Future Changes of Tropical Cyclones in the Midlatitudes in 4-km-mesh Downscaling Experiments from Large-Ensemble Simulations

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Abstract

To understand the impacts of global warming on tropical cyclones (TCs) in midlatitude regions, dynamical downscaling experiments were performed using a 4-km-mesh regional model with a one-dimensional slab ocean model. Around 100 downscaling experiments for midlatitude TCs that traveled over the sea east of Japan were forced by large-ensemble climate change simulations of both current and warming climates. Mean central pressure and radius of maximum wind speed of simulated current-climate TCs increased as the TCs moved northward into a baroclinic environment with decreasing sea surface temperature (SST). In the warming-climate simulations, the mean central pressure of TCs in the analysis regions decreased from 958 hPa to 948 hPa: 12% of the warming-climate TCs were of an unusual central pressure lower than 925 hPa. In the warming climate, atmospheric conditions were strongly stabilized, however, the warming-climate TCs could develop, because the storms developed taller and stronger eyewall updrafts owing to higher SSTs and larger amounts of near-surface water vapor. When mean SST and near-surface water vapor were significantly higher and baroclinicity was significantly smaller, unusual intense TCs with extreme wind speeds and large amounts of precipitation around a small eye, could develop in midlatitude regions, retaining the axisymmetric TC structures.

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1. Introduction

Tropical cyclones (TCs) often bring torrential rainfall, gales, and storm surges that sometimes cause severe disasters in midlatitude coastal regions. Sea surface temperature (SST) is projected to increase as a result of anthropogenic greenhouse warming, and the maximum intensity (the maximum wind speed or central pressure) of future TCs will likely increase as well (e.g., IPCC 2012; Mizuta et al. 2014; Murakami et al. 2012), because the TC intensity generally increases as SST increases (e.g., DeMaria and Kaplan 1994; Emanuel 1986).

In the present climate, TCs that travel to higher latitudes tend to weaken as SST decreases north of 30°N. However, Kossin et al. (2014) reported that the average latitude at which TCs reach their lifetime-maximum wind speed has been shifting poleward over the past 30 years. A number of future projection studies have implied that higher-latitude occurrences of intense TCs will increase (e.g., Kanada et al. 2013; Tsuboki et al. 2015; Yoshida et al. 2017) because the projected future increase in SST is larger at higher latitudes (Mizuta et al. 2017). Furthermore, case studies of TCs that caused record-breaking heavy rainfall in eastern coastal regions of northern Japan have shown that precipitation amounts associated with a TC’s landfall increased in the warming-climate simulations (Kanada et al. 2017a, 2019). These results suggest that large numbers of people living in mid-to-high latitudes may be exposed to unusually intense TCs and associated winds and precipitation in the future, warmer climate.

In midlatitude regions, TCs undergo an extratropical transition and structural changes as they move poleward into a baroclinic environment characterized by a temperature gradient, increased vertical wind shear (VWS), and decreased SST (Evans et al. 2017; Wada 2016). To simulate the detailed inner-core structure of a TC, it is necessary to use models with a horizontal resolution not larger than 5 km (e.g., Gentry and Lackmann 2010; Kanada and Wada 2016).

Regional TC changes include large uncertainty caused mainly by SST warming patterns (Knutson et al. 2010; Murakami et al. 2012). In addition, the projected TC changes vary greatly among individual storms (Gutmann et al. 2018). Therefore, to understand changes in TC activity in the future climate, it is important to use a large ensemble to model storms.

The present study aimed to understand the impact of global warming on TCs likely to affect the large number of people living in eastern midlatitude coastal regions. Changes in TCs traveling over the sea east of Japan were investigated by conducting dynamical downscaling experiments with a 4-km-mesh regional model. The downscaling experiments were forced by large-ensemble climate simulations for both current and 4-K-warming climates (Mizuta et al. 2017). Around 100 dynamical downscaling experiments for both the current and warming climates were conducted to explore changes in the intensity and structures of midlatitude TCs.

2. Models and methodology

Dynamical downscaling experiments of TCs traveling over the sea east of Japan were performed by using the Policy Decision-Making for Future Climate Change (d4PDF) database (Mizuta et al. 2017). This database comprises results of a large ensemble of climate change simulations with a 60-km-mesh atmospheric global circulation model (MRI-AGCM3.2H; Mizuta et al. 2012) and a 20-km-mesh atmospheric regional model (NHRCM; Sasaki et al. 2011). All TCs that made landfall in eastern Hokkaido in northern Japan (142°E–146°E and 42°N–46°N) from the western North Pacific Ocean with no previous landfalls were targeted. Only eight TCs met those criteria according to the Regional Specialized Meteorological Center Tokyo (RSMC) best-track dataset from 1951 to 2018, but 98 and 125 storms were selected from the 3,000 years of current-climate and 5,400 years of 4-K warming-climate runs, respectively, in the d4PDF database. Tracks of the targeted storms are shown in Fig. 1.

Downscaling experiments for all targeted storms were conducted with a high-resolution non-hydrostatic regional model, the Cloud Resolving Storm Simulator version 3.4 (CReSS; Tsuboki and Sakakibara 2002), which has a horizontal resolution of 0.04° (approximately 4 km). The computational domain of CReSS spans 128°E–152°E and 24°N–48°N (Figs. 1a and 1b). SST cooling associated with storm passage is considered by a simple thermal diffusion model. Initial and lateral boundary conditions were provided every 6 h from the NHRCM results. Detailed information on the models and methodology are given in Supplement 1.
3. Results

3.1 Changes in midlatitude TCs with increasing latitude

In the RSMC best-track dataset for 1951–2018, the lowest central pressure over the sea east of Japan between 30°N and 45°N was 925 hPa, during Typhoon Oscar (1995), and that in the current simulation was 922 hPa. In the warming climate, the lowest central pressure in the region dropped to 869 hPa. The mean central pressure of TCs in the analysis regions decreased from 958 hPa to 948 hPa in the warming-climate simulation: 12% of the warming-climate TCs were of an unusual central pressure lower than 925 hPa. The warming-climate TCs tended to travel northward at slower translation speeds than the current-climate TCs. Mean translation speed of the current- and warming-climate TCs between 30°N and 45°N was 9.2 (8.8 in the RSMC TCs) and 8.0 m s\(^{-1}\), respectively. A similar slowdown in the translation speed of midlatitude TCs under a warming climate has been reported by Kanada et al. (2017a) and Yamaguchi et al. (2020).

Changes in the simulated midlatitude TCs with increasing latitude were investigated (Fig. 2) for all storms whose center was located in the region shown in Figs. 1 and S1. List of abbreviations and the definitions in this study were summarized in Table S1. TCs tend to weaken and their radius of maximum wind speed (RMW) increases as they move poleward (Evans et al. 2017). The current-climate simulations showed both a decrease in the maximum wind speed and increases in the central pressure and RMW under the increasing VWS and decreasing SST associated with latitude increases (Figs. 1 and 2). In the warming-climate simulations, mean SST in the inner core of the storms increased in all analysis regions, whereas baroclinicity and VWS decreased (Fig. 1). Mean central pressure decreased in the regions south of 40°N (Fig. 2) were statistically significant at the 95% confidence level (Welch’s t-test). Mean precipitation amounts and wind speeds in the inner core were enhanced in warming-climate storms, but they tended to have a smaller RMW than current-climate storms (Fig. 2).

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Fig. 2. Box-and-whisker plots of (a) central pressure (hPa), (b) maximum 10-m wind speeds (MWS: m s\(^{-1}\)), (c) mean 10-m wind speeds in the inner core (WS200: m s\(^{-1}\)), (d) mean hourly precipitation in the inner core (PR200: mm), (e) radius of the maximum 10-m wind speed (RMW: km), and (f) symmetry (SY: K). A green line with an asterisk in (a) indicated ranges of central pressure of the relevant TCs in the RSMC best-track dataset. Other information is the same as in Fig. 2c–f.

Fig. 3. Storm-centered composite horizontal distributions of 10-m wind speeds when the storm centers were located in 142°E–147°E and 35°N–40°N in the (a) current and (b) warming climates, and (c) changes in the warming climate compared with the current climate. (d)–(f) Same as (a)–(c), but for meridional vertical cross sections of horizontal wind speed. (g)–(i) Same as (a)–(c), but for latitudinal vertical cross sections. ‘A’, ‘B’, and ‘C’ denote areas of high winds, areas of moderate wind speeds, and the jet stream, respectively.
TCs have undergone extratropical transition; in contrast, the mean SY of warming-climate TCs was relatively low at 0.5.

Figure 4 depicts the horizontal distributions of SST and air temperature when the storm centers were located in 142°E−147°E and 35°N−40°N. Because SST and air temperature increases in the vicinity of Japan under a warming climate are larger in the higher latitudes and the Sea of Japan than in the lower latitudes (Fig. 4), temperature gradients (baroclinicity) around Japan are reduced in the warming climate. The reduced temperature gradients are attributable to decrease in thermal wind and hence decreases in northward and eastward winds (Figs. 3 and 4), which is a possible factor contributing to the slower northward translation speed. Decreased SST causes a reduction of surface heat fluxes and a TC begins to interact with the midlatitude baroclinic environment to transform into an extratropical cyclone (Jones et al. 2003). However, in the warming climate, SSTs was significantly high, and the jet stream was weakened, and the altitude of it increased and was farther from the TC inner core (‘C’ in Fig. 3). Thus, the warming-climate storms could retain the axisymmetric TC structures even they arrived around northern Japan.

### 3.2 Changes in intensity and structure of midlatitude TCs

Changes in the structures of TCs were explored in relation to TC intensity (Fig. 5). Changes in the environmental sea level pressure (SLP) from the current to the warming climate can affect the central pressure. Therefore, we used the decrease in the central pressure from the environmental SLP (hereafter, pressure decrease: PD) as an index of TC intensity (see Supplement 1). To avoid topographic effects, TCs whose centers were located in 142°E−147°E and 30°N−40°N were selected (Fig. S2).

Mean PDs increased from 51 hPa to 41 hPa from the current to the warming climate. Furthermore, TCs of unusual intensity, with a mean PD exceeding 70 hPa (central pressure approximately 928 hPa), appeared in the warming climate. In general, MWS, WS200, PR200, and IKE (see Supplement 1) increased and RMW decreased as the PD increased in both the current and warming climates (Fig. 5). The largest difference between current- and warming-climate storms was in SY; SY of warming-climate storms was smaller than 0.4 regardless of PD, whereas SY of current-climate TCs tended to be large.

The appearance of extremely intense TCs and more axisymmetric TC structures in the warming climate can be attributed to more favorable environmental conditions for TC development (i.e., significantly high SST, large amounts of near-surface water vapor, smaller VWS and baroclinicity), as well as the slower TC translation speed and a weaker upper-level jet. The only exception was an increase in the mean static stability (N²) in the inner core (Supplement 1). In the warming climate, the increase in air temperature in the upper troposphere is projected to be large (e.g., Hill and Lackmann 2011; Kanada et al. 2017b) and atmospheric conditions stabilize (Fig. 5). The significant stabilization inhibited convective activity and suppressed TC development. When mean SST (Fig. 5h) and near-surface water vapor (Fig. 5i) were significantly high and baroclinicity (Fig. 5k) was significantly smaller, however, unusual intense TCs with extreme wind speeds and large amounts of precipitation around a small eye, could develop in midlatitude regions despite the strong stabilization.

How do the warming-climate TCs develop to have the same PD as current-climate TCs despite the stabilization? Storm-centered composite azimuthally averaged structures of TCs with a PD between 40 and 60 hPa in the current and warming climates were compared (Fig. 6). The vertical moisture flux and eyewall updrafts of the warming-climate TCs were considerably stronger and located within a smaller RMW at all altitudes, compared with those of the current-climate TCs (Figs. 6a, 6b, 6d and 6e). Furthermore, regions with high inertial stability appeared inside the RMW where the intense updrafts developed. Theoretical studies have shown that the fraction of thermal forcing Q (i.e., heating by latent heat release in the eyewall updrafts), which contributes to TC development, increases when the horizontal extent of Q is small and close to the region of high inertial stability (Schubert and Hack 1982). In other words, the simulated warming-climate TCs exhibited structures of a TC in the developing stage that efficiently uses Q in the eyewall updrafts. The heating by latent heat release induces near-surface inflow around the eyewall region (Stern et al. 2015), and this enhancement of heating-induced near-surface inflow as well as the reduction of the RMW intensified horizontal wind speeds in the vicinity of the smaller eye in the warming-climate TCs. In contrast, current-climate TCs, which had weaker eyewall updrafts that tilted outside the larger RMW, entered a post-mature stage as losing axisymmetric structures of a TC under conditions of lower SSTs and relatively large baroclinicity. The extremely intense TCs in the warming-climate simulations had even stronger and taller eyewall updrafts inside a smaller RMW, where the inertial stability was very high, compared with the updrafts of TCs with a PD between 40 and 60 hPa in both climates (Figs. 6c and 6f).

### 4. Discussion: Changes in RMW and storm size

Using a 14-km-mesh model, Yamada et al. (2017) found that future TCs would become larger because of deeper secondary circulation. However, the results of the present study obtained with a 4-km-mesh regional model showed a reduction in IKE. There...
were no large differences in the horizontal extent of near-surface wind speeds in TCs with the same PD between the current and warming climates (Fig. 6). A reduction in the RMW was also found in future change experiments of intense TCs conducted with high-resolution non-hydrostatic models with horizontal resolutions of 2−5 km (Kanada et al. 2013, 2017b; Wang et al. 2015). In addition, an atmosphere-ocean couple model with a horizontal resolution of 6 km projected a reduction in the size of western North Pacific storms under future warming (Knutson et al. 2015).

According to Schubert and Hack (1982), heating-induced tangential wind acceleration at low levels is larger inside the RMW and leads to a reduction of the RMW. The significantly increased near-surface water vapor in the warming climate can be attributed to the reduction in the RMW by enhancement of the eyewall updrafts (Fig. 6) and hence heating by latent heat release. Furthermore, a delay in the extratropical transition is attributable to the reduction in the RMW of midlatitude TCs in the warming climate. Thus, to project changes in the inner-core structures of TCs, high-resolution models with a horizontal resolution of several kilometers should be used.

5. Summary

The impacts of global warming on TCs in midlatitude regions were investigated by analyzing the results of around 100 dynamical downscaling experiments conducted with a 4-km-mesh regional model forced by a large ensemble of climate simulations for both current and 4-K-warming climates. All TCs that struck eastern Hokkaido in northern Japan from the western North Pacific Ocean without previous landfalls were targeted. In total, 98 and 125 storms were selected from the 3,000 years of current and 5,400 years of 4-K-warming climate runs, respectively.

The results of the downscaling experiments showed increases in the frequency of intense TCs with strong horizontal winds and large precipitation amounts around a smaller eye under a future, warmer climate (Fig. 2). Extremely intense TCs with a mean pressure decrease (PD) exceeding 70 hPa (central pressure approximately 928 hPa), appeared in midlatitude regions. The mean PD was 41 hPa (approximately 964 hPa) in the current-climate TCs and 51 hPa (approximately 953 hPa) in the warmer-climate TCs. Although the RMW and asymmetric property of the current-climate TCs increased as they moved poleward into a more baroclinic environment, the warming-climate TCs exhibited axisym-
metric structures and a smaller RMW. The decreased temperature gradients and increased SST caused a delay in the extratropical transition of midlatitude TCs in a warming climate.

In the warming climate, most environmental conditions such as SST, VWS, and baroclinicity, as well as the slower TC translation speed and a weaker upper-level jet, were more favorable for TC development. However, significant increases in static stability indicated stabilization of atmospheric conditions (Fig. 5l), which inhibited TC development. To overcome the enhanced stability, the warming-climate TCs required significantly high SSTs (Fig. 5h) and large amounts of water vapor in the lower troposphere (Fig. 5i).

The results of the present study suggested a slowdown in the translation speed of TCs under a warming climate. The impact of the SST cooling associated with the storm passage is large in midlatitude regions, because TC heat potential is smaller than in low-latitude regions (Wada 2016). Atmosphere-ocean coupled models that include cold-wake effects should be used for more accurate future projections of TC activity. Furthermore, environmental conditions and TC size differ greatly among ocean basins (Wada et al. 2012). Studies of TCs in each basin using high-resolution models that can capture structural changes in the storm inner cores will be required to gain deeper insights into TC changes in a warming climate.

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Supplement

Supplement 1 describes detailed information on the models and methodology.
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