Future changes in extreme precipitation intensities associated with temperature under SRES A1B scenario

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Abstract:
Recent studies have argued that extreme precipitation intensities are increased in many regions across the globe due to atmospheric warming. This argument is based on the principle of the Clausius-Clapeyron (CC) relationship, which states that the atmosphere can hold more moisture in warmer air temperatures (~6%°C–1). In this study, we investigate the future changes of extreme precipitation intensities associated with temperature over Japan, by analyzing multi-model ensemble downscaling experiments of three RCMs (NHRCM, NRAMS, WRF) driven by one GCM (MIROC3.2) for two climate periods (1981–2000 and 2081–2100, SRES A1B). We find that extreme precipitation intensities are significantly increased by 5–15 mm d⁻¹ for temperatures above ~21°C in the future, compared to the current climate. The extreme precipitation intensities for lower (higher) temperatures below (above) 8–10°C (19–24°C) exhibit super-CC (negative-CC) scaling. The rate of increase of extreme precipitation intensities is also increased by ~2%°C⁻¹ under the SRES A1B scenario (3.4–4.4%°C⁻¹ during 1981–2000 and 5.5–6.5%°C⁻¹ during 2081–2100). We find that the increase of extreme precipitation intensities is associated with strong vertical velocity and substantial increase of water vapor under the future scenario.

KEYWORDS extreme precipitation intensity; multimodel ensemble downscaling; Clausius-Clapeyron relationship

INTRODUCTION

According to recent reports of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007, 2012), extreme precipitation intensities are increasing in many regions across the World. As a consequence, the natural disasters such as floods, coastal erosion, landslides, and water hazards may occur with greater frequency. Recent studies (O’Groismen et al., 2005; Dairaku and Emori, 2006; Kharin et al., 2007; Lenderink and van Meijgaard, 2008; Yamada et al., 2014) have debated the issue of changes in extreme precipitation intensities associated with temperature under future scenario. For instance, Lenderink and van Meijgaard (2008) reported that the extreme hourly precipitation intensities are increased by 10% and extreme daily precipitation intensities by 5–10%, for each degree rise in temperature under future climate scenario over central Europe. Similarly, Yamada et al. (2014) highlighted that the extreme hourly precipitation intensities (99th percentile) are increased by ~1.2 fold under future climate over Sapporo, Japan. In our study, we analyzed multimodel ensemble downscaling experiment results to investigate the future changes in extreme precipitation intensities associated with temperature over Japan, under the Special Report on Emissions Scenarios (SRES) A1B scenario. We explored the multimodel behavior in reproducing the extreme precipitation intensities associated with temperature over Japan and their connection with CC relationship. We also quantified the rate of increase of extreme precipitation intensities in two climate periods.

DATA AND METHODS

We analyzed six ensemble experiments (three experiments for the current climate and three experiments for future climate), conducted over Japan with three Regional Climate Models (RCMs) (NHRCM, NRAMS, and WRF) driven by one General Circulation Model (GCM, MIROC3.2) at 20-km horizontal resolution with the SRES A1B scenario. A brief description of these downscaling experiments has...
been given in previous studies (Ishizaki et al., 2012; Tsunematsu et al., 2013). These products have already been used for various assessment and impact studies over Japan (e.g., Iizumi et al., 2012; Tsunematsu et al., 2013). In our study, we used these datasets with an hourly timescale to explore the extreme precipitation intensities associated with temperature over Japan in two climate periods 1981–2000 and 2081–2100, hereafter referred to as the current climate and future climate respectively. In addition to the model datasets, we used Asian Precipitation–Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) daily observations (Yasutomi et al., 2011) over Japan to validate our results in the current climate.

The analysis includes all the grid points over Japanese land (see Figure 1), and the averaged results over the whole of Japan are considered to be indicative of the overall regional changes in extreme precipitation, in response to climate changes. The model-simulated hourly precipitation and temperature datasets were aggregated to daily sum precipitation and daily mean temperature respectively, to make a comparative analysis with APHRODITE daily observations. The precipitation intensities of wet days (defined as ≥ 0.05 mm d$^{-1}$) were then stratified to different bins with 1°C temperature intervals, to estimate the extreme (85th, 95th, and 99th percentile) precipitation intensities at each temperature. We found that low- and high-ends of temperature bins contained less than 100 samples, while most temperature bins contained more than 150 samples. To avoid the sampling error, we excluded those temperature bins from subsequent analysis which contained less than 150 samples.

The rate of change of extreme precipitation intensities at different percentiles was computed from the exponential relationship:

$$P_2 = P_1 (1 + \alpha)^{\Delta T}$$

Where $P_1$ and $P_2$ are precipitation at two different temperatures $T_1$ and $T_2$ respectively; $\Delta T = T_2 - T_1$ is the change in temperature; and $\alpha$ is the rate of change of extreme precipitation intensities, which is ~0.07 in the case of CC.

**RESULTS**

We first analyzed the probability distribution of precipitation intensities and temperatures of wet days from the multimodel ensemble downscaling experiment datasets, to discuss their current occurrences and future changes over Japan. This is shown in Figure 2. The probability distribution functions of both precipitation intensities and temperatures of wet days in each simulation show relatively good agreement with the observations in the current climate, but with some uncertainties especially at ~5 mm d$^{-1}$ and ~10°C. The ensemble mean of three RCMs indicates that the occurrence of wet days with precipitation intensities above ~10 mm d$^{-1}$ is increased and the occurrence of wet days with precipitation intensities below ~10 mm d$^{-1}$ is decreased under future climate scenario. Similarly, the occurrence of
wet days with temperatures above ~15°C is increased and the occurrence of wet days with temperatures below ~15°C is decreased in the future climate. This implies that future changes in the frequencies of precipitation events and the temperatures of these wet days are somehow related to each other (Figure 2a and 2b). To understand the relationship between them, and its future changes, we analyzed extreme precipitation intensities associated with temperature over Japan in the two climate periods (1981–2000 and 2081–2100).

**Extreme precipitation intensities associated with temperature and its future change**

Figure 3 illustrates the extreme (85th, 95th, and 99th percentile) precipitation intensities associated with temperature calculated from three RCMs in two climate periods and APHRODITE observation. It shows that the extreme precipitation intensities are significantly increased by 5–15 mm d$^{-1}$ for temperatures above ~21°C in future, compared to the current climate. This result is slightly different to the previous study conducted over a few regions of Japan (Yamada et al., 2014) which showed an increase of ~5 mm d$^{-1}$, and this may be due to the use of different ensemble experiments and different regions. A decrease of extreme precipitation intensities by ~5 mm d$^{-1}$ is also observed in the future climate for temperatures below ~8°C.

We found that all percentiles of precipitation intensities increase with temperature up to a certain degree (~19–21°C in the current climate and ~22–24°C in the future climate), above which further increases of temperature cause decreases of precipitation intensities. All three RCMs show a similar pattern (shown as thin lines in Figure 3), with some uncertainties. The 99th percentile of precipitation intensities in the current climate are underestimated in NHRCM at lower temperatures, while all percentiles of precipitation intensities are underestimated in NRAMS at higher temperatures and overestimated in WRF at lower temperatures. However, the extreme precipitation intensities from the ensemble average of three RCMs agree well with observation in the current climate, with an underestimation at 20–22°C in the 95th and 99th percentiles. Previous studies over the interior of Australia (Hardwick Jones et al., 2010) and few regions of Japan (Utsumi et al., 2011; Yamada et al., 2014) also show similar increasing/decreasing characteristics.

In connection to the CC relationship, we found that the 99th percentile of precipitation intensities in each individual model follow super-CC scaling for temperatures below 8–10°C. The 95th and 99th percentiles of precipitation intensities in NHRCM and WRF exhibit CC scaling behavior for temperatures roughly between 14–19°C, while the same in NRAMS exhibit a sub-CC scaling for those temperatures. The 85th percentile of precipitation intensities in NHRCM and NRAMS follows CC scaling behavior for temperatures between 12–18°C, while the same in WRF exhibits super-CC scaling. However, the ensemble average of three RCMs shows that the daily precipitation intensities in the 95th and 99th percentiles exhibited super-CC scaling (nearly twice the CC scaling) for temperatures below 8–10°C, and the precipitation intensities in all the percentiles show sub-CC scaling for temperatures above 10°C. A negative-CC scaling (refers to the rate of change of extreme precipitation intensities as negative) was observed for temperatures above 19–24°C, which is obviously due to the decreasing precipitation intensities. This indicates that precipitation intensities over Japan increase with temperature during wintertime (i.e., at low temperatures), and decrease with temperature during summertime (i.e., at higher temperatures). Seasonal analysis (not discussed in this study, but planned as the subject of our next research) may provide more detailed information on this (e.g., Berg et al., 2009).

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Figure 3. Daily precipitation intensities of wet events (≥ 0.05 mm d$^{-1}$) as a function of daily mean temperature. Solid colored lines represent the results from ensemble average of three RCMs for 1981–2000 and 2081–2100. Dashed color lines represent those from observation (APHRODITE) over Japan for 1981–2000. Thin lines (green for current and grey for future) represent those from individual models. The black dashed (plain) lines represent one multiple (two multiples) of the CC relation and are used here as references.
The rate of change of extreme precipitation intensities, and its future change

We computed the rate of change of extreme precipitation intensities (i.e., $\alpha$) using Equation (1) at different precipitation percentiles (75th, 85th, 90th, 95th, 97th, and 99th) from the ensemble average of the three RCMs in the two climate periods. These are shown in Table I. It shows that the increasing rate of extreme precipitation intensities is significantly increased under the SRES A1B scenario. The rates ($\alpha$) of all percentiles show sub-CC scaling in the current climate, with 3.4–4.4%°C$^{-1}$, which is increased to 5.5–6.5%°C$^{-1}$ under future climate scenario, indicating scaling close to CC-scaling in future. This implies that the temperature increase in the future climate will intensify the extreme precipitation much faster than that in the current climate (Utsumi et al., 2011), and could be due to the thermodynamic influences on the changes in moisture content (Dairaku and Emori, 2006).

### DISCUSSION AND CONCLUSIONS

We investigated the future changes in extreme precipitation intensities associated with temperature over Japan by analyzing multimodel ensemble downscaling experiments of three RCMs (NHRCM, NRAMS, WRF) driven by one GCM (MIROC3.2) at 20-km resolution in two climate periods (current and future, SRES A1B). Our results indicate that the frequencies of wet events with precipitation intensities above ~10 mm d$^{-1}$ are increased in the future (Figure 2a). Previous studies (e.g., Tsunematsu et al., 2013) have also reported an increase in precipitation intensities under SRES A1B over Japan. Temperatures during wet events above ~15°C are also increased under future climate scenario (Figure 2b). This implies that the increases in frequencies of precipitation are somewhat proportional with those in temperature, indicating that the rise in temperature under the SRES A1B scenario will increase the number of extreme precipitation events in future. Figure 3 justifies this. The extreme precipitation intensities are significantly increased in future climates at higher temperatures. This increase of extreme precipitation intensities at higher temperatures is due to the increase in temperature under SRES A1B (~2°C rise is documented in Yamada et al., 2014). This is because an increase in temperature causes more evapotranspiration, and subsequently increases the amount of water vapor in the atmosphere. We analyzed the behavior of specific humidity during the extreme events in two climate periods and found that it was increased for higher temperatures (see Figure 4). All three models show very similar results, and are consistent with the CC reference. This implies that more moisture will be available in the atmosphere under future warming and cause more precipitation (Dairaku and Emori, 2006). To understand the mechanism, we further analyzed the vertical wind velocity, omega at 500 hPa during the extreme events over Japan from NHRCM. This is shown in Figure 5. It shows that the vertical velocity (i.e., upward motion of air) at

### Table I. Rate of increase of extreme precipitation intensities at different percentiles of precipitation for current climate and future scenario

| Percentiles of precipitation intensities | Rate of increase of precipitation (%°C$^{-1}$) |
|----------------------------------------|---------------------------------------------|
|                                        | Current | Future |
| 75                                     | 3.37    | 5.50   |
| 85                                     | 3.90    | 6.18   |
| 90                                     | 4.02    | 6.46   |
| 95                                     | 4.26    | 6.36   |
| 97                                     | 4.41    | 6.33   |
| 99                                     | 4.44    | 5.91   |

Figure 4. Relative and specific humidity as a function of daily mean temperature during extreme events in current and future climate with uncertainty. Solid (thin) plain lines represent relative (specific) humidity for current climate and dashes represent those for future climate. The shaded region indicates (+/-) standard deviation.
higher temperatures (roughly above 21°C) in all percentiles in future climate is significantly stronger than that in current climate. Thus the strong vertical velocity in the future scenario together with the substantial increase of water vapor due to future warming could increase the extreme precipitation intensity at higher temperatures in the future climate. To further understand whether future warming over Japan increase specific humidity irrespective of dry or wet days, we analyzed the change in temperature and specific humidity considering all days in the two climate periods. We found that the average temperature under the A1B scenario is increased by 3.4–5.6°C, and the associated 99th percentile of specific humidity is increased by 3.6–5.8 g kg\(^{-1}\) over Japan (Figure 6). However, the ensemble average of three RCMs indicates that the specific humidity differences tend to decrease as the temperature rises. The reason could be due to the fact that moisture in the atmosphere does not rise endlessly with increasing temperature (Westra et al., 2014).

Furthermore, we found a super-CC scaling in the 95th and 99th percentile of precipitation intensities for lower temperatures, and a negative-CC scaling in all percentiles for higher temperatures. This indicates that at lower temperatures there is sufficient water vapor to achieve saturation and maintain the CC relationship. This perhaps is a consequence of large-scale and convective precipitation in the temperature regime, which causes super-CC (Lenderink and van Meijgaard, 2008). On the other hand, to hold the CC relationship at higher temperatures a greater amount of water vapor is required than the amount available in the atmosphere for saturation (Berg et al., 2009). Thus the relative...
humidity is either decreased or remains constant for higher temperatures (in this study, above 16°C, see Figure 4), causing a decrease of precipitation above a certain temperature. Hardwick Jones et al. (2010) also observed a less relative humidity at higher temperatures over Australia. Evaporative cooling effect could be another reason for the negative-CC of extreme precipitation. This is because net water vapor storage increases for the first few hours when a very heavy precipitation occurs and forces the air temperature to cool down. Another reason could be associated with the changes in the wet-event duration. A steep decrease in the wet-time fraction over Kyushu and southern islands of Japan was reported in Utsumi et al. (2011). Further research will be focused on different seasons and sub-regions over Japan, especially considering the relative importance of dynamic and thermodynamic influences on extreme precipitation associated with temperature increase.

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