

The importance of aerosol scenarios in projections of future heat extremes

Yangyang Xu¹  · Jean-François Lamarque¹ · Benjamin M. Sanderson¹

Received: 6 April 2015 / Accepted: 19 November 2015
© Springer Science+Business Media Dordrecht 2015

Abstract Global climate models project a large increase in the frequency and intensity of heat extremes (HEs) during the 21st century under the Representative Pathway Concentration (RCP8.5) scenario. To assess the relative sensitivity of future HEs to the level of greenhouse gas (GHG) increases and aerosol emission decreases, we contrast Community Earth System Model (CESM)'s Large Ensemble projection under RCP8.5 with two additional ensembles: one keeping aerosol emissions at 2005 levels (but allowing all other forcings to progress as in RCP8.5) and the other using the RCP4.5 with lower GHG levels. By the late 21st century (2060–2080), the 3 °C warmer-than-present-day climate simulated under RCP8.5 could be 0.6 °C cooler (0.9 °C over land) if the aerosol emissions in RCP8.5 were not reduced, compared with a 1.2 °C cooling due to GHG mitigation (switching from RCP8.5 to RCP4.5). Aerosol induced cooling and associated HE reductions are relatively stronger in the Northern Hemisphere (NH), as opposed to GHG mitigation induced cooling. When normalized by the global mean temperature change in these two cases, aerosols have a greater effect than GHGs on all HE statistics over NH extra-tropical land areas. Aerosols are more capable of changing HE duration than GHGs in the tropics, explained by stronger dynamical changes in atmospheric circulation, despite weaker thermodynamic changes. Our results highlight the importance of aerosol scenario assumptions in projecting future HEs at regional scales.

1 Introduction

Heat Extremes (HEs) pose enormous danger to human health (Kovats and Hajat 2008), as well as ecosystems through wildfire activities (Lau and Kim 2011) and damage to crop yields

This article is part of a Special Issue on “Benefits of Reduced Anthropogenic Climate Change (BRACE)” edited by Brian O'Neill and Andrew Gettelman.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-015-1565-1) contains supplementary material, which is available to authorized users.

✉ Yangyang Xu
yangyang@ucar.edu

¹ National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, CO 80303, USA

(Deryng et al. 2014). Consistent with the global mean surface temperature increase in the past few decades, the frequency and intensity of HEs have increased (Meehl et al. 2009; Peterson et al. 2013). Numerous studies have found that anthropogenic factors are responsible for increases in HEs (Stott et al. 2011). Under a business-as-usual scenario of greenhouse gases (GHGs), Meehl and Tebaldi (2004) projected a large increase in HEs over the United States (US) and Europe. Using model outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5), Wuebbles et al. (2014) showed that the hot spell temperature increases range from 5 °C in the Southern US and West Coast to 7 °C in the Midwest. Under this warming condition, current annual maximum temperature extremes are projected to occur every year over the entire US at 2080–2100.

The occurrence of HEs simulated by CMIP5 has been assessed using the concept of return level and return period (Kharin et al. 2013) or simple indices (Sillmann et al. 2013). Both approaches project increases in HEs under the Representative Concentration Pathway (RCP) 8.5, a scenario that assumes a rapid increase in GHG concentrations and total radiative forcing in the 21st century (Riahi et al. 2011). The magnitudes of projected HEs, however, can be uncertain because climate models have different climate sensitivities and therefore different estimates of warming magnitudes (Wuebbles et al. 2014). Other sources of uncertainty in future projection come from uncertainties in climate scenarios, regional differences in warming patterns in different models, and the inherent internal variability in the simulations.

This paper is part of the Benefits of Reducing Anthropogenic Climate Change (BRACE; O'Neill and Gettelman 2015) project, which aims to assess different climate change outcomes under different RCP scenarios. To assess the scenario dependence of projected future HEs, Oleson et al. (2015) analyzed the Community Earth System Model (CESM) projections under both RCP8.5 and RCP4.5. RCP4.5 has a lower carbon dioxide (CO₂) concentration by the end of 21st century (Thomson et al. 2011) than RCP8.5, and therefore the model driven by RCP4.5 simulates less warming. In addition to Oleson et al. (2015), there are a few other studies in this special issue concerning future evolution of HEs (e.g. Tebaldi and Wehner 2015, and Lehner et al. 2015), which used different estimates of HEs (return levels and record setting temperature).

In the RCPs, the total aerosol optical depth increases in the 20th century and decreases in the 21st century (Lamarque et al. 2011), hence there is less negative forcing from aerosols (contributing to warming) during the 21st century. Forcing agents other than GHGs and aerosols (such as land use) have a small effect on global mean temperature (Brovkin et al. 2013; Lawrence et al. 2015). Several studies have attempted to use idealized model experiments with fixed aerosol emissions throughout the 21st century, complemented by simulations under the RCP scenarios, to isolate the climate impact of aerosols. Levy et al. (2013) showed that the Asian monsoon precipitation would intensify in the future in response to aerosol reductions. Rotstayn et al. (2014) used a similar strategy to explore the mid-latitude temperature response and the shift of the jet stream due to aerosol decline. Although it is recognized that the current aerosol cooling implies more heating in the future once the aerosol masking effect is lifted following air pollution controls (Wigley 1991; Ramanathan and Feng 2008), what is less discussed is the effect of aerosols on HEs.

The scenario dependence examined by contrasting RCP8.5 and RCP4.5 (Oleson et al. 2015) is largely determined by the GHGs, because both RCP8.5 and RCP4.5 similarly assume a sharp reduction, globally and regionally, in aerosol emissions. Future climate projections, however, depend on both GHG and aerosol scenarios. Additional simulations are needed to provide insight on the relative contribution of GHGs and aerosols, and in particular the distinct physical mechanisms. As such, we view our paper as complementary to the BRACE by

bringing out the potential (and different) role of aerosols in mitigating climate change. This paper is organized as follows: the methods are described in Section 2. In Section 3, we show that HEs by the end of 21st century are projected to be more severe than those in the present-day, driven by two factors: a hike in GHG concentration, and to a smaller extent, a sharp decline in aerosol emissions. Conclusions are drawn in Section 4.

2 Methods

2.1 Global climate model description

CESM1 is a coupled ocean-atmosphere-land-sea-ice model. CESM1 climate simulations for the 21st century are documented in Meehl et al. (2013), and the simulation results are part of the CMIP5 dataset. Anthropogenic forcing in CESM1 includes GHGs as well as time and space-evolving tropospheric ozone, stratospheric ozone, aerosols and tropospheric oxidants (Lamarque et al. 2011). A three-mode modal aerosol scheme (Liu et al. 2012) prognostically calculates aerosol concentrations and masses using internally mixed representations of number concentrations and mass for Aitken, accumulation, and coarse modes of various aerosol species (sulfate, black carbon, organic carbons, dust, sea salt). Indirect forcing due to aerosols is included (Morrison and Gettelman 2008) for both liquid and ice phase clouds (Gettelman et al. 2010). The resolution of both atmosphere and ocean models is approximately 1 degree.

2.2 Model experiments

To explore the relative contribution of GHGs and aerosols we utilized three sets of simulations:

- (1) RCP8.5 Large Ensemble. The RCP8.5 Large Ensemble (30 members) aims to quantify the role of natural variability in future climate change (Kay et al. 2014). All model simulations (1920–2080) use the same trajectory of GHG and aerosol forcing, and their only difference is their atmospheric initial condition.
- (2) RCP4.5 Medium Ensemble. This 15-member ensemble simulation is similar to the Large Ensemble but follows the RCP4.5 scenario (Sanderson et al. 2015). By contrasting RCP4.5 and RCP8.5 simulations, we can assess the avoided climate change due to a moderate GHG mitigation. There are only slight differences in aerosol surface concentrations between the two scenarios (Fig S1b). And this difference is much smaller (<20 %) than the magnitude of aerosol reduction in RCP8.5 (Fig S1c), which we used to derive “aerosol contribution” with a third set of simulations.
- (3) RCP8.5 with fixed aerosols Medium Ensemble. This 15-member ensemble simulation uses the same forcing as RCP8.5 except that all aerosol emissions and tropospheric oxidants are fixed at 2005 levels. By contrasting this simulation to RCP8.5, we assess the climate change that would occur if the sharp reduction of aerosol emissions in RCP8.5 were not adopted. While most of studies in this special issue focused on avoided impact between RCP8.5 and RCP4.5, Lin et al. (2015) used an approach similar to ours in order to understand relative contributions of aerosols and GHGs to future land aridity. We note that constant aerosols emissions are defensible for a RCP8.5 world, but they would be less likely in RCP4.5, which is a mitigation scenario.

2.3 Definition of HEs

The definition of HEs (frequency, intensity, and duration) used in this paper is the same as Oleson et al. (2015). We use the daily mean temperature at 2 m above the ground exceeding the 98th percentile of the present-day (1980–2005) climate as criteria for identifying HEs. Note that no bias correction based on observations is here applied to the HEs estimates. If two or more consecutive days are identified as HE days, this is counted as a single HE event. The total number of days in all HE events in a given year divided by 365 defines the *frequency* of HEs. The temperature during all HE events defines the *intensity* of HEs. The average number of days in a single HE event defines the *duration* of HEs. The sensitivity to the definition of HEs is discussed in Table 1.

3 Results and discussions

3.1 Avoided warming and HEs due to GHG mitigation vs aerosols

Under RCP8.5, global mean surface temperature by the end of the century (2060–2080) is about 3 °C higher than that in 2005–2015. Fig. 1(a) shows the regional distribution of model projected annual mean temperature under RCP8.5 at 2060–2080, and avoided warming due to GHG mitigation and aerosols. GHG mitigation from RCP8.5 to RCP4.5 leads to 1.2 °C of avoided warming. This is consistent with earlier results (Meehl et al. 2013) and other CMIP5 model results. The land temperature shows a more pronounced avoided warming of 1.6 °C, which is also a robust feature across models.

Similarly, due to GHG mitigation from RCP8.5 to RCP4.5, the intensity, frequency and duration of HEs drop considerably (Table 1 and Fig. 2). Under the RCP8.5, the mean HE frequency (2060–2080) is 36 % (132 days per year) compared to 21 % in RCP4.5. Over land

Table 1 **a** Changes in temperature, frequency, duration and intensity of HEs in response to GHG mitigation and aerosols at 2060–2080, with RCP8.5 projection as baseline. **b** Same as (a) but at 2030–2050. The standard deviations of the results due to ensemble spreads are shown in parentheses. These are calculated from a sample with size of 450 by pairing the 20-year average statistics from each of 30-member RCP8.5 individually with those from each of 15-member RCP4.5 or RCP8.5 with fixed aerosols. The definition of HEs in use may affect the results. For example, warm spell duration in Sillmann et al. (2013) is defined from the daily maximum temperature (Tmax), not Tmean as in our study. We tested the sensitivity of using the daily maximum (Tmax) and the daily minimum temperature (Tmin). If we used Tmin, the HE frequency change in response to GHG mitigation at 2060–2080 is relatively larger (–15.0 %) as opposed to the results if using Tmax (–13.4 %). Conversely, the change in the duration is slightly larger in the Tmax analysis (–13 days) than using Tmin (–7 days). However, the differences between using Tmax and Tmin are not statistically significant considering the ensemble variance. Furthermore, we do not find major difference between using Tmax and Tmin for aerosol cases either, although arguably aerosols cool the planet by reflecting the solar radiation in the day

	Temperature (°C)	Frequency (%)	Duration (day)	Intensity (°C)
(a) 2060–2080				
GHG mitigation	–1.2 (0.3)	–14.5 (3.8)	–10.4 (3.0)	–0.5 (0.2)
Aerosols	–0.6 (0.4)	–6.0 (4.5)	–6.6 (3.8)	–0.3 (0.2)
(b) 2030–2050				
GHG mitigation	–0.4 (0.3)	–5.0 (4.6)	–1.3 (1.4)	–0.1 (0.1)
Aerosols	–0.3 (0.3)	–4.1 (5)	–1.2 (1.5)	–0.1 (0.1)

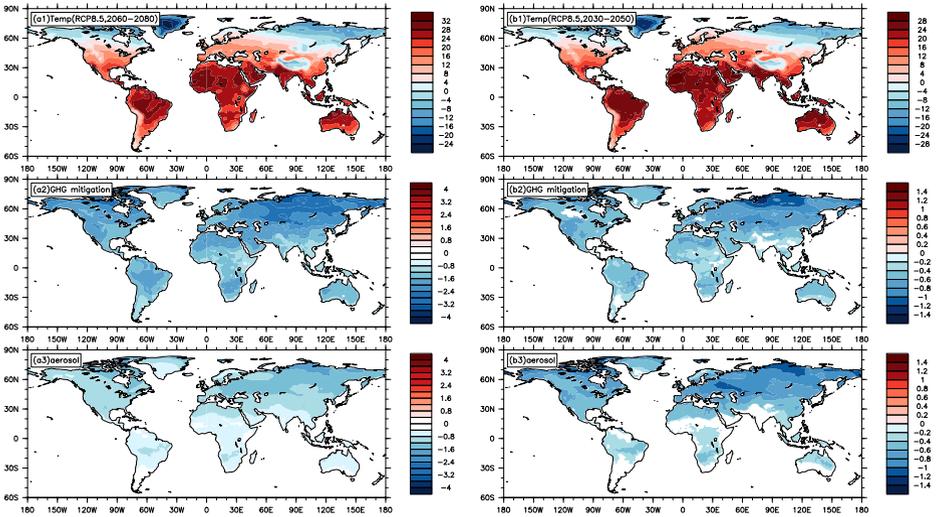


Fig. 1 (a1) Model projected temperature ($^{\circ}\text{C}$) at 2060–2080 under RCP8.5. (a2) Temperature reduction due to GHG mitigation from RCP8.5 to RCP4.5. (a3) Temperature reduction due to fixing present-day aerosols. (b1–b3) are same as (a1–a3) but for 2030–2050. Only statistically significant values at the 90 % confidence level based on Student T-test (von Storch and Zwiers, 1999; test function in NCL) over land are shown. The global (land and ocean) averaged values and ensemble variances are shown in Table 1.

areas only, the frequency drops from 26 % in RCP8.5 to 15 % in RCP4.5, as many HE events occur over tropical oceans. The mean duration of HE events would also drop from 19 days in RCP8.5 to 9 days in RCP4.5 (Table 1a).

The standard deviation of GHG-mitigation avoided warming ($1.2\text{ }^{\circ}\text{C}$) across ensemble members is about $0.3\text{ }^{\circ}\text{C}$ (Table 1a), suggesting that the cooling at 2060–2080 due to GHG mitigation

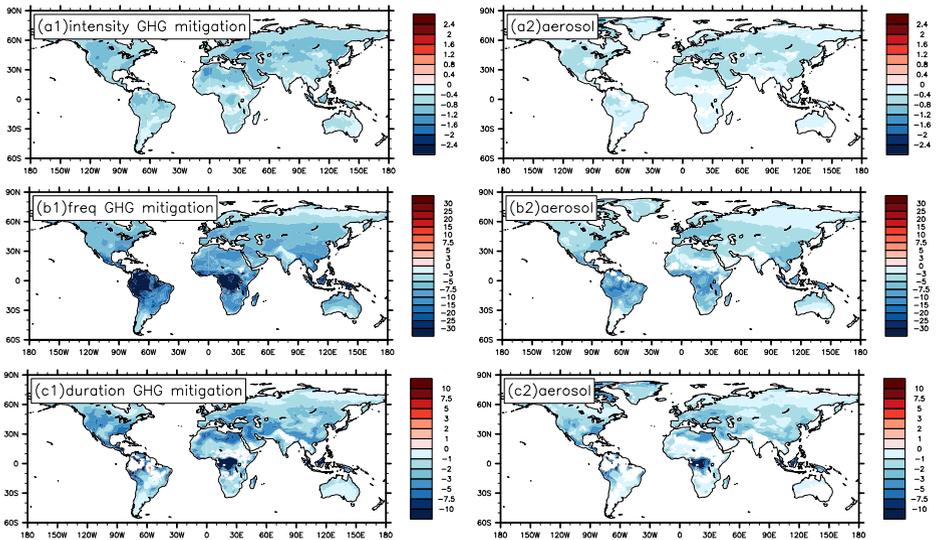


Fig. 2 (a1) The reduction of HE intensity ($^{\circ}\text{C}$) due to GHG mitigation from RCP8.5 to RCP4.5. (a2) The reduction of HE intensity ($^{\circ}\text{C}$) due to fixing present-day aerosols. (b1–b2) The reduction of HE frequency (%). (c1–c2) The reduction of HE duration (days)

(RCP8.5 to RCP4.5) is robust. The changes of HE statistics discussed above are also statistically significant. For 2030–2050, however, the avoided warming and HEs are subject to greater uncertainty (Table 1b), due to the smaller separation of GHG levels between the two scenarios. Moreover, the regionally averaged avoided warming is more uncertain than the global average due to larger natural variability at smaller scales, as demonstrated in Sanderson et al. (2015).

When aerosol emissions are fixed at present day levels, the global mean temperature at 2060–2080 is 0.6 °C lower than in RCP8.5 (Table 1a). This suggests that in the 3 °C warming (from 2005 to 2015 to 2060–2080) under RCP8.5, 20 % can be attributed to a decline in aerosol emissions from present day. Associated with the 0.6 °C cooling, our simulations also show that the global averaged HE frequency are reduced by 6 % along with a 7-day decrease in the duration of HE events due to aerosols (Table 1a). The ensemble variances of these estimates are larger than corresponding GHG cases (parenthesis in Table 1a), but the cooling and HEs reduction is robust.

Comparatively, the avoided global warming at 2060–2080 due to keeping aerosols at current levels is about 50 % of that due to switching from RCP8.5 to RCP4.5 (largely due to GHG mitigation), and this ratio is largely similar for other HE-related statistics (Table 1a). However, the relative contribution of aerosols can be different if we consider other time periods. At 2030–2050, aerosols contribute 0.33 °C of cooling as opposed to 0.38 °C from GHG mitigation (Table 1b). The larger ratio (87 % as opposed to 50 % for 2060–2080) is because the aerosols are projected to decrease sharply after 2010, while the increasing of GHG level is more gradual. Moreover, aerosols cause a relatively larger cooling effect over NH, as opposed to more uniform cooling from GHG mitigation. At 2030–2050, the cooling over some NH regions is even stronger in aerosol case than in GHG mitigation case (Fig. 1b), and similarly for HE changes (Fig. 2).

Aerosols' relative role in climate change is sensitive to the time scale of interest, and short-lived aerosols are shown to play a vital role in mitigating near-term climate change (Hu et al. 2013). Our results reaffirm that declining aerosols cause a fraction of future warming and HE increase, and the relative role of aerosols compared to GHGs is particularly large in the near term and in low-GHG scenario.

3.2 Spatial pattern of HE changes normalized by global temperature change

We now use the 2060–2080 data to calculate diagnostics based on the normalization with respect to the global mean surface temperature change. The motivation for the normalization process is to understand differences in the spatial pattern of climate response due to aerosols or GHGs. In other words, we aim to address the following question: given the similar amount of global cooling due to GHG mitigation or aerosols, would there be any differences in spatial pattern of HE change?

Table 2a shows that under a 1-degree avoided warming (relative to the 2060–2080 projection in RCP8.5) due to either GHGs mitigation or aerosols, the frequencies of HEs decrease by about 10–12 %/°C in both cases, durations decrease by about 9–12 days/°C, and the intensity decreases by 0.45 °C/°C. The influences of aerosols to the duration and the intensity are only slightly larger than those of GHGs. This suggests that the *global mean* temperature change is indeed a good predictor of the *global mean* statistics of HEs, consistent with Lau and Nath (2012).

Despite the similar global mean responses per degree of avoided warming, the geographic distribution of temperature and heat extreme change is of greater interest for pattern scaling

Table 2 **a** Similar to Table 1(a), but all numbers are normalized with respect to global mean surface temperature change in GHG mitigation and aerosol cases, respectively. The normalized temperature changes by definition are -1 . The changes weighted by population density, instead of grid area, are shown in parentheses. **b** Same as (a), but for regional average over the US

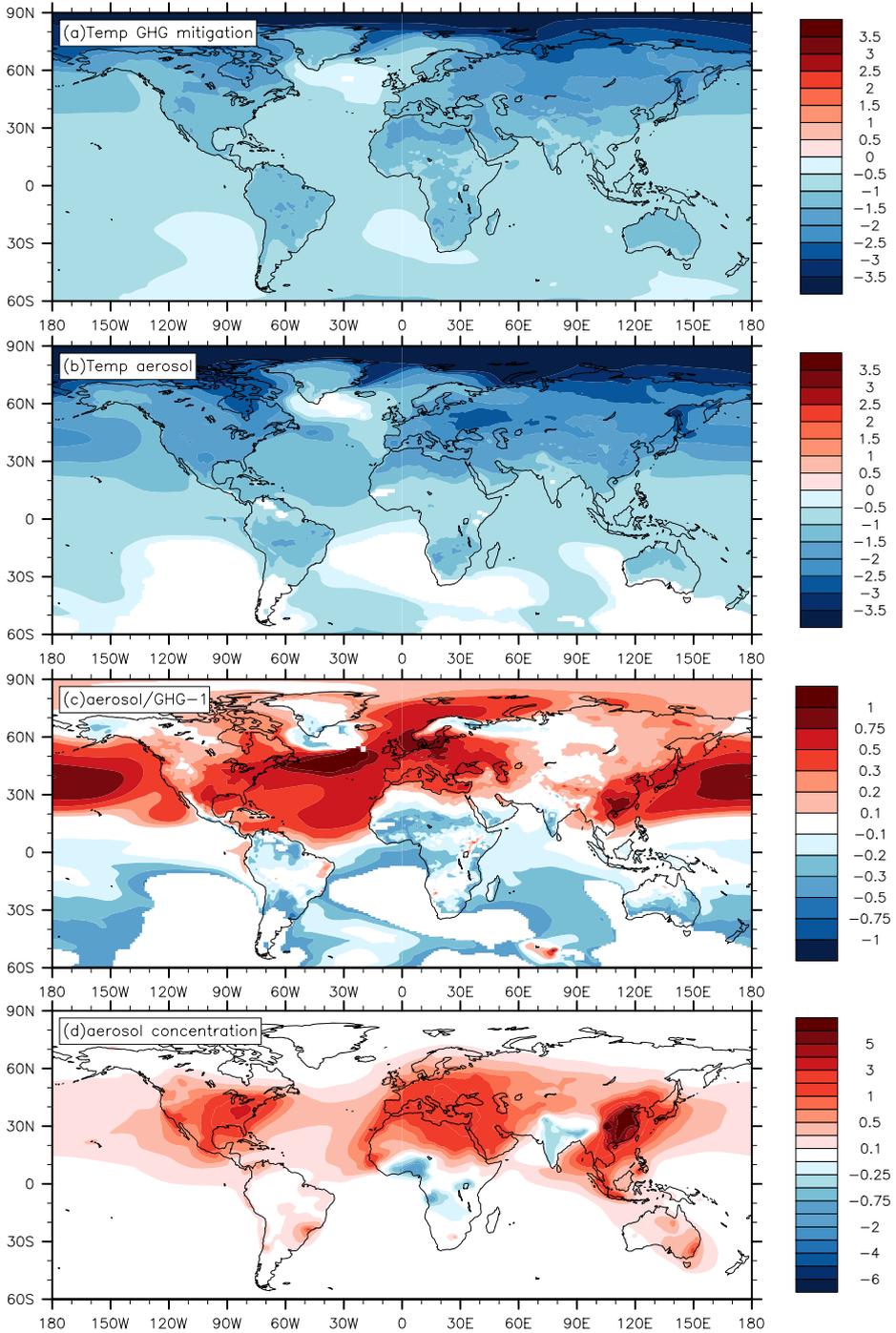
	Temperature ($^{\circ}\text{C}/^{\circ}\text{C}$)	Frequency ($\%/^{\circ}\text{C}$)	Duration ($\text{day}/^{\circ}\text{C}$)	Intensity ($^{\circ}\text{C}/^{\circ}\text{C}$)
(a) Global				
GHG mitigation	-1 (-1.1)	-11.9 (-11.6)	-8.6 (-3.6)	-0.4 (-0.5)
Aerosols	-1 (-1.2)	-10.4 (-10.8)	-11.3 (-4.6)	-0.5 (-0.6)
(b) US				
GHG mitigation	-1.1 (-1.2)	-9.6 (-7.7)	-4.5 (-3.4)	-0.6 (-0.6)
Aerosols	-1.5 (-1.8)	-12.2 (-9.4)	-5.6 (-4.3)	-0.8 (-0.8)

purposes. The normalized temperature change (with respect to global mean temperature change) is shown in Fig. 3. The geographic pattern of avoided warming due to GHG mitigation is largely uniform globally with some amplification over NH high latitude regions (Fig. 3a). In contrast, the cooling patterns associated with aerosols feature strong hemispheric asymmetry with the cooling magnitude decreases in the Southern Hemisphere (Fig. 3b).

The relative contribution of GHGs and aerosols is further assessed in Fig. 3c by plotting the relative ratio of normalized temperature changes between GHG mitigation case and aerosol case minus one. Positive values indicate a larger influence from aerosols to local temperature change. Over North America, Europe and East Asia, the aerosol influence to regional temperature (per unit of global temperature change) is almost 30 % larger than that of GHGs. The tropics and mid-latitudes in the Southern Hemisphere are more influenced by GHGs. The regions where aerosols play a dominant role in reducing warming are collocated with larger changes in aerosol loading (Fig. 3d). Temperature change pattern over NH extra-tropical oceans are also strongly influenced by the aerosols, as the aerosols (despite of smaller loading than over land) have large effects through brightening marine clouds over dark ocean surfaces.

A similar picture is found in the HE intensity and frequency (Fig. 4a, b), which follow the temperature pattern change closely. In the RCP8.5 scenario, at the end of the 21st century, more than 90 % of the days in the tropics and 30 % of the days in most mid-latitude regions (e.g., North America and Asia) are classified as HEs. In response to GHG mitigation or the continued emission of present-day aerosols, the largest reduction in HE frequency is seen in the tropics (where climatological HEs persist), as well as in some mid-latitude regions, especially for the aerosol case (Fig. 4b). Hence, per degree of global mean avoided warming, aerosols play a large role in controlling HEs over the NH extra-tropical land regions.

Over the United States (US), the aerosol influence to regional cooling (per degree of avoided global warming) is 40 % larger than GHGs, especially over the Eastern and Southern US, consistent with larger aerosol emission changes (Fig. 3d). This is consistent with earlier studies that related the observed warming hole over the Eastern US in the mid-20th century to the aerosol increases at that time (Leibensperger et al. 2012). The frequency change is also larger in the aerosol case (a 12.2 $\%/^{\circ}\text{C}$ decrease as opposed to a 9.6 $\%/^{\circ}\text{C}$ decrease in the GHG mitigation case, Table 2b), especially along the West Coast, Texas, and the Eastern US. Only in a smaller fraction of regions (e.g., Montana) is the GHG influence larger. The



change in the duration of HE events is mostly found in the Eastern US, with a reduction of more than 10 days.

Fig. 3 **a** Normalized temperature reduction ($^{\circ}\text{C}/^{\circ}\text{C}$) due to GHG mitigation from RCP8.5 to RCP4.5. **b** Normalized temperature reduction ($^{\circ}\text{C}/^{\circ}\text{C}$) due to fixing present-day aerosols. Both values are normalized with respect to the global mean surface temperature change as in Table 1a. The global and regional averaged values are shown in Table 2. **c** The relative role of **(b)** and **(a)** calculated as $(b)/(a)-1$. **(d)** Change in the surface mass concentration ($\mu\text{g}/\text{m}^3$) of sulfate aerosols between present-day and 2060–2080 in RCP8.5, which is largely responsible for the cooling in **(b)**

From the regional pattern of HEs response to aerosols and GHG mitigation (Fig. 3 and Fig. 4), as well as the regional statistics at the continental scale (Table 2b), we conclude that global mean temperature is not a good predictor of regional changes in HEs. However, HE changes mostly due to GHGs (Oleson et al. 2015) are expected to scale well with the global mean temperature change (Lau and Nath 2012).

3.3 Understanding the changes of HE durations over the tropics

Given the same number of days of HEs per year (frequency), the duration of HE periods is an additional factor to consider in assessing health impacts. The tropics feature long lasting HEs by the end of the 21st century under RCP8.5, with single HE event as long as 50 days. Based on our simulations, we find that per degree of global temperature change the aerosols play a stronger role in controlling HE duration not only in NH but also in the tropics (Fig. 4c). This is in contrast with stronger role of GHGs in controlling intensity and frequency change over the tropics (Fig. 4a, b). Such a different perspective regarding the patterns of HE frequency/intensity and duration has received little attention in the literature. It is often assumed that HE-related metrics all follow surface temperature and that warmer places will experience longer-lasting HEs. We now examine under 1°C global cooling, why the aerosols in the tropics induce less cooling (Fig. 3) and smaller reduction in the intensity and frequency (Fig. 4a, b), but larger reduction in the duration of HEs.

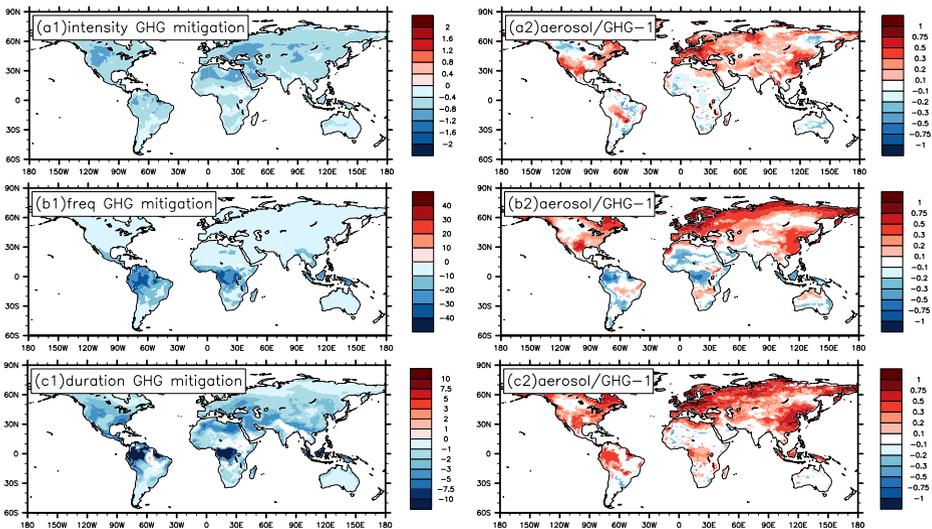


Fig. 4 **(a1)** Normalized changes in HE intensity ($^{\circ}\text{C}/^{\circ}\text{C}$) due to GHG mitigation from RCP8.5 to RCP4.5. **(a2)** The ratio between aerosol induced changes and GHGs mitigation induced changes minus one. **(b1-b2)** Same as **(a)**, but showing normalized changes in HE frequency ($\%/^{\circ}\text{C}$). **(c1-c2)** Same as **(a)**, but showing normalized changes in duration of HEs (days/ $^{\circ}\text{C}$)

We use two metrics to diagnose the atmospheric variability at short time scales (days to weeks) that influences HE duration. The first one is the standard deviation of sea level pressure (std(PSL)). This metric has been related to the occurrence of mid-latitude cyclones with implications on air quality extremes (Leibensperger et al. 2008). The climatological std.(PSL) is lower in the tropics indicating lower variability (Fig. 5a1). Larger std.(PSL) in the cooling cases (either due to aerosols and GHG mitigation) indicates more variability (not shown). The difference between aerosols and GHG mitigation cases (Fig. 5a2) suggests a larger increase in std.(PSL) from the aerosols (red areas, in particular over South America) that contributes to a shorter duration of HEs.

Secondly, we assess the occurrence of stagnation days. Days with wind speed at 500mb (millibar, approximately 5000–6000 m above the sea level) less than 6.5 m/s and wind speed at the surface less than 1.6 m/s are classified as stagnation days. Note this definition is modified from that in Horton et al. (2014). Notably, we did not include daily precipitation as part of stagnation index definition, because the local rainfall changes, especially zero rainfall days, are less robust across the simulations. Moreover, precipitation component of stagnation index is most relevant to air pollution dispersion issue than HEs. Under the modified stagnation definition, tropical regions are occupied by more stagnation days (Fig. 5b1) than mid-latitudes, indicative of a lower atmospheric variability. Similar results in present-day distributions can be found in some earlier studies (e.g, Leibensperger et al. 2008; Tai et al. 2012; Horton et al. 2014).

Horton et al. (2014) showed that stagnation days would generally increase under global warming. Conversely, in the cooling cases (either due to aerosols or GHG mitigation), tropical stagnation days would decrease in number. The decrease in number of stagnation days per year is larger in the aerosol-induced cooling case (Fig. 52, red areas), also accompanied by larger decrease of stagnation event duration (0.5–1 days). Fewer

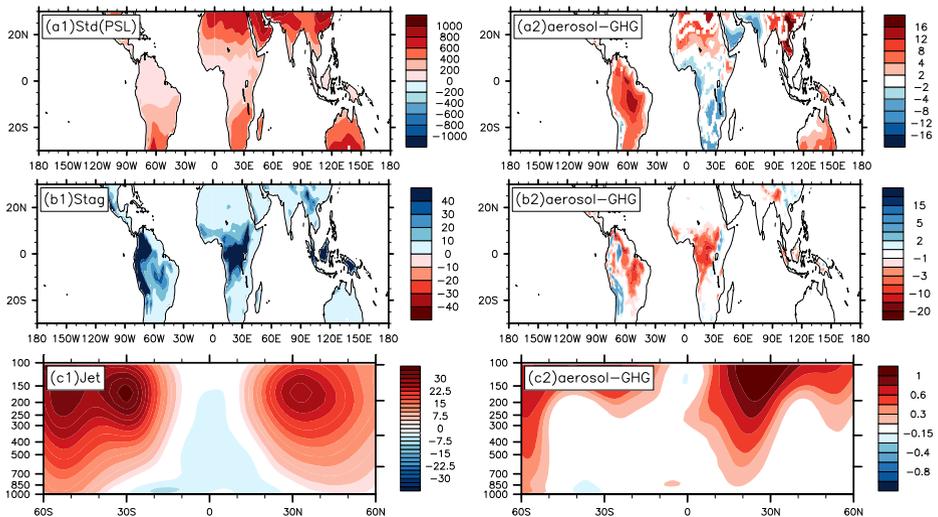


Fig. 5 (a1) The climatology of the standard deviation of sea level pressure (std(PSL), mb) over the tropics (30°S to 30°N). (a2) The change of std.(PSL) due to aerosols minus that due to GHG mitigation. (b1-b2) Same as (a), but showing stagnation days per year. Note that to be consistent with (a), color code in (b) is reversed with red color indicating more tropical variability. (c1-c2) Same as (a), but showing zonal mean zonal wind (jet stream, m/s) as a function of latitude and altitude

stagnation days in the aerosol cooling case indicate more variability in the tropics and a larger tendency toward reducing HE duration.

In line with the theory of tropical expansion under global warming conditions (Lucas et al. 2014), the tropics could contract under a cooling scenario. This contraction of tropics is characterized by an equatorward shift of jet stream (the climatology shown in Fig. 51), both in response to GHG mitigation and aerosol induced cooling. Again, the equatorward shift of the mid-latitudes jet stream is stronger in response to aerosols than to GHG mitigation (Fig. 52). The stronger impact of aerosols in influencing jet streams was examined by Xu and Xie (2015), who argued that aerosols cause a stronger perturbation to the north-south sea-surface temperature gradient than GHGs, and aerosols consequently lead to southward shift of the NH branch of the Hadley cell. The jet stream shift is in the same direction of the Hadley cell shift, and it brings more extra-tropical atmospheric variability into the tropics.

Summarizing from multiple lines of arguments, aerosols have an edge in perturbing the atmospheric variability in the tropics. This stronger dynamical perturbation leads to a larger reduction in the *duration* of HEs by reducing the stagnant meteorological conditions that favor HEs. Despite of a stronger *dynamical* impact in the tropics, aerosols have a weaker *thermo-dynamic* impact than GHGs that governs the changes of *intensity* and *frequency* of HEs.

3.4 Population exposures to HE changes

Because HEs have negative impact on human health, it is worth considering the HE statistics in terms of population-weighted averages instead of area-weighted averages, which is directly relevant to issues of human mortality and morbidity (Anderson et al. 2015). The population density projection at 2070 we use here is based on the Shared Socioeconomic Pathways 5 (SSP5, methods in Jones and O'Neill 2013). Population-weighted aerosol influence is even larger, because more people live in the NH and most aerosol emissions are from NH land. Under the 1-degree avoided warming scenario, cooling experienced by the population is 20 % larger due to aerosols (parenthesis in Table 2a). Due to the collocation of aerosol emissions and population density, changes in aerosol concentrations may induce regional changes in HEs that even outweigh the influences of GHGs in certain regions (US, Europe, and East Asia). Jones et al. (2015) compared population exposure to HEs using the same definition as used here under various RCPs and SSPs. The additional insight of our study is that aerosol effects may be especially important, as they are co-located with high population density.

Therefore, to better quantify future human exposure to HEs, we need to improve understanding of the regional climate impact of aerosols. Although a future decline in aerosols would induce more HEs, the direct benefits to public health from cutting particulate matter pollutions (e.g. Fang et al. 2013) may still outweigh the indirect negative consequence of HEs. Nevertheless, such a trade-off in pollution-related health impacts should be studied in a systematic way (Ming et al. 2005).

4 Concluding remarks

Given the short lifetimes of aerosols, their atmospheric concentrations and radiative forcing are strongly influenced by economic activities and the intensity of local to regional emission sources, all of which are highly uncertain for the future. Earlier scenarios such as used in CMIP3 have adopted various aerosol scenarios, including a sharp reduction after 2025 in A1B

and B1, as well as a near-constant value in A2. In contrast, all four scenarios of the current RCPs used in CMIP5 assume sharp reductions in global aerosol emissions, making it difficult to assess the dependence of the scenarios on aerosols. But there is no guarantee that aerosol decreases will be as sharp as in the RCPs or that the aerosol emissions will decrease at all. For example, the upper bound of the non-mitigation scenario of van Vuuren et al. (2008) maintains a present-day level of sulfur dioxide emissions. There are also observational evidences from satellites (e.g. Zhang and Reid 2010) that the aerosol optical depth over the ocean has not declined since 2005, contrary to what is projected in the RCPs. Scenarios used in future CMIP6 (SSPs) are likely to have more diversity in aerosol projections. The RCP8.5 fixed-aerosol simulations in this study are designed to test the sensitivity of future climate projections on the aerosol scenarios.

Although we aimed to separate the effect of GHG and aerosol scenarios on future warming and to explain the physical mechanism behind the distinct spatial pattern, it should be noted that in real world, GHG and aerosol emission are from similar sources. Most of the aerosol decrease is through the implementation of pollution controls, but changes in the energy sources could also contribute. A recent study estimated possible ranges of air pollutant emissions consistent with four RCPs under various levels of air pollution control (Rogelj et al. 2014). While constant present-day aerosols might materialize in RCP8.5 world due to failure of air-pollution controls, even a failure of more stringent air-pollution controls would not allow for aerosol emissions to stay at present day in RCP4.5, in which overall fossil fuel consumption is projected to decrease.

This study demonstrates that the HE projections and the avoided impact assessments based on global climate model simulations will be affected not only by differences in GHG levels, but also by differences in aerosol emissions. By analyzing large ensembles of global climate model output under different GHG and aerosol scenarios, we show that a significant fraction of global warming at 2060–2080 is contributed by declining aerosols (20 % under RCP8.5), and the fraction of contribution is larger for the near term (2030–2050). GHG mitigation or continued present day aerosol loading would avoid the warming projection at 2060–2080 under RCP8.5 by 1.2 °C and 0.6 °C, respectively, accompanied by reductions in HE statistics.

To focus on the spatial pattern of HE response, we apply the normalization to the avoided warming at 2060–2080 with respect to the global mean temperature change. Per degree of temperature change, aerosols have a greater effect on all HE-related statistics (frequency, duration and intensity) over NH extra-tropical land, related to greater aerosol loadings there. Moreover, for the near term (2030–2050, Table 1b), the conclusion that aerosols have a larger role over NH holds true even without normalization because of a large aerosol reduction in the near term. Over the tropics, GHGs appear to have a stronger thermodynamic role in reducing HE intensity and frequency because of lower anthropogenic aerosol emissions in the tropics. However, we highlight that the tropical HE duration is more strongly influenced by aerosols because of dynamic changes to atmospheric variability. Overall, our study highlights the importance of aerosol scenarios in projections of future HEs.

These estimated changes in HEs are consistent with other estimates using CESM (Oleson et al. 2015) and from other CMIP5 models (Sillmann et al. 2013). The regional distribution might be different because of model structure differences, although Fischer et al. (2014) claimed that the forced responses in temperature extremes are in better agreement across models than the mean temperature. Therefore, our analysis based on one model is likely to be robust across models, but more research using a similar approach is needed to assess the generality of our results.

Acknowledgments The authors thank Claudia Tebaldi and Keith Oleson for discussions and Bryan Jones for data. We acknowledge helpful comments from Andrew Gettelman and two anonymous reviewers. This study was partially funded by Regional and Global Climate Modeling Program (RGCM) of the US Department of Energy's Office of Science (BER), Cooperative Agreement (DE-FC02-97ER62402). Y Xu is also supported by Advanced Study Programme of National Center for Atmospheric Research (NCAR). The CESM project is supported by the National Science Foundation and the Office of Science (BER) of the US Department of Energy. NCAR is funded by the National Science Foundation.

References

- Anderson GB, Oleson KW, Jones B, Peng RD (2015) Predicting high-mortality heatwaves: Developing health-based models to predict whether a heatwave is high-mortality or less dangerous based on heatwave and community characteristics. Submitted to *Climatic Change*
- Brovkin V, Boysen L, Arora V, et al. (2013) Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century. *J. Climate* 26:6859–6881. doi:10.1175/JCLI-D-12-00623.1
- Deryng D, Conway D, Ramankutty N, et al. (2014) Global crop yield response to extreme heat stress under multiple climate change futures. *Environ Res Lett* 9:34011
- Fang Y, Mauzerall DL, Liu J, et al. (2013) Impacts of 21st century climate change on global air pollution-related premature mortality. *Clim Chang* 121:239–253. doi:10.1007/s10584-013-0847-8
- Fischer EM, Sedláček J, Hawkins E, Knutti R (2014) Models agree on forced response pattern of precipitation and temperature extremes. *Geophys Res Lett* 41:2014GL062018. doi:10.1002/2014GL062018
- Gettelman A, Liu X, Ghan SJ, et al. (2010) Global simulations of ice nucleation and ice supersaturation with an improved cloud scheme in the community atmosphere model. *J Geophys Res Atmos* 115:D18216. doi:10.1029/2009JD013797
- Horton DE, Skinner CB, Singh D, Diffenbaugh NS (2014) Occurrence and persistence of future atmospheric stagnation events. *Nat Clim Chang*. doi:10.1038/NCLIMATE2272
- Hu A, Xu Y, Tebaldi C, et al. (2013) Mitigation of short-lived climate pollutants slows sea-level rise. *Nat Clim Chang* 3:730–734
- Jones B, O'Neill B (2013) Historically grounded spatial population projections for the continental United States. *Environ Res Lett* 8(4):044021
- Jones B et al. (2015) Population exposure to heat-related extremes: Demographic change vs climate change. Submitted to *Climatic Change*.
- Kay JE, Deser C, Phillips A, et al. (2014) The community earth system model (CESM) large ensemble. A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability. *Bull Am Meteorol Soc*, Project. doi:10.1175/BAMS-D-13-00255.1
- Khariin VV, Zwiers FW, Zhang X, Wehner M (2013) Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Clim Chang* 119:345–357. doi:10.1007/s10584-013-0705-8
- Kovats RS, Hajat S (2008) Heat stress and public health: a critical review. *Annu Rev Public Health* 29:41–55. doi:10.1146/annurev.publhealth.29.020907.090843
- Lamarque J-F, Kyle GP, Meinshausen M, et al. (2011) Global and regional evolution of short-lived radiatively-active gases and aerosols in the representative concentration pathways. *Clim Chang* 109:191–212. doi:10.1007/s10584-011-0155-0
- Lau WKM, Kim KM (2011) The 2010 Pakistan flood and Russian heat wave: teleconnection of hydrometeorological extremes. *J Hydrometeorol* 13:392–403. doi:10.1175/JHM-D-11-016.1
- Lau NC, Nath MJ (2012) A model study of heat waves over North America: meteorological aspects and projections for the twenty-first century. *J Clim* 25:4761–4764. doi:10.1175/JCLI-D-11-00575.1
- Lawrence et al. (2015) Attribution of the biogeochemical and biogeophysical impacts of CMIP5. Submitted to *Climatic Change*
- Lehner F et al. (2015) Increasing risk of record-breaking summer temperatures with global warming and the potential for mitigation. Submitted to *Climatic Change*
- Leibensperger EM, Mickley LJ, Jacob DJ (2008) Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change. *Atmos Chem Phys Discuss* 8:12253–12282. doi:10.5194/acpd-8-12253-2008
- Leibensperger EM, Mickley LJ, Jacob DJ, et al. (2012) Climatic effects of 1950–2050 changes in US anthropogenic aerosols; part 2: climate response. *Atmos Chem Phys* 12:3349–3362. doi:10.5194/acp-12-3349-2012
- Levy H, Horowitz LW, Schwarzkopf MD, et al. (2013) The roles of aerosol direct and indirect effects in past and future climate change. *J Geophys Res Atmos* 118:4521–4532. doi:10.1002/jgrd.50192

- Lin L, et al. (2015) Simulated differences in 21st century aridity due to different scenarios of greenhouse gases and aerosols. Submitted to Climatic Change
- Liu X, Easter RC, Ghan SJ, et al. (2012) Toward a minimal representation of aerosols in climate models: description and evaluation in the community atmosphere model CAM5. *Geosci Model Dev* 5:709–739. doi: [10.5194/gmd-5-709-2012](https://doi.org/10.5194/gmd-5-709-2012)
- Lucas C, Timbal B, Nguyen H (2014) The expanding tropics: a critical assessment of the observational and modeling studies. *Wiley Interdiscip Rev Clim Chang* 5:89–112
- Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305:994–997. doi:[10.1126/science.1098704](https://doi.org/10.1126/science.1098704)
- Meehl GA, Tebaldi C, Walton G, Easterling D, McDaniel L (2009) Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S. *Geophys Res Letts* 36:L23701. doi: [10.1029/2009GL040736](https://doi.org/10.1029/2009GL040736)
- Meehl GA, Washington WM, Arblaster JM, et al. (2013) Climate change projections in CESM1(CAM5) compared to CCSM4. *J Clim* 26:6287–6308. doi:[10.1175/JCLI-D-12-00572.1](https://doi.org/10.1175/JCLI-D-12-00572.1)
- Ming Y, Russell LM, Bradford DF (2005) Health and climate policy impacts on sulfur emission control. *Rev Geophys* 43:RG4001. doi:[10.1029/2004RG000167](https://doi.org/10.1029/2004RG000167)
- Morrison H, Gettelman A (2008) A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: Description Numer tEsts *J Clim* 21:3642–3659. doi:[10.1175/2008JCLI2105.1](https://doi.org/10.1175/2008JCLI2105.1)
- B. O'Neill, A. Gettelman. (2015) Introduction to the special issue. Submitted to Climatic Change.
- Oleson et al., (2015) Avoided impacts of urban and rural heat and cold waves over the U.S. using large climate model ensembles for RCP8.5 and RCP4.5. Submitted to Climatic Change.
- Peterson TC, Heim RR, Hirsch R, et al. (2013) Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: state of knowledge. *Bull Am Meteorol Soc* 94:821–834. doi:[10.1175/BAMS-D-12-00066.1](https://doi.org/10.1175/BAMS-D-12-00066.1)
- Ramanathan V, Feng Y (2008) On avoiding dangerous anthropogenic interference with the climate system: formidable challenges ahead. *Proc Natl Acad Sci U S A* 105:14245–14250. doi:[10.1073/pnas.0803838105](https://doi.org/10.1073/pnas.0803838105)
- Riahi K, Rao S, Krey V, et al. (2011) RCP8.5—a scenario of comparatively high greenhouse gas emissions. *Clim Chang* 109:33–57. doi:[10.1007/s10584-011-0149-y](https://doi.org/10.1007/s10584-011-0149-y)
- Rogelj J, Rao S, McCollum DL, et al. (2014) Air-pollution emission ranges consistent with the representative concentration pathways. *Nat Clim Chang* 4:446–450
- Rotstayn LD, Plymin EL, Collier MA, et al. (2014) Declining aerosols in CMIP5 projections: effects on atmospheric temperature structure and midlatitude jets. *J Clim* 27:6960–6977. doi:[10.1175/JCLI-D-14-00258.1](https://doi.org/10.1175/JCLI-D-14-00258.1)
- Sanderson et al. (2015) A new large CESM initial condition ensemble to assess avoided impacts in a climate mitigation scenario. Submitted to Climatic Change
- Sillmann J, Kharin VV, Zwiers FW, et al. (2013) Climate extremes indices in the CMIP5 multimodel ensemble: part 2. Future Clim pRojections *J Geophys Res Atmos* 118:2473–2493. doi:[10.1002/jgrd.50188](https://doi.org/10.1002/jgrd.50188)
- Stott PA, et al (2011) Attribution of weather and climate-related extreme events. *Climate Science for Serving Society: Research, Modelling and Prediction Priorities*, J. W. Hurrell and G. Asrar, Eds., Springer.
- Tai APK, Mickley LJ, Jacob DJ, et al. (2012) Meteorological modes of variability for fine particulate matter (PM_{2.5}) air quality in the United States: implications for PM_{2.5} sensitivity to climate change. *Atmos Chem Phys* 12:3131–3145. doi:[10.5194/acp-12-3131-2012](https://doi.org/10.5194/acp-12-3131-2012)
- Tebaldi C, Wehner (2015). Benefits of mitigation for future heat extremes under RCP4.5 compared to RCP8.5. Submitted to Climatic Change
- Thomson AM, Calvin KV, Smith SJ, et al. (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Clim Chang* 109:77–94. doi:[10.1007/s10584-011-0151-4](https://doi.org/10.1007/s10584-011-0151-4)
- van Vuuren DP, Meinshausen M, Plattner GK, et al. (2008) Temperature increase of 21st century mitigation scenarios. *Proc Natl Acad Sci* 105:15258–15262. doi:[10.1073/pnas.0711129105](https://doi.org/10.1073/pnas.0711129105)
- von Storch H, Zwiers FW (1999) *Statistical Analysis in Climate Research*, Cambridge
- Wigley TML (1991) Could reducing fossil-fuel emissions cause global warming? *Nature* 349:503–506
- Wuebbles D, Meehl G, Hayhoe K, et al. (2014) CMIP5 climate model analyses: climate extremes in the United States. *Bull Am Meteorol Soc* 95:571–583. doi:[10.1175/BAMS-D-12-00172.1](https://doi.org/10.1175/BAMS-D-12-00172.1)
- Xu Y, Xie SP (2015) Ocean mediation of tropospheric response to reflecting and absorbing aerosols. *Atmos Chem Phys* 15:5827–5833. doi:[10.5194/acp-15-5827-2015](https://doi.org/10.5194/acp-15-5827-2015)
- Zhang J, Reid JS (2010) A decadal regional and global trend analysis of the aerosol optical depth using a data-assimilation grade over-water MODIS and level 2 MISR aerosol products. *Atmos Chem Phys* 10:10949–10963. doi:[10.5194/acp-10-10949-2010](https://doi.org/10.5194/acp-10-10949-2010)