Future Changes in Typhoon-Related Precipitation in Eastern Hokkaido

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Abstract

From 16 to 23 August 2016, typhoons T1607, T1609, and T1611 hit eastern Hokkaido in northern Japan and caused heavy rainfall that resulted in severe disasters. To understand future changes in typhoon-related precipitation (TRP) in midlatitude regions, climate change experiments on these three typhoons were conducted using a high-resolution three-dimensional atmosphere–ocean coupled regional model in current and pseudo-global warming (PGW) climates. All PGW simulations projected decreases in precipitation frequency with an increased frequency of strong TRP and decreased frequency of weak TRP in eastern Hokkaido.

In the current climate, snow-dominant precipitation systems start to cause precipitation in eastern Hokkaido about 24 hours before landfall. In the PGW climate, increases in convective available potential energy (CAPE) developed tall and intense updrafts and the snow-dominant precipitation systems turned to have more convective property with less snow mixing ratio (QS). Decreased QS reduced precipitation area, although strong precipitation increased or remained almost the same. Only TRP of T1607 increased the amounts before landfall. In contrast, all typhoons projected to increase TRP amount associated with landfall, because in addition to increased CAPE, the PGW typhoon and thereby its circulations intensified, and a large amount of rain was produced in the core region.

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1. Introduction

Extreme weather events such as tropical cyclones (TCs) and heavy rainfall events have become more violent as the surface air temperature has increased in the current climate (Kawase et al. 2019; Imada et al. 2019). The frequency of extremely intense precipitation has increased in the past several decades (e.g., Trenberth 2011; Fujibe 2015). Furthermore, Kossin et al. (2014) have found that the average latitude where TCs reach their peak intensity has been shifting poleward over the past 30 years and suggested that the past migration in the western North Pacific Ocean (NWP) coincided with increased TC exposure in the regions of the East China Sea, including Japan (Kossin et al. 2016).

By the late 21st century, sea surface temperature (SST) in the vicinity of Japan is projected to increase by 4°C under the RCP8.5 scenario (Mizuta et al. 2017). A high SST is a condition that favors intense TCs (e.g., Emanuel 1986). Most climate change studies conducted based on state-of-the-art global and cloud-resolving models have therefore indicated that the maximum intensity and precipitation rate of TCs will increase in the future climate (e.g., IPCC 2012; Murakami et al. 2012; Kanada et al. 2013; Tsuboki et al. 2015; Yoshida et al. 2017; Kitoh and Endo 2019).

A typhoon (Northwest Pacific TC) transports a large amount of water vapor from the subtropical ocean and often causes heavy rainfall events in Japan (Fujita and Sato 2017; Nayak and Takemi 2015; Yoshida et al. 2017; Kitoh and Endo 2019). Recent studies of TCs based on state-of-the-art global and cloud-resolving ocean coupled regional models in current and pseudo-global warming (PGW) climates. In the current climate, snow-dominant precipitation systems start to cause precipitation in eastern Hokkaido about 24 hours before landfall. In the PGW climate, increases in convective available potential energy (CAPE) developed tall and intense updrafts and the snow-dominant precipitation systems turned to have more convective property with less snow mixing ratio (QS). Decreased QS reduced precipitation area, although strong precipitation increased or remained almost the same. Only TRP of T1607 increased the amounts before landfall. In contrast, all typhoons projected to increase TRP amount associated with landfall, because in addition to increased CAPE, the PGW typhoon and thereby its circulations intensified, and a large amount of rain was produced in the core region.

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2. Models and methodology

The model used in the present study is a high-resolution, three-dimensional atmosphere–ocean coupled regional model composed of the Cloud Resolving Storm Simulator version 3.4 (CRESS; Tsuboki and Sakakibara 2002) for the atmospheric part and the Non-Hydrostatic Ocean model for the Earth Simulator (NHOES; Aiki et al. 2006, 2011) for the oceanic part. The coupled model is referred to as the CRESS–NHOES (Aiki et al. 2015). The horizontal domain of the coupled model spans 132°E−155°E and 25°N−50°N (Fig. 1), and is discretized with a grid spacing of 0.04° by 0.04°.

The climate change simulations were conducted using the same PGW method used by Kanada et al. (2017a,b). First, we performed control simulations in the current climate (the CTNL simulations) of typhoons T1607 (Chanthu), T1609 (Mindulle), and T1611 (Kompasu). Initial and lateral boundary conditions for the atmosphere and ocean models were provided by the Japan Meteorological Agency 55-year Reanalysis dataset (Kobayashi et al. 2015) and the Japan Coastal Ocean Predictability Experiment reanalysis product (Miyazawa et al. 2009), respectively. The PGW climate simulations were conducted using the results of climate runs by the MRI-AGCM version 3.2 with a horizontal resolution of 20 km under the RCP8.5 scenario (Mizuta et al. 2012, 2014). More detailed information for the models, data, and the PGW method are found in Supplement 1.

Following Kanada et al. (2017a), we focused on precipitation in eastern Hokkaido, which we defined as the land east of a straight line between Wakkani (41.678°E, 45.415°N) and Cape Erimo (43.243°E, 41.925°N) (Fig. 1a). There were 110 Auto...
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The domain of simulations with six-hourly tracks of the RSMC best-track (thin line with dots) and the CNTL (black dashed line with black open circles) and PGW (red dashed line with red open circles) simulations for (a) T1607, (b) T1611, and (c) T1609. Stars in (a), (b), and (c) indicate the center locations at 1800 UTC on 17 August, 0000 UTC on 22 August, and 0000 UTC 23 August 2016, respectively.

Table 1. The minimum central pressure (MCP) during the analysis period and times that the storm arrived at 32°N (it32), 40°N (it40), and 46°N (it46). BT indicates the RSMC best-track data.

|        | T1607 | T1611 | T1609 |
|--------|-------|-------|-------|
| MCP    |       |       |       |
| it32   | 980   | 997   | 971   |
| 0600UTC16-0900UTC16 | 0900UTC16-1200UTC16 | 0000UTC18-0300UTC18 | 0000UTC18-0300UTC18 |
| it40   | 994   | 999   | 996   |
| 0900UTC17-1200UTC17 | 1200UTC17-1500UTC17 | 0000UTC18-0300UTC18 | 0000UTC18-0300UTC18 |
| it46   | 975   | 996   | 991   |
| 1800UTC17-2100UTC17 | 2100UTC17-0000UTC19 | 0000UTC19-0300UTC20 | 0000UTC19-0300UTC20 |

3. Results

The CNTL simulations represented well the tracks and minimum central pressures (MCPs) of T1607, T1609 and T1611 compared with the Regional Specialized Meteorological Center Tokyo (RSMC) best-track dataset, although the MCP for T1609 was higher in the simulation than in the best-track dataset (Table 1 and Fig. 1). Under PGW conditions, the simulated MCPs of all the typhoons decreased. Furthermore, the PGW typhoons tended to travel northward at slower translation speeds than they did in the CNTL simulations. The weakening of the jet streak due to the reduction of baroclinicity around northern Japan (Kanada et al. 2017a; Itô et al. 2016) was a possible factor for the slower translation speeds.

The temporal evolutions of area-mean precipitation observed in eastern Hokkaido were examined (Fig. 2). The peak amounts which corresponded to the precipitation associated with the time that the typhoons made landfall, appeared at the end of the precipitation periods for T1607 and T1609, at 1000 UTC on 17 August and 2200 UTC on 22 August 2016, respectively. The peak for T1611 was indistinct because the typhoon was weakened when it made landfall; the MCP at 1200 UTC on 21 August 2016 was 1000 hPa. Considerable amounts of precipitation had already started in eastern Hokkaido about 24 hours before the typhoons made landfall.

The CNTL simulations captured the temporal evolutions and mean amounts of TRP in eastern Hokkaido associated with T1607, T1609, and T1611 (Figs. 2a, 2b, and 2c). In the PGW climate, the peak amounts of precipitation associated with the typhoon landfalls increased and appearance times of the peaks tended to be delayed by a few hours, respectively, compared with the current climate (Figs. 2d, 2e, and 2f). The delays in their northward movement occurred during TRP remote periods (Table 1). Despite the longer TRP remote period due to the slower movement in the PGW climate, the amount of TRP remote increased only for T1607, whereas the amounts of TRP direct increased for all typhoons (Table 2).

The frequency of precipitation, defined as the number of model grid points with hourly precipitation amounts not smaller than 0.5 mm, decreased during the TRP remote period for all the typhoons (Figs. 2g, 2h, and 2i). Figure 2j showed that frequency of weak TRP, defined as hourly precipitation smaller than 20 mm, increased for all typhoons. The ratio of strong TRP frequency to the precipitation frequency increased in all typhoons, although the simulations overestimated the ratio of strong TRP frequency (Fig. 2j). Considerable decreases in the frequency of weak precipitation occurred in TRP remote for all typhoons (Fig. 2k).

Kanada et al. (2017a) have attributed the increase in PRE in the PGW climate to the increase in convective available potential energy (CAPE) due to increases in water vapor in the low levels from the southern sea. We therefore investigated the temporal evolution of CAPE for air masses transported to eastern Hokkaido from the southern sea (Fig. 3). In the current climate, all typhoon had larger CAPE during TRP remote period, compared with those during TRP direct period. Under the PGW conditions, the CAPE increased for all typhoons. The maximum CAPE exceeded 1000 J kg⁻¹ during TRP remote period for T1607 and T1611 in the PGW climate. The maximum CAPE approached to 2000 J kg⁻¹ during TRP remote period for T1609.
9 m s\(^{-1}\) during TRP remote period.

For all PGW typhoons, CAPE increased and tall and intense updrafts developed as mentioned in Kanada et al. (2017). However, the TRP remote amounts for T1611 and T1609 showed no increase in the PGW climate, while the TRP direct amounts increased for all typhoons (Table 2).

To understand changes in precipitation systems under the PGW conditions, the temporal evolutions of 50th percentile (the medians) of vertical winds, mean relative humidity (RH), and mixing ratios of snow (QS), graupel (QG), and rain (QR) were investigated (Fig. 4). The medians were made of 3070 grid points over the eastern Hokkaido in the simulations. The positive median values indicate that updrafts are predominant. Model grid points with QS not smaller than 0.05 kg kg\(^{-1}\) were defined as snow-coverage grids (Figs. 4a, 4b, 4c, 4g, 4h, and 4i). The temporal evolutions of vertically integrated QS (IQS), QG (IQG), and QR (IQR) are also shown in Fig. 5.

In the current climate, regions with QS larger than 0.1 g kg\(^{-1}\) spread widely over eastern Hokkaido for all typhoons (Figs. 4d, 4e, 4f, 4j, 4k, and 4l). IQS was twice larger than IQG for most of periods (Figs. 5a, 5b, and 5c). For T1607, more than half of eastern Hokkaido was covered by the snow-coverage grids (Fig. 4a). Two regions with updrafts (> 5 cm s\(^{-1}\)) and downdrafts appeared above and below the 0°C isothermal level around 5 km until 0400 UTC on 17 August (Fig. 4a). The regions with updrafts on the order of centimeters per second corresponded to regions with QS larger than 0.1 g kg\(^{-1}\). Widespread snow-coverage regions and a pair of weak updrafts and downdrafts below are typical of the stratiform region of organized precipitation systems (Houze 1989a, b).

In the PGW climate, snow-coverage grids during TRP remote periods decreased for all typhoons (Figs. 4a, 4b, 4c, 4g, 4h, and 4i). IQS was twice larger than IQG for most of periods (Figs. 5a, 5b, and 5c). For T1607, more than half of eastern Hokkaido was covered by the snow-coverage grids (Fig. 4a). Two regions with updrafts (> 5 cm s\(^{-1}\)) and downdrafts appeared above and below the 0°C isothermal level around 5 km until 0400 UTC on 17 August (Fig. 4a). The regions with updrafts on the order of centimeters per second corresponded to regions with QS larger than 0.1 g kg\(^{-1}\). Widespread snow-coverage regions and a pair of weak updrafts and downdrafts below are typical of the stratiform region of organized precipitation systems (Houze 1989a, b).

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Fig. 3. Temporal evolutions of CAPE (J kg⁻¹) averaged between 143°E–146°E at 42°N in the current (black) and PGW (red) climates for (a) T1607, (b) T1611, and (c) T1609. The horizontal lines indicate the periods between it₃ and it₄ (blue), and it₄ and it₅ (orange) shown in Table 1. Temporal evolutions of the 99.9th of vertical velocity for each altitude (m s⁻¹) in eastern Hokkaido in the CNTL simulations for (d) T1607, (e) T1611, and (f) T1609. (g)–(l): Same as (d)–(f), but in the PGW simulations.

Fig. 4. Temporal evolutions of the median (color) of vertical velocity and snow-coverage grids (1500 grids: magenta contour) for each altitude in eastern Hokkaido in the CNTL simulation for (a) T1607. The horizontal lines indicate the periods between it₃ and it₄ (blue), and it₄ and it₅ (orange) shown in Table 1 and atmospheric temperature of 0°C (dotted black line). Same as (a), but snow-coverage grids (600 grids: magenta contour) for (b) T1611, and (c) T1609. (d)–(f): Same as (a)–(c), but for mean relative humidity (color) and mixing ratios of snow (0.1 and 0.3 g kg⁻¹: magenta contour), graupel (0.1 and 0.3 g kg⁻¹: black contour), and rain (0.1 and 0.3 g kg⁻¹: white contour). (g)–(l): Same as (a)–(f), but in the PGW simulations.
During the period, IQG became comparable to IQS (Fig. 5) and produced large amounts of precipitation, although the precipitation areas decreased in the PGW simulation (Figs. 4d and 4g). Decreases in the weak precipitation frequency and precipitation areas in TRP Remote periods could be attributed to the reduction of QS under the PGW conditions.

On the other hand, snow-coverage grids remained during TRP Remote periods in the PGW climate for all typhoons. In the PGW climate, all typhoons intensified (Table 1) and thereby the typhoon circulations of the core regions intensified. In addition to increased water vapor in the low levels (e.g., Kanada et al. 2017a) under the PGW conditions, the intensified typhoon circulations produced large amounts of IQS, IQG, and IQR in the typhoon core regions and led increases in TRP Remote, amounts (Fig. 5).

4. Discussion: The potential reasons for decreases in QS

According to Houze (1989a, b), stratiform precipitation systems with widespread QS cause relatively weak precipitation over wide areas, whereas convective systems with large amounts of OG and less QS cause strong precipitation. In the present study, updrafts and QS were predominant above the melting level during TRP Remote periods in the current climate (Figs. 4a, 4b, 4c, 4d, 4e, and 4f). In the PGW climate, tall and intense updrafts developed and ratios of IQG to IQS increased during TRP Remote periods. The results indicated that the snow-dominant precipitation systems in the current climate turned to have more convective property with vigorous updrafts with less QS. Indeed, snow-coverage grids during TRP Remote periods decreased for all typhoons in the PGW (Figs. 4a, 4b, 4c, 4g, 4h, and 4i).

Another potential cause for the QS reduction is stabilization of atmospheric conditions in the future climate (Hibino et al. 2018). Most studies have pointed out that the increase in air temperature is large in the upper troposphere (e.g., Hill and Lackmann 2011). In the present study, the 0°C isothermal level and the top of snow-coverage grids increased by 1 km in the PGW climate (Fig. 4). Because increases in air temperature exceeds 4°C above an altitude of 7 km (Kanada et al. 2017b), convection and formation of QS above the altitudes could be suppressed under the warming conditions. During TRP Remote period, however, the increase in water vapor in the lower layer could overcome the enhanced stability as suggested by Watanabe et al. (2019).

5. Summary

Future changes of typhoon-related precipitation (TRP) in eastern Hokkaido were investigated based on the results of climate change experiments of three typhoons that hit the region in August of 2016: T1607, T1609, and T1611. The current and pseudo-global warming (PGW) climate experiments were conducted by using a high-resolution, three-dimensional, atmosphere–ocean coupled regional model with a horizontal resolution of approximately 4 km.

All PGW simulations projected decreases in TRP frequency with an increased frequency of strong TRP and decreased frequency of weak TRP in eastern Hokkaido (Fig. 2j). The results indicated that strong precipitation concentrated in the small precipitation area. Considerable decreases in weak precipitation frequency and increases in ratio of strong precipitation frequency to the total precipitation frequency were found in TRP Remote for all typhoons (Fig. 2k).

Changes in precipitation systems under the PGW conditions were investigated based on the simulation results. The precipitation systems for TRP Remote, in the current climate tend to show wide snow-coverage and amounts of QS is about twice larger than those of OG (Figs. 4 and 5). In the PGW simulations, the snow-dominant precipitation systems for TRP Remote, turned to have more convective property with intense updrafts and less QS. Decreases in QS resulted in decreases in the frequency of weak precipitation. Since the frequency of strong precipitation increased or remained almost the same, ratio of strong precipitation frequency to the precipitation frequency increased in the PGW simulations.

On the other hand, during landfall, in addition to the increased CAPE, all typhoons intensified and thereby the intensified typhoon circulations produced large amounts of rain in the core region (Fig. 5). It should be noted that the enhancement of PRE (TRP Remote) suggested by Kanada et al. (2017a) only occurred in T1607. The simulations in the present study also overestimated the ratio of strong TRP frequency. Improvements of models and studies using a large ensemble simulation with higher-resolution models should be required in future work. Furthermore, no significant change was found in the translation speed of the typhoons in Watanabe et al. (2019), although the analysis region of Watanabe et al. (2019) differed from the present study. To study changes in track and frequency of tropical cyclones (TCs), a large ensemble of climate simulations with global circulation models, such as d4PDF (Mizuta et al. 2017), will be necessary to reduce the uncertainty.

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Supplement

Supplement 1 describes detailed information for the models and methodology.

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