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# Characterization of the 2012 and 2013 Metro Manila "Enhanced *Habagat*" Heavy Rainfall Events

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**The strong southwest monsoon episodes in August 2012 and 2013, locally referred to as the "Enhanced *Habagat* " 2012 and 2013, respectively, resulted in rainfall that exceeded the monthly mean rainfall of the affected regions along western Luzon, including Metro Manila. The prolonged heavy rainfall events were the result of tropical cyclone enhancement of the monsoon winds. The synoptic environment in the two events was characterized by the deepening of the Asian monsoon trough depicted by the zonally-oriented and eastward-extended 1000 hPa isobar. The deep troughs were caused each year by a combination of tropical cyclones located to the northeast of the Philippines – Typhoon Haikui in 2012 and Severe Tropical Storm Trami in 2013, and remnant tropical cyclones in the northern South China Sea region that formed several days prior to the enhanced *Habagat* episodes. The monsoon trough induced a low-level westerly jet in the South China Sea toward the western Luzon region that transported a narrow stream of moisture-laden air mass to Metro Manila and surrounding areas. Consequently, heavy precipitation ensued. Analysis showed the remnant lows are as important as the enhancing tropical cyclones Haikui and Trami in inducing the westerly jets. Removal of the enhancing tropical cyclones in numerical model simulations still showed a relatively deep monsoon trough that led to heavy rainfall along western Luzon. In addition, the intrusion of low potential vorticity area to the eastern and northern flanks of the tropical cyclones facilitated the strengthening of the steering ridge that resulted in their westward and slow translational motion, making the events last for several days and exacerbating the impacts. Furthermore, the Madden-Julian Oscillation possibly serves as a precursor to heavy rainfall events. Compounded with a populous megacity, understanding the mechanisms that lead to these extreme hazards is vital to future forecasting and disaster risk management of similar events.**

Keywords: enhanced *Habagat*, the Philippines, rainfall, southwest monsoon, tropical cyclones

## INTRODUCTION

In August 2012 and 2013, two heavy rainfall events – both with return periods of 20 years – occurred in Metro Manila, Philippines. Continuous rains were observed with the highest rain rates recorded from 06–10 Aug 2012 and 18–22 Aug 2013. In 2012, the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) Science Garden station in Quezon City recorded an accumulated rain of 1007.4 mm in the 4-d period, whereas the highest accumulated rainfall for the 2013 event was recorded in Sangley Point station in Cavite (southwest of Science Garden) with 1067.4 mm (Lagmay *et al.* 2015). The Greater Metropolitan Manila – which consists of Metro Manila and the neighboring provinces of Bulacan to the north, Rizal to the east, and Cavite, Laguna, and Batangas to the south – had an estimated

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population of 26.5 million people in 2010 (PSA 2010). Heavy precipitation during both events exposed a large portion of the Greater Metropolitan Manila population to severe flooding. The Philippines' National Disaster Risk Reduction and Management Council (NDRRMC) in 2012 reported 109 fatalities in 17 provinces, where most were due to drowning and an estimated damage cost of PHP 3 billion (Philippine Peso). In 2013, there were 27 reported fatalities in 12 provinces and PHP 688 million worth of property damages (NDRRMC 2013).

This type of continuous heavy rainfall event is commonly referred to as "enhanced *Habagat*" or "*Habagat* rains", wherein distant tropical cyclones enhance the southwest monsoon by strengthening the zonal component of monsoon winds and moisture flow that results in heavy rainfall events. Enhanced *Habagat* events especially affect the western regions of Luzon and are not uncommon. In fact, around nine out of ten heavy rainfall days along western Luzon, excluding rainfall from landfalling tropical cyclones, are due to enhanced *Habagat* episodes (Bagtasa 2019). In another study, Bagtasa (2020a) used 118 years' worth of rainfall data in Metro Manila and reported several heavy rainfall and flooding events over the past century. Some of the most remarkable episodes are the excessive rains of August 1919 and August 1923, the great Philippine flood of July 1972 (Gordon 1973), and the La Niña year 2000, all due to enhanced Habagat rains. Despite its impacts on life and property, to the author's knowledge, there are only a few studies that focused on this particular topic.

Cayanan *et al.* (2011) looked at the effects of tropical cyclones on southwest monsoon rainfall by analyzing heavy rainfall events along western Luzon from 2002–2006. They found that heavy rainfall episodes occur with anomalously strong zonal wind from around 10–22°N latitude at longitude 120°E that were coincident with the presence of tropical cyclones to the northeast of Luzon. They then decomposed the total stream function into two flow regimes to isolate the synoptic monsoon winds from that of the tropical cyclones to determine the latter's effect on the monsoonal activity. Their analysis showed that southwest winds are strengthened by distant tropical cyclones. Moreover, they hypothesized that the interaction of the strong westerlies and the Cordillera Mountain ranges by orographic lifting produced heavy precipitations along the west coast of Luzon. Bagtasa (2019) investigated the mechanism that drives this tropical cyclone-monsoon interaction. Results showed that the Asian monsoon trough deepens as intense tropical cyclones move in an area near an imaginary line connecting Okinawa and Luzon, together with weak low disturbances present in the northern South China Sea region. The deepening of the monsoon trough induces strong westerlies towards western Luzon, which enhances moisture flow. This happens when the westerlies from a tropical cyclone overlap with existing monsoon westerlies, paving the way for the establishment of the "moisture conveyor belt," where moisture from the Indian Ocean is transported to tropical cyclones in the western Pacific region passing through Luzon (Kudo *et al.* 2014; Fujiwara *et al.* 2017). Bagtasa (2022) quantified the remote tropical cyclone (> 550 km away) precipitation amounts and estimated their contributions to the total seasonal rainfall at 8.85, 66.58, and 35.76% for the months of February–May, June–September, and October–January, respectively.

Heisterman *et al.* (2013) did a reconstruction of the *Habagat* 2012 event using the then-newly installed radar system located in Subic Bay, Zambales. Accumulated radar returns converted to rain rate show an overall underestimation of radar-based precipitation estimation as compared to rain gauges. Spatial distribution of rainfall showed a heavy concentration of rain that fell on Manila Bay (west of Metro Manila), missing landmass by 20 km, and concluded that if a slight shift in the rain field occurred, it would have affected the discharge of the Marikina river with an increase of 30%, equivalent to a 200-yr return flooding. Lagmay *et al.* (2015) proposed an explanation of the rain field distribution observed in the radar signals for both the 2012 and 2013 Habagat events. Two stratovolcanoes along the Central Luzon volcanic arc – Mount Mariveles and Mount Natib located approximately 60–70 km west of Metro Manila – had a significant impact on the precipitation field. The height and shape of the volcanoes created a dispersive tail of rain clouds directed toward Metro Manila. Simulations using the Weather Research and Forecasting (WRF) model validated the orographically-enhanced leeward rainfall, which showed significant differences in precipitation patterns when the topographic features were modified.

The Philippines gets significant amounts (~ 44%) of rainfall during the southwest monsoon or *Habagat* season, which typically occurs during the months of June, July, August, and September (Bagtasa 2020b). Some studies (Cruz *et al*. 2013; Villafuerte *et al.* 2014) discussed decreasing trends in rainfall along the western portion of the Philippines during the southwest monsoon season in the past decades. However, there are increasing trends in the tropical cyclone rain amounts, the number of heavy precipitation days due to enhanced *Habagat* episodes (Bagtasa 2017, 2019), and overall southwest monsoon rainfall (Basconcillo *et al.* 2023). These results suggest that the regional climate may be having wetter wets and drier dries in more recent times. While most Enhanced Habagat episodes in the past decade did not reach the intensity and duration of the 2012 and 2013 events, such extreme events are bound to happen again in the future. Hence, the importance of characterizing these past events is to better understand and prepare for future occurrences.

The aim of this study is to investigate the regional synoptic conditions and the mechanisms that led to the extreme rainfall of the *Habagat* events of 2012 and 2013, as well as to identify other factors that influenced the events apart from the enhancing tropical cyclones. A combination of reanalysis data and numerical simulations using the WRF model was done to examine the synoptic conditions that induced the heavy rain events. The next section will describe the data and method used in this study and will present the numerical model experiment and setup. In Section 3, the environment and mechanisms that led to the indirect TC rain and the result of the model experiments are discussed. Finally, Section 4 summarizes this study.

## DATA AND METHODS

### Observations and Reanalysis of Data

This study used the 6-hourly Japanese 55-year Reanalysis Project (JRA55) downloaded from http://rda.ucar.edu/datasets/ds628.0/. JRA55 is a global atmospheric reanalysis of the Japan Meteorological Agency (JMA) that covers the period from 1958 to the present (Kobayashi *et al.* 2015). While a higher model resolution is available, the 1.25° x 1.25° horizontal resolution data was deemed sufficient in representing synoptic-scale weather patterns and, thus, used in this study. Particularly, the zonal and meridional wind at 850 hPa level, the total column (surface to model top level) vertically-integrated water vapor flux, geopotential height at 500 hPa level, pressure reduced to mean sea level, and the potential vorticity at 310 k isentropic level were used. Tropical cyclone best track data used is from the Regional Specialized Meteorological Center – Tokyo / JMA (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html). Precipitation data from the Global Precipitation Measurement (GPM) Integrated Multi-Satellite Retrievals for GPM (IMERGE) Final Precipitation L3 1-day V06 (downloaded from https://disc.gsfc.nasa.gov/) was used. The GPM-IMERG rainfall data uses combined multi-satellite precipitation products to estimate precipitation from various passive microwaves and infrared satellite observations at 0.1° x 0.1° resolution (Kirschbaum *et al.* 2017). To determine the phase of the Madden-Julian Oscillation (MJO), the real-time multivariate MJO index was used to define the phases of MJO (Wheeler and Hendon 2004). Lastly, observed rainfall data from PAGASA stations (Science Garden located at 121.0°E 14.3°N, Manila at 120.4°E 16.1°N, and Sangley Point at 120.9°E 14.5°N) are downloaded from the Global Summary of the Day website (https://www.ncei.noaa.gov/data/global-summary-of-the-day/access/).

### WRF Model Setup

Numerical simulations were performed using Advanced Research WRF (WRF-ARW ver.4.2.1) model developed at the National Center for Atmospheric Research (NCAR) (Skamarock *et al.* 2008). WRF solves a fully compressible, non-hydrostatic equation formulated on a terrain-following vertical coordinate and the Arakawa C-grid. The WRF domain covered portions of East and Southeast Asia and the western Pacific (99–144°E and 2–37°N), configured with a grid spacing of 15 km. The model simulations used the 0.25°-resolution ERA5 (Hersbach *et al.* 2020) 6-hourly reanalysis data as initial and boundary conditions. Vertically, 38 layers are included from the surface to the pressure level of 10 mb, with higher resolution below the boundary layer. The model settings follow the configuration of a previous sensitivity study (Delfino *et al.* 2022).

Four numerical experiments were done in this study. Two control runs from 00 UTC of 04–11 Aug 2012 and 00 UTC of 16–23 Aug 2013. Then, to analyze the effects of the distant tropical cyclones on the synoptic environment, the initial conditions were subjected to the tropical cyclone bogussing scheme of the WRF model, wherein the center positions of the tropical cyclones were manually identified and removed by adjusting the first-guess vorticity and divergent winds within 300 km of the cyclone center (Fredrick *et al.* 2009). After this, the "no-vortex" run simulations were done using the initial conditions with the tropical cyclones removed. In addition, the imbalances in the resulting initial conditions arising from the tropical cyclone removal were minimized by applying the digital filter initialization with 1-h backward and forward integration (Skamarock *et al.* 2008). The control and no-vortex runs were compared to investigate the impacts of tropical cyclones on the environmental features. The use of two different reanalysis data (*i.e.* JRA55 and ERA5) was done to take advantage of their respective strengths; ERA5 has a higher spatial resolution and good global rainfall correlation that is suitable for the WRF downscaling and bogussing experiments, whereas JRA55 represents tropical cyclones well (Hodges *et al.* 2017), thus deeming it suitable for tropical cyclone synoptic analysis. Nonetheless, it has been shown that there is good agreement between the ERA5 and JRA55 reanalysis data (Hersbach *et al.* 2020).

## RESULTS AND DISCUSSION

### Synoptic Conditions

At 00UTC of 01 Aug 2012, JMA classified a tropical disturbance in the southeast of Iwo Jima as a tropical depression. It then intensified while moving west-northwest towards eastern China and was named Haikui. On 06 Aug, at the time when the 2012 heavy rainfall event in Metro Manila started, Haikui reached typhoon category with a minimum central pressure of 965 mb and was located to the northeast of Luzon (126.1°E 27.1°N), a distance of 1300 km from the megacity. Meanwhile, the remnants of Typhoon Saola (locally named "*Gener*") – which developed a week earlier (26 Jul) and made landfall in southern China – still had a low-level weak cyclonic circulation located to the northwest of Hainan Island. The tracks of the two tropical cyclones together with the accumulated rainfall from GPM-IMERG from 06–11 Aug are shown in Figure 1A.

In the case of the *Habagat* 2013 event, the synoptic environment is similar to the previous year. On 08 Aug 2013, Typhoon Utor ("*Labuyo*") developed in the east of the Philippines and traversed a west-northwest track toward southern China. It made landfall in Luzon on 12 Aug and affected a large swath of area in Central Luzon. On 16 Aug, Utor weakened into a tropical depression located in southern China (111.6°E 24.7°N). Another tropical cyclone that formed to the east of Taiwan and intensified into Severe Tropical Storm Trami ("*Maring*") interacted with an unnamed tropical depression to its north. This interaction reversed Trami's initial eastward movement to a westward track toward southeast China. The tracks of the two 2013 tropical cyclones together with the accumulated rainfall from GPM-IMERG from 18–23 Aug are shown in Figure 1B.

Both *Habagat* events occurred in ENSO-neutral years. Moreover, both occurrences of heavy rainfall events were in the MJO Phase 8, with Typhoon Haikui and Severe Tropical Storm Trami forming at MJO Phases 6–7, which are the phases conducive for tropical cyclone formation in the western North Pacific (WNP) and enhanced *Habagat* episodes in the northwestern Philippines (Bagtasa 2020b). Table 1 shows the observed daily accumulated rainfall of Science Garden, Manila, and Sangley Point stations from 06–11 Aug for the 2012 and 18–23 Aug for the 2013 *Habagat* events. The mean spatial rainfall distribution for both events over the Greater Metropolitan Manila Area can be seen in Figure 4 of the work by Lagmay *et al.* (2015).

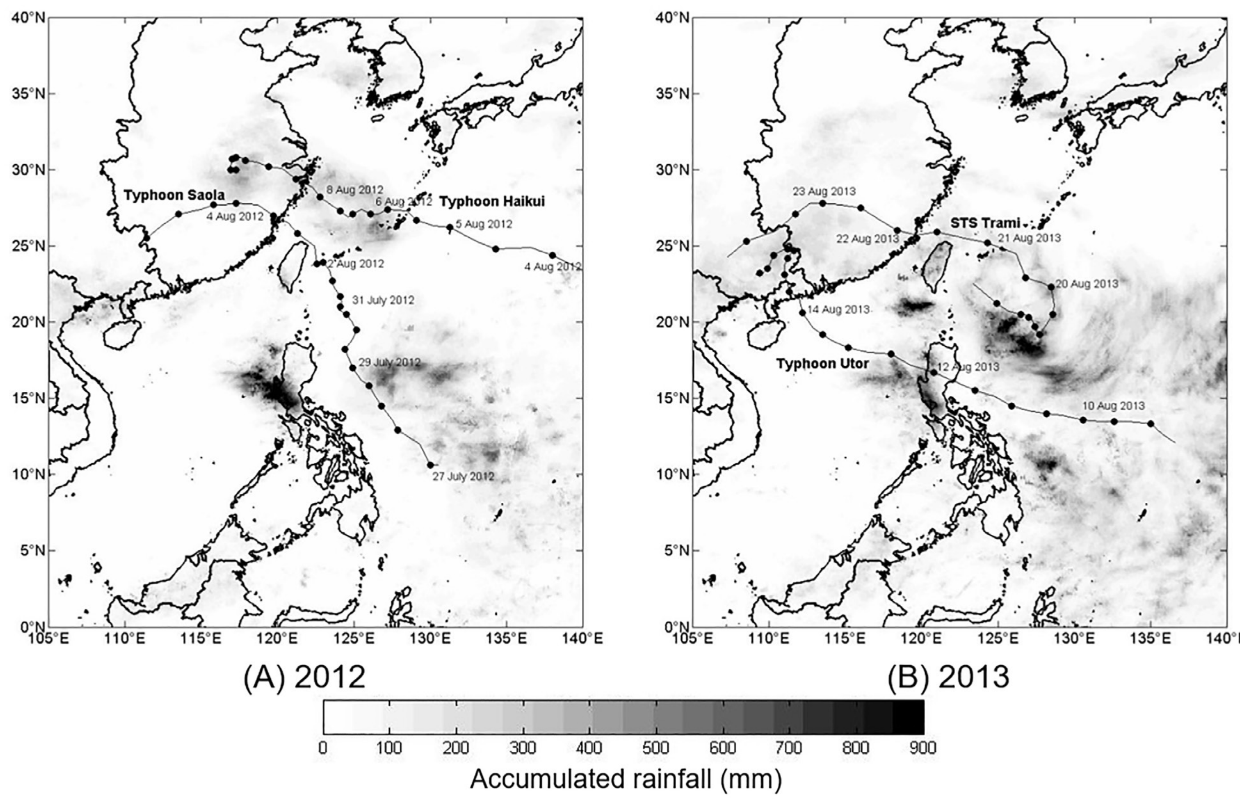


**Figure 1.** Accumulated rainfall (GPM-IMERG) and tracks of tropical cyclones during the [a] 2012 and [b] 2013 *Habagat* events.

**Table 1.** Daily accumulated rainfall from the PAGASA Science Garden (SG), Manila, and Sangley Point (SP) stations for the *Habagat* 2012 and 2013 events (units in mm).

| **2012 *Habagat* event** | | | | **2013 *Habagat* event** | | | |
|---|---|---|---|---|---|---|---|
| | **SG** | **Manila** | **SP** | | **SG** | **Manila** | **SP** |
| 06 Aug | 64.8 | 37.5 | 98.4 | 18 Aug | 20.2 | 63.0 | 56.2 |
| 07 Aug | 323.4 | 302.0 | 312.8 | 19 Aug | 174.3 | 277.0 | 335.0 |
| 08 Aug | 363.7 | 358.0 | 354.2 | 20 Aug | 105.5 | 290.0 | 475.4 |
| 09 Aug | 292.6 | 192.0 | 120.8 | 21 Aug | 225.7 | 119.0 | 168.0 |
| 10 Aug | 38.2 | 51.5 | 13.0 | 22 Aug | 166.1 | 70.0 | 85.6 |
| 11 Aug | 19.4 | 27.3 | 19.7 | 23 Aug | 16.6 | 10.0 | 8.6 |
| **Total** | **1102.1** | **968.3** | **918.9** | | **708.4** | **829.0** | **1128.8** |

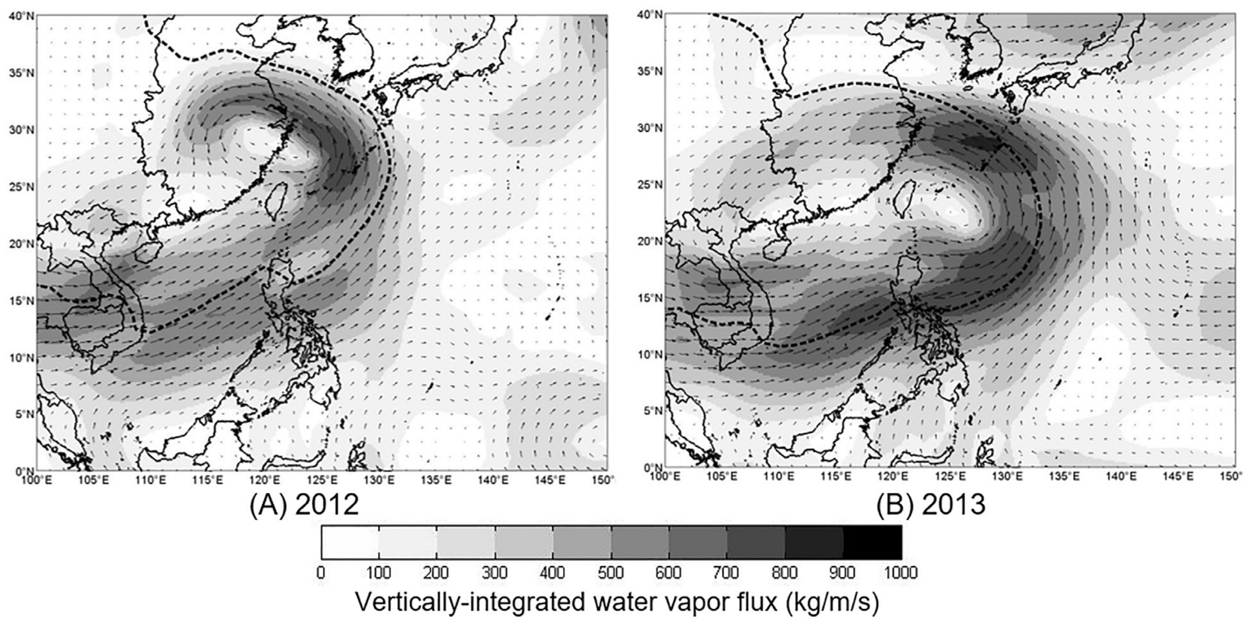


**Figure 2.** Mean vertically-integrated water vapor flux during the [a] 2012 (06–11 Aug 2012) and [b] 2013 (18–23 Aug 2013) *Habagat* events. The arrows show the direction of the column moisture flow and the 1000 hPa isobar (bold dashed line) to represent the extent of the Asian monsoon trough.

In both events, there was the presence of remnant low-pressure systems located in southern China/ northern South China Sea from previous tropical cyclones and intense tropical cyclones (*e.g.* severe tropical storm or typhoon) around the vicinity of an imaginary line segment connecting Okinawa and northern Luzon. These occurrences and positions of the tropical cyclones are consistent with the climatological analysis of southwest monsoon enhancement of tropical cyclones by Bagtasa (2019). Both tropical cyclones simultaneously occurring, albeit at different intensities, induced the deepening of the Asian monsoon trough shown in Figure 2. Other than the tropical cyclones, there were anomalous westerlies in the South China Sea region starting from 28 Jul 2012 and 16 Aug 2013 (not shown). These anomalously strong zonal winds to the west of the Philippines are likely due to the cloud clusters in the western Pacific region associated with the MJO. On 28 Jul 2012, the MJO phase shifted to Phase 6, whereas on 16 Aug 2013, MJO was at Phase 7. The results are consistent with anomalous westerlies in the South China Sea region in MJO Phases 5–7 during the southwest monsoon season described by Bagtasa (2020b). This indicates that prior to westerlies of the tropical cyclones affecting the country, there were already anomalous monsoon westerlies existing. Once the cyclone westerlies overlapped with the monsoon westerlies, it paved the way for the establishment of the "moisture conveyor belt" (Kudo *et al.* 2014). Figure 2 also shows the resultant vertically-integrated water vapor flux emanating from the Indochina region to the Philippines after traversing the central part of the South China Sea and the 1000 hPa contour isobar (bold dashed line) extended to around 130–135°E depicting the eastward extension of the Asian monsoon trough, which is lower than the 1004 hPa isobar used to characterize the mean extent of the trough corresponding to the upper 99$^{th}$ percentile heavy rain events along northwestern Luzon in Bagtasa (2019). This deepened monsoon trough induces the moisture conveyor belt, which is driven by both westerlies from the monsoon and tropical cyclone wind field flows. Also, there is a positive feedback effect from the diabatic heating on top of the tropical cyclone itself wherein heating-induced equatorial Rossby waves propagate westward and produces low-level westerlies in the Indochina region that further intensify the existing monsoon westerlies (Fujiwara *et al.* 2017; Bagtasa 2019). On the other hand, the remnant lows in the northern South China Sea region serve as a channeling mechanism that creates the low-level westerly jet of the moisture conveyor belt. This moisture flow, as shown in Figure 2, mainly traverses the southwest region of Luzon with higher moisture fluxes to the Metro Manila area in the 2013 case. Condensation then ensues in the Greater Metropolitan Manila driven by mesoscale dynamics (Cayanan *et al.* 2011; Lagmay *et al.* 2015). The mean column water vapor fluxes in the west Philippine Sea (12–18°N along 119.5°E) are estimated to be about 542 and 698 kg/m/s for the 2012 and 2013 *Habagat* events, respectively, both exceeding the 99$^{th}$ percentile climatological column moisture flow of 521.6 kg/m/s (Bagtasa 2019).

**Potential Vorticity Dynamics**

In the previous section, the mechanisms that explain the excessive rainfall episodes in Metro Manila were presented. One of the reasons for the damaging effects of the 2012 and 2013 *Habagat* events was their long duration, which was not explicitly discussed above. This persistence of heavy monsoon rains is mainly explained by the slow movement of Typhoon Haikui in 2012 and Severe Tropical Storm Trami in 2013 when they were in the vicinity of the imaginary line segment connecting Okinawa and Luzon – during the time of intense continuous rains. Here, the potential vorticity of the environment is analyzed to investigate the motion of the enhancing tropical cyclones. Potential vorticity is chosen as the parameter for this investigation because potential vorticity is conserved on isentropic surfaces, thereby making it easy to trace its movement, and local changes in its values are directly related to local diabatic heating or cooling (Hoskins *et al.* 1985; Davis and Emanuel 1991).

The maritime continent is characterized as a region of low (near-zero to negative) potential vorticity, which induces several anticyclonic flows in the equatorial region during the southwest monsoon season; this is shown in Figure 3. Figure 3 also shows Typhoon Haikui (2012; left panels) and Severe Tropical Storm Trami (2013; right panels) with high potential vorticity around their respective circulations. The arrows are the 850 hPa level wind vectors that also show the location of the enhancing tropical cyclones to the northeast of the Philippines. In addition, regions of high potential vorticity for both 2012 and 2013 events are found in southern China, particularly off the coast of the Vietnam-China border located around 117.5°E 20°N. These high potential vorticity regions are from the remnant lows of previous tropical cyclones, as discussed above. In both the 2012 (left panes) and 2013 (right panes) events, it is observed that low potential vorticity areas to the southeast of the tropical cyclones, shown with red arrows, are advected northward and then northwestward around their circulations. The advection of low potential vorticity by tropical cyclones in the East China Sea/Ryukyu Island region was documented in previous studies (Wang 2009; Yoshida and Itoh 2012). The cases of Typhoon Haikui and Severe Tropical Storm Trami are similar to the cases of Typhoons Maggie (1999) and Songda (2004). The advection of low potential vorticity on the eastern flank of the tropical cyclones coincides with the location of the western North Pacific subtropical high (WNPSH), which is an important steering mechanism for tropical cyclones (Bagtasa 2017, 2020b), shown in Figure 3 as bold dashed lines. As the low potential vorticity moved to the east of the said tropical cyclones, there is a visible strengthening of the WNPSH, as indicated by the blue arrows in Figures 3A–C in 2012 and Figures 3D–F in 2013. This likely prevented the recurvature of the tropical cyclones towards the central North Pacific region and ultimately slowed down the translational movement of both Typhoon Haikui and Severe Tropical Storm Trami.

In addition, a moderately positive potential vorticity zone emanating from the southern half of Taiwan in the 2012 event is seen in Figures 3A and B, as well as some moderate positive potential vorticity regions coming from the mountain ranges of Luzon in Figures 3A–C and E–F, similar to the reports of Yoshida and Itoh (2012) for Typhoon Maggie, indicates diabatic heating from the topography of both mountain ranges likely produced by low-level convergence as the monsoon wind fields are altered by the terrains, resulting in moist convection in those areas (Liu *et al.* 2016). This result also indicates the role of the Luzon mountain ranges in the condensation of the transported moisture and in enhancing the monsoon rainfall, which confirms the hypothesis of Cayanan *et al.* (2011).

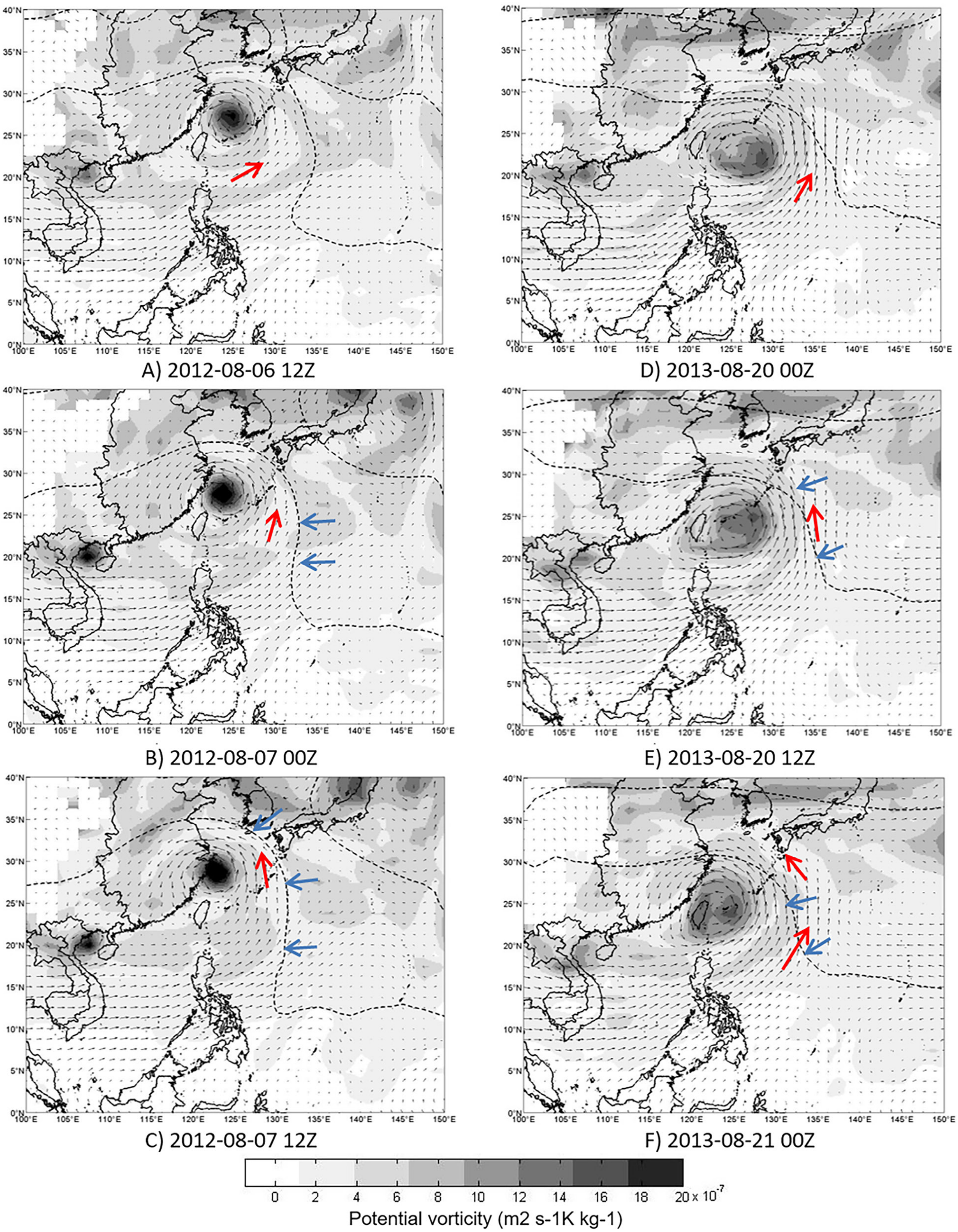


**Figure 3.** The potential vorticity on the 310 k isentropic surface (shading), 5870 m geopotential at 500 mb (dashed lines) representing the NWPSH, 850 hPa wind vector (black arrows) for [A] 12Z of 06 Aug 2012, [B] 0Z of 07 Aug 2012, [C] 12Z of 07 Aug 2012, [D] 0Z of 20 Aug 2013, [E] 12Z of 20 Aug 2013, and [F] 0Z of 21 Aug 2013. The red arrows show the advection of the low potential vorticity around the tropical cyclones and the blue arrow depicts the strengthening or the movement of the western extent of the NWPSH.

**WRF Modelling Experiments**

Figures 4A and C show the 1000 hPa contour isobar and the vertically-integrated water vapor flux vector (shading for magnitude and arrows for direction) from the results of the WRF simulations for the 2012 and 2013 *Habagat* events averaged over the 4-d peak-rainfall period from 6 to 9 of August 2012 and from 19 to 22 of August 2013. Figure 4 also shows the mean 5870 m 500 hPa geopotential heights (blue dashed line) to depict the extent of the steering ridge (*i.e.* WNPSH and the South Asian subtropical high) averaged over 48 h on 05 and 06 Aug 2012 and on 20 and 21 Aug 2013, when the enhancing tropical cyclones were about to traverse the Ryukyu Islands until around they made landfall in eastern China (see Figure 1). The model results with the tropical cyclones removed (no-vortex runs) are also shown (Figures 4B and D for 2012 and 2013, respectively). Note that there are two vortices present in each of the enhanced *Habagat* events – the remnant low and the tropical cyclones to the northeast of the Philippines. In the no-vortex simulations, only the tropical cyclones to the northeast were removed. The remnant lows remained in the initial conditions of the model runs. It is apparent that there are changes in the no-vortex runs compared to the control runs. In the case of *Habagat* 2012 shown in Figures 4A–B, whereas the WRF model was able to remove Haikui, another tropical cyclone formed around 133°E 23°N from 08 Aug onwards, thereby keeping the eastward-extended trough, albeit slightly retracted. Nevertheless, moisture flux values around Taiwan and the East China Sea due to Typhoon Haikui were almost non-existent, indicating its absence. It can be noticed that the remnant low has a stronger circulation

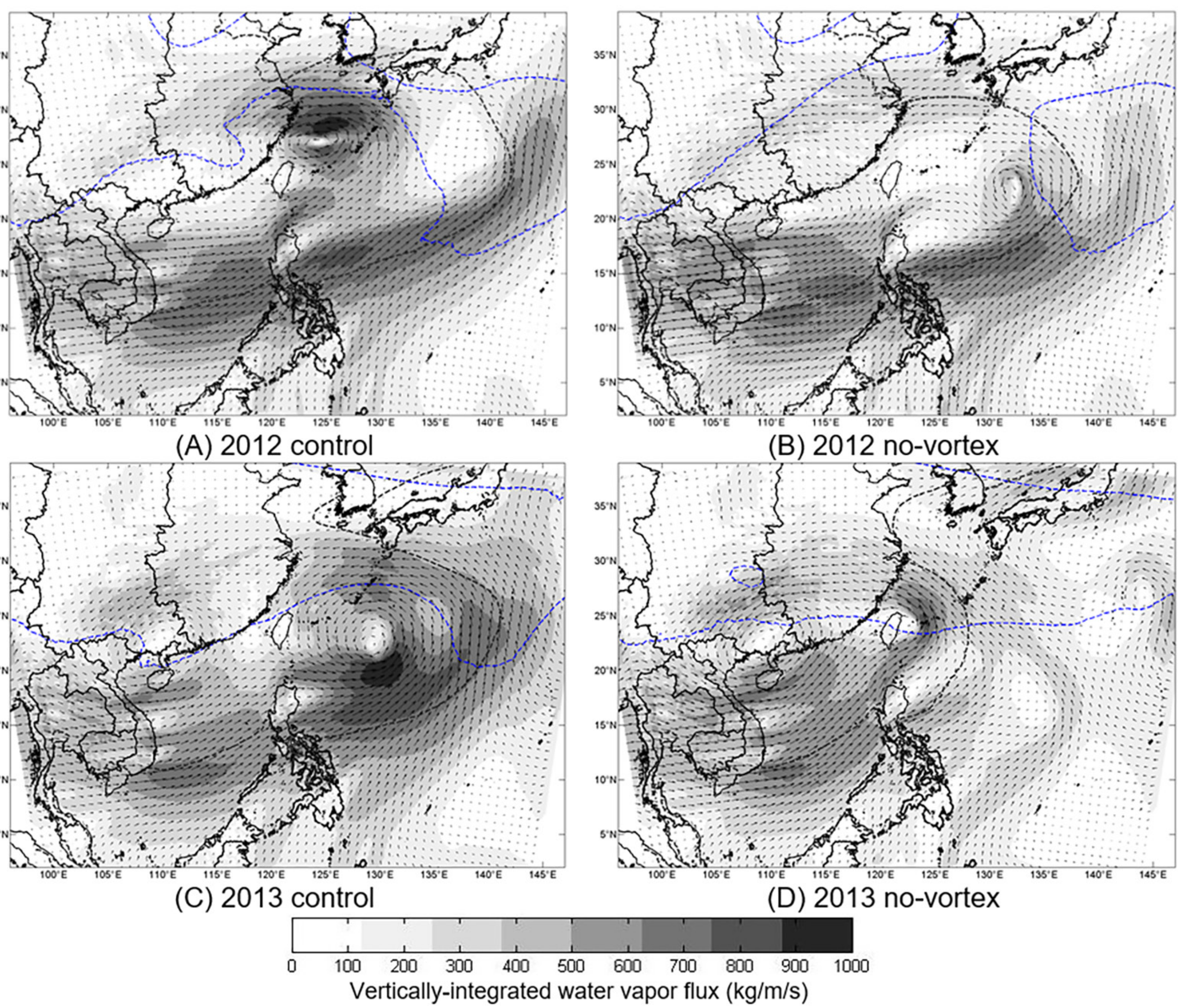


**Figure 4.** WRF simulation outputs of vertically-integrated water vapor flux vectors (shading and arrows), the 1000 hPa isobar (dashed black lines), averaged over 4 d from 06–09 Aug 2012 and 19–22 Aug 2013, and the simulated 5870 m 500 hPa geopotential steering ridge (dashed blue lines) averaged during their peak at 05–06 Aug 2012 and 20–22 Aug 2013: [A] 2012 control and [B] 2012 no-vortex runs, and [C] 2013 control and [D] 2013 no-vortex runs.

in the no-vortex run (Figure 4B), which increased the moisture flow across the Indochina and South China Sea regions. However, the absence of enhancing tropical cyclones resulted in lower overall moisture transport and a slightly different moisture distribution. Despite the apparent differences in the moisture flow distribution along the western Philippines, there is still a relatively strong westerly moisture flow.

The tropical cyclone removal scheme of the WRF worked better for the 2013 Habagat event. Figures 4C–D show an apparent difference in the eastward extent of the Asian monsoon trough, as indicated by the 1000 hPa isobar. The weaker monsoon trough indicates weaker westerlies in the central South China Sea region, consequently, weakening the moisture conveyor belt. Similar to the 2012 case, the remnant low has a stronger low-level circulation in the no-vortex run but with reduced moisture transport overall. In addition, the moisture flow direction significantly shifted. The presence of the enhancing tropical cyclones in the control runs likely weakened the remnant lows due to the subsidence along their western peripheries. Strong moisture flows towards the western Philippines persisted in the no-vortex runs due to the stronger remnant lows but with weaker flow compared to when the enhancing tropical cyclone existed, as indicated by the lower column moisture flux values. Figure S1 shows the same features in the control and no-vortex runs as Figure 4, even when the synoptic environment is shown in time slices following the 12-hourly time intervals of Figure 3. It is important to note, however, that there are limitations in decomposing the monsoon and tropical cyclone flow by the vortex removal scheme presented in this study. The model spin-up time can only be extended to two days prior to the start of heavy precipitation in Metro Manila because the moisture conveyor belt would have established itself already for a shorter spin-up, whereas the tropical cyclones Haikui and Trami were not fully developed if using longer spin-up times (> 2 d), making the tropical cyclone removal scheme less effective. Therefore, the 2-d spin-up time was selected. Nevertheless, the simulation results imply that characterization of enhanced *Habagat* events entails the diagnosis of the Asian monsoon trough as a whole, consisting of the enhancing tropical cyclone and a low-pressure area in the northern South China Sea, instead of just focusing on the tropical cyclones to the northeast of Luzon. The depth and extent of the trough are influenced by both systems and while removal of the enhancing tropical cyclone weakens the trough, the remnant low is shown to still induce the moisture conveyor belt, albeit at reduced flux values. Bagtasa (2020b) showed that 18% of boreal summer season days with anomalously strong westerly moisture flow occur without an enhancing tropical cyclone but transports only about half the amount of vertically-integrated moisture flux to the west Philippine Sea region, which is consistent with the findings in the present study.

Furthermore, the steering ridge is also shown (as blue dashed lines) for the control and no-vortex runs for both events in Figure 4. In the 2012 no-vortex run, there is a large gap in the steering ridge located across Japan that is not present in the control run. This is further evidence that the northwest-ward advection of low potential vorticity discussed in the previous section strengthened the ridge to Typhoon Haikui's north and prevented it from recurving towards Japan. In the 2013 case, the ridge was already strong initially but further strengthening to the east of Severe Tropical Storm Trami is apparent. The main reason for the persistence of Trami, however, was due to its interaction with another unnamed tropical depression.

## SUMMARY AND CONCLUSION

This study characterized the synoptic environment conditions that led to two heavy rainfall events known as the Habagat 2012 and 2013 events. The two Habagat events are so remarkable that the estimated rainfall volumes of 158.25 and 150.07 $km^3$ for the southwest monsoon seasons of 2012 and 2013, respectively, are the highest from indirect tropical cyclone precipitation data starting in 1951 (Bagtasa 2022). In both the Habagat events, the environments were characterized by the presence of an intense tropical cyclone located in an area around the vicinity of an imaginary line segment that connects Okinawa and northern Luzon, northeast of the Philippines. These tropical cyclones also coexisted with low-pressure systems off the coast of the Vietnam-China border, which are remnants of tropical cyclones that formed several days earlier. Both the remnant lows and the tropical cyclones to the northeast of the Philippines, Typhoon Haikui in 2012 and Severe Tropical Storm Trami in 2013, deepened the Asian monsoon trough that induced strong low-level westerly jets from the Indochina region towards the WNP region, passing through the Philippines. This long-range transport of moisture from the Indian Ocean to the WNP region is known as the "moisture conveyor belt" (Kudo *et al.* 2014; Fujiwara *et al.* 2017), and its establishment is the main mechanism that produces the Habagat rainfall events (Bagtasa 2019). When this narrow stream of moisture-laden air mass was channeled toward the southwestern region of Luzon, condensation ensued on land around the Greater Metropolitan Manila area. In both cases, there were already westerly anomalies existing in the South China Sea region prior to the westerlies from the tropical cyclone circulations overlapping with the monsoon. This is attributed to the MJO (Phases 6–7), where its location just southeast of the country induced westward-propagating Rossby waves

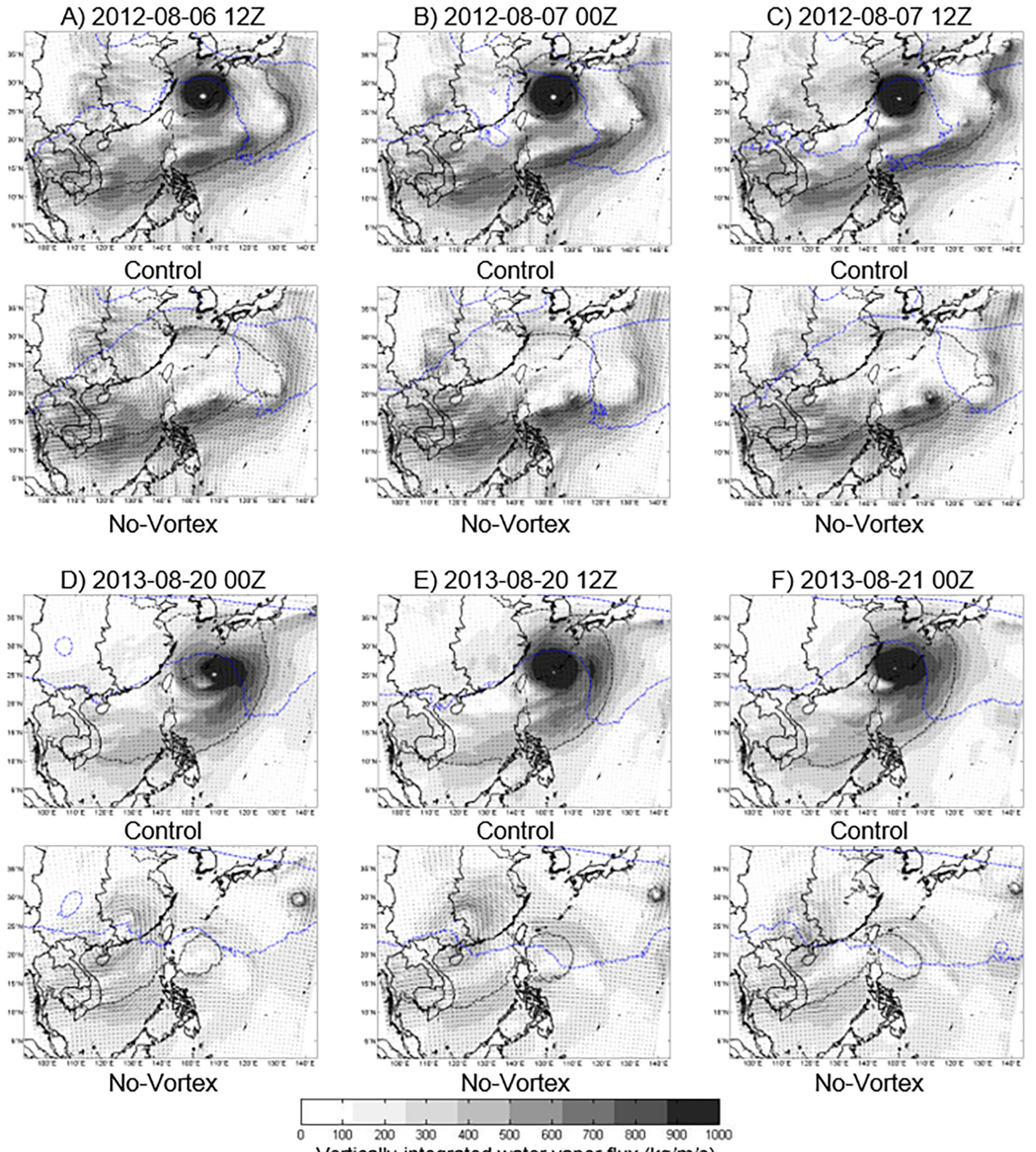


**Figure S1.** Similar to Figure 4 but follows the time slices of Figure 3. Control and no-vortex runs for 2012: [A] 12Z of 06 Aug, [B] 0Z of 07 Aug, [C] 12Z of 07 Aug; and for 2013: [D] 0Z of 20 Aug, [E] 12Z of 20 Aug, and [F] 0Z of 21 Aug.

that enhanced the monsoon westerlies in the South China Sea (Bagtasa 2020b). The existing westerlies were then even further enhanced by their interaction with the tropical cyclone westerlies. This result shows MJO as a possible precursor to enhanced *Habagat* rains that may be utilized in its early prediction.

Another aspect of the 2012 and 2013 *Habagat* events was their durations with continuous heavy rains. Analysis of environmental potential vorticity showed an intrusion of low potential vorticity regions to the eastern, then northern flank of Typhoon Haikui in 2012 and Severe Tropical Storm Trami in 2013. The advection of low (near-zero) potential vorticity along the enhancing tropical cyclone's eastern periphery can be interpreted as the strengthening of the westward propagation of the WNPSH to the east and north of the tropical cyclones. Consequently, this prevented the tropical cyclones that were enhancing the monsoon to recurve northeastward to the central North Pacific but instead steered the tropical cyclones further westward, ultimately slowing them down. This is particularly true in the case of Typhoon Haikui (2012). This slowing down of the tropical cyclone translational speed happened around the previously-mentioned imaginary line, thereby causing the prolonged heavy rainfall event.

The Habagat events were also simulated using the WRF model. To distinguish between the effects of the monsoon and the tropical cyclone circulation, the tropical cyclone removal scheme of the WRF model was used. Control simulations were compared to simulations with the tropical cyclones removed, referred to as the no-vortex runs. The tropical cyclone removal scheme of the WRF model did remove the enhancing tropical cyclones but showed stronger low-level circulations for the remnant lows. The lows partly maintained a relatively weaker monsoon trough, which still induced an anomalous but reduced (compared to the control runs) moisture flow toward the western regions of the Philippines. The results here showed that the characteristics of the Asian monsoon trough can better describe the heavy rain events than the enhancing tropical cyclones alone. However, there are caveats in the modeling of the heavy rainfall events. The short spin-up time in bogussing experiments and the development of other vortices limits the numerical simulations. The use of improved vortex removal schemes in the future in numerical weather prediction models such as the WRF and filtering techniques to remove imbalances in the initial conditions will better aid in understanding such events.

Not all tropical cyclones traversing the northeast of the Philippines during the boreal summer season necessarily lead to enhanced *Habagat* rains. At the same time, climatologically, nine out of 10 heavy rainfall days along western Luzon without landfalling tropical cyclones are due to enhanced *Habagat* events (Bagtasa 2019). Furthermore, enhanced *Habagat* involves multi-scale processes that include the establishment of a moisture conveyor belt (Bagtasa 2019) and the interaction of the transported moisture-laden air mass with the Philippine landmass (Lagmay *et al.* 2015). Hence, there is a need to further understand its mechanisms for better prognosis and early prediction. Enhanced *Habagat* events are the cause of many disastrous flooding events in the past. However, they are also a significant source of freshwater for agricultural needs or to fill reservoirs for domestic consumption. While there are many studies that deal with tropical cyclone characteristics (Corporal-Lodangco 2016, 2017; Bagtasa 2017, 2022) and future projections (Gallo *et al.* 2019; Delfino *et al.* 2023) in the WNP and how they can affect the Philippines, remote tropical cyclone precipitation effects or enhanced *Habagat* episodes are less studied in terms of what we need to expect in the future. A thorough understanding of past events is necessary to increase our confidence in future projections.

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