 15a and 15b), it was previously mentioned that based on the CMORPH estimates and WRF simulations, TY Labuyo (Figure 6) did not bring in as much precipitation compared to TS Ondoy (Figure 5). As such, while the increase in precipitation along the SMMR was observed for both cases, the orographic effect along the southwestern windward side of the mountain range was not as prominent in the TY Labuyo case.

CONCLUSION

In this study, the orographic effect of the Sierra Madre Mountain Range on TCs was explored using WRF modeling. Validated WRF models for different storms provided insight on how TCs interact with the SMMR. Because of its height, the SMMR is believed to protect plains located in the leeward side of the Philippines from rainfall especially from TCs (Lapeña. 2010). However, the model results suggest that there is higher precipitation towards different portions of the mountain range due to the movement of the winds associated with the circulating TC. Were it not for the increased rainfall due to the orographic effect caused by the SMMR, flooding would probably have not occurred during the storms TS Ondoy, TY Labuyo and TS Mario in Metro Manila.

It is worthy to note how during TCs, depending on the location of the TC, the leeward and windward sides of the mountain shift in location. At the moment where the TC hits the mountain range, the south west and the north east portions of the intersection between the center of the storm and the mountain range becomes the windward side, hence, increasing precipitation in those general areas. This is contrary to the storm direction, wherein the winds towards the south of the storm direction are actually moving towards the opposite direction of the storm. This is contradictory as well with the idea of SMMR blocking rainfall associated with TCs coming from the East, as the TC in fact brings in more rain along the southwestern areas of the mountain range due to the reversed flow of winds. Another phenomenon worth noting is that the presence of the SMMR slows down the translational speed of the TC. This causes the TC to generate more precipitation over land as it stays longer over the country. While it

is expected that TCs decrease in speed when they enter land, the SMMR causes the TC to move much slower compared to TCs moving over flatter areas.

All previously mentioned results have suggested that the unique climatological and geological environment of the Philippines poses dynamic risks for the country. As such, it would be important to consider in predicting the distribution of precipitation where the TC actually passes. Knowing the possible additional precipitation that the SMMR introduces for certain regions, disaster management authorities can prepare in advance by identifying locations in which enhanced precipitation can occur. Regions towards the northeastern and southwestern of the intersection between the SMMR and the center of the TC experience additional rainfall due to the orographic effect, and must be considered.

Finally, a limitation of this study is that while the WRF model captures the distribution of the rainfall pretty well, it was observed that the WRF model overestimates precipitation compared with observed data. It would be necessary to further modify the WRF input parameters for the simulation values to agree well with observed data particularly for the Philippines. Unfortunately this is a whole different research in itself to be tackled by further studies. Another limitation of this study is that it only presents four cases. Further studies with more test cases are recommended to be able to derive more comprehensive analyses of the effects of the SMMR on the precipitation of TCs.

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