Robust responses of typhoon hazards in northern Japan to global warming climate: cases of landfalling typhoons in 2016

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Abstract
In August 2016, an unusual occurrence of the landfall of four typhoons in northern Japan caused severe and widespread damage by excessive rainfall and high wind. This study examines the characteristics and structure of these typhoons and the responses to the global warming climate to explore the robust features of typhoon hazards in northern Japan in a future warming climate. By obtaining similar typhoon tracks under the 2016 conditions and a pseudo global warming (PGW) climate, we found that the typhoon intensity under the PGW climate becomes stronger with higher lifetime maximum wind up to $\sim 10 \, \text{m} \cdot \text{s}^{-1}$ and lower lifetime minimum sea level pressure of $\sim 20 \, \text{hPa}$. Rainfall associated with the typhoons indicated a robust increase in northern Japan in the PGW climate, while the changes in surface winds in the PGW climate depend on the case. A higher rate of intensification and more availability of energy are expected in the future warming climate especially over the landfall regions. All the typhoons except Typhoon Lionrock, after making landfall over Hokkaido region, exhibited a much deeper cold core structure in the future climate. Overall results suggest that the hazards related to typhoons over northern Japan will be more severe in the future warming climate.

KEYWORDS
higher-latitude typhoons, pseudo global warming, typhoon hazards, WRF

1 | INTRODUCTION
Tropical cyclones (TCs) are life-threatening natural hazards that cause significant disasters in many regions across the world (Mendelsohn et al., 2012; Farfán et al., 2014; Staid et al., 2014; Mei and Xie, 2016; Chen et al., 2018). Every year, TCs bring strong winds and heavy rainfall to the coastal regions and lead to serious societal impacts. Recent research (Lavender and Walsh, 2011; Murakami et al., 2012; IPCC, 2014; Takemi et al., 2016a; Nayak and Takemi, 2019a; 2019b) has raised concerns that TCs in future climate will be more intense and may cause more severe social and economic damage (Staid et al., 2014; Mei and Xie, 2016). Thus, understanding TC activities in the present and future warming climates has become a challenging issue in recent decades, although a large number of studies have examined various TCs in the present day climate (e.g. Emanuel, 2005;
Mendelsohn et al., 2012; IPCC, 2014; Yamada et al., 2017; Takemi et al., 2019; Nayak and Takemi, 2020; Takemi and Ito, 2020) and under different warming scenarios (e.g. Bengtsson et al., 2007; Sugi et al., 2009; Lavender and Walsh, 2011; Mori and Takemi, 2016; Takemi et al., 2016b; 2016c; Kanada et al., 2017). However, most of the studies suggest an increase in TC intensities under future warming climate (Bengtsson et al., 2007; Sugi et al., 2009; Takayabu et al., 2015; Takemi et al., 2016c; Kanada et al., 2017; Nayak and Takemi, 2019a; 2019b).

In August 2016, severe and widespread damage by excessive rainfall and high wind was spawned by an apparently unusual occurrence of the landfall of four TCs in northern Japan: Typhoons Chanthu, Mindulle, Lionrock and Kompasu. According to the Regional Specialized Meteorological Center (RSMC) Tokyo best track datasets, Typhoons Chanthu, Mindulle and Kompasu made landfall over the Hokkaido region, while Typhoon Lionrock made landfall over the Tohoku region (Figure 1). The lifetime maximum wind speed and lifetime minimum pressure of these four typhoons were analyzed in the range 35–90 knots and 994–940 hPa, respectively.

Recent studies on typhoons that made landfall over Japan indicated that the typhoons would bring more precipitation to landfall regions in future warming climate (e.g. Takemi et al., 2016b; Kanada et al., 2017; Nayak and Takemi, 2019a; 2019b). Some typhoons in the future climate are expected to carry stronger wind to southern regions of Japan and weaker wind to northern regions (e.g. Ito et al., 2016; Takemi et al., 2016a), while a few other typhoons in the warmed climate are expected to bring stronger winds to northern regions of Japan (e.g. Nayak and Takemi, 2019a). This implies that the impact of climate change on typhoons is not the same for all typhoons and depends on the latitude of the landfall regions. For instance, Typhoon Lionrock (2016) is expected to bring high winds to the Tohoku region in a future climate (Nayak and Takemi, 2019a), while Typhoon Mireille (1991) in a warmed climate is likely to be weaker over Tohoku (Takemi et al., 2016a). One feasible difference between these two typhoons is their approaching direction and location. Typhoon Lionrock (2016) approached from the Pacific Ocean side, while Typhoon Mireille (1991) approached from the Sea of Japan side. It is thus of much interest to understand the characteristics of different typhoons and to explore the robust features of typhoon hazards in a future warming climate.

The main purpose of this study was to investigate the characteristics of typhoons (i.e. track, intensity, precipitation amount and wind) for the cases occurring in August 2016, namely Typhoons Chanthu, Mindulle, Lionrock and Kompasu, over northern Japan and their response to the pseudo global warming (PGW) climate. The PGW climate refers to a future climate condition which is

![Figure 1](image-url)
prepared by adding the warming increment of climate change components to reanalysis fields in the present climate (Sato et al., 2007). The environmental conditions and phase spaces of each typhoon are also analyzed to understand the typhoon structures in the present and future warming climate.

2 | NUMERICAL EXPERIMENTS AND DATA USED

In this section we describe details of the model configuration, domain setup and data used for all numerical experiments conducted in this study.

2.1 | Model configuration and domain setup

Nayak and Takemi (2019a) downscaled Typhoon Lionrock in the present day and PGW climates. We used the same model configuration as used by Nayak and Takemi but with different domain setups. The Advanced Research Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) was integrated in a set of two-way, three nested domains for each typhoon case with the finest grid size of 1 km for the innermost domain. The outer (middle-inner) domains were configured at 15 km (5 km) grid spacing for Typhoon Chanthu and Typhoon Mindulle and at 9 km (3 km) for Typhoon Lionrock and Typhoon Kompasu. A detailed summary of each domain setup is given in Table 1. The non-hydrostatic dynamics were set for all domains with Lambert conformal conic map projection and were integrated in time with a 30 s time step for the outermost domain. A spectral nudging technique was used on the horizontal wind components and geopotential in the x and y directions of the outer domains with wave number 5 to include synoptic-scale influences (Cha et al., 2011; Choi and Lee, 2016; Moon et al., 2018; Takemi, 2019). Nudging coefficients of $2.8 \times 10^{-4} \text{s}^{-1}$, which correspond to a roughly 1 hr time scale, and nudging-layer heights from the 200 hPa level up to the model top were used. The physics used in this study included the WRF single moment 6-class microphysics scheme (Hong and Lim, 2006), the Kain–Fritsch cumulus scheme (Kain and Fritsch, 1993) (not used for the innermost domain), the Yonsei University planetary boundary scheme (Hong et al., 2006) and the Rapid Radiative Transfer Model radiation scheme (Mlawer et al., 1997). The model top of all the domains was set as 10 hPa with 28 vertical levels.

2.2 | Data used

The initial and boundary conditions were forced to the model at 6 hr intervals from the 55 year Japanese Reanalysis (JRA-55) dataset with 1.25° resolution (Kobayashi et al., 2015). The brightness temperature at the surface in 2D instantaneous diagnostic fields of JRA-55 is used as the sea surface temperature (SST). The warming increments of SST (mostly 2–4°C), geopotential height (~700–900 m) and temperature (roughly 2–5°C) were used for each typhoon in this study (Figure 2). These climate change components, namely SST, 3D air temperature, 3D geopotentials and surface temperature, were calculated by taking the 25 year monthly mean differences between two climate periods (1979–2003 and 2003–2016) prepared by adding the warming increment of climate change components to reanalysis fields in the present climate. The environmental conditions and phase spaces of each typhoon are also analyzed to understand the typhoon structures in the present and future warming climate.

Table 1: Domain setup of each typhoon

| Typhoon name and number | Domain size and resolution | Simulation period (0000 UTC) | Version of WRF model used |
|------------------------|--------------------------|------------------------------|---------------------------|
| Typhoon Chanthu (T1607) | 120–160° E and 26–56° N (15 km) | 15 Aug 2016 – 19 Aug 2016 | WRF 4.0 |
| Typhoon Mindulle (T1609) | 118–162° E and 22–56° N (15 km) | 20 Aug 2016 – 25 Aug 2016 | WRF 3.8.1 |
| Typhoon Lionrock (T1610) | 130–170° E and 20–50° N (9 km) | 26 Aug 2016 – 31 Aug 2016 | WRF 4.0 |
| Typhoon Kompasu (T1611) | 119–158° E and 22–52° N (9 km) | 19 Aug 2016 – 22 Aug 2016 | WRF 4.0 |

Note: The values in parentheses indicate the grid resolution of the domain. WRF, Weather Research and Forecasting.
2075–2099) from Meteorological Research Institute Atmospheric General Circulation Model version 3.2 (MRI-AGCM3.2) climate simulations with the Representative Concentration Pathway 8.5 (RCP8.5) scenario at 20 km resolution (Mizuta et al., 2012). The control future climate simulation data (Mizuta et al., 2014) were used here. The climate change components were used in the PGW experiments, as in Ito et al. (2016), Takemi et al. (2016a; 2016b; 2016c) and Nayak and Takemi (2019a; 2019b). We set relative humidity as unchanged between the present and PGW climates. Therefore, specific humidity was assumed to be larger in the PGW experiment than in the present climate experiment, according to the increment of temperature in the PGW experiment. The RSMC Tokyo best track dataset was used to validate the typhoon track and intensity in the model simulations. The hourly analyzed precipitation datasets from the Radar-Automated Meteorological Data Acquisition System (Radar-AMeDAS) were used to validate the model simulated precipitation.

2.3 | Numerical experiments

Eight numerical experiments (two experiments for each typhoon in the present and the PGW climates) were conducted. The model was integrated for each typhoon separately. Typhoon Chanthu, Typhoon Mindulle, Typhoon Lionrock and Typhoon Kompasu were initialized at 0000 UTC on August 15, August 20, August 26 and August 19, 2016, respectively, and were integrated until 0000 UTC on August 19, August 25, August 31 and August 22, 2016, respectively (see Table 1). The numerical simulations for the PGW climate were conducted by adding the warming increment of the climate components to the present reanalysis data (the warming increments are

![Figure 2](image-url)
shown in Figure 2). More detailed information on the PGW climate is described by Sato et al. (2007).

3 | RESULTS

In this section, we discuss the characteristics of the typhoons including the track and intensity of the typhoon precipitation and wind in the present climate and the PGW simulations. The local characteristics including equivalent potential temperature and extratropical transitions were also investigated.

3.1 | Track and intensity

The typhoon tracks of the four typhoons as obtained from the best track and the model simulations are shown in Figure 1a and the tracks of each individual typhoon are presented in Figure 1b–e. The typhoon tracks are plotted by examining the minimum sea level pressures (SLPs) at 6 hr intervals for each typhoon separately. We find that all the tracks in the model simulations have reasonable agreement with the RSMC best track especially around the landfall region (Figure 1a). The landfall location of the first three typhoons (Typhoon Chanthu, Typhoon Mindulle and Typhoon Lionrock) shows a deviation of 1–2° in longitude and/or latitude (Figure 1b–d). The simulated track of Typhoon Komapsu shows a westward shift of the landfall location probably owing to its westward movement from the beginning of the integration (Figure 1e). We obtained similar typhoon tracks in the future warming climate and in the present climate for each typhoon with an eastward (westward) shift of the typhoons after making landfall over the Hokkaido (Tohoku) region. The shift of tracks under PGW may be due to the change in SST pattern (Walsh et al., 2016) and large scale steering flow (Murakami and Wang, 2010), which is uncertain in a future warming climate. However, the maximum wind speed and minimum SLP associated with these typhoons are found to be significantly stronger under PGW climate (Figure 3). We sampled the 10 m maximum wind and minimum SLP at 6 hr from each typhoon and analyzed the intensity of each typhoon over northern Japan. The relationship between wind speed and SLP for the Typhoons Chanthu and Lionrock agrees well with RSMC best track data, while that for the Typhoons Mindulle and Komapsu shows weak intensities. The minimum SLP and the 10 m maximum wind under PGW conditions are noticed to be stronger by ~10 hPa and ~5 m s⁻¹.

**FIGURE 3** Central pressure versus 10 m wind speed for (a) Typhoon Chanthu (T1607), (b) Typhoon Mindulle (T1609), (c) Typhoon Lionrock (T1610) and (d) Typhoon Komapsu (T1611). Central pressure refers to the minimum sea level pressure and wind speed refers to the maximum wind speed at 10 m.
respectively in Typhoon Chanthu and Typhoon Mindulle, while those in Typhoon Lionrock are expected to be stronger by ~20 hPa and ~10 m·s⁻¹ respectively. The intensity of Typhoon Kompasu in future climate does not show substantial increase. Overall, the intensities of all four typhoons show an increase of lifetime maximum wind speed up to ~10 m·s⁻¹ and a decrease of lifetime minimum SLP of ~20 hPa during this period under PGW climate, indicating possible stronger typhoons over northern Japan in future warming climate.

3.2 Precipitation and wind

In this subsection, precipitation and wind induced by the typhoons are examined. These are directly related to typhoon hazards.

The 24 hr (±12 hr of landfall) accumulated precipitation induced by each typhoon in four different prefectures of Japan is shown in Figure 4a–d. We examined precipitation over the prefectures in the Tohoku region except for prefectures which are located far from the typhoon path. The model simulated 24 hr accumulated precipitations from each typhoon in the present climate indicate a very good agreement with Radar-AMEDAS precipitations over the landfall regions (circled in Figure 4). All the landfall areas are noticed to receive more precipitation associated with the typhoons in the future climate. The decrease of precipitation amounts over Iwate seems to be quite sensitive to the landfall time and regions of the typhoons: the precipitation amount under the PGW climate over Iwate becomes smaller during the landfall of three typhoons (except Lionrock) which landed over Hokkaido, while it becomes larger for

![FIGURE 4](image_url) (a)–(d) The 24 hr (±12 hr of landfall) accumulated precipitation induced by each typhoon derived over each target prefecture from Radar-Automated Meteorological Data Acquisition System (Radar-AMeDAS) observation, present climate and future climate; (e) 12 hr (±6 hr of landfall) accumulated precipitation induced by each typhoon over Hokkaido. The results in (a), (b), (c) and (d) correspond to the precipitation amount from Typhoon Chanthu (T1607), Typhoon Mindulle (T1609), Typhoon Lionrock (T1610) and Typhoon Kompasu (T1611) respectively. Circles in (a)–(d) indicate the landfall region. (f) Each target region. The magenta dots show the location of the landfall of each typhoon
Lionrock (Nayak and Takemi, 2019a). It is also noticed that Typhoon Mindulle in future warming climate shows a slight decrease of 24 hr accumulated precipitation over the landfall region (i.e. Hokkaido). The reason could be associated with the translation speed and typhoon size which are not discussed in this study. However, the 12 hr (±6 hr of landfall) accumulated precipitation induced by all these four typhoons shows an increase of precipitation over Hokkaido under PGW conditions (Figure 4e), indicating heavier rainfall events during the landfall passage of these typhoons in future warming climate. It should be noted that we focused on the total precipitation that occurred over land in northern Japan due to the landfall of four typhoons. So, it is attempted to investigate 24 hr or 12 hr total precipitation over the target regions by considering ±12 hr or ±6 hr from the landfall time of each typhoon separately. This implied that the precipitation amounts discussed above include the precipitations associated with some

![Figure 5](image_url)
hours of pre-landfall, over-landfall and after-landfall of the typhoons. However, the total precipitation associated with each typhoon can be more accurately computed by considering the typhoon size and translation speed (e.g. Su et al., 2012; Chang et al., 2013), because slow moving typhoons may bring more precipitation to the target regions, and recent studies (e.g. Kossin, 2018) highlighted that TC intensity increase before landfall (Takemi et al., 2004; 2012; Mousavi et al., 2009; Lin et al., 2014; Črniec et al., 2016; Unuma and Takemi, 2016; Nayak and Takemi, 2019a). The vertical cross-section of the north–south wind at the time of landfall also shows an increase of wind speed at most of the pressure levels for each typhoon in the future climate (Figure 8). Typhoon Lionrock and Typhoon Chanthu show a significant increase of north–south wind under the PGW climate, compared to the other two typhoons.

3.3 | Typhoon structure

The typhoon structure is diagnosed by equivalent potential temperature ($\theta_e$) from the following equation:

$$\theta_e = T_e \left( \frac{p_o}{p} \right) \frac{R_d}{c_p} \approx \left( T + \frac{L_v}{c_p} r \right) \left( \frac{p_o}{p} \right) \frac{R_d}{c_p}$$

where $T_e$ is the equivalent temperature, $p_o$ is the standard reference pressure (1,000 hPa), $p$ is the pressure at the point, $R_d$ is the specific gas constant for air (287 J·kg$^{-1}$·K$^{-1}$), $c_p$ is the specific heat of dry air at constant pressure (1,004 J·kg$^{-1}$·K$^{-1}$), $T$ is the air temperature at pressure $p$, $L_v$ is the latent heat of evaporation and $r$ is the mixing ratio of water vapor.

The equivalent potential temperature at the 700 hPa level is examined and is shown in Figure 9. We find that the equivalent potential temperatures for all typhoon cases are significantly increased in future warming climate. This indicates that a higher atmospheric instability under the PGW climate may lead to more convective activity of each typhoon to reproduce heavy rainfall events. Typhoons Chanthu and Lionrock are found to be

![FIGURE 6](image-url) The 6 hr ($\pm$3 hr) area averaged accumulated precipitation within a radius of 100 km from the typhoon center in the present and future climate. The dates or times in parentheses show the results for the future climate. First dates correspond to the typhoon locations over the Tohoku region.
associated with more convection activity in future climate. This could bring heavy precipitation to landfall areas under PGW climate (Figure 4a,c,e) compared to the other two typhoons.

The environmental conditions for the typhoons are examined by focusing on the atmospheric stability with $\frac{d\theta_e}{dz}$. Here, $\frac{d\theta_e}{dz}$ is diagnosed with the 500 hPa and 850 hPa fields, which are based on the idea of

**FIGURE 7** (a)–(h) The spatial distribution of 24 hr (±12 hr of landfall) mean wind at 10 m brought by each typhoon from the model simulation: (a)–(d) present climate; (e)–(h) future climate. (i)–(p) The future change of (i)–(l) 24 hr (±12 hr of landfall) mean wind and (m)–(p) maximum wind during landfall. The results in each column correspond to the results from each typhoon: column 1, Typhoon Chanthu (T1607); column 2, Typhoon Mindulle (T1609); column 3, Typhoon Lionrock (T1610); column 4, Typhoon Kompasu (T1611)
FIGURE 8  Vertical cross-section of north–south wind during the landfall time at the latitude where the typhoon made landfall. (a)–(d) The results from the present climate; (e)–(h) the results in future climate. The results in each column correspond to the north–south wind from each typhoon: column 1, Typhoon Chanthu (T1607); column 2, Typhoon Mindulle (T1609); column 3, Typhoon Lionrock (T1610); column 4, Typhoon Kompasu (T1611). The dotted lines in each figure indicate the longitudes of each landfall location.

FIGURE 9  Equivalent potential temperature at 700 hPa during the landfall time. The dates above each figure correspond to the landfall time. (a)–(d) The results from the present climate; (e)–(h) the results in future climate. The results in each column correspond to the equivalent potential temperature from each typhoon: column 1, Typhoon Chanthu (T1607); column 2, Typhoon Mindulle (T1609); column 3, Typhoon Lionrock (T1610); column 4, Typhoon Kompasu (T1611)
Takemi (2007) and Unuma and Takemi (2016), examined for each typhoon in the present and future climate and shown in Figure 10. Negative values indicate more unstable conditions. We find that the $\frac{d\theta_e}{dz}$ associated with all typhoons except Typhoon Lionrock is decreased in future climate. This implies that Typhoons Chanthu, Mindulle and Kompasu would be stronger in a warmer climate. In general, lower values of $\frac{d\theta_e}{dz}$ indicate highly unstable areas (e.g. Takemi, 2007; 2010; Rowe and Hitchman, 2015). Although the $d\theta_e/dz$ for Typhoon Lionrock shows a high value at the landfall region, closer investigation shows wider areas of much lower values over surroundings in future climate, particularly around the east side of the ring regions between ~100 and 400 km radius from the typhoon center.

3.4 Extratropical transition

The extratropical transition is diagnosed from the frontal nature and cold or warm core structure of each typhoon from phase space analysis for tropical/extratropical cyclones. Hart (2003) suggested the following three parameters to describe these features of a TC.

1. Parameter $B$: This parameter represents the strength of a TC and is defined as the storm-motion-relative 900–600 hPa thickness asymmetry across the TC within 500 km radius:

$$B = h \left( \frac{Z_{600 \text{ hPa}} - Z_{900 \text{ hPa}}}{R} - \frac{Z_{600 \text{ hPa}} - Z_{900 \text{ hPa}}}{L} \right)$$

where $Z$ is the isobaric height, $R$ indicates right of the current storm motion and $L$ indicates left of the storm motion. The overbar indicates the areal mean over a semicircle of radius 500 km. The integer $h$ takes a value of +1 (-1) for the Northern (Southern) Hemisphere.

2. Parameter $-V_T^L$: This parameter represents the thermal wind in the lower atmosphere and is defined as the vertical derivative of the horizontal height gradient between 900 and 600 hPa:

$$-|V_T^L| = \frac{\partial (\Delta Z)}{\partial \ln p} \bigg|_{600 \text{ hPa}}^{900 \text{ hPa}}$$

where $\Delta Z$ is the isobaric height perturbation ($Z_{\text{max}} - Z_{\text{min}}$) evaluated within a radius of 500 km.

3. Parameter $-V_T^U$: This parameter measures the thermal wind in the upper atmosphere and is defined as the...
vertical derivative of the horizontal height gradient between 600 and 300 hPa:

$$-\left| V_T^U \right| = \frac{\partial(\Delta Z)}{\partial p} \bigg|_{300 \text{ hPa}}^{\text{600 hPa}}$$ (4)

The typical structure of a conventional TC corresponds to $B \approx 0$ and positive values of $-V_T^L$, while extratropical cyclones correspond to positive $B (>10)$ and negative values of $-V_T^L$ (Hart, 2003; Jones et al., 2003; Kitabatake, 2008; 2011). In our study, we selected different radii ranges between 250 and 500 km from the typhoon center to calculate the above three parameters, but we did not find substantial differences between the results. Hart (2003) also highlighted that a radius chosen within the range 250–1,000 km does not significantly impact the analysis.

Figure 11 represents the phase space diagram of each typhoon in the present climate and future climate plotted using the parameters $B$, $-V_T^L$ and $-V_T^U$ within a radius of 250 km from the typhoon center. The parameter $B$ in Figure 11 indicates that all the typhoons in the present climate started as conventional TCs and decayed as extratropical cyclones except Typhoon Lionrock. The period of extratropical transitions for the three typhoons shows about 12 hr which starts around a few hours before landfall. During the extratropical transition periods, all three typhoons (except Lionrock) have small $B$ values except for the last 12 hr, indicating mostly a nonfrontal nature until landfall. Typhoon Lionrock does not seem to be extratropical, although it showed a frontal nature at some stage (Figure 11e). Perhaps due to exhibiting a warm core structure in its lifetime (Figure 11f), Lionrock was considered not to become extratropical. All four typhoons under PGW conditions are noticed to maintain mostly similar tendencies in frontal nature to those in the present climate, indicating a negligible impact of climate change on the frontal nature of these typhoons. Typhoons Chanthu and Lionrock exhibited a warm core structure at most times in both the present and future climates, while Typhoon Mindulle indicated a cold core structure at some stages and Typhoon Kompasu showed mostly cold core structure. All the typhoons except Typhoon Lionrock under PGW show strong warm core structures (Figure 11b,d,h). Typhoon Lionrock does not show substantial differences in structure under PGW conditions. The $d\theta_e/dz$ fields
shown in Figure 10 also indicated higher instability under PGW in all the typhoons except Typhoon Lionrock. Overall, all the typhoons except Typhoon Lionrock, after making landfall over the Hokkaido region, exhibited frontal characteristics and a deep cold core structure in the present as well as in the future climate. The composite of winds and temperature was also analyzed at 600 hPa within a radius of 250 km from the typhoon center of each typhoon at different times (figures not shown). The results indicated that all four typhoons have a warm core structure initially with thermal symmetry and later lost the thermal symmetry except for Typhoon Lionrock. All four typhoons under future warming climate are also detected to maintain a similar typhoon structure but with higher magnitudes in temperature as well as wind compared to the present climate, indicating that the typhoons are likely to be stronger under future warming climate.

4 | DISCUSSION AND CONCLUSIONS

In this study we investigated typhoon characteristics including track, intensity, precipitation and wind and local characteristics including equivalent potential temperature and extratropical transitions of four landfalling typhoons (namely Typhoons Chanthu, Mindulle, Lionrock and Kompasu) over northern Japan and their response to a pseudo global warming (PGW) climate. We found robust results for each typhoon. Similar typhoon tracks as in the present climate were well reproduced in a future warming climate, but with higher maximum wind and lower minimum sea level pressure, indicating that stronger typhoons are likely to occur over northern Japan under PGW conditions.

The reason for stronger typhoons under PGW could be associated with the increase of sea surface temperature and moisture in future climate (Takemi et al., 2012; Miyamoto and Takemi, 2013; Nayak and Takemi, 2019a; 2019b). Because of the increase of sea surface temperature (Figure 2) and the resulting increased surface fluxes, equivalent potential temperature rises (Črnivec et al., 2016) lead to higher convective instability in future warming climate. Our results also show an increase of equivalent potential temperature (Figure 9) with more unstable atmosphere (Figure 10) during the landfall of each typhoon under PGW conditions. All the typhoons except Typhoon Lionrock under PGW conditions exhibited much deeper cold core structures after landfall.
We also found that the typhoons under future warming climate are expected to maintain thermal symmetry until a few hours before landfall as in the present climate but with higher magnitudes of temperature and wind speed. This is considered to make the typhoon intensities stronger in future warming climate.

We further found a significant increase of precipitation amounts over landfall areas under PGW conditions. Previous studies on Typhoon Chanthu (Kanada et al., 2017) and Typhoon Lionrock (Nayak and Takemi, 2019a) also highlighted an increase of precipitation in a future warming climate. The reason for the increase of precipitation amounts under PGW could be associated with the atmospheric moisture content which is expected to increase in future warming climate (Nayak and Dairaku, 2016; Kanada et al., 2017). Our results also show higher equivalent potential temperature under PGW (Figure 9) which may be a consequence of increased surface moisture. We found an increase of specific humidity (Figure 12) and relative humidity (Figure 13) associated with each typhoon in future climate. In addition, we found that the typhoons in future climate are likely to bring high winds to landfall regions over Tohoku and southern regions of Hokkaido (Figure 7i–l). On the other hand, three typhoons (Typhoons Chanthu, Lionrock and Kompasu) in future climate showed weakening of winds over large areas of the Hokkaido region (Figure 7i,k–l). Previous studies on Typhoon Mireille (1991) (Takemi et al., 2016a) and Typhoon Songda (2004) (Ito et al., 2016) also showed that the typhoons under PGW conditions weakened over the northern part of Japan. However, Typhoon Mindulle in future climate shows high winds over Hokkaido (Figure 7i). The maximum wind during the landfall of each typhoon also showed higher magnitudes in future warming climate (Figure 7m–p). The seemingly contradictory results for the mean surface winds (Figure 7i–l) and the maximum winds at landfall (Figure 7m–p) are due to the maintained intensity of typhoons over the Pacific with the rapid weakening of typhoons after landfall. Note that Typhoon Songda (2004) rapidly weakened under the PGW climate over the Sea of Japan (Ito et al., 2016), suggesting that the impact of typhoons under global warming is different depending on the typhoon track before landfall (the Pacific side or the Sea of Japan side). The differences of sea surface temperature and atmospheric stability between the Pacific and the Sea of Japan sides may play a role.

The present study overall explored the robust features of typhoon hazards in northern Japan from four typhoons in a future warming climate. The landfall areas of each typhoon are likely to experience heavier precipitation events in future climate and all four typhoons are likely to bring high winds to landfall regions of northern Japan. Typhoon Chanthu and Typhoon Lionrock are noticed to bring relatively high winds and heavy rainfall

**FIGURE 13** As Figure 12 but with relative humidity at 850 hPa
events in future climate. The overall results have an implication for damage over northern Japan through strong surface winds, flooding and storm hazards associated with future typhoons.

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