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Changes in precipitation extremes projected by a 20-km mesh global atmospheric model

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ABSTRACT

High-resolution modeling is necessary to project weather and climate extremes and their future changes under global warming. A global high-resolution atmospheric general circulation model with grid size about 20 km is able to reproduce climate fields as well as regional-scale phenomena such as monsoonal rainfall, tropical and extratropical cyclones, and heavy precipitation. This 20-km mesh model is applied to project future changes in weather and climate extremes at the end of the 21st century with four different spatial patterns in sea surface temperature (SST) changes: one with the mean SST changes by the 28 models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) under the Representative Concentration Pathways (RCP)-8.5 scenario, and the other three obtained from a cluster analysis, in which tropical SST anomalies derived from the 28 CMIP5 models were grouped. Here we focus on future changes in regional precipitation and its extremes. Various precipitation indices averaged over the Twenty-two regional land domains are calculated. Heavy precipitation indices (maximum 5-day precipitation total and maximum 1-day precipitation total) increase in all regional domains, even where mean precipitation decrease (Southern Africa, South Europe/Mediterranean, Central America). South Asia is the domain of the largest extreme precipitation increase. In some domains, different SST patterns result in large precipitation changes, possibly related to changes in large-scale circulations in the tropical Pacific.

1. Introduction

Both too much water and too little water are of great concern for human life because the contrasts in precipitation between wet and dry regions and between wet and dry seasons are projected to increase in a coming future world (Intergovernmental Panel on Climate Change (IPCC), 2013). Warmer climate should theoretically lead to more precipitation extremes due to increasing atmospheric water vapor content (Allen and Ingram, 2002; Allan and Soden, 2008). The intensity of precipitation extremes, however, depends on not only water vapor content but also on atmospheric environmental changes (O'Gorman and Schneider, 2009). Based on global climate model (GCM) simulations of the Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl et al., 2007), it is assessed that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will likely increase in the 21st century over many areas of the globe (IPCC, 2012). The same assessment was made with the CMIP5 (Taylor et al., 2012) models under Representative Concentration Pathways (RCPs) such that extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases (IPCC, 2013).

The CMIP5 models have better performance than the previous CMIP3 models in simulating precipitation extremes in the present climate (Sillmann et al., 2013a). A part of this improvement may come from increasing horizontal resolution, about 280 km in CMIP3 versus about 200 km in CMIP5. Spatial distribution of precipitation indices is reasonably reproduced but differences are still found in precipitation intensity where the magnitude of precipitation extremes is underestimated by climate models (Sillmann et al., 2013a; Mehran et al., 2014).

In a future warming world, change rate of heavy precipitation amounts will generally increase more than that of annual mean precipitation (Tebaldi et al., 2006; Sun et al., 2007; Sillmann et al., 2013b). The increasing rate of annual mean precipitation at the end of the 21st century projected by CMIP5 models in RCP8.5 scenario is 9% (median value), while that in simple daily intensity

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index (SDII) defined as annual total precipitation divided by the number of wet days is 12% and that in annual maximum 5-day precipitation total (R5d) is 20% (Sillmann et al., 2013b). This increasing rate depends on the scenario, where the change ratio of R5d is 6% in RCP2.6 and 10% in RCP4.5, respectively. Similarly, 20-year or 50-year return values of daily precipitation are projected to increase and 20-year or 50-year return periods for the present precipitation events will reduce in the future almost everywhere except for subtropical dry regions (Kharin et al., 2013; Toreti et al., 2013). The 20-year return values increase about 6% per a degree change in annual mean surface temperature, but with considerable inter-model variability (Kharin et al., 2013). Large variability is also known among models in simulated increase of precipitation extremes, particularly in summer when organized convection matters (Toreti et al., 2013).

Both thermodynamical and dynamical factors are responsible for regional precipitation changes, with the former dominating the latter for extreme precipitation changes (Emori and Brown, 2005). Increase in maximum atmospheric water vapor due to temperature rise is a principal factor for increasing the intensity of individual precipitation events (Kunkel et al., 2013). There are additional factors such as changes in updrafts, which controls changes in moisture flux convergence, and soil moisture over land. Representation of precipitation, particularly its intensity, depends on the horizontal resolution of models. Coarse horizontal resolution of GCMs tends to prevent simulating realistic extreme events (Sun et al., 2006; Min et al., 2011). High-resolution modeling or statistical downscaling is then necessary to project weather and climate extremes and their future changes under global warming.

Dynamical downscaling is able to simulate more realistic, though not perfect, extreme events. Regional climate models (RCMs) would add values on more realistic topography and lower boundary conditions and better representation of dynamical processes (e.g., Takayabu et al., 2015). Therefore RCMs are widely used to project future changes in extremes. For example, Fowler et al. (2007) used six RCMs integrations under the SRES A2 scenario to downscale extreme precipitation changes over Europe at the end of the 21st century. Horizontal resolution of these RCMs is about 50 km. They found that all RCMs project increases in magnitude of extreme precipitation from 1-day to 10-day duration for most of Europe. It is also found that the magnitude of change is influenced by the driving GCMs but projected scatter is moderated by the RCM probably due to better representation of extreme events in RCM. RCMs also give different spatial pattern of precipitation extremes than that obtained by parent GCMs.

Another way for downscaling is to use an atmospheric general circulation model (AGCM) with horizontally high-resolution (Kitoh et al., 2009, 2015). Higher resolution model is needed to better reproduce precipitation climatology such as the East Asia summer rain band (Kitoh and Kusunoki, 2008), over India (Rajendran et al., 2013), South America (Kitoh et al., 2011), Central America and the Caribbean (Nakaegawa et al., 2014). Kamiguchi et al. (2006) analyzed future changes of precipitation indices between the present climate and the future climate at the end of the 21st century under the IPCC Special Report on Emission Scenario (SRES) A1B scenario by two 10-year simulations with the global 20-km mesh AGCM developed at the Meteorological Research Institute (MRI) version 3.1 (MRI-AGCM3.1, Mizuta et al., 2006). They found significantly increased heavy precipitation in South Asia, the Amazon and West Africa. Over the Amazon, an increase in dry spell is found during the dry season in the future, which is related to the Walker circulation changes associated with the El Niño-like SST changes in the future.

The MRI-AGCM has been updated recently (MRI-AGCM3.2, Mizuta et al., 2012), which improved heavy precipitation climatology around the tropical western Pacific and the global distribution of tropical cyclones (Murakami et al., 2012). In this paper, after evaluating the present-day precipitation extremes of 20-km mesh MRI-AGCM3.2, we analyze projected future changes in precipitation extremes at the end of the 21st century. The scenario is based on RCP8.5, and four different spatial patterns in sea surface temperature (SST) changes are used as boundary conditions. This type of simulations, which uses the observed present-day interannually varying SST plus ensemble mean future SST changes obtained by CMIP-class models, can minimize the effects of climate model bias (Kitoh et al., 2015). In particular, the 20-km mesh MRI-AGCM has superiority in reproducing precipitation extremes in its present-day experiments; the results obtained in the future climate projections can be used widely for impact studies from future changes of extremes.

2. Model and experiment

2.1. MRI AGCM

We used the MRI-AGCM3.2 (Mizuta et al., 2012), which is the updated version from the MRI-AGCM3.1 (Mizuta et al., 2006). The model is based on a hydrostatic primitive equation system using a spectral transform method of spherical harmonics. The 20-km mesh version uses a triangular truncation at wave number 959 (TL959) in the horizontal, which has 1920 × 960 grid points. There are 64 layers in the vertical with a top at 0.01 hPa. A two-time-level semi-implicit semi-Lagrangian scheme is employed for time integration. For cumulus parameterization scheme, a new mass-flux type scheme (Yoshimura et al., 2015) is used. This Yoshimura scheme is based on Tiedtke (1989) scheme with a detailed entraining and detraining plume within a single grid cell, but also allows multiple convective updrafts with different heights to exist as with the Arakawa-Schubert (1974) type scheme. Prognostic variables include cloud water and cloud amount. The radiation code considers absorptions by greenhouse gases in the long wave scheme. The direct effect of aerosol (sulfate, black carbon, organic carbon, mineral dust, and sea salt) is included, but indirect effects are not considered in this experiment.

2.2. Experiment method

We have conducted the Atmospheric Model Intercomparison Project (AMIP)-type simulations for the present climate (1979–2003) and the future climate at the end of the 21st century (2075–2099). The present climate simulation used the observed interannually varying monthly mean SST and sea-ice concentration during 1979–2003 based on the HadISST1.1 data (Rayner et al., 2003). For the future climate, the boundary SST data were prepared by superposing the future change in the multi-model ensemble of SST projected by CMIP5 multi-model dataset to the present-day observed SST. In short, the future SST is the sum of (i) the trend in the multi-model ensemble (MME) of SST projected by CMIP5 multi-model dataset, (ii) future change in MME of SST for 2075–2099 and (iii) de-trended observed SST for the period 1979–2003. See Mizuta et al. (2008, 2014) for the details. Fig. 1a shows the annual mean SST changes of the 28 CMIP5 models. It is noted that there is a large contrast in SST warming between the Northern Hemisphere and the Southern Hemisphere, with the former warming more than the latter. In the tropics, relatively larger warming is noted in the central and eastern equatorial Pacific. Over the Indian Ocean, a warming in the western Indian Ocean is larger than that in the eastern Indian Ocean.

In order to assess the uncertainty in projections, we made three other simulations with different SST spatial patterns in the future. Three SST patterns are obtained by a cluster analysis of 28 CMIP5