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Quantifying Orographic Precipitation during Typhoon Bopha (Pablo) in 2012 Using Weather Research Forecasting Model (WRF)

Grethyl C Jamero[1]*, Jerome A Azul[2], Emmanuel C Garing[3], Jackie Ibañez[4]

[1]Department of General Education, Caraga State University, Cabadbaran City, Agusan Del Norte, 8605, Philippines, [2]Department of Science, College of Arts and Natural Sciences, Iloilo Science and Technology, Iloilo City, 5000, Philippines, [3]Department of Physics, Ateneo de Manila University, Quezon City, Philippines, [4]Manila Observatory, Ateneo de Manila Campus, Quezon City, Philippines. *Corresponding Author's Email: gcjamero@csucc.edu.ph

Abstract

In Philippines, most of the tropical cyclones being investigated are those typhoons having landfall in Luzon of which located in the northern part. Physical mechanisms that could influence typhoon's associated rainfall, track and intensity might be already known. Investigation of typhoons having landfall in Mindanao, the southern part of the Philippines gradually increased yet still very limited. An understanding of typhoons that affecting Mindanao is still of a challenge for it is not yet thoroughly investigated. This study intends to simulate the Super Typhoon Bopha using the Weather Research Forecasting model (WRF) to investigate the effect of the topography on the amount and rainfall distribution. It also looks for the horizontal winds, vertical winds and convergence as a consequence of orographic lifting. Another aim of this study is to look for the suitable combination of convective cumulus parameterization (CU) and microphysics parameterization schemes for the simulation of an accurate track of the Super Typhoon Bopha. Results show that 110-140 mm of rainfall was augmented over the mountain range that causes more damage in nearby areas. Mt. Tagubod in Davao Oriental have the ability to enhance the orographic precipitation of a typhoon. High terrain such as mountain plays an important role in enhancing precipitation especially during the onset of the typhoon.

Keywords: Horizontal Wind, Orographic Lifting, Topography, Vertical Wind.

Introduction

Philippines, particularly in Mindanao, experienced widespread flooding and severe debris flow during the passage of tropical cyclone Bopha, locally known as Typhoon Pablo. It made its first landfall at Baganga, Davao Oriental, at 2130 UTC on 03 December 2012, with a Category 5 on the Saffir–Simpson scale and was considered the strongest typhoon to make landfall in Mindanao within the year. Report states that the major triggering factor of the flash flood within the vicinity is climatological (1). Thus, this study is motivated to support the DENR-MGB 2012 report investigating the major controlling factor of the flash floods and landslides within Compostella Valley, contributing to disaster risk reduction in the region.

Triggering climatological factors such as storm intensity, track, moisture availability and large-scale atmospheric circulation can establish potential for heavy rainfall, however, this cannot be the sole basis for the actual spatial distribution and magnitude of rainfall since it can be modulated by local topography (2). Terrain features over the mountainous region in eastern Mindanao interact with incoming moist flow, enhancing uplift and rainfall through orographic processes. Therefore, a combination of atmospheric forcing and topography influences the orographic rainfall which give rise to extreme events. In addition, the complexity of interaction between tropical cyclones and the landscape vary significantly across different locations contributing to the variation of timing, duration and structure of typhoon-induce rainfall.

Simulation of a tropical cyclone to look at the effect of topography towards the track and associated precipitation is already widely investigated but over a mountainous region of Taiwan (3-6). This is because Taiwan is ideal for research on the orographic effect. After all, it is isolated in nature. Steep mountain, strong synoptically forced upward and high moisture upstream are just few of the several factors that could encourage to orographic precipitation (2). Previous study identified the available convective potential

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energy (CAPE) as the most important ingredient responsible for producing heavy precipitation (5). These studies contribute to the understanding of orographic rainfall mechanisms, such as the seeder-feeder processes, upslope lifting and the enhancement of convection due to topographic orientation. However, despite its understanding, geographic location and climatic conditions of Taiwan is quite different from Mindanao, which presents a unique challenge in extrapolating findings.

The previous studies over Taiwan substantially advanced the understanding of orographic effects on tropical cyclone rainfall; however, their findings cannot be directly extrapolated to Mindanao due to its distinct geographical and meteorological mechanism (7, 8). For example, over Taiwan, different orographic rainfall mechanisms were identified in different areas of the Central Mountain Range during the passage of a single cyclone event. The initiation and enhancement of rain during the passage are also different across the various areas, as rainfall enhancement can be due to a seeder-feeder mechanism or the common upslope lifting mechanism, which is also differs across different locations under different meteorological conditions (8, 9). Thus, different location has varying extents of these common components, leading to distinct key factors responsible for orographic rainfall under tropical cyclone conditions.

Although, in the Philippines it is known that the topography has a great impact on the storm track, intensity and size of tropical cyclones (10, 11), most of the tropical cyclones being investigated are those typhoons having landfall in Luzon (12), as Northern Island of Luzon is frequently hit by typhoon (13). Physical mechanisms that influence the associated rainfall amount and distribution, typhoon track and intensity vary in Mindanao as it is situated in the southeastern part of the Philippines. Typhoon passing these areas can be affected by the prevailing southwest monsoon (14). Very limited studies have been conducted over Mindanao (15). Thus, there exists limited understanding on how rainfall is being initiated and enhanced during the passage of a typhoon over the mountainous Mindanao area. By analyzing the spatial distribution of tropical cyclone rainfall, thereby providing observational evidence on typhoon-related orographic rainfall processes specific to the region can provide insights to address the knowledge gap. The goal of this study is to improve scientific understanding of how local topography over Mindanao modulates and/or enhance rainfall during tropical cyclone passage. Specifically, the study intends to quantify rainfall variability across different terrains and evaluate the role to orographic processes. The distinct of this research lies in its focus on Mindanao-a region that has received limited scientific attention despite its vulnerability to tropical cyclones.

Methodology

The model used in the study is the high resolution, nonhydrostatic Weather Research Forecast Model Version 3.6.1 (WRF). The study used two nested domains with 25 km and 5 km grid resolutions, respectively. The runs used NCEP FNL Operational Model Global Tropospheric Analysis data from the Research Data Archive at National Center for Atmospheric Research (NCAR). The Static Geographical data (geogrid) and Gridded data (ungrib) were used for domain-1 and domain-2 in the WRF Preprocessing system (WPS). The initial data were obtained from the UCAR & NCAR Research Data Archive.

Model Domain

The simulations employed a two-level nested domain configuration. The domain-1 (D1), which is the parent domain, has 25 km resolution and covers the entire Philippines with location located at approximately 5°–20° N latitude and 115°–130° E longitude to capture the synoptic-scale circulation and tropical cyclone evolution. The domain-2 (D2), the child domain, has a 5 km resolution which focuses on the study area, the Central and Northeastern Mindanao Region-located at approximately 7°–9° N latitude and 125°–127° E longitude, as seen in Figure 1 and is used to sufficiently resolve mesoscale convection and orographic effects over the area. This domain configuration was similar to the intermediate domain presented by Dave Gill. The second domain has a finer grid resolution over the coarse grid resolution. This is acceptable domain configuration based on the real data lateral boundary condition where location of specified and relaxation zones was considered (16).

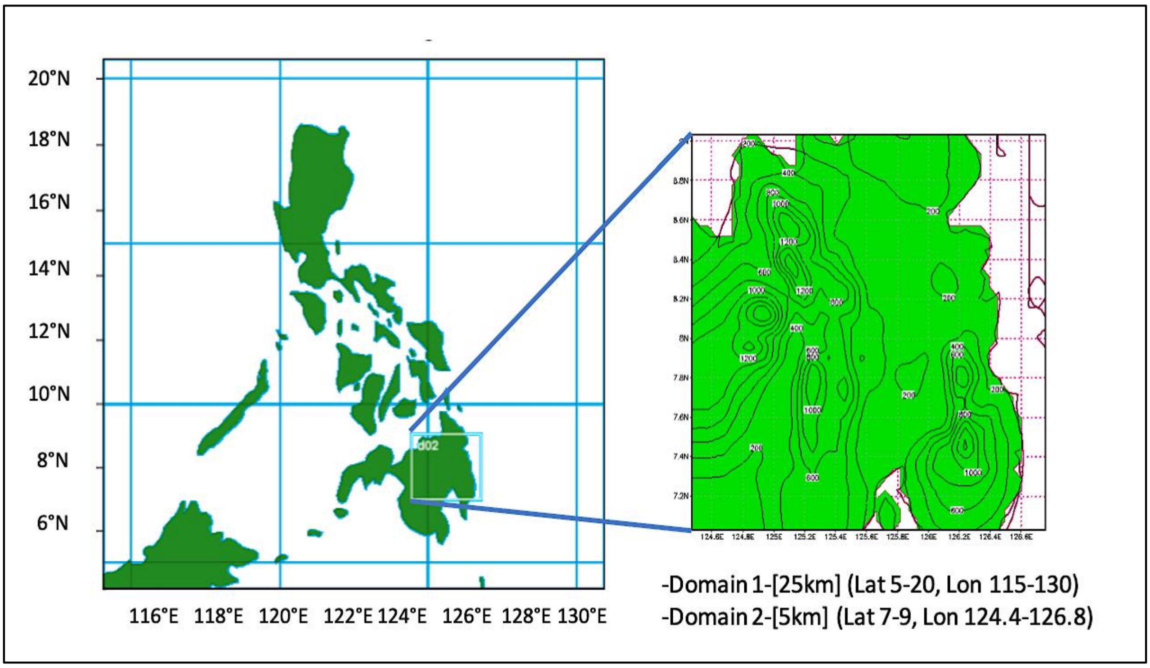

Figure 1: WPS Domain Configuration with Two Nested Domains Used in Simulation

Experimental Run

The study carried out five days simulation of Typhoon Bopha which takes account of the two days before, during and two days after the landfall using Weather Research Forecast Model Version 3 (WRF). The simulation helped the researcher investigate topography effects on the amount and rainfall distribution. Thus, two experimental runs were designed; a control run (CTRL) with the presence of the mountain as seen in Figure 2A and experimental run (EXP) where terrain was assumed to be flat as seen in Figure 2B.

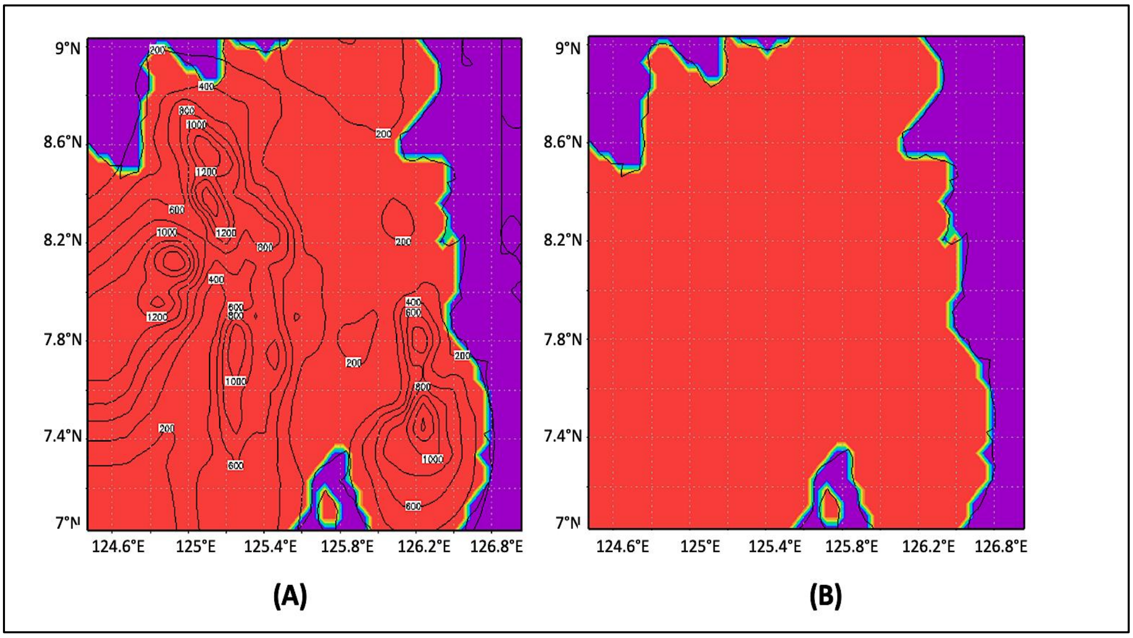

Figure 2: Topographic Map of The Domain-2 - (A) Control Run with Mountain Ranges, (B) Experimental Run with Flat Terrain

The control and experiment run where re-run with different schemes, the Ondoy scheme and Yolanda scheme. Parameterization schemes control the representation of unresolved physical processes in WRF, including convection and microphysics, which directly influence rainfall production and wind structure. Thus, differences in parametrization can lead to variations in simulated typhoon rainfall and wind patterns. The nomenclature "Ondoy scheme" and "Yolanda scheme" is used in this study to denote two selected physics parameterization combinations. These labels are adopted for convenience, as the configurations were inspired by setups previously used in simulations of Typhoon Ondoy and Typhoon Yolanda. The Yolanda scheme uses Goddard GCE microphysics parametrization while the Ondoy scheme uses the WRF Single-Moment 6-class (WSM6) (17). Both schemes used -Fritsch Cumulus Parameterization (18). However, the Yolanda scheme applied Yonsei University Scheme (YSU) in the Planetary Boundary Layer while Ondoy scheme used ACM2. To represent mixed-phase processes and graupel formation, WSM6 and Goddard GCE microphysics schemes were selected. This scheme is important to simulate intense tropical cyclone rainfall hence it directly influences rainfall intensity and vertical latent heating. The YSU planetary boundary layer scheme was chosen for its non-local closure approach and demonstrated performance in simulating tropical cyclone structure and boundary layer processes. Another scheme, the ACM2-Pleim was used to combine the local and non-local mixing. This is included to assess and represent the turbulent transport and surface fluxes. Since moisture convergence and convection is greatly affected by the boundary layer processes, scheme selection affects simulated rainfall distribution and intensity.

The codes CTRL1 and CTRL2 are the control runs with mountain ranges run in Ondoy scheme (WSM6, ACM2-Pleim PBL, Kain-Fritsch) and Yolanda scheme (Goddard GCE, YSU, Kain-Fritsch), respectively. While, EXP1 and EXP2 were experiments with flat terrain run in Ondoy scheme (WSM6, ACM2-Pleim PBL, Kain-Fritsch) and Yolanda scheme (Goddard GCE, YSU, Kain-Fritsch), respectively. Figure 2 shows the topographic map of the study area for CTRL and EXP runs with the used of Grid Analysis and Display System (GrADS). This interactive desktop tool is used to visualize science data for analysis (19). This commonly used tool support different data formats and data models.

Data Validation

For data validation, the simulated track of typhoon Bopha was compared with the real-time data provided by the Joint Typhoon Warning Centre (JTWC).

Results and Discussion

Data Validation

Figures 3A and 3B shows the comparison between the WRF-simulated tracks and the observed JTWC track of Super Typhoon Bopha. The blue- and red-line on the left are the tracks of the typhoon simulations using the Ondoy and Yolanda schemes, respectively.

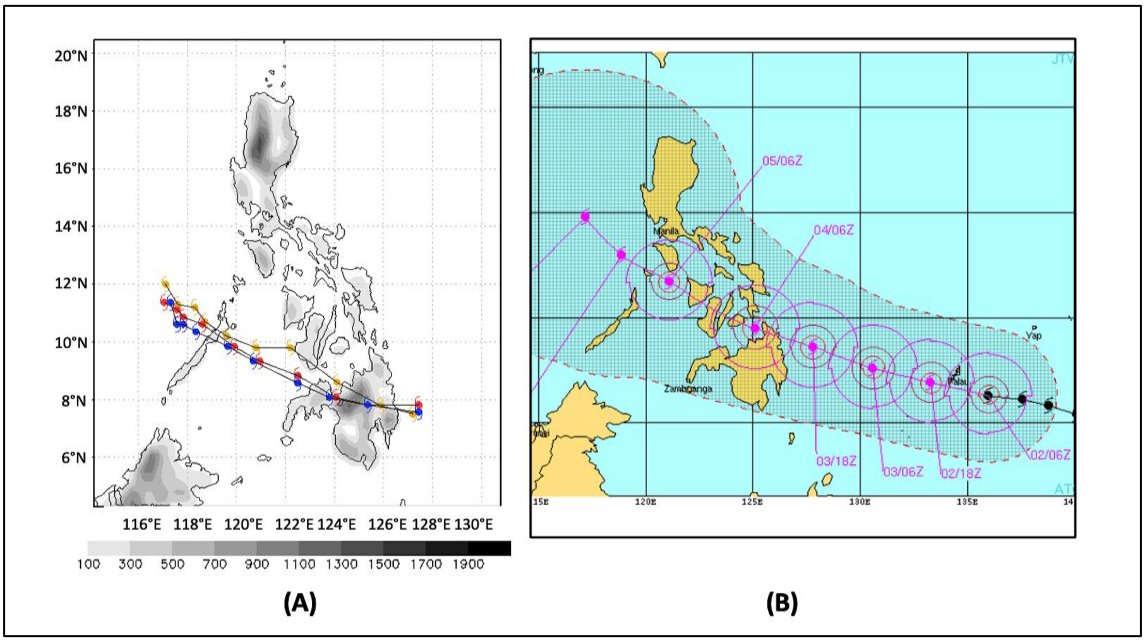

Figure 3: Comparison of the Tracks of Super Typhoon Bopha - (A) WRF-Simulated Tracks, (B) JTWC Observed Track

As observed, the Yolanda scheme shows more closely matches the JTWC track, especially before and during landfall. Hence, the Yolanda setup produced a more accurate track, reinforcing the value of scheme tuning in regional typhoon modeling. On the other hand, a slight southward shift was observed in the Ondoy scheme, indicating some deviation in storm steering. These differences suggest that model output can vary depending on the chosen physics schemes. However, both runs follow the general path of the storm.

Difference in Rainfall

The map shows the difference in the rainfall amount of the simulation of Typhoon Bopha for domains with mountains and with flat terrain as seen in Figures 4A and 4B. In the mountainous area (with arrow), it is shown in both parameter schemes that there is a high amount of rainfall difference. The amount of rainfall difference between the simulation of the typhoon with mountains and with flat terrain is approximately 140 mm of rain in the Ondoy scheme and 100 mm of rain in the Yolanda scheme.

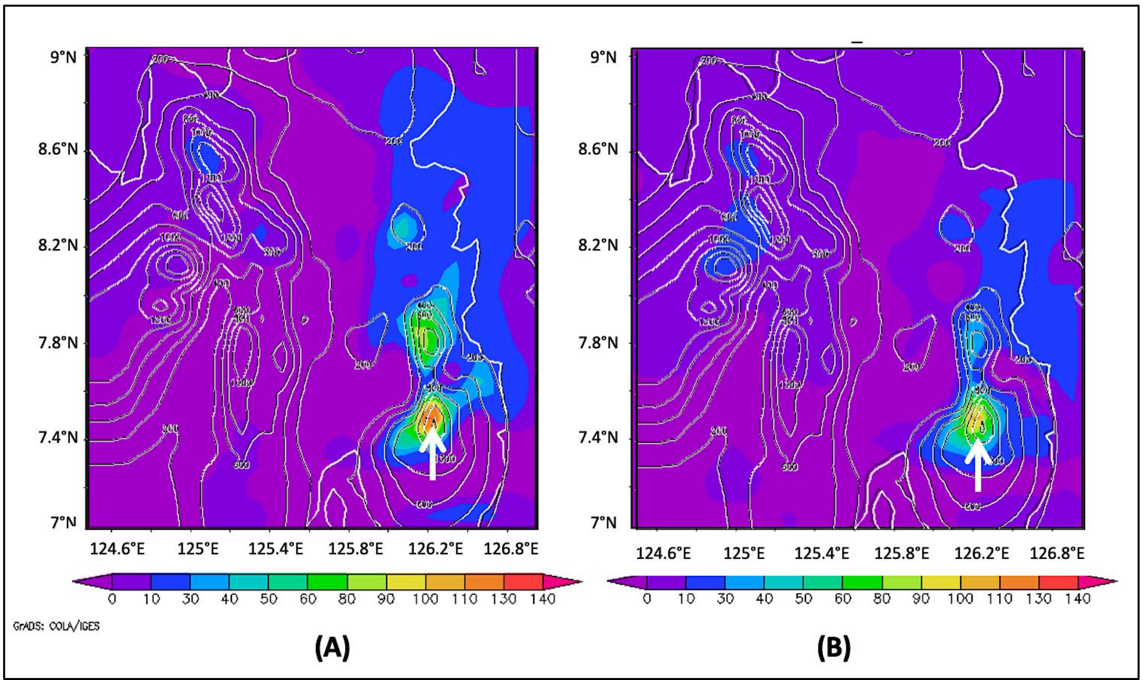

Figure 4: Comparison of the Tracks of Super Typhoon Bopha - (A) WRF-Simulated Tracks, (B) JTWC Observed Track

The differences prove that there are enhancements in the precipitation due to the mountain ranges present in the area. This means that Mt. Tagubod in Davao Oriental is one of the factors in the enhancement of the rainfall amount upon the passage of Typhoon Bopha. In other simulation studies conducted over the mountainous area in Mindanao near Cagayan de Oro City, Mt. Malindang and Mt. Ragang have the ability to enhance the orographic precipitation of a typhoon (15). Hence, not all mountain ranges can enhance the precipitation upon the passage of a typhoon due to the complexity and several factors that affect orographic precipitation (20). However, in other locations, different extents of the common components can lead to discrete key components that are responsible for orographic rainfall.

To quantify the rainfall, we present the spatial distribution and magnitude of rainfall between runs with mountains and runs with flat terrain in different areas, as seen in Figure 5. Mt. Tagubod (CTRL-Yellow, EXP-Red) recorded an accumulated rainfall of 280 mm in the run with mountains compared to 140 mm in the run with flat terrain, representing a 100% increase in rainfall due to the presence of the mountain. In New Bataan (CTRL-Black, EXP-Green), accumulated rainfall is 250 mm in the run with mountains, compared to 140 mm in the run with flat terrain, corresponding to a 78.6% increase in rainfall. In Baganga (CTR-Pink, EXP-Purple), rainfall increased only to 145 mm in the run with mountains from 120 mm in the run with flat terrain, representing an increase of only 20.8%. The results imply that elevation greatly influences the enhancement of rainfall; hence, Mt. Tagubod, which has the greatest enhancement, also has the highest elevation as its peak is 2,670 m above sea level. It is followed by the New Bataan area with an elevation of 942 m, while Baganga has the lowest rainfall enhancement, as it has the lowest elevation.

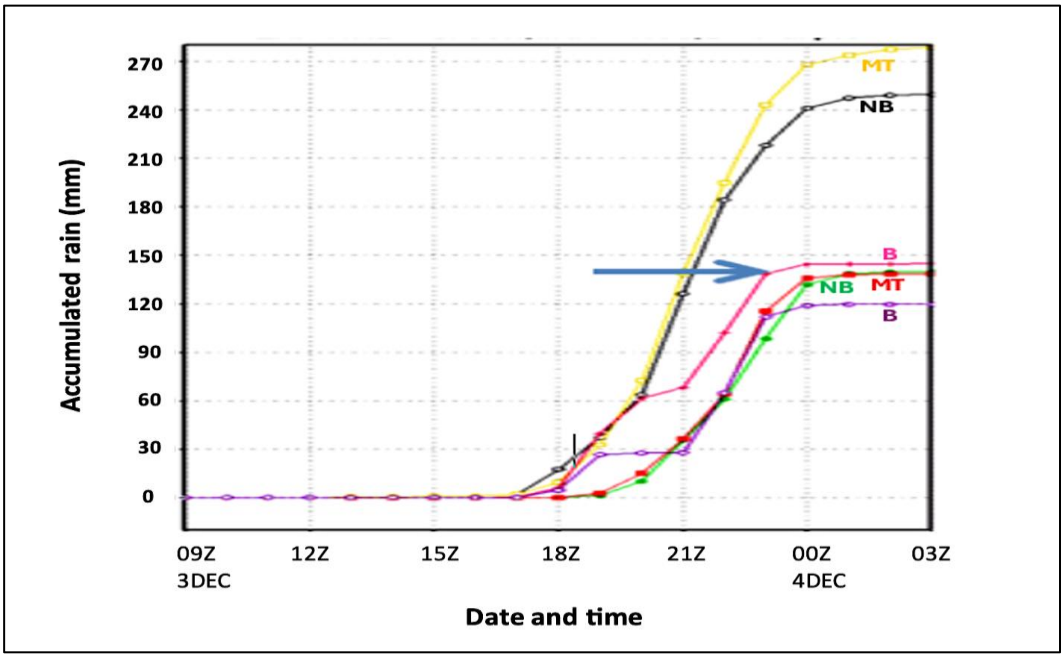

Figure 5: Spatial And Temporal Accumulated Rainfall Amount of Control Run [Black - New Bataan (NB); Yellow – Mt. Tagubod (MT); Pink – Baganga (B); And Experimental Run (Green - New Bataan (NB); Red – Mt. Tagubod (MT); Purple – Baganga (B)

This means that there might be no so much enhancement of rainfall in this area. This might be due to the aspect ratio of mountain height-width (h/a), favorable mountain geometry and steepness of the nearby mountain range that were necessary in heavy orographic rainfall (21). This case study demonstrates the role of Mindanao topography in modulating rainfall during Typhoon Bopha in 2012. However, the magnitude and spatial distribution of orographic enhancement may vary for other storms with different structures and environmental conditions. Although in previous study over Taiwan shows that less rainfall on lower-terrain runs was exhibited on the simulation of Typhoon Nari in 2001.

Horizontal Wind

The result shows that in the control run with the presence of mountainous ranges the speed of the wind slows down as it approaches the mountain ranges. Figure 6A shows uneven arrow sizes, long and shorts arrows. The short arrows mean that the wind speed is already slow. While Figure 6B is the experiment run without the presence of the mountain ranges shows that the wind speed is much stronger since there is no mountain range to block or slow down the horizontal wind.

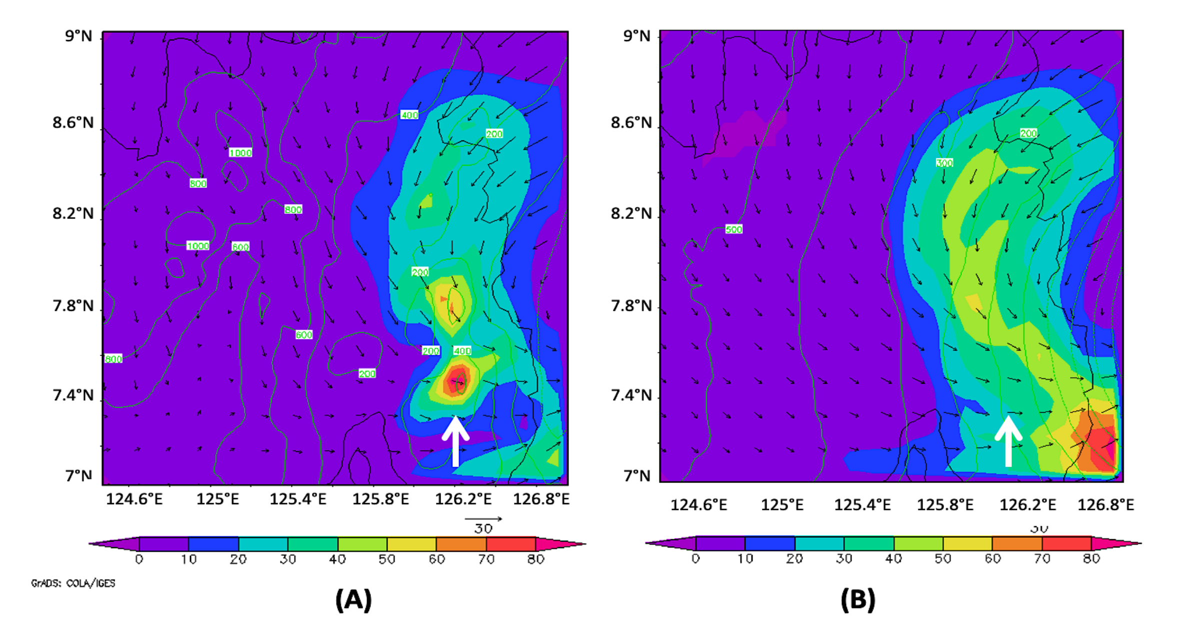

Figure 6: Horizontal Wind Profiles - (A) Control Run with Mountain Ranges, (B) Experimental Run with Flat terrain

Vertical Wind

The result shows that the vertical winds in the CTRL1 with mountain ranges have strong synoptically forced upward vertical motion presented in Figure 7A. This is one of the necessary conditions to exist the orographic precipitation (22, 23). While, Figure 7B, the experiment run (EXP1) without the presence of the mountain ranges shows that the winds were not induced vertically.

Based on the entire findings, enhancement is not determined by mountain alone such as its steep terrain and mountain height. It is supported by previous studies that high precipitation efficiency, strong low-level jet, high moisture upstream, large convective system and slower movement of the typhoon (24, 25). Other primary contributor of the heavy precipitation due to the passage of typhoon over a mountainous area is the direction of movement of a tropical cyclone as well as its adjacent areas (26).

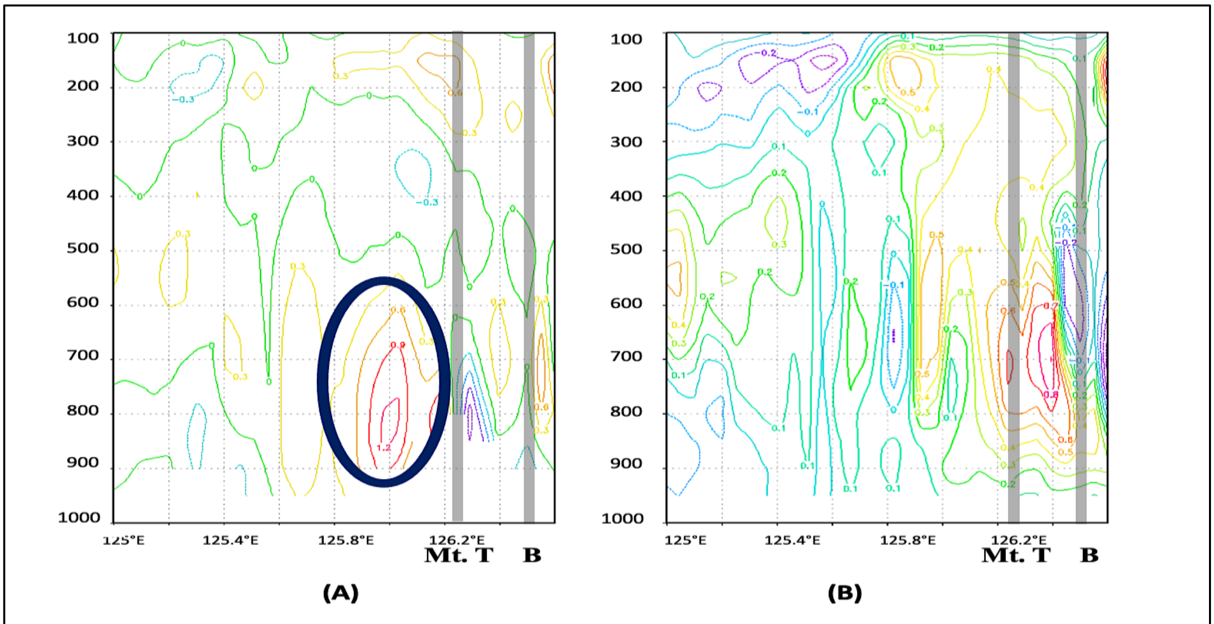

Figure 7: Vertical Wind Profiles - (A) Control Run with Mountain Ranges, (B) Experimental Run with Flat Terrain.

Conclusion

In this study, the WRF model successfully simulated and produced the structure and topographic-induced rainfall characteristics during the passage of Super Typhoon Bopha wherein essential ingredients were present during the event. It revealed that the presence of mountain, particularly Mt. Tagubod, significantly enhanced rainfall accumulation, indicating the critical role of topography in rainfall enhancement during typhoon landfall.

These key results contribute to improved understanding of terrain-induced rainfall process during typhoon events affecting eastern Mindanao. It also provides practical implications for disaster risk reduction planning, as enhanced rainfall due to orographic lifting suggests that existing flood-warning thresholds may underestimate potential hazards in mountainous watersheds and nearby communities, where many residents assume that mountains can protect them during a typhoon.

However, this investigation is limited to a single event and the results reflect only on specific storm track, structure and atmospheric conditions of typhoon Bopha. The notable specific responses observed in a specified area suggest that orographic rainfall effect vary depending on the terrain, moisture transport, wind direction and typhoon intensity. Thus, the conclusion cannot be generalized to other tropical cyclones and regions without further investigations.

Future research may focus on multi-event simulations to evaluate the consistency of orographic rainfall enhancement across different typhoon tracks and intensities. Additional work integrating hydrological modelling and land cover would also help translate meteorological findings into a more comprehensive forecasting particularly in Mindanao area.

Abbreviations

CAPE: Convective Potential Energy, FNL: Final Operational Global Analysis, NCAR: National Center for Atmospheric Research, NCEP: National Centers for Environmental Prediction, UCAR: University Corporation for Atmospheric Research, WPS: WRF Preprocessing system, WRF: Weather Research Forecasting,

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Author Contributions

Grethyl C Jamero: conceptualization, design, data collection, analysis, interpretation, writing, Jerome A Azul: conceptualization, design, data collection, analysis, interpretation, writing, Emmanuel C Garing: conceptualization, design, data collection, analysis, interpretation, writing, Jackie Ibañez: conceptualization, design, data collection, analysis, interpretation, writing. Each author reviewed and approved the final version of the paper.

Conflict of Interests

The authors declare no conflict of interests.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI And AI Assisted Technologies in the Writing Process

This work was supported by the use of artificial intelligence (AI) to refine grammar and improve the manuscript's coherence and structure. Although AI tools were employed for linguistic editing, the authors maintain full responsibility for all interpretations, conclusions and the original conceptual content of the study.

Ethics Approval

This study did not involve human participants, animals, or sensitive data. Therefore, ethical approval and informed consent were not required.

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