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Key Points:
- Biases in the unperturbed climatology contribute to the uncertainty in climate change projections
- Biases in the climatological SST have a larger impact on regional projections over land than do uncertainties in the pattern of SST change
- AGCMs with observed SSTs should provide a simple and immediate step toward reducing the intermodel spread

Supporting Information:
- Supporting Information S1

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The impact of SST biases on projections of anthropogenic climate change: A greater role for atmosphere-only models?

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Abstract There is large uncertainty in the model simulation of regional climate change from anthropogenic forcing. Recent studies have tried to link such uncertainty to intermodel differences in the pattern of sea surface temperature (SST) change. On the other hand, coupled climate models also contain systematic biases in their climatology, largely due to drift in SSTs. To the extent that the projected changes depend on the mean state, biases in the present-day climatology also contribute to the intermodel spread in climate change projections. By comparing atmospheric general circulation model (AGCM) simulations using the climatological SSTs from different coupled models, we show that biases in the climatological SST generally have a larger impact on regional projections over land than do intermodel differences in the pattern of SST change. These results advocate for a greater application of AGCM simulations with observed SSTs or flux-adjusted coupled models to improve regional projections of anthropogenic climate change.

1. Introduction

There is growing demand by the scientific community, policy makers, and stakeholders for realistic projections of anthropogenic climate change. The main tools for such an endeavor are the coupled ocean-atmosphere models (CGCMs). However, the current CGCM projections are very uncertain, particularly at regional scales. Furthermore, the past few generations of CGCMs have shown little improvement in regional robustness, despite the substantial development in climate models and computational capacity [*Knutti and Sedlacek*, 2013]. This limits the utility of CGCMs for regional planners when considering the potential impacts of climate change, and improving the fidelity of regional climate projection should take high priority.

A number of recent studies have tried to understand the source of regional uncertainties. Among them, a link was established to the uncertainty in the pattern of sea surface temperature (SST) change. The pattern of SST change dominates local precipitation changes through a “warmer-get-wetter” mechanism [*Xie et al*., 2010] and is a major source of uncertainty in precipitation changes over tropical [*Ma and Xie*, 2013; *Kent et al*., 2015] and extratropical [*Long and Xie*, 2015] oceans. Over land, however, the impact of the pattern of SST change is less clear. *Kent et al*. [2015] found a moderate relationship between changes in East African long rains and Indian Ocean SST anomalies. On the other hand, *He et al*. [2014] found that climate over land is insensitive to the Coupled Model Intercomparison Project Phase 3 (CMIP3) ensemble mean pattern of SST change, although they did not investigate the pattern of SST change from individual CGCMs.

In addition, CGCMs are known for their large biases in climatology. Because many aspects of the changes in regional climate depend upon the unperturbed climatology [e.g., *Held and Soden*, 2006; *Matsueda and Palmer*, 2011; *Scheff and Frierson*, 2012; *Huang et al*., 2013], climatological biases in CGCMs could lead to unrealistic projections of anthropogenic climate change. However, the full importance of having an unbiased climatology for the projection of anthropogenic climate change has been insufficiently addressed and possibly underappreciated. Although correcting the climatology in a free-running CGCM is extremely difficult, correcting the climatological SST can be easily done in an atmosphere-only (atmospheric general circulation model (AGCM)) or flux-adjusted coupled framework. Recent studies have shown a much-improved simulation of regional climatology by correcting biases in the climatological SST and, as a result, a much-improved seasonal prediction [*Magnusson et al*., 2013; *Vecchi et al*., 2014; *Jia et al*., 2015]. Could the use of AGCMs with observed SST climatology improve regional projections of anthropogenic climate change?

In this paper, we address the impact of climatological biases on the simulation of anthropogenic climate change. We also compare the relative influence of biases in the climatological SST and pattern of SST change, as they both introduce uncertainty to projections as boundary conditions. We focus on climate change over land where the societal demand for accurate regional predictions is the greatest.

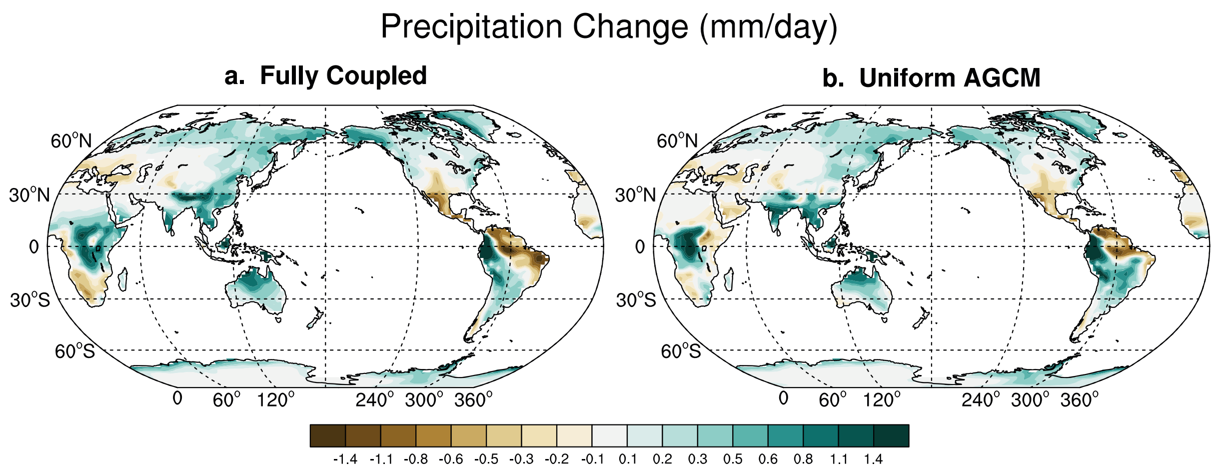

Figure 1. Land precipitation change from (a) the fully coupled simulation and (b) the uniform AGCM simulation using the CESM model.

2. Model Simulations

We conduct a suite of simulations with the Community Earth System Model (CESM) [*Hurrell et al*., 2013] to assess the relative importance of climatological SST and pattern of SST change. The fully coupled simulation is run with the 1pctCO2 scenario starting with the preindustrial CO_2 concentration. The base climate is defined as year 11 to 40 when the CO_2 level is similar to the observation during 1982 to 2011, whereas the perturbed climate is defined as years 131 to 160, when CO_2 is 3.3 times that from years 11 to 40.

The "obsSST" simulation is run with the same CO_2 and SST anomaly as the fully coupled simulation but uses the merged Hadley-NOAA/Optimal Interpolation SST [*Hurrell et al*., 2008] from years 1982 to 2011 as the climatological SST. The "modelSST" simulations are run with the same CO_2 and SST anomaly as the fully coupled simulation but use the historical SST (years 1982 to 2011) from five CMIP5 CGCMs, namely, CanESM2, CNRM-CM5, GISS-E2-H, HadGEM2-ES, and MRI-CGCM3. These five CGCMs are the only CMIP5 models to provide extended historical simulation to year 2011 and are used here for the convenience to compare against the observation.

The "ensemblePattern" and "modelPattern" simulations are run with the SST anomalies from the CMIP5 ensemble mean and the five individual CGCMs, respectively. As shown in the supporting information Table 1, these five models cover a wide range of SST biases and SST anomalies from the CMIP5 models. The SST anomalies are scaled linearly by its global mean in order to have the same global mean as the coupled CESM simulation. The "uniform AGCM" simulation is run with a uniform SST warming calculated as the global mean SST change from the fully coupled simulation. The "uniform AGCM," the "ensemblePattern," and the "modelPattern" simulations all use the climatological SST from the fully coupled simulation. The sea ice is taken from the coupled CESM simulation for all AGCM simulations. There is no interannual variability in the boundary conditions, but the seasonal cycle is included. All AGCM simulations are run for 34 years with the first 4 years discarded. All simulations are run with an approximate 2° resolution for the atmospheric model.

3. Results

In a typical global warming simulation, the atmosphere-land model is driven externally by two sources of forcing: the direct atmospheric radiative forcing, which is mainly due to the increasing CO_2, and the warming of the ocean surface, which can be separated into the global mean warming and the pattern of warming. While the CO_2 concentration and the global mean warming are relatively easy to determine, the pattern of SST change is much more uncertain [e.g., *Ma and Xie*, 2013]. Recently, the pattern of SST change has received much attention as a potential source of uncertainty in regional climate projection [*Ma and Xie*, 2013; *Kent et al*., 2015; *Long and Xie*, 2015].

Here we compare climate changes in the fully coupled CESM simulation and AGCM with uniform SST warming (uniform AGCM). As shown in Figure 1, the change in precipitation over land is very similar in the

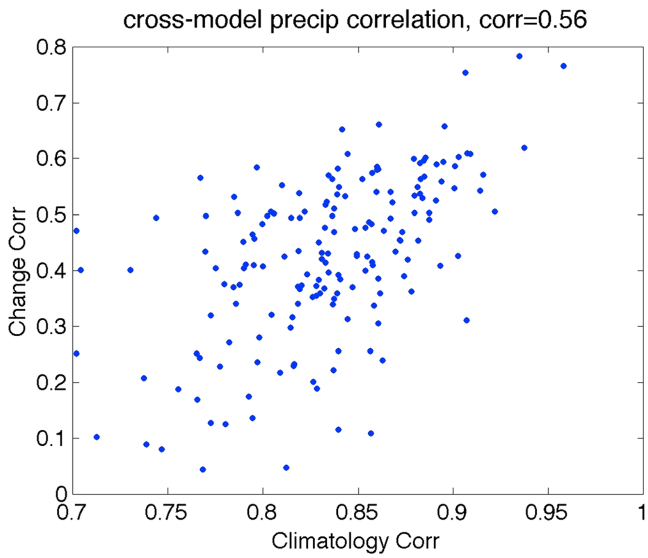

Figure 2. Scatterplot of cross-model spatial correlation of global precipitation climatology versus the corresponding spatial correlation of the change in precipitation. The positive correlation indicates that a higher degree of similarity in precipitation climatology generally leads to a higher degree of similarity in projected change in precipitation. Nineteen CGCMs from the CMIP5 1pctCO2 experiment are analyzed: ACCESS1-0, bcc-csm1-1, BNU-ESM, CanESM2, CCSM4, CESM1-CAM5, CMCC-CM, CNRM-CM5, CSIRO-Mk3-6-0, FGOALS-s2, GFDL-CM3, GISS-E2-R, HadGEM2-ES, inmcm4, IPSL-CM5B-LR, MIROC5, MPI-ESM-MR, MRI-CGCM3, and NorESM1-M.

two simulations, with a spatial correlation of 0.82. Discrepancy can be found in certain regions particularly close to tropical oceans where the pattern of SST change can influence land through shift of convection (e.g., the Eastern China, the central East Africa, and parts of South America [*Kent et al*., 2015]). For these regions, the pattern of SST changes is indeed important. However, over most land regions, the magnitude and structure of precipitation is almost identical. The similarity between the fully coupled and the uniform AGCM simulations is also evident in land surface temperature change and sea level pressure (SLP) change (supporting information Figure S2). The overall ineffectiveness of the pattern of SST change is likely due to the insensitivity of Rossby wave generation to the anthropogenically forced patterns of SST change, as detailed in *He et al*. [2014].

On the other hand, regional projections may suffer from biases in the models' climatology. Here we compare the cross-model correlation of CGCMs' simulations of precipitation climatology with the corresponding projections of precipitation change (Figure 2). Overall, models that have more similar precipitation climatology project more similar precipitation change. The dependence of climate change on the unperturbed climate is understandable since many spatial structures of future climate change are positioned relative to the structures of the contemporary climate [e.g., *Held and Soden*, 2006; *Matsueda and Palmer*, 2011; *Scheff and Frierson*, 2012; *Huang et al*., 2013]. Therefore, it is important to have an accurate climatology for regional climate projection.

Because the climatology of most atmospheric variables largely depends on the underlying SST, biases in models' climatological SSTs should have a large impact on the simulation of the atmospheric climatology, which has been demonstrated in recent studies of seasonal climate forecast using the Geophysical Fluid Dynamics Laboratory climate model [e.g., *Vecchi et al*., 2014; *Jia et al*., 2015]. Figure 3 shows the biases in the climatological SSTs from CMIP5 CGCMs. All CGCMs contain substantial SST biases in almost every basin. Although the SST biases vary from model to model, most CGCMs show a warm bias in the southeastern tropical Pacific and the Southern Ocean and a cold bias in the extratropical North Atlantic, north midlatitude Pacific, and equatorial Pacific. The cold tongue bias has been shown to have an important influence on regional rainfall simulations [*Li et al*., 2016]. The impact of these SST biases on the simulation of anthropogenic climate change over land is yet to be determined.

To understand the impact of SST biases and its importance relative to the uncertainty in the pattern of SST change, we calculate the spatial correlation of some key variables over land between simulations in which either the climatological SST or the pattern of SST change is altered (section 2). In Figure 4a, we first use the CESM model to compare the impact of model biases in the climatological SST and the impact of model biases in the pattern of SST change, which is defined as the deviation from the CMIP5 ensemble mean pattern of SST change. The impact of the climatological SST biases is assessed by the spatial correlation between the coupled simulation and the AGCM simulation with observed climatological SST—a low correlation indicates a large impact from the SST biases (*y* axis); likewise, a low correlation between the coupled simulation and the AGCM simulation with the CMIP5 ensemble mean pattern of SST change indicates a large impact from differences in the pattern of SST change (*x* axis). Therefore, we can compare the relative

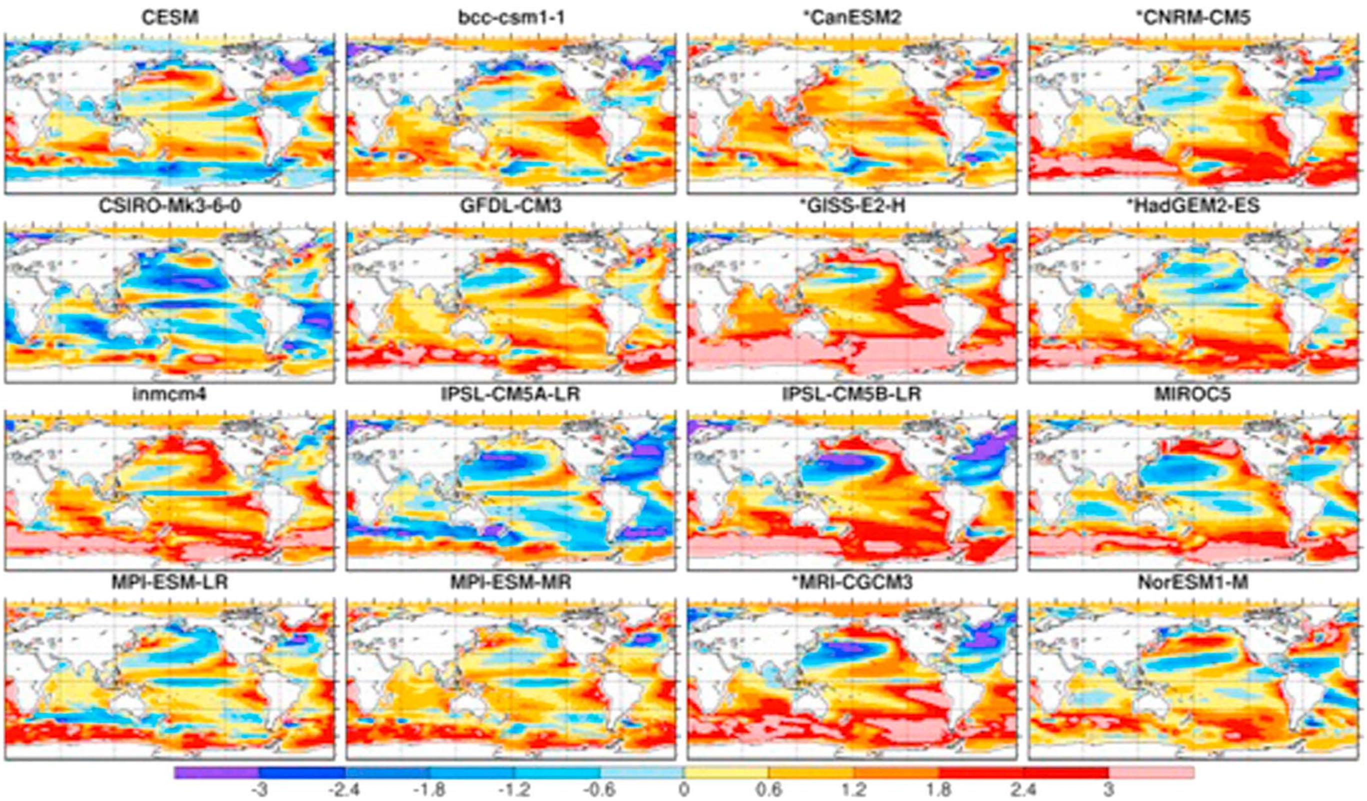

Figure 3. SST climatology biases in the CESM model and the 15 CGCMs from CMIP5. Biases are calculated against the observation (merged Hadley-NOAA/OI SST) from years 1982 to 2011. An asterisk indicates that the model's climatological SST is taken from the historical simulation (years 1982–2011). The other models' SST is taken from years 11 to 40 of the 1pctCO2 simulation.

impact of SST biases and pattern of SST change through the position of the data points relative to the diagonal line.

As shown in Figure 4a, almost all variables show a correlation below the diagonal line, which indicates that biases in the climatological SST has overall greater impact on the projected changes in the variables than differences in the pattern of SST change. Figure 4b offers a complementary perspective to Figure 4a and shows that even the extreme case of a total removal of the pattern of SST has overall less impact than biases in the climatological SST.

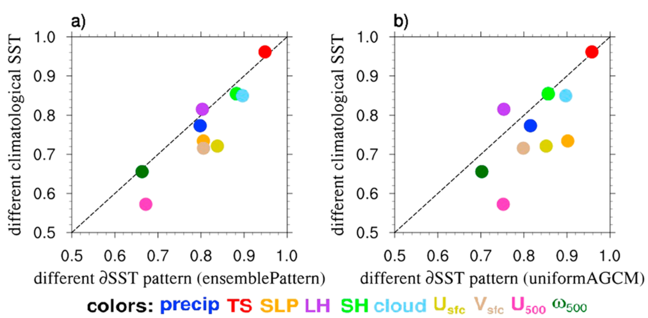

Figure 4. Scatterplots of spatial correlation between simulations with different SST climatology versus simulations with different patterns of SST change. The *y* axis represents the spatial correlation between the coupled CESM and the "obsSST" simulation. The *x* axis represents the spatial correlation (a) between the coupled CESM and the "ensemblePattern" simulation and (b) between the coupled CESM and the "uniform AGCM" simulation. The spatial correlation is calculated for changes over global land. Colors indicate variables, which are precipitation, surface temperature, sea level pressure, surface latent heat, surface sensible heat, total cloud cover, surface *U*, surface *V*, 500 mbar *U*, and 500 mbar vertical pressure velocity.

In Figure 5, we show results from similar investigations in which we conduct AGCM simulations with the climatological SSTs and the patterns of SST change from individual CGCMs. The five CGCMs that we took cover a wide spectrum of models and provide historical SSTs of the same time period as the observation (section 2). As shown in Figures 5a and 5b, surface temperature shows little sensitivity to either climatological SST biases or pattern of SST change.

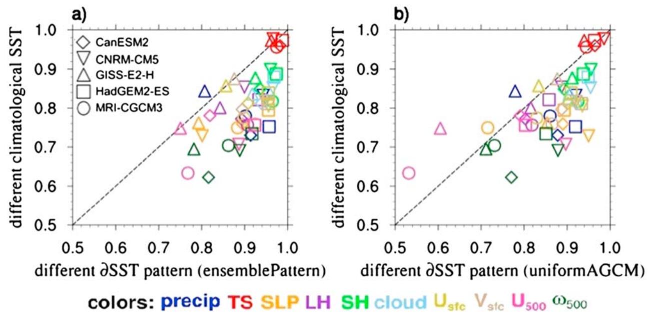

Figure 5. Scatterplots of spatial correlation between simulations with different SST climatology versus simulations with different pattern of SST change. This is similar to Figure 4 except using the climatological SST and patterns of SST change from different CGCMs. The *y* axis represents the spatial correlation between the "modelSST" and the "obsSST" simulation. The *x* axis represents the spatial correlation (a) between the "modelPattern" and the "ensemblePattern" simulation in and (b) between the "modelPattern" and the "uniform AGCM" simulation. The markers annotate the CGCMs from which the climatological SSTs and the patterns of SST change are taken. The numbers of models that fall below the diagonal line out of a total of 5 are 4 (4), 3 (2), 5 (4), 5 (5), 5 (5), 5 (5), 4 (4), 5 (5), 5 (3), and 5 (5) in Figure 5a (5b) for each variable, respectively.

For the other variables, however, most data points fall below the diagonal line, indicating that the CGCMs are in general more sensitive to biases in the climatological SST than differences in the pattern of SST change. For certain CGCMs, biases in the climatological SST lead to a substantial misrepresentation of changes in precipitation, SLP, 500 mb vertical velocity, and zonal wind (with a spatial correlation below or close to 0.7 against the obsSST simulation). As shown in Figure 5b, such degradation of model projections resulting from the SST biases is overall larger than that caused by the extreme case of a total removal of the pattern of SST change. In supporting information Figures S3 and S4, we show the same comparison as Figures 4 and 5 but using RMS instead of correlation, which yield consistent results. These results indicate the importance of calibrating the SST climatology for the simulation of anthropogenic climate change over land, which has not been sufficiently recognized or addressed.

4. Conclusions and Discussion

Projections of regional climate change are uncertain at regional scales. Previous studies have demonstrated the dependence of certain characteristics of anthropogenic climate change on climatology [e.g., *Held and Soden*, 2006; *Scheff and Frierson*, 2012; *Huang et al.*, 2013]. This paper investigates how the uncertainty in regional projections may be related to the climatological biases in CGCMs. We showed that CGCMs with more similar precipitation climatology generally project more similar precipitation change, which indicates a large impact of climatological biases. Since the current observation is not adequate to directly calibrate projections of anthropogenic climate change, improving the simulation of the contemporary climate should be an important step toward more realistic projections, which has also been recognized by other studies [*Matsueda and Palmer*, 2011; *Sobolowski and Pavelsky*, 2012].

Because most atmospheric variables are structured relative to the underlying SST, most of the biases in the atmospheric climatology result from the biases in SST. To understand the impact of SST biases on the projection of anthropogenic climate change, we conducted AGCM simulations in which the climatological SST was prescribed from observation and different CGCMs. Results showed that many atmospheric variables over land, including precipitation, SLP, and wind, are strongly influenced by biases in the SST. For land climate projections, biases in the climatological SST generally have a greater impact than a total removal of pattern of SST change, although the latter has proven crucial for climate change over ocean [*Ma and Xie*, 2013; *Kent et al.*, 2015; *Long and Xie*, 2015].

It is useful to think of the uncertainty in regional projections as a combined result of the imprecision of the AGCMs and the uncertainty in the boundary conditions (i.e., the SST). As boundary conditions of AGCMs, both the climatological SST and pattern of SST change have large uncertainties in our current CGCMs. Understanding the relative impact of the two has important implications for improving the accuracy and efficiency of climate projections. The pattern of SST warming has not changed much from CMIP3 to CMIP5 (supporting information Figure S1), despite the substantial effort and computational resources devoted to model development. Therefore, it is reasonable to assume that the general structure of SST warming will remain unchanged for the near-future generations of CGCMs. By exploiting the insensitivity of land climate to the pattern of SST change, the pattern of SST change from the current generation of CGCMs should be adequate for the pragmatic purpose of projecting the anthropogenic climate change over land.

Compared to the pattern of SST change, biases in the climatological SST generally have a greater impact on projections over land and, fortunately, can be fixed at a much cheaper cost. Both AGCM and flux-adjusted CGCM simulations are designed for such purpose and have been proven successful for seasonal climate predictions [*Magnusson et al*., 2013; *Vecchi et al*., 2014; *Jia et al*., 2015]. The flux-adjusted CGCMs could be particularly useful if initialized predictions are required and if changes in SST are influenced by climatological biases [*Brown et al*., 2015]. Although the fidelity of flux-adjusted CGCMs for the simulation of anthropogenic climate change is yet to be tested [*Tziperman*, 2000], AGCMs can precisely downscale the anthropogenic climate changes from CGCMs despite their lack of “two-way” coupling [*He and Soden*, 2015]. Therefore, improved regional projections over land can be achieved by AGCMs with the incorporation of observed SST.

We recognize that simply fixing the SSTs does not remove all of the intermodel spread and the imprecision in AGCMs may still account for a substantial portion of the uncertainty in regional projections. Reducing this part of uncertainty requires continued efforts in improving model physics and may not be accomplished in the near future. However, AGCMs with observed SSTs could potentially provide a simple and immediate step toward reducing the intermodel spread over land. Although our current projections are still dominated by the traditional CGCM simulations with SST biases, by taking advantage of the SST changes from these CGCM simulations, a “two-tier” projection with high-resolution AGCMs (similar to the procedure used in short-term climate forecast) could be a very practical enhancement.

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