Future Projections of Heavy Precipitation in Kanto and Associated Weather Patterns Using Large Ensemble High-Resolution Simulations

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Abstract

Heavy precipitation in Japan is caused by various phenomena, such as tropical cyclones and the Baiu front, and shows regional-scale variation. Here we investigate extremely heavy precipitation events exceeding the 100-year return period in the Kanto area and future projections of such events using large ensemble climate simulations for periods of several thousand years. To understand these extreme events, associated sea level pressure anomalies over Japan and the surrounding region are classified into four clusters. These cluster means are characterized by (1) a strong anomalous cyclone, (2) a weak anomalous cyclone, (3) an anomalous cyclone accompanied by an anomalous anticyclone to the north, and (4) an anomalous anticyclone to the north. The cluster with a strong anomalous cyclone is accompanied by widely distributed heavy precipitation, and its area-averaged precipitation is predicted to be more enhanced under global warming than that of other clusters, partly because of an increase in the strength of strong tropical cyclones approaching Kanto. The cluster dominated by an anomalous anticyclone is characterized by localized heavy precipitation in the plains area. The relative frequency of this cluster will increase, whereas that of other clusters will decrease under global warming.

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1. Introduction

As global warming caused by increasing greenhouse gas concentrations has continued, Japan in recent years has experienced heavy precipitation events and associated infrastructure damage. For example, Typhoon Hagibis in October 2019 caused unprecedented flooding in eastern Japan including the area of Kanto. The Heavy Rain Event of July 2018 was generated by a continuous supply of moisture into the Baiu front and caused severe flooding and landslides over an extensive area, including western Japan (Shimpo et al. 2019; Sekizawa et al. 2019). Northern Kyushu was severely damaged by the localized heavy precipitation in July 2017 (Takemi 2018). As global warming is expected to lead to increased moisture levels in the atmosphere and enhanced precipitation, future projections of extremely heavy precipitation are important for planning with respect to flood mitigation and prevention to protect human lives, infrastructure, and socioeconomic activities. Because of limited observational records, extremely heavy precipitation has often been investigated using extreme value statistics. Large ensemble simulations can enable investigation of extreme events in a robust manner even for extreme events (Mizuta et al. 2017; Kawase et al. 2019). Heavy precipitation

in Japan is known to be caused by various phenomena, such as typhoons and the Baiu front.

As mechanisms of heavy precipitation and the influence of global warming on these mechanisms show variation at the regional scale (Kawase et al. 2019), future projections of heavy precipitation should be investigated for different area for the purposes of flood mitigation/prevention planning under anticipated global warming. The Ministry of Land, Infrastructure, Transport and Tourism (2019; hereafter MLIT19) concluded that the 100-year return value of extremely heavy precipitation in Japan will be enhanced by 20%–40% under a 4-K warmer climate based on extreme value statistics for annual maximum precipitation through depth-area-duration analysis, which measures precipitation intensity for a particular duration and area. The analysis of MLIT19 was based on an ensemble dataset with 5-km grid spacing and dynamically downscaled from a large ensemble simulation (Kawase et al. 2018; Sasai et al. 2019), namely, the Database for Policy Decision Making for Future Climate Change (d4PDF; Mizuta et al. 2017; Fujita et al. 2019). Although that downscaling was conducted using a very high resolution, simulations were conducted for only limited ensemble members. Therefore, the 100-year return value was estimated on the basis of extreme value statistics for the 360-year simulation in most areas, under a mixture of precipitation caused by different mechanisms.

In the present study, heavy precipitation in Kanto is investigated based on several-thousand-year simulations of the large ensemble dataset d4PDF. Dataset d4PDF comprises a global version using a general circulation model (GCM; hereafter d4PDF-GCM) and a regional version using a regional climate model (RCM; d4PDF-RCM) with horizontal resolutions of 60 km and 20 km, respectively. Dataset d4PDF-RCM can reproduce more realistic precipitation than can d4PDF-GCM because of finer orography (Fig. 1d). Kawase et al. (2019) identified differing characteristics of heavy precipitation to the east of mountain ranges compared with the west on Kyushu. Dataset d4PDF-RCM has been used to investigate the relationships between summertime heavy precipitation in Japan and atmospheric circulation (e.g., Ohba and Sugimoto 2018; Osakada and Nakakita 2018) and to determine future changes in heavy precipitation induced by typhoons approaching Japan (Hatsuzuka et al. 2020).

To conduct a comprehensive investigation of heavy precipitation, the present study considers all phenomena, including typhoon and the Baiu front. We present future projections of extremely heavy precipitation in Kanto with a focus on weather patterns. A classification of weather patterns is proposed to describe those weather conditions that favor extremely heavy precipitation and associated area-scale precipitation distribution, which should be useful for flood mitigation/prevention planning.

2. Data and methods

We used a large ensemble climate simulation dataset d4PDF-RCM, which is dynamically downscaled from d4PDF-GCM (Mizuta et al. 2017; Fujita et al. 2019). Dataset d4PDF-GCM was constructed using the Meteorological Research Institute Atmo-

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Fig. 1. (a) Relative frequency of daily precipitation in the Kanto area (from grid cells in Fig. 1d–e) based on d4PDF-RCM. (b) Area average precipitation percentiles for grid cells in the Kanto area. (c) Area average future change in precipitation percentile relative to HIST. In (b–c), dashed black lines indicate return periods of 1, 10, and 100 years. (d) Orography of d4PDF-RCM (color) and Kanto grid cells. (e) Percentage change in 100-year extreme precipitation from HIST to +4K_F. (f) Monthly frequency of 100-year extreme precipitation events.

spheric GCM version 3.2 (MRI-AGCM3.2) and has a horizontal resolution of 60 km (Mizuta et al. 2012). Dataset d4PDF-RCM was constructed for Japan and the surrounding region using the MRI Non-Hydrostatic RCM (NHRCM) and has a 20-km horizontal resolution (Sasaki et al. 2008). Four sets of simulations were conducted: (1) a historical simulation (hereafter HIST) with observed sea surface temperature (SST) dataset COBE-SST2 (Hirahara et al. 2014), (2) a non-warming simulation (hereafter NonW) with detrended COBE-SST2 (Shiogama et al. 2016), and (3 and 4) warming simulations for climates that are 4-K and 2-K warmer (hereafter +4K_F and +2K_F) than the pre-industrial climate with the NonW SST superimposed on SST warming in six models of the Coupled Model Intercomparison Project phase 5 (CMIP5). The anthropogenic forcings were fixed at a value of 1850 in Non-W, while the forcings in +2K_F and +4K_F were based on CMIP5. HIST and NonW are 6000-year simulations for 1951–2010 (100 members of a 60-year simulation), and +4K_F and +2K_F are 5400-year and 3240-year simulations, respectively (15 and 9 members of a 60-year simulation for 6 SST warming distributions, respectively). We analyzed daily data for all calendar months. The climatology is defined as an ensemble mean of a 60-year mean for each calendar day, then weakly smoothed using a 15-day running mean. In warming simulations, daily climatology was evaluated for each of the six SST distributions.

Extremely heavy precipitation events were defined as those days with the 60 heaviest daily precipitations in each model grid for 6000-year simulations of HIST and NonW, which corresponds approximately to precipitation exceeding the 100-year return value (hereafter, 100-year extreme precipitation events). For the +4K_F (+2K_F), 100-year extreme precipitation events were defined as days with the heaviest 9 (5) daily precipitations for each SST warming distribution, comprising 54 (30) days in total. In composite and cluster analyses, the days for which a 100-year extreme precipitation event was detected in any of the 97 grid cells covering the Kanto area (Fig. 1d) were analyzed (1788 days and 1856 days in HIST and +4K_F, respectively). Our analyses thus included extremely heavy precipitation at all spatial scales from Kanto scale to sub-regional scale. The Kanto area was defined on the basis of orography as in MLIT19.

To classify weather patterns associated with 100-year extreme

precipitation events, sea level pressure (SLP) anomalies in the whole domain of d4PDF-RCM (Fig. 2a) were decomposed into four clusters. K-means clustering was performed for HIST, then SLP anomalies of +4K_F were decomposed into clusters of HIST by using the smallest Euclidian distance from the cluster mean of HIST. This allowed future changes in the classified weather patterns to be examined with respect to changes in the relative frequency and modification of atmospheric circulation.

To investigate the influences of tropical cyclones (TCs) including typhoons, 6-hourly TC track data of d4PDF-GCM (Murakami et al. 2012; Yoshida et al. 2017) were used. A domain within 500 km of the TC center was considered to be under the direct influence of the TC.

3. Results

Under warmer climates, the frequency of heavy precipitation tends to increase in Kanto, whereas the frequency of weak precipitation tends to decrease (Fig. 1a). In +4K_F and +2K_F, extremely heavy precipitation (exceeding the heaviest precipitation in HIST) occurs. Precipitation percentiles indicate that the heavier extreme precipitation is more enhanced under global warming, with 27% and 32% (13% and 15%) enhancement of 10-year and 100-year return values of +4K_F (+2K_F) compared with HIST, respectively (Figs. 1b and 1c). Enhancement from HIST to +2K_F and +4K_F is stronger than that from NonW to HIST, suggesting that damage by flooding and landslides due to heavy precipitation could increase in severity as a result of global warming.

Future changes in 100-year extreme precipitation show regional variation (Fig. 1e). The increase in extreme precipitation tends to be larger in Kanto than that in adjacent areas. The 100-year extreme precipitation strengthens by an average of 35% for the Kanto area, with a maximum strengthening of 58% (Fig. 1e). The 100-year extreme precipitation occurs from May to November and most frequently in August (Fig. 1f). Under global warming, the frequency of these events from July to August is forecast to decrease, whereas that from September to October will increase, especially in September in +4K_F (Fig. 1f). This suggests that future projections of extreme precipitation should be investigated

Fig. 2. Composites of (a–b) SLP anomalies, (c–d) precipitable water, and (e–f) precipitation of 100-year extreme events in (a, c, and e) HIST and (b, d, and f) +4K_F. Values in the upper right of each panel indicate (a–b) minimum SLP anomaly in composites, (c–d) Kanto-area average of composited precipitable water, counterpart using daily climatology for the event days, and counterpart using anomaly from daily climatology, and (e–f) Kanto-area average of precipitation.

not only for the Baiu season (early summer) but also for autumn.

To determine the typical atmospheric conditions for 100-year extreme precipitation events, composite analysis was conducted. The composite precipitation shows a typical distribution for extreme events (Figs. 2e and 2f) and differs from 100-year return values for the grid cells (Fig. 1b), as the 100-year extreme precipitation does not occur in all grid cells over Kanto at the same time. This analysis was conducted to ascertain the characteristics of extremely heavy precipitation rather than the mechanism of enhancement of the 100-year return value of precipitation.

Composites of SLP anomalies show cyclonic anomalies to the south of Kanto in both HIST and +4K_F, which indicates anomalous transport of warm humid air from the Pacific (Figs. 2a and 2b). Precipitation averaged for Kanto increases by 14% from 85 to 97 mm/day (Figs. 2e and 2f) under global warming, although the central SLP anomaly weakens by 14% from -5.6 to -4.8 hPa. Atmospheric moisture measured by precipitable water increases by 25% from 55 to 69 mm (Figs. 2c and 2d). These changes under 3.9-K warming over Kanto suggest that moisture tends to increase closely to that of the Clausius-Clapeyron (CC) relationship of $\sim 7\%$ per K (Trenberth et al. 2003), whereas precipitation does not reach that predicted by CC relationship, probably because of weakened circulation resulting in weakened updrafts by mountainous slope

and weakened dynamical updrafts by synoptic disturbances. In that sense, the thermodynamic effect appears to be more important than the dynamic effect for enhancement of heavy precipitation. It is noted that 86% of the total precipitable water increase (14 mm) is contributed by climatic increase (12 mm), suggesting that enhancement of heavy precipitation is closely related to climatic moisture increase under global warming.

As composites for all 100-year extreme precipitation events may include contributions by different mechanisms of heavy precipitation, the events were decomposed into four clusters by applying K-means clustering for SLP anomalies (Fig. 3). Two clusters are characterized by strong and weak cyclonic anomalies, respectively, just to the south of Kanto (hereafter C4 and C3, respectively). Another cluster is characterized by meridional SLP anomaly dipole comprised of cyclonic and anticyclonic anomalies to the south and north, respectively (C2). The other cluster is characterized by an anticyclonic anomaly to the north and weak local cyclonic circulation over Kanto (C1).

C4 includes more TC events than do other clusters (34.9% and 37.8% in HIST and +4K_F, respectively). Cyclonic anomalies in this cluster are enhanced under global warming, unlike in composites of all extreme events (Figs. 2a, 2b, 3d, and 3h), suggesting that the dynamic effect also contributes to enhanced precipitation

Fig. 3. Composites of SLP anomalies of the four determined clusters for 100-year extreme precipitation events in (a–d) HIST and (e–h) +4K_F. Values in the upper right of each panel indicate the percentage of each cluster in the total events, the percentage of tropical cyclone events in each cluster, and the minimum SLP anomaly.

Fig. 4. As for Fig. 3 but for precipitation. Values in the upper right of panels indicate precipitation averaged over the Kanto area, and values in parentheses indicate future change in precipitation.

for this type of extremely heavy precipitation. Precipitation in C4 is strong in the western part of Kanto along the mountains (Figs. 4d and 4h). Area-averaged precipitation in C4 is enhanced by 30% from 122 to 160 mm/day, indicating the strongest enhancement of all clusters. The percentage of C4 events in all extreme events decreases slightly by 2.0% from 16.5% to 14.5%.

In C2 and C3, cyclonic anomalies weaken under global warming (Figs. 3b–3c and 3f–3g), similar to composites for all extreme events. Precipitation increases by 15% and 11%, respectively (Fig.

4b–4c and 4f–4g). Percentages of C2 and C3 events in all extreme events decrease slightly by 4.6% and 1.9%, respectively.

The percentage of C1 events in all extreme events is the highest for all clusters and increases under global warming (31.9% and 40.4% in HIST and +4K_F, respectively), in contrast to the decrease seen in the other clusters. C1 is dominated by an anticyclonic anomaly, unlike the other clusters, which have clear cyclonic anomalies. It is therefore inferred that the heavy precipitation in C1 is associated with unstable atmospheric conditions associated

Fig. 5. Averages of the spatial percentile of precipitation for each extreme event in HIST.

with mid-tropospheric cold anomaly (Fig. S1). It is known that summertime Kanto often receives localized showers under unstable atmospheric conditions (Yonetani 1975; Nomura and Takemi 2011). The spatial scale of heavy precipitation, which is measured by the spatial percentile of precipitation, shows that C1 has the most localized structure of precipitation of the four clusters (Fig. 5). The typical coverage of precipitation exceeding 100 mm/day accounts for about 20% of precipitation in C1, whereas that in C4 accounts for 50%. Localized heavy precipitation occurs frequently in C1 (Fig. S2e). Similar localized heavy precipitation without an anomalous cyclone has been observed (Fig. S3). Such convective precipitation in summertime Kanto without synoptic disturbances is projected to be enhanced because of enhanced unstable condition (Takemi 2012; Takemi et al. 2012). Berg et al. (2013) showed that an enhancement of convective precipitation is larger than

that of stratiform precipitation in warmer condition, which may contribute to the increased percentage of C1.

The relative frequency of the 100-year extreme precipitation shows regional differences among clusters (Fig. 6). The 100-year extreme precipitation associated with C4 tends to occur over mountainous slopes in the western parts of Kanto owing to strong anomalous southeasterlies caused by strong cyclonic anomalies, whereas that associated with C1 tends to occur over the plains, and that associated with C3 and C2 tends to occur in the southeastern and northwestern parts of Kanto. In +4K_F, the relative frequency of extreme precipitation shows similar distributions to those in HIST, although C1 tends to occur more frequently in +4K_F than in HIST.

It is noted that the percentage of C4 is projected to decrease under global warming, whereas previous studies showed an increase of strong TCs in the northwestern Pacific (Yoshida et al. 2017) and an increasing frequency of extremely heavy precipitation induced by TCs across Japan (Watanabe et al. 2019). The frequency of TCs with centers within 500 km of Kanto shows that strong TCs increase and weak TCs decrease with respect to both the central SLP and maximum surface wind speed (Figs. 7c and 7d), consistently with Hatsuzuka et al. (2020). Clear dependence on global warming can be confirmed in decreasing and increasing frequencies of moderate TCs (960–1000 hPa or 20–40 m/s) and strong TCs (< 940 hPa or > 50 m/s), respectively. Precipitation intensity near TCs strengthens for 100-year extreme precipitation events (Fig. 7a) and for all precipitation near TCs (Fig. 7b). It is suggested that increasing and decreasing percentages of C1 and C4, respectively, are associated with the future projection, in which increasing frequency of C1 overcomes that of strong TCs.

4. Summary

The several-thousand-year simulations of the large ensemble simulation dataset d4PDF have allowed us to investigate future projections of extremely heavy precipitation for Kanto, eastern Japan, without any assumptions such as those required by extreme

Fig. 6. As for Fig. 3 but for the frequency of 100-year extreme precipitation events in each cluster. The area average is given in the upper right of each panel. Grid cells with no event in a cluster are not colored.

Fig. 7. Future change in daily precipitation under the direct influence of TCs for (a) 100-year extreme precipitation events and (b) all days from March to October. In (a), future change is not evaluated where no TC event is detected in 100-year extreme precipitation events in +4K_F. (c–d) Frequency of 6-hourly (c) central SLP and (d) maximum surface wind speed of TCs whose centers are located within 500 km of the Kanto area from March to October.

value statistics. We find that the heavier precipitation in Kanto is more enhanced under global warming, with 27% and 32% enhancement of 10-year and 100-year return values of 4-K warmer climatic conditions. Weather pattern classification using K-means clustering for SLP anomalies of 100-year extreme precipitation events identifies three clusters with pronounced cyclonic anomalies to the south of Kanto, whereas the most frequent cluster is dominated by anticyclonic SLP anomalies with weak cyclonic circulation over Kanto. The latter cluster occurs more frequently under global warming than in historical simulation. Although all clusters show enhancement of precipitation, cyclonic anomalies weaken except for one cluster with a strong cyclonic anomaly, suggesting that the thermodynamic effect is important for the enhancement of precipitation. The classification reveals that extremely heavy precipitation shows different spatial characteristics among clusters and tends to occur in different parts of Kanto. Furthermore, the relative frequency of extremely heavy precipitation events without the influence of TCs increases, although strengthened TC does contribute to an enhancement of precipitation. The increased relative frequency of extreme events in autumn is associated not with TCs but predominantly with localized heavy precipitation.

Since observational records are too short to validate our analysis for 100-year extreme events, the present study should be revisited in future works. SLP anomaly clustering seems to well classify weather patterns, suggested by small Euclidian distance from cluster mean for ~90% events (Fig. S4). Meanwhile, the reproducibility of heavy precipitation and TCs may affect relative percentage of the clusters. For validation of our analysis, more deeply understanding of the mechanisms of heavy precipitation formation and future changes in the relative frequency of the main weather patterns are necessary, as well as revisits based on large ensemble simulation dataset using a cloud-resolving model, which has finer resolution than d4PDF.

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Supplements

Supplement 1: Supplemental figures.

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