Quantitative estimations of hazards resulting from Typhoon Chanthu (2016) for assessing the impact in current and future climate

Sridhara Nayak and Tetsuya Takemi
Disaster Prevention Research Institute, Kyoto University, Japan

Abstract:

Many recent studies have argued that tropical cyclones will become severer in future warming climate and may cause various catastrophic damages to human life and economy. This study explores the impact of climate change on Typhoon Chanthu (2016) by performing a high-resolution (1 km) simulation for current and future climate. We focused on the typhoon intensity, size, heat fluxes, associated precipitation and wind speed over northern Japan under global warming with different initial times at 6-hour interval. We find that the typhoon tracks in the present and future climates remained similar, however with stronger intensity and heat fluxes in warming climate condition. In the landfall region of Hokkaido in future climate, the maximum wind speed and precipitation amount associated with the typhoon is significantly increased. The results imply that the damages associated with Typhoon Chanthu in future climate over northern Japan would be enhanced through strong wind, heavy rainfall and flooding.

KEYWORDS Typhoon Chanthu; pseudo global warming; typhoon intensity; typhoon size

INTRODUCTION

Tropical cyclones (TCs) are among the most powerful weather disturbances on Earth that cause various catastrophic damages to human life and economy (IPCC, 2014; Farfán et al., 2014; Staid et al., 2014; Kure et al., 2016; Mei and Xie, 2016). To understand the potential disastrous impacts of TCs on society, several studies have investigated the impact of dangerous TCs over many regions across the globe in present as well as future climate (Knutson et al., 2010; Lavender and Walsh, 2011; Chen et al., 2018). Over the years, a number of dangerous TCs have made landfall over Japan [e.g. Typhoons Vera (1959), Mireille (1991), Songda (2004), Haiyan (2013), Chanthu (2016), Lionrock (2016), Jebi (2018)] and caused severe damage over the TC track. To assess the impacts of TCs over a specific region, many studies have conducted high-resolution simulations on dangerous typhoons over Japan (Oku et al., 2010; Mori et al., 2014; Takemi et al., 2016a, 2016b; Kanada et al., 2017; Nayak and Takemi, 2019; Takemi et al., 2019). Recently, Typhoon Lionrock (2016) caused severe damage in the Tohoku region of Japan and the impacts of climate change were examined by Nayak and Takemi (2019) with 1-km-resolution downscaling experiments. Their study indicated that Typhoon Lionrock would be stronger in the future climate and produce more precipitation over the Tohoku region. Similarly, Takemi et al. (2016a) downscaled Typhoon Mireille (1991) at 1-km-grid resolution and highlighted that the typhoon in warmed climate would cause stronger winds over the Kyushu Island of Japan but weaker winds over Tohoku. Takemi et al. (2016b) investigated the impact of climate change on Typhoon Vera (1959) at 1-km resolution and highlighted stronger intensity of the typhoon in future climate. Similarly, Ito et al. (2016) performed 1-km-resolution simulations of Typhoon Songda (2004) and highlighted that it would induce stronger winds at its maturity under global warming. Kanada et al. (2017) explored the impact of global warming on Typhoon Chanthu (2016) with about 4-km grid spacing and highlighted that precipitation associated with the typhoon would increase under future climate. All these studies clearly indicate that the typhoons in future climate will become a severer threat to human life and economy.

Typhoon Chanthu made landfall on 17 Aug 2016 over the southern area of central Hokkaido of Japan and brought heavy rain and very strong winds. Although Kanada et al. (2017) downscaled this typhoon at 4-km resolution in present and future climate, their main objective was to understand the impact of global warming on typhoon-related precipitation. However, finer resolution data may provide more accurate information at local-scales for better assessing impacts over the target/landfall region more quantitatively as emphasized in Takemi et al. (2016c). Carefully representing the actual track of a specific typhoon in both the present and future climates is critical since the typhoon hazards appear differently depending on the track as well as the intensity. In the present study, we downscaled Typhoon Chanthu (2016) at 1-km grid resolution to understand its wind structure, size, heat fluxes and associated precipitation amount for assessing the impact and its response to climate change with different initial times at 6-hour interval by using the Weather Research and Forecasting (WRF) model. To our knowledge, this resolution will be the highest resolution used so far for this typhoon simulation and may provide typhoon features to be suitable for impact assessments.
MODEL SETUP AND SIMULATION METHODOLOGY

We configured the Advanced Research WRF model version 4.0 (Skamarock et al., 2008) on two-way three nested domains at horizontal resolutions of 15 km (outer domain: d01), 5 km (middle inner domain: d02) and 1 km (innermost domain: d03) with 28 vertical levels with model top at 10 hPa (Figure 1a). We used spectral nudging technique for the outer domain in the x and y directions with 5 wave number. The model’s physics used during simulation includes the Kain-Fritsch cumulus scheme (used for d01 and d02), the WRF single moment 6-class microphysics scheme, and the Yonsei University planetary boundary scheme. The initial and boundary conditions are imposed on the model at 6-hour interval from 1.25° resolution Japanese 55-year Reanalysis (JRA55) (Kobayashi et al., 2015).

We conducted five numerical experiments: one for the present climate with JRA55; and four for the future climate with JRA55 plus warming increment. Present climate experiment is integrated in time for 4 days from 00 UTC 15 Aug to 00 UTC 19 Aug, while the future climate experiments are integrated with four initial times at 6-hour interval starting from 00 UTC 15 Aug to 00 UTC 19 Aug. The four future climate experiments are hereafter referred to as 00UTC15Aug_PGW, 06UTC15Aug_PGW, 12UTC15Aug_PGW and 18UTC15Aug_PGW. Warming increments added to JRA55 refer to the increments for sea surface temperature (SST), geopotential height, and temperature from MRI-AGCM3.2 20-km climate simulations with the RCP-8.5 scenario conducted for the period 1979–2003 and 2075–2099 (Mizuta et al., 2012, 2014). This way of adding the warming increments to present reanalysis fields is known as Pseudo Global Warming (PGW) conditions (Sato et al., 2007). All the results are analyzed in the innermost domain (i.e. d03) with 1-km resolution. However, some results of the typhoon tracks, intensities and size fall outside of the d03, so we used the data from d02 and d01 to fill the gaps.

RESULTS

Track and intensity

We analyzed the track and intensity of the simulated typhoons in the present and PGW climate conditions and compared the results obtained in the present climate with the best track dataset from the Regional Specialized Meteorological Center (RSMC) Tokyo (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm). This is shown in Figure 1a. We find that the track in the present climate simulation follows reasonably well the best-track data, especially over the landfall region (Figure 1a), while the intensity (central pressure and maximum wind speed) of the simulated typhoon deviates from the best-track (Figures 1b and 1c). Furthermore, the simulated track in the present climate closely follows the best track also after landfall over Hokkaido, while the tracks in PGW conditions shift towards east from the best-track. The simulation shows the landfall timings in the present and future climates with same initial time are almost the same (12
UTC 17 Aug 2016) and about 3 hours delayed compared to the best-track observation, meaning a slower translation speed of the simulated typhoons before landfall (Figure 1d), while the landfall timings in the other three future climate simulations (06UTC15Aug_PGW, 12UTC15Aug_PGW and 18UTC15Aug_PGW) almost coincide with best-track observation. The root mean square errors (RMSE) in the central pressure, wind and translation speed in present climate, found to be 8 hPa, 5.1 m s\(^{-1}\) and 2.6 m s\(^{-1}\) respectively, could be due to the higher central pressure and weaker wind speed in initial days of the simulation. The central pressure and maximum wind speed associated with the typhoon under PGW conditions are stronger by ~10 hPa and ~5 m s\(^{-1}\), respectively, on the day of landfall. This indicates that Typhoon Chanthu in the future warming climate may produce stronger surface winds and more damage around the landfall region. Each simulation in future climate shows similar results with some uncertainties. Simulations initialized after 12 UTC 15 Aug shows relatively higher central pressure and weaker wind speed compared to the simulations initialized before 06 UTC 15 Aug, especially after the landfall. However, overall results show robust features of Typhoon Chanthu in future climate simulations with various initializations. It is worth mentioning that the intensity of the typhoon may be weaker in the present climate due to making landfall near Boso Peninsula on 16 Aug 2016, although the intensity was not exactly weakened during the landfall over Hokkaido region (Figure 2). We found that the surface wind during the landfall in the present climate has a good agreement with the 3-hourly forecast wind datasets from the JRA-55 of Japan Meteorological Agency (JMA). We compared the wind field in the present climate simulation with JMA forecast dataset to confirm the model’s capability in reproducing the wind because these datasets provide the spatial information of the wind speed over land and ocean at 3-hour interval. We also analyzed the tangential velocity during the landfall time and found that the tangential velocity at the surface in the present climate simulation agrees well with the JMA forecast (not shown here). The tangential velocity in the future climate was found to be stronger than that in the present climate, indicating stronger surface winds under the PGW conditions (which is also seen in our study).

**Precipitation and wind distribution during landfall time**

The precipitation distribution associated with Typhoon Chanthu from the present and future climate simulations and the Radar-Automated Meteorological Data Acquisition System (Radar-AMeDAS) observations are shown in Figure 2a–f. The spatial distribution of the precipitation amounts in the simulation with JRA55 closely follows that of the Radar-AMeDAS observation at the time of landfall (Figures 2a and 2b). It is noticed that the precipitation amount in western Hokkaido is overestimated in the present climate simulation and slightly underestimated over central Hokkaido at the time of landfall. The precipitation distribution in the future climate simulations shows an increase of

![Figure 2](image-url)
precipitation amount at the time of landfall of the typhoon (Figure 2c–f). The central Hokkaido region experiences more precipitation at the landfall of the typhoon under PGW. Kanada et al. (2017) also highlighted a similar increase of precipitation over Hokkaido during the passage of the typhoon in a future climate. The wind speed at 10 m height during landfall time from the present and future climate simulations and JMA forecast are shown in Figure 2g–l. The simulated wind speed in present climate has a good agreement with that of the JMA forecast during landfall time (Figures 2g and 2h). The wind speed in the future climate is significantly increased during landfall of the typhoon (Figure 2i–l). The radial distribution of azimuthally averaged precipitation amount (wind speed) in the present climate also shows good agreement with that of the Radar-AMeDAS observation (JMA forecast). This is shown in Figures 2m and 2n. We find that the regions beyond 150 km from the landfall region will experience more precipitation in the future warming climate (Figure 2m). The region within 50 km from landfall shows a decrease of wind speed, indicating increased eye region of the typhoon in future climate. However, we did not find any significant difference in the mean wind speed associated with the typhoon in future climate simulations from the landfall region. We extended our analysis of precipitation and maximum wind speed over Hokkaido land only during the landfall time at each ±1 hour up to 6-hours. This is shown in Figure 3a–d. We find that the precipitation amount and maximum wind speed associated with Typhoon Chanthu in future climate simulations are significantly increased by ~10 mm and ~5 m s\(^{-1}\), respectively, within 3 hours of the landfall. All the simulations in future climate show increases of precipitation amount and maximum wind speed. The uncertainty in the 12-hours accumulated precipitation in future climate simulations is noticed to be ~7 mm (maximum value–minimum value), while the uncertainty in the 12-hours maximum wind speed is found to be ~5 m s\(^{-1}\). This indicates a possible increase in strong winds and heavy precipitation associated with the typhoons over landfall region in future climate.

**Typhoon structure and size**

Figure 4a shows the spatial distribution of the wind at 850 hPa on 10 UTC 17 Aug from the present and future climate with same initial times i.e. with 00UTC 15 Aug 2016. It also shows stronger winds of about 90 knots spread over a larger area over the ocean in the future climate than in present climate. This indicates that Typhoon Chanthu is expected to become stronger under PGW conditions before it makes landfall over the Hokkaido region. We analyzed the pressure and wind structure on a fixed latitude at 10 UTC 17 Aug i.e. during the approach of the typhoon until the landfall over Hokkaido in the two climate periods (Figure 4b). The results indicate that the central pressure and surface wind speed become stronger by ~10 hPa and ~10 m s\(^{-1}\), respectively, in the PGW conditions before it makes landfall over the Hokkaido region.

We next computed the typhoon size with R17 and R25 from the wind at 850 hPa in present and one future climate simulation (00UTC15Aug_PGW) (Figure 4c). R17 is known as the gale-force wind which refers to the radius of wind speed exceeding 17 m s\(^{-1}\) from the center of the typhoon. The radius is based on the quadrant-maximum i.e. the maximum distance from the typhoon center in all quadrants. Similarly, the radius of wind speed exceeding 25 m s\(^{-1}\) is used as R25. In addition to R17 and R25, we analyzed TC fullness of the typhoon in both climate periods. This is shown in Figure 4d. TC fullness (TCF) is a concept defined by Guo and Tan (2017) as the ratio of the extent of the outer-core wind skirt to the outer-core size of the TC. Mathematically,

\[
TCF = 1 - \frac{RMW}{R17}
\]

where RMW is the radius of maximum wind from the center of the typhoon.
We find that the typhoon size with R17 and R25 is increased in future climate before it made landfall i.e. during 03–09 UTC 17 Aug. It is also noticed that R17 is decreased in the future climate from 12 UTC 17 Aug i.e. after making landfall, while the typhoon size with R25 is increased in the future climate from 02 UTC 17 Aug (Figure 4c). The RMW is decreased and TC fullness is increased in future warming climate until 03 UTC 17 Aug (Figure 4d), indicating stronger intensity of the typhoon while passing over the ocean along Tohoku side because higher $\text{TCF}$ implies higher TC intensity (Guo and Tan, 2017).

**Heat fluxes and instability**

We attempted to study the surface latent heat flux, surface sensible heat flux, potential vorticity and equivalent potential temperature at the same cross section (discussed in previous section) from the present and future climate simulations. This is shown in Figure 5. We find that latent heat flux associated with Typhoon Chanthu is increased by ~150 W m$^{-2}$ in future climate and sensible heat flux is increased by ~20 W m$^{-2}$ before it makes landfall over Hokkaido region (Figures 5a and 5b). This implies that more amount of energy will be available for evaporation from ocean surface to the air to feed more moisture to the typhoon in future climate. The heat fluxes in the simulation with the initial time at 06 UTC 15 Aug shows relatively high values compared to other simulates. This may attribute to the high precipitation amount noticed in the simulation with the initial time at 06 UTC 15 Aug (Figure 2m). The potential vorticity between 500 hPa and 850 hPa is also found to be increased before the typhoon makes landfall in future climate (Figure 5c), while the equivalent potential temperature at 500 hPa is increased by ~10°C (Figure 5d). This implies that the atmosphere associated with Typhoon Chanthu is expected to be highly unstable under PGW condition.

**SYNTHESIS**

We find that the central pressure of the typhoon is decreased in the warming climate condition and maximum wind speed at 10 m height is significantly increased from the day before until its landfall (during 12 UTC 16 Aug to 09 UTC 17 Aug, Figures 1b and 1c). Similar characteristics are noticed in each simulation with different initial times. The stronger intensity may be due to the increase of SST under PGW and the associated moisture change. Because the increase of moisture due to the rise in SST results in convective instability, the condition will lead to the intensification of the typhoon. We also find an increase of heat fluxes and more unstable conditions associated with the typhoon under PGW condition (Figure 5). This may facilitate the low-level convergence and speeding up the tangential winds to make the typhoon intensity stronger (Takemi et al., 2004, 2012; Miyamoto and Takemi, 2013; Camargo et al., 2013; Lin et al., 2014; Sun et al., 2017; Parker et al., 2018). It is also noticed that the stronger winds are spread over larger areas during this period (e.g. Figure 3a), implying larger typhoon sizes of stronger winds in the future climate.
We further find that the typhoon size with R25 under PGW is found be increased over the ocean areas before making landfall i.e. during 06–09 UTC 17 Aug. The increase of typhoon size over this region could be due to the increase of relative humidity (Hill and Lackmann, 2009). Figure 6a shows the relative humidity (24-hours average on the days of landfall) at 850 hPa and 2 m height. It clearly indicates that the relative humidity under PGW is significantly increased by 10–15% over the ocean areas particularly where the typhoon size is increased in the future climate before making landfall. We also find that the relative humidity at 2 m height and 850 hPa is increased under PGW over the northern Tohoku region and the entire Hokkaido region. This may cause the increase of precipitation amount associated with Typhoon Chanthu in the future warming climate (Figure 2c–f). Moreover, the specific humidity is also increased over the entire domain possibly due to the increase of SST (Figure 6b). A recent study (Nayak and Takemi, 2019) also reported that the water vapor under PGW is increased at all layers for the Typhoon Lionrock (2016) case. This could increase moisture for the development of sustained convection to feed more moisture to the typhoon to produce more precipitation in the future climate (Takemi et al., 2004).

We also find that the size of the typhoon and the TC fullness are gradually decreased under PGW although not significant when the typhoon moves northwards (Figure 4c). This implies a possible weaker intensity of the future typhoon after landfall over northern Japan. The radial distribution of azimuthally averaged wind speed justifies this (Figure 2n), which shows a possible weaker wind speed in the future climate within a 50 km radius of the landfall region compared to that in the present climate. Previous studies (e.g. Takemi et al., 2016a, 2016b; Ito et al., 2016) on other typhoons made landfall over northern Japan also highlighted weaker intensity of the typhoons in future climate. The reason could be associated with the meridional gradient of temperature. Ito et al. (2016) highlighted that environmental meridional gradient of temperature becomes smaller in the warming climate, thus weakening the baroclinicity which is more unfavorable for the extratropical transition.

**CONCLUSIONS**

In this study we performed a high-resolution simulation at 1 km in two climate periods (present and future) for Typhoon Chanthu that made landfall over northern Japan in Aug 2016. We find that the WRF model reproduced the typhoon features reasonably well in present climate simulation. The typhoon track is well represented in current climate simulation and remain mostly similar under PGW condition, but with stronger surface wind and central pressure. Our results show robust features of Typhoon Chanthu in future climate simulations with different initial times at 6-hour interval. The typhoon size with R17 remained almost same with some variations, while the typhoon size with R25 under PGW is increased over the ocean areas before making landfall. The atmosphere associated with this typhoon is expected to be highly unstable with more available-energy in future warming climate. The overall
results imply that the damage associated with Typhoon Chanthu in future climate over northern Japan would be enhanced through high wind and heavy precipitation. We would like to further extend the analysis to the hazard assessment over the landfall region.

ACKNOWLEDGMENTS

This study was supported by the TOUGOU Program, funded by the Ministry of Education, Culture, Sports, Science, and Technology, Government of Japan. Japan Meteorological Agency (JMA) is acknowledged for providing the Automated Meteorological Data Acquisition System (AMeDAS) data. We acknowledge the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm) for providing access to the typhoon best track dataset.

REFERENCES

Camargo SJ, Ting M, Kushnir Y. 2013. Influence of local and remote SST on North Atlantic tropical cyclone potential intensity. Climate Dynamics 40: 1515–1529. DOI: 10.1007/s00382-012-1536-4.

Chen CJ, Lee TY, Chang CM, Lee JY. 2018. Assessing typhoon damages to Taiwan in the recent decade: return period analysis and loss prediction. Natural Hazards 91: 759–783. DOI: 10.1007/s11069-017-3159-x.

Farfán LM, D’Sa EJ, Liu KB, Rivera-Monroy VH. 2014. Tropical cyclone impacts on coastal regions: the case of the Yucatán and the Baja California Peninsulas, Mexico. Estuaries and Coasts 37: 1388–1402. DOI: 10.1007/s12237-014-9797-2.

Guo X, Tan ZM. 2017. Tropical cyclone fullness: A new concept for interpreting storm intensity. Geophysical Research Letters 44: 4324–4331. DOI: 10.1002/2017GL073680.

Hill KA, Lackmann GM. 2009. Influence of environmental humidity on tropical cyclone size. Monthly Weather Review
HIGH-RESOLUTION SIMULATION OF TYPHOON CHANTHU

Nayak S, Takemi T. 2019. Dynamical downscaling of Typhoon Lionrock (2016) for assessing the resulting hazards under global warming. *Journal of the Meteorological Society of Japan Ser. II*: 27–49. DOI: 10.2151/jmsj.2019-004.

Okyu T, Takemi T, Ishikawa H, Kanada S, Nakano M. 2010. Representation of extreme weather during a typhoon landfall in regional meteorological simulations: a model intercomparison study for Typhoon Songda (2004). *Hydrological Research Letters*: 1–5. DOI: 10.3178/HRL.4.1.

Parker CL, Bruyère CL, Mooney PA, Lynch AH. 2018. The response of land-falling tropical cyclone characteristics to projected climate change in northeast Australia. *Climate Dynamics*: 3635–3645. DOI: 10.1007/s00382-018-4091-9.

Sato T, Kimura F, Kito A. 2007. Projection of global warming onto regional precipitation over Mongolia using a regional climate model. *Journal of Hydrology*: 333: 144–154. DOI: 10.1016/j.jhydrol.2006.07.023.

Skamarock WC, Klemp JB, Dudia J, Gill DO, Barker DM, Duda MG, Huang X, Wang W, Powers JG. 2008. A description of the advanced research WRF version 3. Tech. Note: 1–96.

Staud A, Guikema SD, Nateghi R, Quiring SM, Gao MZ. 2014. Simulation of tropical cyclone impacts to the U.S. power system under climate change scenarios. *Climatic Change*: 125: 535–546. DOI: 10.1007/s10584-014-1272-3.

Sun Y, Zhong Z, Li T, Yi L, Hu Y, Wan H, Chen H, Qianfeng L, Chen M, Li Q. 2017. Impact of ocean warming on tropical cyclone size and its destructiveness. *Scientific Reports*: 7: 8154. DOI: 10.1038/s41598-017-08533-6.

Takemike A, Hirayama O, Liu C. 2004. Factors responsible for the vertical development of tropical oceanic cumulus convection. *Geophysical Research Letters*: 31: L11109. DOI: 10.1029/2004GL020225.

Takemi T, Nomura S, Oku Y, Ishikawa H. 2012. A regional-scale evaluation of changes in environmental stability for summertime afternoon precipitation under global warming from super-high-resolution GCM simulations: A study for the case in the Kanto Plain. *Journal of the Meteorological Society of Japan*: 90A: 189–212. DOI: 10.2151/jmsj.2012-A10.

Takemi T, Ito R, Arakawa O. 2016a. Effects of global warming on the impacts of Typhoon Mireille (1991) in the Kyushu and Tohoku regions. *Hydrological Research Letters*: 10: 81–87. DOI: 10.3178/hrl.10.81.

Takemi T, Ito R, Arakawa O. 2016b. Robustness and uncertainty of projected changes in the impacts of Typhoon Vera (1959) under global warming. *Hydrological Research Letters*: 10: 88–94. DOI: 10.3178/hrl.10.88.

Takemi T, Okada Y, Ito R, Ishikawa H, Nakakita E. 2016c. Assessing the impacts of global warming on meteorological hazards and risks in Japan: Philosophy and achievements of the SOUSEI program. *Hydrological Research Letters*: 10: 119–125. DOI: 10.3178/hrl.10.119.

Takemi T, Yoshihoshi T, Yamasaki S, Hase K. 2019. Quantitative Estimation of Strong Winds in an Urban District during Typhoon Jebi (2018) by Merging Mesoscale Meteorological and Large-Eddy Simulations. *SOLA*: 15: 22–27. DOI: 10.2151/sola.2019-005.