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Multi-model event attribution of the summer 2013 heat wave in Korea

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ABSTRACT

To assess the anthropogenic influence on the summer 2013 heat wave in Korea, this study employed a fraction of attributable risk (FAR) approach to three Atmospheric General Circulation Models (AGCMs) with a large ensemble simulation, participating in the C20C+ Detection and Attribution Project. Monthly and daily temperatures were compared between two experiments. The real world (ALL) experiments were simulated under the observed variations in sea surface temperature, sea ice, greenhouse gas, and aerosol concentrations, while the counterfactual world (NAT) experiments were performed under adjusted boundary conditions by removing anthropogenic warming and with preindustrial levels of greenhouse gases and aerosols. Results from the three AGCMs consistently show that anthropogenic influences had an important role in the extreme heat event over Korea, increasing the chance of the occurrence of extreme warming in summer mean temperature as observed in 2013 by at least 20 times, which supports results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) coupled GCMs (CGCMs). A comparison of individual CMIP5 CGCMs suggests that inter-model difference in FAR values is highly correlated with the amplitude of surface warming centered over Korea, which is also supported by the three AGCMs. Further analysis of individual forcing experiments suggests that the inter-model difference in the regional surface warming is closely linked to the model's response to the aerosol forcing, with stronger influence than that of greenhouse gas forcing. Anthropogenic influences also result in a 5–6 times greater likelihood of extreme daily heat events as observed in 2013, which supports a robust mean-extreme relation in the attribution of extreme heat waves. Generally good agreement between AGCM and CGCM results increases the robustness of the conclusion of anthropogenic influences on the summer 2013 Korean heat wave.

1. Introduction

East Asia (i.e., Korea, eastern China, and Japan) experienced a severe heat wave in summer 2013, which had major impacts on society and the economy. Previous studies compared general circulation model (GCM) outputs simulated with and without human influences and consistently argued that human activities were the main contribution to this extreme event occurrence (Table 1). In South Korea, the summer mean daily minimum temperature in 2013 broke the existing maximum record (Min et al., 2014). To assess the possible impacts of anthropogenic influences on the 2013 Korean heat extremes, Min et al. (2014) compared CMIP5 coupled GCM (CGCMs) with and without anthropogenic forcings using a large-scale sea surface temperature (SST) based indicator that is closely linked with Korean temperature. They found that the summer 2013 like extreme temperature in Korea became 10 times more probable due to human-induced warming.

For eastern China, Zhou et al. (2014) and Ma et al. (2017) found that the anthropogenic influence increased the chance of the 2013 heat wave by 2–3 times based on CMIP5 CGCMs by comparing distributions of anomaly temperatures from simulations performed with and without human influences for a long-term period of 1900–2013 and 1955–2014, respectively. Sun et al. (2014) estimated that human activity contributed a greater than 60-times increase in the likelihood of the occurrence of the 2013 hottest summer over eastern China by constructing distributions including future projections of CMIP5 CGCMs. For Japan, anthropogenic influence was assessed to be the main cause with 7–20 times increase in risk of the 2013 heat wave based on MIROC5 AGCM ensemble simulations (Imada et al., 2014).

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Table 1
List of previous studies on the event attribution of the East Asia summer heat wave in 2013.

Reference	Focusing Area/ Season	Models and experiments	FAR values and increase in risk
Min et al. (2014)	South Korea/JJA	CMIP5 ALL Forcing: 31 models (105 runs) historical+RCP4.5 (1954–2013) NAT Forcings1: 30 models (102 runs) historical (1860–1919) NAT Forcings2: 7 models (27 runs) historicalNat (1953–2012)	FAR(NAT1) = 0.90 10 times
Zhou et al. (2014)	Central eastern China (24–33°N, 102.5–122.5°E)/ JA	CMIP5 ALL Forcing: 31 models historical+RCP4.5 (1900–2013) NAT Forcing: 30 models piCTL simulations	FAR = 0.58 2.12 times
Sun et al. (2014)	Eastern China (20–45°N, 105–125°E)/JJA	CMIP5 ALL Forcing: 26 models (125 runs) historical+RCP4.5 (1955–2072) NAT Forcing: 41 models (308 chunks) piCTL simulations	>60 times
Ma et al. (2017)	Central eastern China (25–36°N, 104–123°E)/JA	CMIP5 ALL Forcing: 17 models (36 runs) historical+RCP8.5 (1955–2014) NAT Forcing: 17 models (36 runs) historicalNAT (1955–2005) and 17 models piCTL simulation C20C+ AGCMs CAM5.1 by 400 ALL and NAT ensemble members for 2013 MIROC5 by 110 ALL and NAT ensemble members for 2013	FAR (CMIP5) = 0.58 2–3 times FAR(CAM5.1) = 0.94 17 times FAR (MIROC5) = 0.78 4 times
Imada et al. (2014)	Japan (30–37°N, 130–140°E)/JA	MIROC5 (AGCM) 100 ensemble members for 2013 ALL Forcing: Prescribed to HadISST NAT Forcing 1: SST reduced based on HadISST trend NAT Forcing 2: SST reduced based on CMIP5 (ALL- NAT)	FAR(NAT1) = 0.86 7 times FAR(NAT2) = 0.96 20 times

Most previous studies of event attribution were based on limited number of CGCMs and the estimated changes in risk of the occurrence of extreme events exhibited a large range from 2 to 60 times, depending on the analysis domains, target variables, climate models, and sampling methods for constructing temperature distributions for the real and counterfactual worlds (Imada et al., 2014; Min et al., 2014; Sun et al., 2014; Zhou et al., 2014; see Table 1). Moreover, many CMIP5 CGCMs have a relatively coarse horizontal resolution (larger than 100 km), and the robustness of the attribution results needs to be confirmed by comparison with those from other models with higher resolutions. In this respect, the Climate of the 20th Century Plus Project (C20C+) Detection and Attribution (D&A) subproject (http://portal.nersc.gov/c20c) has produced a large pool of outputs from atmospheric GCMs (AGCMs) with a relatively high spatial resolution to help understand changes in extreme weather events in the context of past and current climate change (Stone et al., 2018a). Recently, Ma et al. (2017) analyzed large ensembles of two AGCMs, CAM5.1 and MIROC5, participating in this subproject. They suggested that a hot summer over central eastern China such as the 2013 event was 17 times (CAM5.1) and 4 times (MIROC5) more probable due to human influences, confirming the anthropogenic influences but also indicating a strong model dependence of the attribution results.

The C20C+ D&A project includes the generation and comparison of two climate change scenarios, the observed boundary condition (ALL) and a counterfactual "natural" world (NAT). A large ensemble of single AGCMs has the advantage of generating many simulations to enable robust sampling under different initial conditions. Moreover, model uncertainty can be reduced based on the prescribed observed boundary condition (Christidis and Stott, 2014). It should, however, be noted that a lack of air–sea coupling can affect event attribution results (Dong et al., 2017). Although attribution of large-scale surface air temperature (SAT) changes was suggested to be relatively insensitive to the air–sea coupling (Dong et al., 2017), the impact of air-sea interaction on local scale phenomena such as Korean heat waves needs to be assessed. For this purpose, a comparison of AGCM-based results with those from CGCMs provides an important way of evaluating the robustness of the attribution statements for the local temperature extreme events.

Hence, this study assessed the event attribution of the summer 2013 heat wave in Korea by comparing the C20C+ D&A models with a CMIP5 multi-model ensemble (MME). The anthropogenic contribution to the extreme event was quantified by comparing the probability of exceeding the observed temperature between simulations with natural forcings alone and simulations with both natural and anthropogenic forcings by using a fraction of attributable risk (FAR) approach. Moreover, we conducted sensitivity tests of the FAR values, focusing on the role of the climate model sensitivity and the difference in the boundary conditions in order to explore physical mechanisms for determining the uncertainty in the event attribution results for the local temperature extremes.

2. Data and methods

For the observation data, we used daily mean/minimum temperature data measured by 12 Korea Meteorological Administration weather stations from 1954 to 2013. In addition, we used monthly SAT data from HadCRUT4 (Morice et al., 2012) to identify a large-scale indicator associated with Korean summer temperature changes, using an upscaling approach (Min et al., 2014, 2015a). This approach is suitable for analyzing local climate changes, such as those on the Korean Peninsula, because global climate models cannot well capture local-scale weather and climate processes due to their relatively low spatial resolutions.

We used three AGCMs that participated in the C20C+ D&A project: CAM5.1 (Neale et al., 2012; Stone et al., 2018), MIROC5 (Shiogama et al., 2013, 2014), and HadAM3P-N96 (Wolski et al., 2014), which were run at resolutions of ~1°, ~1.4°, and ~1.8°, respectively. The three AGCMs generated two different types of ensemble simulations with and without the effect of anthropogenic influences. The simulations with anthropogenic influences prescribed the observed boundary conditions as greenhouse gases (GHGs), aerosols, SST, sea ice coverage, and land use/cover, referred to as "ALL". The simulation without anthropogenic influences used a CMIP5 estimate of the change in SST, which was subtracted from the observed boundary SST (with sea ice coverage data modified accordingly), which is referred to as "NAT" (Stone and Pall, 2018). GHGs, aerosols, and ozone were set to pre-industrial levels for the NAT simulation (Stone et al., 2018a; the data can be accessed at http://portal.nersc.gov/c20c/data.html).

The CAM5.1 and HadAM3P-N96 used monthly SST and sea ice coverage from the Hurrell et al. (2008) dataset. The MIROC5 prescribed monthly SST and sea ice coverage which were taken from the HadISST dataset (Rayner et al., 2003). MIROC5 used the prescribed aerosol