Climate Change Impacts on Extreme Events in the United States: An Uncertainty Analysis

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This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Erwan Monier*† and Xiang Gao*

Abstract

Extreme weather and climate events, such as heat waves, droughts and severe precipitation events, have substantial impacts on ecosystems and the economy. However, future climate simulations display large uncertainty in mean changes. As a result, the uncertainty in future changes of extreme events, especially at the local and national level, is large. In this study, we analyze changes in extreme events over the US in a 60-member ensemble simulation of the 21st century with the Massachusetts Institute of Technology (MIT) Integrated Global System Model–Community Atmosphere Model (IGSM-CAM). Four values of climate sensitivity, three emissions scenarios and five initial conditions are considered. The results show a general intensification of extreme daily maximum temperatures and extreme precipitation events over most of the US. The number of rain days per year increases over the Great Plains but decreases in the northern Pacific Coast and along the Gulf Coast. Extreme daily minimum temperatures increase, especially over the northern parts of the US. As a result, the number of frost days per year decreases over the entire US and the frost-free zone expands northward. This study displays a wide range of future changes in extreme events in the US, even simulated by a single climate model. Nonetheless, it clearly shows that under a reference emissions scenario with no climate policy, changes in extreme events reach dangerous levels, especially for large values of climate sensitivity. On the other hand, the implementation of a stabilization scenario drastically reduces the changes in extremes, even for the highest climate sensitivity considered.

Contents

1. INTRODUCTION

Extreme weather and climate events, such as heat waves, droughts and severe precipitation events, have received increasing attention in recent years, due to the often large impacts on society and ecosystems. Extreme events can impact, directly or indirectly, all sectors of the economy. They can destroy large infrastructure and private properties, and lead to the severe human loss. Various studies have examined the impacts of extreme events on infrastructure (Penning-Rowsell and Wilson, 2006; Wright *et al.*, 2012), air quality and human health (Leibensperger *et al.*, 2008; Mahmud *et al.*, 2012), terrestrial ecosystems (Parmesan *et al.*, 2000; Xiao *et al.*, 2009), agriculture and forestry (Rosenzweig *et al.*, 2001; Maracchi *et al.*, 2005), water demand (Strzepek *et al.*, 2010), as well as energy demand and production (Smoyer-Tomic *et al.*, 2003; Yergin, 2006). In addition, the economic impact and human loss due to extreme weather events have been substantial in recent history. For agriculture, single extreme weather events in the US can lead to

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economic damages that exceed $1 billion (Rosenzweig *et al.*, 2001). The most severe extreme weather events for agriculture in the US in recent history were the 1988 drought and the 1993 flood. Hurricanes Katrina and Rita shut down 27 percent of oil production in the US (Yergin, 2006) and Hurricane Sandy inflicted economic damages that could reach $50 billion, based on early estimates (Craft, 2012). In 1998, flooding and landslides due to Hurricane Mitch resulted in more than 10,000 deaths in Central America (Easterling *et al.*, 2000) while the European summer heat wave of 2003 resulted in more than 70,000 deaths in 16 countries (Robine *et al.*, 2008).

At the same time, extreme temperature and precipitation events have experienced significant changes in the last decades (Christidis *et al.*, 2005; Kunkel *et al.*, 2008). In the US, extreme high temperatures have generally increased, while the occurrence of extreme cold temperature has generally decreased (DeGaetano and Allen, 2002). The US has also experienced an increasing probability of intense precipitation events (Groisman *et al.*, 2005). With global warming, it is anticipated that extreme weather events such as droughts and floods will become more frequent, widespread and intense during the 20$^{\text{th}}$ century (IPCC, 2007b), yet there is a large uncertainty in these projections, particularly at the national and regional spatial scales. Future climate simulations generally project increases in the greatest precipitation events over northwestern and northeastern North America (Meehl *et al.*, 2005). However, there is a substantial level of disagreement between models for the magnitude and the sign of extreme precipitation events.

Climate change experiments and the assessments of the economic impacts of global climate change have mostly focused on changes in the mean rather than on extremes. However, the primary social impacts and economic costs associated with climate change are likely to result from shifts in the frequency and magnitude of extreme events. A combination of observed trends, theoretical understanding of the climate system, and numerical modeling experiments is needed to better understand how future climate change may impact the frequency and intensity of extreme events. Additionally, investigating changes in extreme events under climate change should take into account the large uncertainty in future projections of climate change.

In this paper, we present an analysis of future changes in the tails of daily-scale temperature and precipitation distribution over the US for climate simulations of future climate change. This study focuses on three sources of uncertainty in projections of climate change: (i) uncertainty in the emissions projections, using different climate policies; (ii) uncertainty in the climate system parameters, represented by different values of climate sensitivity and the strength of aerosol forcing; and (iii) natural variability, obtained by perturbing initial conditions. The simulations used in this analysis are part of a multi-model project to achieve consistent evaluation of climate change impacts in the US (Waldhoff *et al.*, 2013).

2. METHODOLOGY

2.1 Model Description

For this study, we use an ensemble of climate simulations with the Massachusetts Institute of Technology (MIT) Integrated Global System Model–Community Atmosphere Model (IGSM-CAM) (Monier *et al.*, 2013b). The IGSM is an integrated assessment model that couples an earth system model of intermediate complexity to a human activity model. The earth system component of the IGSM includes a two-dimensional zonally averaged statistical dynamical representation of the atmosphere, a three-dimensional dynamical ocean component with a thermodynamic sea-ice model and an ocean carbon cycle (Dutkiewicz *et al.*, 2005, 2009) and a Global Land Systems (GLS) that represents terrestrial water, energy and ecosystem processes (Schlosser *et al.*, 2007), including terrestrial carbon storage and the net flux of carbon dioxide, methane and nitrous oxide from terrestrial ecosystems. The IGSM2.3 also includes an urban air chemistry model (Mayer *et al.*, 2000) and a detailed global scale zonal-mean chemistry model (Wang *et al.*, 1998) that considers the chemical fate of 33 species including greenhouse gases and aerosols. Finally, the human systems component of the IGSM is the MIT Emissions Predictions and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005), which provides projections of world economic development and emissions over 16 global regions along with analysis of proposed emissions control measures.

Since the IGSM includes a human activity model, it is possible to analyze uncertainties in emissions resulting from both uncertainty in model parameters and uncertainty in future climate policy decisions. Another major feature is the flexibility to vary key climate parameters controlling the climate response: climate sensitivity, strength of aerosol forcing and ocean heat uptake rate. Because the IGSM has a two-dimensional zonal-mean atmosphere, it cannot be directly used to simulate regional climate change. To simulate climate change over the US, the IGSM is linked to the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM) (Collins *et al.*, 2006), with new modules developed and implemented in CAM to allow climate parameters to be changed to match those of the IGSM. In particular, the climate sensitivity of CAM is changed using a cloud radiative adjustment method (Sokolov and Monier, 2012). In the IGSM-CAM framework, CAM is run at a horizontal resolution of 2° x 2.5°. More details on the IGSM-CAM framework can be found in (Monier *et al.*, 2013b).

2.2 Description of the Simulations

Uncertainty in future climate change is considered by running the IGSM-CAM with four values of climate sensitivity and three emissions scenarios, resulting in 12 core simulations. The three emissions scenarios considered are (i) a reference scenario with unconstrained emissions after 2012 (REF), with a total radiative forcing of 9.7 W/m^2 by 2100; (ii) a stabilization scenario (POL4.5), with a total radiative forcing of 4.5 W/m^2 by 2100; and (iii) a more stringent stabilization scenario (POL3.7), with a total radiative forcing of 3.7 W/m^2 by 2100. The four values of climate sensitivity (CS) considered are 2.0, 3.0, 4.5 and 6°C, which represent respectively the lower bound (CS2.0), best estimate (CS3.0) and upper bound (CS4.5) of climate sensitivity based on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007a), and a low probability/high risk climate sensitivity (CS6.0). The associated net aerosol forcing was chosen to ensure a good agreement with the observed climate change over the 20th century. More details on the emissions scenarios and the economic implications, along with the choice of climate sensitivity are given in Paltsev *et al.* (2013). For each set of climate sensitivities and emissions scenarios, a five-member ensemble is run with different initial conditions to account for the uncertainty in natural variability in the climate system, resulting in a total of 60 simulations. Results are presented for the five-member ensemble means in order to better extract any long-term signal from the year-to-year variability and provide more robust results.

Monier *et al.* (2013a) provides an overview of the projected changes in mean temperature and precipitation over the US, along with an analysis of the contributions of various sources of uncertainty. Monier *et al.* (2013a) shows that the choice of the climate model has a large impact on the range and patterns of precipitation changes, less so for changes in temperature. As a result, a limitation of this study is that we only use one atmospheric model. The consideration of other models would likely give a wider range of changes in extreme precipitation events and should be the focus of further research.

2.3 Calculation of Extreme Events

In this study we analyze the changes in number of frost days (nFD) between present day (defined as the 1981–2010 period) and the 2086–2115 period (hereinafter referred to as 2100). The number of frost days is defined as the number of days with daily minimum temperature less than 0°C. We also analyze the changes in the 30-year means of annual 95th percentile daily maximum temperature (T95), annual 5th percentile daily minimum temperature (T05), and annual 95th percentile daily precipitation events (P95) over the US from present day to 2100. Each of these metrics is calculated following the method presented in Diffenbaugh *et al.* (2006); Walker and Diffenbaugh (2009). For each 30-year period considered (present day and future), T95 is calculated at each grid cell for each year, and the T95 30-year mean is then calculated. The same approach is used for the T05. Essentially, we are taking the mean of the 18th warmest event (or 18th coldest event) of each of the years considered in each period and analyzing how this metrics changes from present day to 2100. The method differs slightly for precipitation, because precipitation does not necessarily occur every day of the year at every grid cell. As a result, we first determine for each grid cell the days when precipitation occurs—defined as daily precipitation exceeding 1.0 mm following (Mesinger *et al.*, 2006)—and then calculate the 95th percentile of rain days for each year. Finally we present an analysis of the changes in the annual number of rain days (nRD), defined as the number of days per year with precipitation exceeding 1.0 mm.

3. RESULTS

Figure 1 shows maps of changes in annual 5th percentile in daily minimum temperature (T05) from present day to 2100 for the 12 core simulations, averaged over the five initial conditions. The range of changes in T05 varies greatly among the different emissions scenarios and climate sensitivities. All simulations show increases in T05, with a general north-south dipole pattern. The largest increases take place in the Northern US and over the Rocky Mountains, and the least amount of change occurs over the Southern States. The impact of the climate sensitivity is strong among all emissions scenarios. Under the REF scenario, the maximum increases in T05 range

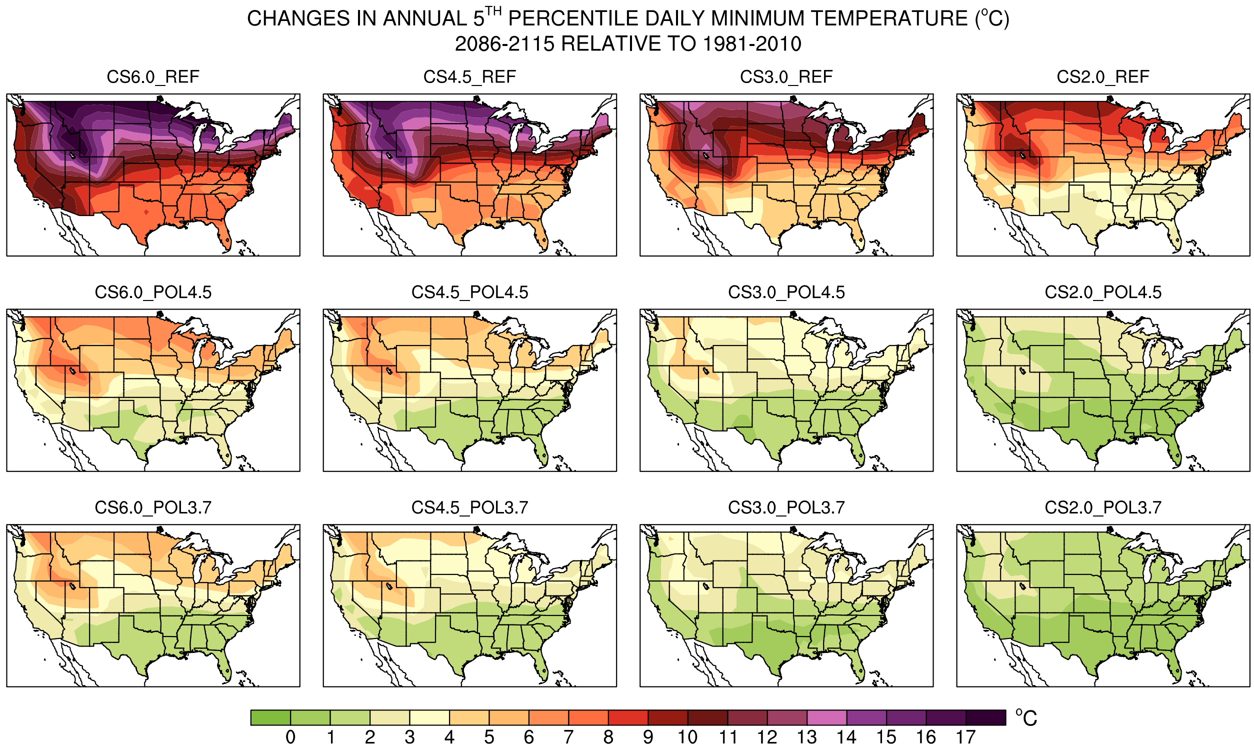

Figure 1. Changes in annual 5th percentile of daily minimum temperature (in °C) for the 2085–2115 period relative to the 1981–2010 period each of the 12 core scenarios, averaged over the five different initial conditions.

from about 16°C for CS6.0 to around 10°C for CS2.0. In comparison, the the implementation of either policy scenario limits the increases in T05 to under 7°C, regardless of the value of climate sensitivity. For the lowest climate sensitivity (CS2.0), changes in T05 are less than 3°C over most of the US. This underlines the risk of severe changes in extreme events under a reference scenario and the strong mitigating impact the stabilization scenarios.

Figure 2 shows a similar analysis for changes in annual 95th percentile in daily maximum temperature (T95). Unlike for T05, the general patterns of change in T95 exhibit a strong east-west dipole pattern. The largest increases in T95 are found over the Western US, and to a lesser extent over the Great Lakes and New England. Under the reference scenario, the magnitude of increase in T95 ranges from 5° to 12°C over the Western Coast and from 2° to 7°C in the Eastern US. Such increases in the top 18 warmest events per year would likely have devastating impacts on both ecosystems and humans. To put this in perspective, during the European summer heat wave of 2003, Europe experienced summer surface air temperature anomalies (based on the June-July-August daily averages) reaching up to 5.5°C with respect to the 1961–1990 mean (Garcia-Herrera *et al.*, 2010). Instead of 5°C anomaly from the mean, the present results suggest that, under the reference scenario, the present-day extreme temperatures are likely to increase by 5°C over a large part of the US. However, under either policy scenario, the intensification of T95 would be drastically reduced, with increases of less than 1°C over most of the US for the CS2.0_POL3.7 scenario.

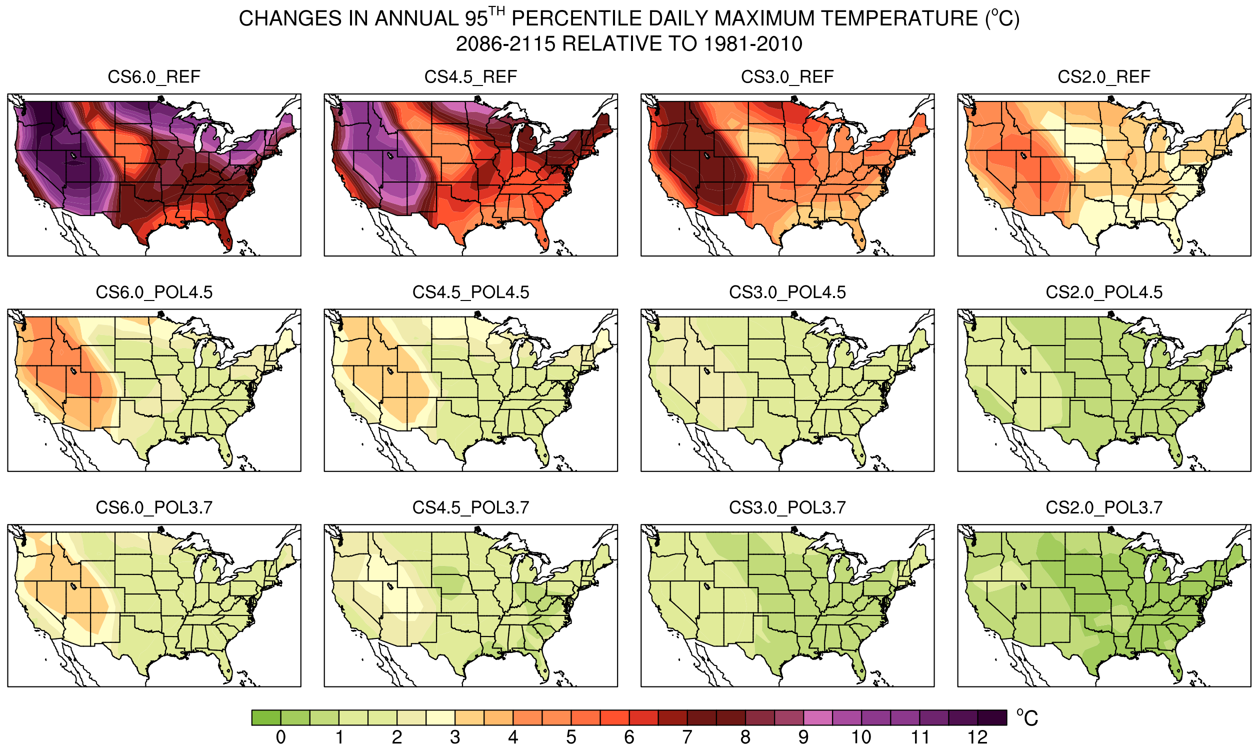

Figure 2. Changes in annual 95th percentile of daily maximum temperature (in °C) for the 2085–2115 period relative to the 1981–2010 period each of the 12 core scenarios, averaged over the five different initial conditions.

Figure 3 shows a comparison of the IGSM-CAM simulation of present-day annual mean number of frost days (nFD) with observational data from the North American Climate Extremes Monitoring Project (NACEM, information online at www.ncdc.noaa.gov/nacem/). The model simulation agrees reasonably well with the observations and clearly captures the spatial distribution of frost days over the US. The distribution shows a strong latitude gradient, ranging from the almost frost-free region over the Southern US (Texas, Florida, Arizona, and California) to the frost-dominated Northern US (with an average of 150 frost days per year). The latitudinal gradient is modulated by the presence of the Rocky Mountains where the nFD is as large as in the Northern US. Finally coastal regions usually display fewer frost days than inland. Figure 3 also shows the annual mean nFD in 2100 under each set of climate sensitivities and emissions scenarios. There is a great deal of resemblance in the spatial distributions of frost days among all the simulations. Compared with present day, all the simulations show decreases in nFD across the US in response to the ubiquitous temperature rise. The largest decreases occur for the REF scenario and for the highest climate sensitivity (CS6.0), where no region experiences more than 40 days of frost per year on average. This is equivalent to a decrease in nFD of about 20 days for warmer regions and of more than 100 days for colder regions. Furthermore, the frost-free zone expands to all of California, the northern Pacific Coast, most of Arizona, the Gulf Coast and the coast of the Carolinas. Under the reference scenario, the range of number of frost days in 2100 between the different values of climate sensitivity is large, indicating the impact of the uncertainty

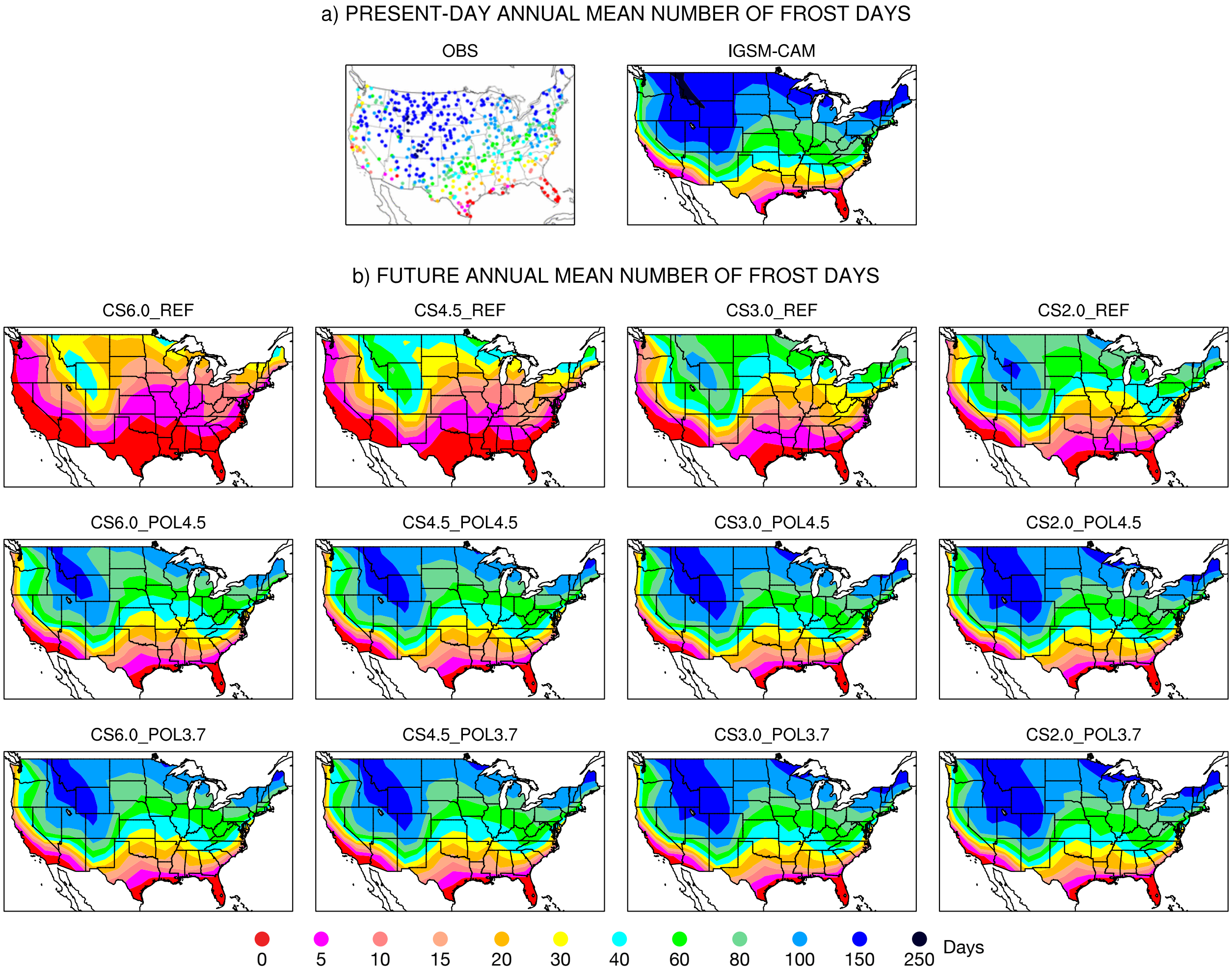

Figure 3. Annual number of frost days a) for NACEM observations and IGSM-CAM simulation of present day (1981–2010 period) and b) for IGSM-CAM simulations of the 2086–2115 period for each of the 12 core scenarios, averaged over the five different initial conditions.

in climate sensitivity. The implementation of any of the two stabilization policies greatly reduces the decrease in nFD from present day to 2100 compared to the REF scenario. Finally, the maps of nFD in 2100 are very similar amongst stabilization scenarios, even for different values of the climate sensitivity. This indicates that constraining future emissions would greatly constrain future changes in frost days, regardless of our understanding of the climate system response.

Figure 4 shows the changes in annual 95th percentile in rain day (P95) events. The IGSM-CAM simulations show a general increase in the intensity of extreme precipitation events over most of the US. The largest changes are coincident with the simulations with the largest warming, highest climate sensitivity and highest levels of greenhouse gases concentrations in the atmosphere). Therefore, the implementation of any stabilization policy will inevitably have great impact. For example, changes in P95 in the CS6.0_POL4.5 scenario are about the same as in the CS2.0_REF scenario. Unlike changes in extreme temperature events, precipitation changes show more heterogeneity in their spatial distributions. A number of local changes are not consistent

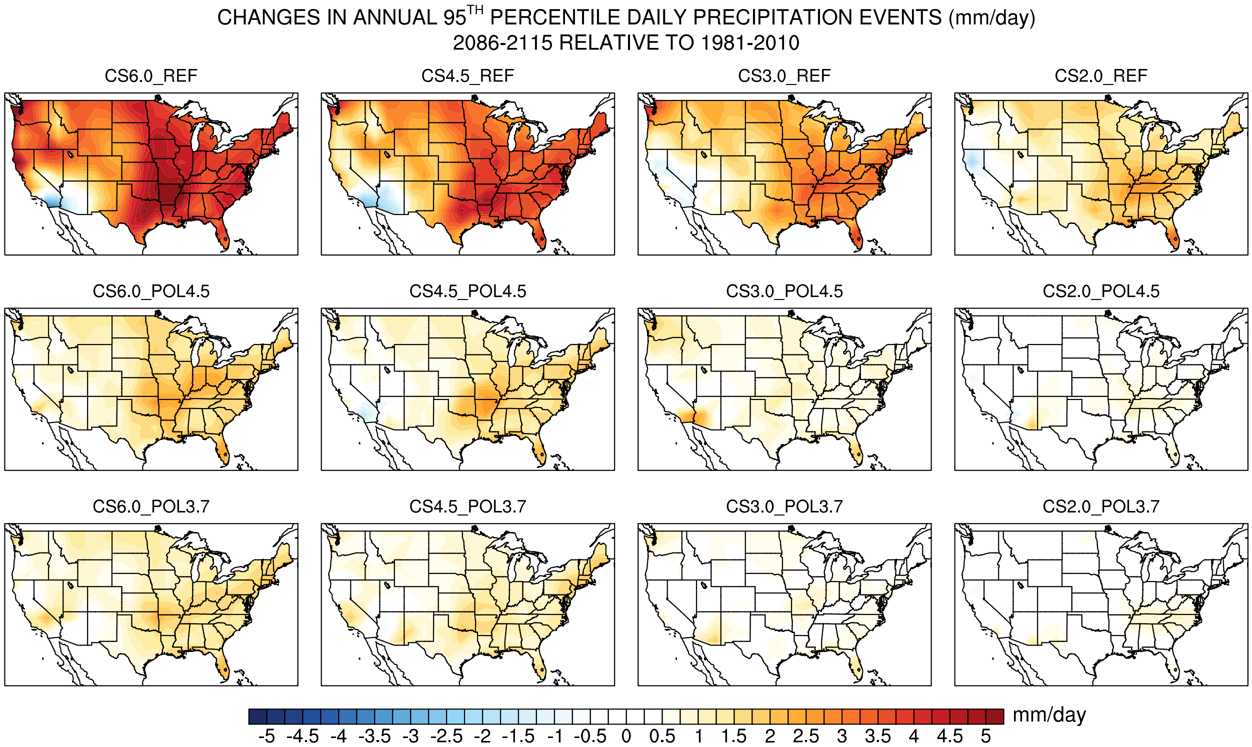

Figure 4. Changes in annual 95th percentile of daily precipitation events (in mm/day) for the 2085–2115 period relative to the 1981–2010 period each of the 12 core scenarios, averaged over the five different initial conditions.

among the various simulations. For example, P95 over Southern California decreases in the CS6.0_REF and CS4.5_REF scenarios but increases in the CS3.0_POL4.5. This is caused by the small size of the ensemble simulation with perturbation of initial conditions. These results are essentially dominated by large inter annual variability in a particular member of the ensemble simulation. This underlines the importance of running multiple simulations with different initial conditions to extract a robust signal.

Changes in the average number of rain days (nRD) per year from present day to 2100 are show in **Figure 5**. All simulations show an increase in nRD over most of the US, and particularly over the Great Plains, with decreases in nRD only over the northern Pacific Coast and along the Gulf Coast. The magnitude of the changes varies greatly among the 12 simulations, and is affected equally by climate sensitivity and emissions scenario. The changes in nRD also display a latitudinal migration of the location of the maximum increases and decreases in nRD with various emissions scenarios. Under the POL3.7 scenario, the maximum increase in nRD occurs over the Southern Great Plains, while the maximum decrease takes place over Oregon. Under the REF scenario, the location of the maximum increase and decreases tends to shift north, in particular for the higher values of climate sensitivity. Changes in nRD for the CS2.0_POL3.7 scenario remain under 10 rain day events per year over most of the US.

It should be noted that, in this analysis, the northern Pacific Coast experiences a decrease in the number of rain day events but an increase in the magnitude of heavy precipitation events. In

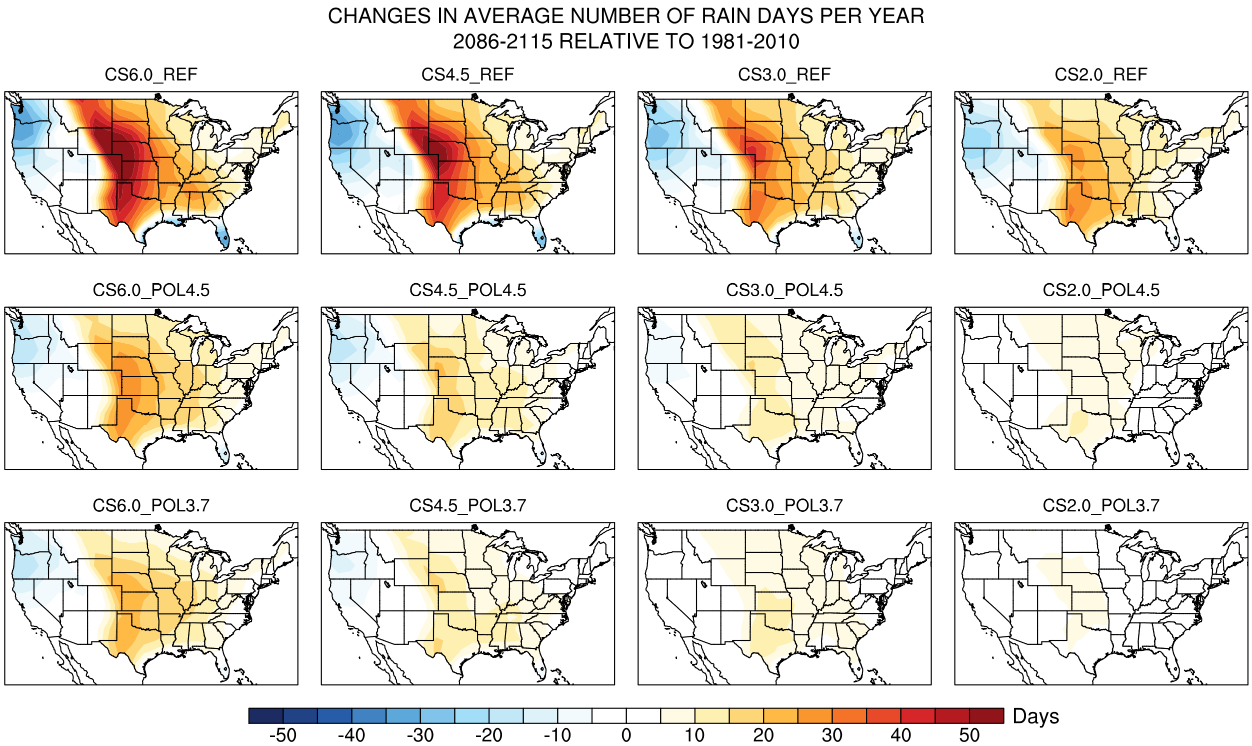

Figure 5. Changes in annual number of daily precipitation events for the 2085–2115 period relative to the 1981–2010 period each of the 12 core scenarios, averaged over the five different initial conditions.

contrast, the simulations project increases in extreme precipitation over the Great Plains concurrently with an increase in the number of rain days. This demonstrates the heterogeneous spatial response of extreme events to climate change.

4. SUMMARY AND CONCLUSION

In this study, we analyze changes in extreme events from 60 IGSM-CAM simulations of climate change used in a multi-model project to achieve consistent evaluation of climate change impacts in the US. The IGSM-CAM simulations are built around a core of 12 scenarios with three different emissions scenarios and four values of climate sensitivity. For each of the 12 core simulations, a five-member ensemble simulation is run with different initial conditions to account for uncertainty in natural variability. This modeling framework considers three sources of uncertainty in future climate projections: projected emissions, global climate response and natural variability.

The results show a general intensification of extreme daily maximum temperatures and extreme precipitation events over most of the US. The number of rain days per year increases over the Great Plains but decreases in the northern Pacific Coast and along the Gulf Coast. This means that the Northern Pacific Coast is likely to experience fewer rain days on average but more intense extreme precipitation events. Extreme daily minimum temperatures increase, especially over the northern parts of the US. As a result, the number of frost days per year decreases over the entire US and the frost-free zone expands northward. This study displays a wide range of future changes in extreme events in the US, even simulated by a single climate model. Nonetheless, it clearly shows that under a reference emissions scenario with no climate policy, changes in extreme events reach dangerous levels, especially for large values of climate sensitivity. On the other hand, the implementation of a stabilization scenario, drastically reduces the changes in extremes, even for the highest climate sensitivity considered.

Under the reference scenario, the increase in the coldest days temperature over the northern parts of the US would likely lead to positive impacts on energy demand during the winter. However, the intensification of extreme hot days reach seriously dangerous levels, with an increase of 5°C in T95 over a large part of the US, regardless of the climate sensitivity. The economic impacts of the intensification of extreme hot days are likely to be significant as it would affect agriculture, energy and water demand (especially in California) and human health. The significant decreases in annual number of frost days over most of the US would likely have benefits for agriculture as it would bring an earlier spring and would result in a longer growing season. This has already been observed in the past few decades (Hicke *et al.*, 2002). At the same time, milder winters and a decrease in frost days would increase the survival of many insects and pests (Bale *et al.*, 2002), which could lead to the spread of crop diseases. Meanwhile, the implementation of stabilization policies significantly limits the changes in annual number of frost days, regardless of the climate sensitivity. The complex interaction between the various changes in extreme events and the numerous impacts on economic sectors makes a comprehensive analysis of the climate change impacts difficult. This emphasizes the need for multi-model projects to achieve consistent evaluation of climate change impacts in the US (Waldhoff *et al.*, 2013).

A particular difference between changes in extreme temperature and extreme precipitation is the presence of local changes in precipitation with different signs in different scenarios. These local changes arise from large year-to-year variability in the individual simulation with different initial conditions. This indicates that the five-member ensemble is not large enough to filter out all the noise at the local scale and extract robust signals over the entire US. This further emphasizes the need for large ensemble simulation sampling for various sources of uncertainty in climate change.

Finally, a limitation of this study is that only one atmospheric model is considered. However, considering the large range of future changes in extreme events simulated by a single climate model, this study emphasize the great deal of uncertainty in both future climate change and its impacts on extreme event in the US. In addition, we realize that the relatively low resolution of the IGSM-CAM might lead to biases in the realism of key atmospheric processes controlling extreme events. Walker and Diffenbaugh (2009) find that higher resolution could confer more accurate simulations of the tails of daily-scale distribution. However, an uncertainty analysis based on a large ensemble simulation with different values of climate sensitivity, different emissions scenarios and multiple initial conditions would prove particularly difficult with a variety of climate models including high-resolution models. Nonetheless, we intend to extend this uncertainty analysis of changes in extreme events under climate change to take into account structural uncertainty and the influence of horizontal resolution.

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