Great Plains Precipitation and its SST Links in 20th Century Climate Simulations, and 21st and 22nd Century Climate Projections

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Abstract

The present work assesses spring and summer precipitation over North America as well as summer precipitation variability over the Central U.S. and its SST links in simulations of the 20\textsuperscript{th} century climate and projections of the 21\textsuperscript{st} and 22\textsuperscript{nd} century climates for the A1B scenario.

The observed spatial structure of spring and summer precipitation poses a challenge for models, particularly over the Western and Central U.S.. Tendencies in spring precipitation in the 21\textsuperscript{st} century agree with the observed ones at the end of the 20\textsuperscript{th} century over a wetter North-Central and a drier Southwestern U.S., and a drier Southeastern Mexico. Projected wetter springs over the Great Plains in the 21\textsuperscript{st} and 22\textsuperscript{nd} centuries are associated with an increase in the number of extreme springs. In contrast, observed summer tendencies have demonstrated little consistency in their projections. The associated changes in SSTs bear the global warming footprint which is not well captured in the 20\textsuperscript{th} century climate simulations.

Precipitation variability over the Great Plains presents a coherent picture in spring but not in summer. Models project an increase in springtime precipitation variability due to an increased number of extreme springs. The number of extreme droughty/pluvial events during the spring-fall part of the year is under-/over-estimated in the 20\textsuperscript{th} century without consistent projections.

Summer precipitation variability over the Great Plains is linked to SSTs over the Pacific and Atlantic oceans, with no apparent ENSO link in spite of the exaggerated variability in the equatorial Pacific in climate simulations; this has been identified already in observations and atmospheric models forced with historical SSTs. This link is concealed due to the increased warming in the 21\textsuperscript{st} century. Deficiencies in land-surface-atmosphere interactions and global teleconnections in the climate models prevent them from a better portrayal of summer precipitation variability in the Central U. S..
1. Introduction

Global climate change due to increased man-induced greenhouse gases threatens societies and ecosystems around the planet. In the same way that climate is not equal everywhere, climate change will impact differently around the globe. Thus interest in regional climate change, especially hydroclimate, has increased. As a result of society’s dependence on water supply, as well as the need for prevention and mitigation of extreme hydroclimate events, current and projected regional hydroclimate research has become an issue of fundamental interest.

Carbon dioxide is the most important greenhouse gas which fuels the discussion of anthropogenic climate change. Increased burning of fossil fuels and deforestation have caused carbon dioxide concentrations to increase globally in the 20th century. In an effort to simulate past, present and future climates under the stress of growing greenhouse concentrations, the World Meteorological Organization through the Intergovernmental Panel on Climate Change (IPCC), has lead the assessment of climate simulations of the 20th century and climate projections of the 21st and 22nd centuries from models participating in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3). Findings of the latest assessment are included in the fourth assessment report, highlighting the anthropogenic nature of the current global warming trend (IPCC 2007).

Some of the most difficult aspects of understanding and projecting changes in regional hydroclimate are associated with changes in the circulation of the atmosphere and oceans. This is particularly challenging over Central U.S. where regional hydroclimate strongly depends on the moisture transport from the Gulf of Mexico via the Great Plains low-level jet (e.g., Ruiz-Barradas and Nigam 2005, 2006; Cook et al 2008, Weaver and Nigam 2008). Several empirical and atmosphere model-based studies have documented the importance of the SST links of the
Central U.S. hydroclimate. Both Pacific SST variability (e.g. Ting and Wang 1997, Barlow et al. 2001, Schubert et al. 2004, Seager et al. 2005, Ruiz-Barradas and Nigam 2005, 2010, McCabe et al. 2004, 2008) and Atlantic SST variability (e.g. Enfield et al. 2001, Ruiz-Barradas and Nigam 2005, 2010, Sutton and Hodson 2005, Wang et al. 2006, McCabe et al. 2004, 2008) have the potential to induce anomalous hydroclimatic conditions over North American. It has been shown that SST structures with contrasting signs in the Pacific and Atlantic Oceans (cold/warm Pacific and a warm/cold Atlantic) are conducive to the most extreme (droughty/pluvial) conditions over the Central Great Plains (e.g. Hoerling and Kumar 2003, Schubert et al. 2009). If both basins have the same sign, they are still capable of producing extreme hydroclimatic conditions over the Central U.S. (Schubert et al. 2009). In any case, model experiments suggest that the tropical component largely forces the Central U.S. hydroclimate variability (e.g., Schubert et al. 2004, 2009, Seager et al. 2005, Sutton and Hodson 2005), however, the nature of the tropical anomalies needs some clarification as they may be the result of extratropical activities.

However the influence of the oceans in generating precipitation variability in several models is obscured by their overactive local land-surface-atmosphere interactions (Ruiz-Barradas and Nigam 2005, 2006). Simulations of the 20th century climate based on some models from international research centers, which are part of the CMIP3 multi-model data set (Meehl et al. 2007), revealed difficulties in two aspects of their simulations: the observed distribution of climatological summer precipitation, and the observed link between precipitation variability and moisture flux convergence over Central U.S. (Ruiz-Barradas and Nigam 2006). While it is likely that at the end of the 21st century the Northern half of the U.S. (~north of 45°N) will experience an increase in winter precipitation, the Western U.S. will suffer a deficit in summer precipitation, leaving the conditions of the Central U.S. unclear during spring and summer seasons (e.g.,
Chapter 11 in IPCC 2007). In a recent study by Cook et al. (2008) climate projections of the 21\textsuperscript{st} century were analyzed from models of the CMIP3 data set under a scenario of rapid CO\textsubscript{2} increase (SRES A2; see Nakicenovic et al. 2000); the study concluded that over Central U.S. at the end of the 21\textsuperscript{st} century, climatological springtime precipitation will increase as a result of an increase in the intensity of the Great Plains low-level jet.

The present paper assesses North American climatological spring and summer precipitation, as well as warm-season precipitation variability over the Great Plains and its links with SSTs from simulations of the 20\textsuperscript{th} century climate (20C3M) and from climate projections of the 21\textsuperscript{st} and 22\textsuperscript{nd} centuries. The models used are from leading international climate research institutions that contributed to the WCRP's CMIP3 multi-model data set. The purpose of the study is to find common traits between observations, simulations and projections of climatological precipitation over North America, as well as to provide insights into the current and projected SST structures that may be driving hydroclimate variability over Central U.S. in the present and future centuries. While climate change is implicit throughout the paper via century-to-century comparisons of mean precipitation, precipitation variability and its association with global anomalies, its focus is varied. The paper is organized beginning with Section 2 which provides some basic information about the models and runs, in addition to the observational data sets used as reference for the 20\textsuperscript{th} century climate simulations. Next Section 3 analyzes spring and summer climatology over North America and its changes. Then Section 4 elaborates on precipitation variability, including the presence of extreme events over the Great Plains. Section 5 contrasts the summer SST structures associated with their change and variability in the 20\textsuperscript{th} century. Section 6 analyses the global SST links of Great Plains summer
precipitation variability. Finally, the paper ends with Section 7 which summarizes the main conclusions.

2. Data Sets and Methods

Simulations and projections from four models are assessed from representatives of major climate research centers in the world, including: 1) version 3 of National Center for Atmospheric Research’s Community Climate System Model CCSM3 (Collins et al. 2006, and additional references in the CCSM special issue in the Journal of Climate), 2) version 2.1 of NOAA’s Geophysical Fluid Dynamics Laboratory Coupled Climate Model GFDL-CM2.1 (Delworth et al. 2006), 3) version 3 of United Kingdom’s Meteorological Office and Hadley Centre Coupled Climate Model UKMO-HadCM3 (Gordon et al. 2000, Pope et al. 2000), and 4) Germany’s Max Planck Institute for Meteorology European Centre Hamburg Model ECHAM5/MPI-OM (Roeckner et al. 2003, Marsland et al. 2003). Apart from the ECHAM5/MPI-OM climate model, the others were assessed in their capacity to simulate the observed interannual variability of Great Plains precipitation and its links to moisture fluxes in the 20th century in a previous study (Ruiz-Barradas and Nigam 2006). From this analysis it was found that while the UKMO-HadCM3 model portrays best the observed relationship between precipitation variability and moisture flux convergence, CCSM3 and GFDL-CM2.1 both prioritize a precipitation-evaporation relationship; additional analyzes (not shown) on ECHAM5/MPI-OM model indicate that this model behaves like the UKMO-HadCM3 model regarding the summer precipitation variability over the Central Great Plains. Details of the models and runs analyzed in the current study are summarized in Table 1.
Historical simulations of the 20th century are initialized from a point early in the pre-industrial period. These simulations come from coupled GCMs that are being forced by observed solar irradiance, volcanic and anthropogenic aerosols, and atmospheric concentrations of ozone, carbon dioxide, and other well-mixed greenhouse gases (http://wwwpcm.dl.llnl.gov/ipcc/climate_forcing.php). In general, the model simulations extend over a century long, starting in the second half of the 1800s and ending in 1999 for some and in 2000 for others (Table 1).

The climate projections of the 21st and 22nd centuries that are analyzed are runs under the emission scenario A1B (SRES A1B; Nakicenovic et al. 2000). The A1B scenario describes a world in the future with very rapid economic growth in the 21st century characterized by the rapid introduction of new and more efficient technologies, where global population peaks in mid-century and declines thereafter. Under this scenario, fossil fuels and other energy sources are balanced in the sense that there is not a heavy dependence on one particular source of energy over another. Initial conditions in SRES A1B runs are from simulations of the climate at the end of the 20th century. Carbon dioxide mixing ratios in these runs change from 369 ppmv in the year 2000 to 717 ppmv in 2100; the CO2 concentration almost doubles at the end of the 21st century simulations, after which it is fixed during the 22nd century.

Observed precipitation for the 20th century is obtained from the CRUTS2.1 data set of the United Kingdom’s Climate Research Unit, of East Anglia (Mitchell 2005). This data set includes monthly temperature and precipitation data on a 0.5º grid for the land areas of the globe and spans the time period from 1901 through 2002. An observed global Palmer Drought Severity Index (PDSI) is also used (Dai et al. 2004); the data set is defined over global land areas on a 2.5º grid at monthly resolution for the time period of 1870–2003 using in situ temperature and
precipitation data. The SST links are then obtained using the Hadley Centre’s Sea Ice and SST analysis that spans the time period of 1870-2002 on a 1º grid (Rayner et al. 2003) but is used on a coarser 5º×2.5º grid.

Unless noted otherwise, climatology and long-term variability of the 20\textsuperscript{th}, 21\textsuperscript{st}, and 22\textsuperscript{nd} centuries span the following ninety-nine-year base periods: 1901-1999, 2001-2099, and 2101-2199 respectively. In order to avoid intra seasonal variability, the basic data is seasonal and is defined in terms of the typical three-month means: December to February for winter, March to May for spring, June to August for summer, and September to November for fall; thus, for a given century the data starts in spring and ends in fall.

3. Precipitation Climatology and Change

Spring and summer seasons comprise the bulk of the distribution and amount of precipitation over North America, particularly in the Central U.S. (east of the 100ºW meridian) and Mexico; its amount and distribution can lead to conditions of normality, abundance, or scarcity for the region. The climatological march of the seasons brings routine or normal conditions to a region, so it must be one of the basic points of evaluation in any climate simulation. Climatological spring and summer precipitation in simulations of the 20\textsuperscript{th} century and projections of the 21\textsuperscript{st} and 22\textsuperscript{nd} centuries are analyzed here.

a. Climatology

Spring and summer climatologies of precipitation in the simulations of the 20\textsuperscript{th} century are compared against observations and displayed in Figure 1. Observations reveal a dry West and humid East over the United States in the spring and summer seasons. Also apparent are increases
in precipitation from spring to summer through the Central U.S. and decreases over the Pacific Northwest. Regions of maximum precipitation are seen through the Southern Gulf states in spring and along the coastal regions of the Gulf and South Atlantic states in summer. The dry spring and wet summer seasons in Mexico are also evident along the coasts, sierras and the central plateau.

Models reveal, with the exception of CCSM3, a wetter Western U.S. in spring and wetter Central U.S. in summer when compared against observations. Across all models, and following the general seasonal evolution seen in observations, precipitation increases over Central United States from spring to summer. Models reproduce the increase in precipitation over Mexico from spring to summer, however they only do so on the Western coast and fail to do so on the Eastern side, most likely because the coarse resolution in the models prevent them from a proper representation of the eastern sierra as well as the tropical systems that interact with it (particularly in UKMO-HadCM3); the oceanic part, however, suggests that the land-ocean competition for convection in the models is very large in summer and pushes the ITCZ very far to the north along the Mexican northwest. The maximum over the Pacific Northwest seen in observations in spring is reasonably reproduced by the models, in spite of their resolution, as well as its subsequent reduction in summer; this is likely to happen in the models due to vorticity balance considerations associated with the Aleutian Low and Pacific High seasonal appearance (Nigam and Ruiz-Barradas 2006). Observations also reveal that the maximum of spring precipitation over the United State emerges from the Southeastern Gulf of Mexico states; however, the models seem to reveal that the maximum of spring precipitation comes out of the east. On the other hand, the maximum of summer precipitation in observations lying along the coasts of the Gulf and South Atlantic states is reproduced with varied success by the models.
b. Projected Changes

Comparisons of the climate projections with the simulated climate of the 20th century provide a reference to assess the climate projections under the scenario A1B, where carbon dioxide concentrations almost double in the 21st century and get stabilized during the 22nd century. Figure 2 displays differences in spring and summer climatologies of the 21st century, as well as the summer climatology of the 22nd century, with respect to the corresponding seasonal climatologies in the 20th century. It is apparent that climatological spring precipitation in the 21st century, when compared with the spring of 20th century, will increase in parts of the U.S., particularly in the Eastern half and to the North of 35°N, and decrease over the Southwestern region of the U.S. and over Mexico; however, the structure of these differences is not coherent among the models. These results are consistent with those obtained by Cook et al. (2008), even though a different scenario is used. Differences in summer precipitation are less consistent. While CCSM3 and ECHAM/MPI-OM suggest an increase in precipitation, largely on the Central and Southeastern portions of the U.S., GFDL-CM2.1 and UKMO-HadCM3 indicate a decrease. Similarly, and except for ECHAM/MPI-OM, a decrease along the Pacific Northwest coast of the U.S. and Canada is projected by the rest of the models. However, all of the models do agree in an increase in summer precipitation over the northeastern coast of the U.S. and a decrease along the Eastern and Southeastern portions of Mexico. Differences in the summer climatologies of the 21st century are exacerbated in the 22nd century when carbon dioxide has been stabilized at its highest level.

The projected changes for the 21st century chime with those of the multi-model mean from the latest assessment report by the IPCC (2007, Chapter 11, Figure 11.12), even though the periods of comparison are different. Figure 3 displays the spring and summer percent changes (or
fractional changes), with respect to the 20th century seasonal precipitation, from the mean of the four models analyzed here. The projected changes in spring of the 21st century are marked by a decrease in precipitation all over Mexico and the U.S. southwest, with a maximum over northwestern Mexico, as well as an increase in precipitation over the rest of the U.S. and Canada. The projected changes in spring progress in a southwest-northeast direction in summer of the same century. Decrease in summer precipitation covers now the whole Western, Central and Southeastern regions of the U.S., and the Mexican coastal regions in the northwest, east and south. Increased summer precipitation occupies now small pockets over the northeast/southeast of the U.S./Canada and central Mexico. Changes in summer precipitation for the 22nd century are essentially similar to those in the 21st century but larger. Agreement from a large percentage of the models from the latest IPCC report (2007, Chapter 11, Fig.11.2) exists over the following zones. Regions of decreased precipitation are found over the U.S. Pacific Northwest and southern and southeastern Mexico (17 or more out of 21 models), and a region of increased precipitation is found over the northeastern U.S. (14 or more out of 21 models); all models in the current study present the mentioned changes in precipitation. Agreement also exists over the Central U.S. where the projected decrease in precipitation has a large uncertainty (between 8 and 13 out of 21 models); 2 out of 4 models in the present analysis. Thus, changes given by the 21-model mean used in the IPCC report (2007) are very similar to changes given by a 4-model mean calculated with the models used here.

A couple of cautionary notes are needed here regarding the use of a figure like Figure 3, and widely used in the IPCC report (2007). The most obvious is that the multi-model mean may be the result of a few dominant set of models, so one has to be careful when drawing conclusions that represent the majority of the models. The less evident note is regarding the choice of how to
represent the changes. The regions of maximum fractional changes displayed in Figure 3 do not
align with the regions of maximum change seen in Figure 2, and that may be misleading. For
instance, the fractional changes in summer precipitation in figure 3 show a large decrease over
California (middle panel), but the four maps in Figure 2 (panels in middle column) show nothing
close to this (i.e., conditions in the 21st century are very similar to those in the 20th century with
differences smaller than 0.3 mm day$^{-1}$).

The large uncertainty in the projections of summer precipitation over Central U.S. is a
reflection of the difficulty that the region imposes over the climate models. The difficulty arises
from an unreal hierarchy of processes driving precipitation variability in some models (e.g. Ruiz-
Barradas and Nigam 2006, 2010).

c. 20th Century Changes

One only can wonder if the changes displayed by the projections of the climatological
spring and summer precipitation have some resemblance with the observed changes in the 20th
century; similarities will give some reassurance on the projections. A second order question, just
for the time being, is if the projected changes by the models are consistent with the changes
simulated by them at the end of the 20th century. The imposed changes in CO$_2$ in the 20th century
are not as strong as those imposed in the 21st century under the A1B scenario, so the changes in
spring and summer precipitation in the 20th century are particularly sensitive to the ability of the
coupled models to simulate the natural variability of the global (and regional) climate. Thus, just
because the natural variability in the models is still work in progress, it is fairer to compare the
projected changes in climatological spring and summer precipitation in the 21st century with
respect to the observed changes (and no the simulated ones) of those seasons in the second half
of the 20th century. Changes in the century-long spring and summer climatologies of the 20th century in observations and simulations have been calculated as the difference between the second half of the century (1951-1999) minus the first half of the century (1901-1950) climatologies as shown in Figure 4. Observations show that spring precipitation particularly over the Pacific Northwest, Central and Eastern regions of the U.S. and Eastern Mexico has been increasing, but in areas like the Southwestern U.S. and Southeastern Mexico spring precipitation has been decreasing in the second part of the century. In summers, however, the situation is reversed for some regions like Eastern and Southeastern U.S. where precipitation decreases and for Western, Central and Southeastern Mexico where summer precipitation increases in the second half of the 20th century. On the other hand, the increase in spring precipitation in the second half of the 20th century is followed by an increase in summer precipitation over the Pacific Northwest and Central regions of the U.S. as well as in the Eastern portion of Mexico.

The changes in spring and summer precipitation in the 20th century simulated by the models are not consistent throughout and have limited resemblance with the observed changes. While CCSM3 and, in a lesser degree, ECHAM5/MPI-OM agree with observations on a wetter spring over the Pacific Northwest, UKMO-HadCM3 and ECHAM5/MPI-OM, on the other hand, marginally reproduce the observed wetter Eastern and Central U.S., respectively. The drying of Southeastern Mexico in the spring is partially captured by both ECHAM5/MPI-OM and GFDL-CM2.1. The observed wetter summer in the Pacific Northwest is only weakly captured by UKMO-HadCM3. While the wetter North-Central U.S. is captured in different ways by the models, the wetter Central U.S. is partially captured by GFDL-CM2.1 and ECHAM5/MPI-OM. Spring and summer changes in Mexico are not better represented by the models. While ECHAM5/MPI-OM weakly captures the observed wetter summer over the Eastern and Southern
regions in Mexico, CCSM3 and GFDL-CM2.1 only capture the wetter coasts to the East and West, respectively. The observed drying in the Eastern U.S. in the summer is weakly captured by CCSM3 while the drying over the Southeastern U.S. is reasonably captured by GFDL-CM2.1 and weakly by ECHAM5/MPI-OM.

Generally speaking, the significant changes projected by the models for the 21st century, particularly a wetter North-Central U.S., a dryer Southeastern U.S. and a dryer Southeastern Mexico, resemble the similarly significant observed changes in spring precipitation in the second half of the 20th century. The projected significant changes in summer for the 21st century have less correspondence with the significant observed changes in summer precipitation in the second half of the 20th century than the corresponding changes in spring precipitation. Two models, CCSM3 and ECHAM5/MPI-OM agree in a wetter North-Central U.S. (Figs. 2b, k), while the other two models, GFDL-CM2.1 and UKMO-HadCM3, agree in a drier Southeastern U.S. coast (Figs. 2e, h). The projected wetter U. S. Northeast in summer of the 21st century is not backed up by the current observed drying tendency at the end of the 20th century. A striking point is that the projected wide spread drying of the western and southwestern U.S. in summer of the 21st century, highlighted by the multi-model mean, has little support from the current tendency in precipitation observed in the second half of the 20th century.

4. Great Plains Precipitation Variability

The Central U.S. is characterized by its large interannual variability in precipitation during the warm-season (Ruiz-Barradas and Nigam 2005). Models, except for ECHAM5/MPI-OM, tend to displace this large center of variability to the west, as portrayed by the summer
mean of monthly standard deviation of precipitation (not shown but present in Ruiz-Barradas and Nigam 2006).

Interannual variability of seasonal precipitation over the region can be captured and analyzed in two ways, first by calculating the regional standard deviation, and second by developing a Great Plains precipitation (GPP) index of seasonal anomalies from which a histogram of events can be obtained. The largest precipitation variability over the U.S. during the warm-season can be located in the 100ºW-90ºW, 35ºN-45ºN box, and within the box, the index can be created from area-averaged seasonal precipitation anomalies (Ruiz-Barradas and Nigam 2005, 2006). Similarly, spring and summer standard deviations, from seasonal anomalies, can also be used to get area-averaged standard deviations using the same domain as for the GPP index from observations, simulations of the 20th century climate, and from projections of the 21st and 22nd century climates, as shown in Tables 2 and 3. Variability in observations during spring is ~0.6 mm day$^{-1}$, but model simulations of the 20th century climate provide a range of similar values including 0.5 mm day$^{-1}$ for CCSM3 and GFDL-CM2.1, 0.6 mm day$^{-1}$ for UKMO-HadCM3, and 0.8 mm day$^{-1}$ for ECHAM5/MPI-OM. On the other hand, summer variability is similar in observations, UKMO-HadCM3 and CCM3 (~0.6 mm day$^{-1}$), but it is higher in GFDL-CM2.1 (~0.8 mm day$^{-1}$) and ECHAM5/MPI-OM (~0.7 mm day$^{-1}$). Summer precipitation variability is practically the same than spring variability in observations and UKMO-HadCM3, but it is lower in ECHAM5/MPI-OM, and it is higher in CCSM3 and GFDL-CM2.1. It is interesting to point out that the largest variability in spring is seen in the ECHAM5/MPI-OM model, but the largest variability in summer is in the GFDL-CM2.1 model; in both cases, the increase is above 40% with respect to the observed values suggesting the presence of extreme events in the simulations by those models.
Precipitation variability over the Great Plains in the climate projections of the 21st and 22nd centuries is more consistent throughout the models in spring than in summer when compared to the 20th century variability. All of the models suggest that spring precipitation variability will increase in the 21st century, but excluding CCSM3, the rest of the models also indicate an increase in variability in the 22nd century. There is less agreement among all of the models regarding summer precipitation variability in the 21st century. While GFDL-CM2.1 and ECHAM5/MPI-OM suggest that summer precipitation variability in the 21st century remains the same as in the 20th century, CCSM3 and UKMO-HadCM3 both indicate an increase. Summer precipitation variability in the 22nd century has conflicting results, while CCSM3 and ECHAM5/MPI-OM suggest an increase, GFDL-CM2.1 and UKMO-HadCM3 indicate a decrease. The increase in spring variability in the 21st century (Table 2) goes together with an increase in the spring precipitation, as can be seen by the positive changes (north of 35°N and east of 100°W) in Fig. 2a, d, g, j. However, changes in summer variability are not directly associated with changes in the mean summer precipitation.

Inconsistencies in summer precipitation variability are related to a different hierarchy of processes generating that variability in the models. Spring and summer climatic conditions differ in the Central U.S. by the intensity of the land-surface-atmosphere feedback. In summer this feedback is stronger than in spring due to the larger energy and moisture supplies over the region in summer (Nigam and Ruiz-Barradas 2006). Models tend to prioritize this mechanism as a generator of precipitation variability in summer, via local evapotranspiration, which is not supported by observations (Ruiz-Barradas and Nigam 2005, 2006). Observations suggest a more important role of remote SSTs driving moisture fluxes as generators of summer precipitation variability by moisture flux convergence over Central U.S.. These model deficiencies result in
the lack of coherence in summer precipitation variability as it was shown in a previous study (Ruiz-Barradas and Nigam 2006).

\textit{a. Extremes}

The distribution of hydroclimate events, including extremes, is an important aspect of regional precipitation variability that deserves some attention. The presence of extreme events contributes towards a large regional standard deviation. Histograms of seasonal events that the Great Plains experiences and the models simulate and project during spring and summer are displayed in Figure 5. Spring and summer histograms of observations of the 20\textsuperscript{th} century, displayed as continuous thick black lines in all panels, highlight the large concentration of those seasons in the range of -1 to +1 mm day\textsuperscript{-1}, 91 out of 99 in both cases\textsuperscript{1}. Less apparent is the fact that there are more pluvial (53) than dry springs (46), and more dry (53) than pluvial (46) summers.

Spring and summer histograms from the 20\textsuperscript{th} century simulations, displayed as dashed thick black lines, show that UKMO-HadCM3 has distributions similar to those observed, with 87/90 springs/summers (out of 99) in the -1 to +1 mm day\textsuperscript{-1} range. This model also produces a number of pluvial/dry seasons, 51/48 for spring and 48/51 for summer, which are comparable to those in observations. The spring histograms in the 20\textsuperscript{th} century from GFDL-CM2.1 and ECHAM5/MPI-OM reveal contrasting distributions. While the former is narrow in the -1 to +1 mm day\textsuperscript{-1} range, with 94 out of 99 events, the latter is wide in the same range of anomalies with 80 out of 99 events; this is also consistent with the spring standard deviation which is small in

\textsuperscript{1}Although the -1 to +1 mm day\textsuperscript{-1} range is arbitrary, it covers the range of spring and summer standard deviations shown in Tables 2 and 3. Thus, the difference between the total number of seasons (99) and the number of seasons tallied in the -1 to +1 mm day\textsuperscript{-1} range, gives the
GFDL-CM2.1 and large in ECHAM5/MPI-OM, respectively. The distribution in the spring histogram from CCSM3 has the largest number of seasons, 97 out of 99, in the -1 to +1 mm day\(^{-1}\) range due to the large number of dry springs. Summer histograms in the 20\(^{th}\) century simulations underestimate the number of seasons in the -1 to +1 mm day\(^{-1}\) range; GFDL-CM2.1 has the lowest number of summers inside this range, 75 out of 99, which is consistent with the large summer standard deviation by the model.

The distribution of pluvial and dry seasons in the projected climates of the 21\(^{st}\) and 22\(^{nd}\) centuries, as seen in the histograms, are not consistent throughout the models. However, changes in the spring histograms under the projected 21\(^{st}\) century climate, displayed as a continuous thin line with triangles, are consistent among the models when compared with histograms of their simulated 20\(^{th}\) century climate. All of them suggest a decrease in the number of springs in the -1 to +1 mm day\(^{-1}\) range, and an increase in the +1 to +2 mm day\(^{-1}\) range. The subsequent changes in spring histograms from the projected 22\(^{nd}\) century climate, displayed as a continuous thin line with plus signs, suggest an additional decrease in the number of springs in the -1 to +1 mm day\(^{-1}\) range, and an increase in the +1 to +2 mm day\(^{-1}\) range by the models, except by the slight decrease in the +1 to +2 mm day\(^{-1}\) range shown by CCSM3. Changes in the number of summers in the -1 to +1 mm day\(^{-1}\) range are less consistent throughout the models. While both CCSM3 and UKMO-HadCM3 indicate a decrease in the number of such summers in the 21\(^{st}\) century, GFDL-CM2.1 and ECHAM5/MPI-OM suggest an increase. On the other hand, CCSM3 and ECHAM5/MPI-OM both suggest a decrease in the number of such summers in the 22\(^{nd}\) century, where as GFDL-CM2.1 and UKMO-HadCM3 indicate an increase.
A clearer picture regarding the presence of extremes emerges when anomalies are calculated using the 20\textsuperscript{th} century climatology. Changes from century to century are not included in the Great Plains precipitation anomalies that made the indices used to elaborate the histograms. The histograms for the projected distribution of springs and summers in the 21\textsuperscript{st} and 22\textsuperscript{nd} centuries were obtained from the Great Plains precipitation anomalies calculated with respect to their own 21\textsuperscript{st} and 22\textsuperscript{nd} century climatologies, as shown by the continuous thin lines with triangles and plus signs respectively. The changes from century to century are incorporated in the Great Plains indices by calculating anomalies with respect to the models’ 20\textsuperscript{th} century climatologies. In this case, the distributions in the 22\textsuperscript{nd} century, displayed as continuous thin lines with multiplication signs, show clear biases. There is a tendency toward wetter springs in all the models and drier summers in GFDL-CM2.1 and UKMO-HadCM3, but wetter summers in CCSM3 and ECHAM5/MPI-OM. Histograms of the 21\textsuperscript{st} century (not shown) display similar tendencies than those in the 22\textsuperscript{nd} century histograms but less shifted.

Thus models tend to show that an increase in the number of extreme events, with respect to their 20\textsuperscript{th} century climatology, impacts the changes in the mean seasonal precipitation. However, consistency among the models is only seen for spring and not for summer projections. It is clear that the increased number of extreme pluvial springs in the +1 to +2 mm day\textsuperscript{-1} range for the 21\textsuperscript{st} and 22\textsuperscript{nd} centuries have a larger impact than the reduction of springs in the -1 to +1 mm day\textsuperscript{-1} range for the projected increase in the mean spring precipitation over the Central Great Plains (e.g. Figure 2).
b. Low-frequency precipitation variability

Precipitation variability can drive droughty and pluvial conditions which can be exacerbated by the land-surface conditions. A frequent way to incorporate both of these factors in a single variable, is by using the Palmer Drought Severity Index, however, it is not available from climate model simulations and projections\(^2\). Therefore, a proxy that mimics the PDSI is devised by means of maximizing the correlation between the PDSI and the proxy. By successive applications of a binomial filter to Great Plains indices of seasonal precipitation and PDSI anomalies, the proxy is obtained as a smoothed precipitation index.

Observed Great Plains indices of smoothed seasonal precipitation and PDSI anomalies that highlight interannual and longer time scales are displayed in Figure 6. Both indices were smoothed by applying twelve consecutive times a 1-2-1 binomial filter\(^3\). Simultaneous correlation is 0.84, but precipitation leads PDSI by two seasons in which case correlation increases by 0.92. Thus, given the high correlation between the smoothed seasonal precipitation and PDSI indices over the Great Plains, the smoothed precipitation index can be used as a proxy for the seasonal PDSI index, or in other words, for the precipitation and land-surface conditions; if the seasonal indices are not smoothed, then their correlation is 0.54, thus the importance of the smoothing in creating the proxy. In view of these results, variability of the surface conditions

\(^2\) If potential evapotranspiration is properly calculated, that is, if it is not overestimated because the foretold increase in air temperature for the 21\(^{st}\) climate projection, then the PDSI is still a valid tool to track meteorological droughts in the climate of the 21\(^{st}\) century (Burke et al. 2006).

\(^3\) If the filter is applied 50-55 times one can eliminate interannual variability of the indices and maximize decadal to inter-decadal variability as well as the simultaneous correlation to 0.92. Precipitation leads PDSI by two seasons in which case the correlation slightly increases to 0.94.
from the climate simulations and projections can be generated via their corresponding smoothed seasonal precipitation indices (not shown).

Devastating hydroclimate events over the Great Plains include multi-year droughts, such as the spring-summer Dust Bowl in the 30s, and summer-fall season in the 50s, and single-year pluvial events, such as those in 1993 and 2008, which excluding the 2008 event, can be identified in Figure 6. Simulation of such events is of great importance, however doing so is a challenging task for global models. Using smoothed Great Plains precipitation indices from the climate simulations and projections, similar to the one from observations displayed in Figure 6, it is possible to assess the total number of events that exceed one standard deviation during the spring-summer-fall period of every year4 (Figure 7). This portion of the year is chosen not only because more precipitation falls in the region but also because the interannual variability of seasonal precipitation is maximum too; histograms using the whole year (not shown –that is, including winter) have mostly minor changes in the 22nd century. However, it should be pointed out that a preconditioning outside the region and during the antecedent winter-spring portion of the year has been also important in some of those events.

Histograms of events, displayed in Figure 7, indicate that all of the four models tend to underestimate the total number of extreme droughty events, and to overestimate the total number of extreme pluvial events in the 20th century but projections of the 21st and 22nd centuries are varied among the models. Models like CCSM3 and ECHAM5/MPI-OM indicate an increase in droughty events in the 21st century followed by a decrease in the 22nd century; the number of droughty events in GFDL-CM2.1 remains the same in the 21st century but, as in the other two

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4 The total number of events is made of single year events, and multi-year events where anomalies exceed one standard deviation for at least two consecutive years.
models, they also decrease in the 22nd century. In UKMO-HadCM3 it is projected that a decrease in the number of droughty events in the 21st century and then an increase in the 22nd century will result. In the case of pluvial events, models like GFDL-CM2.1 and UKMO-HadCM3 project equal number of events in the 20th and 21st centuries that decrease in the 22nd century, meanwhile, the number of pluvial events in CCSM3 decreases in the 21st century and decreases more in the 22nd century. The number of pluvial events in ECHAM5/MPI-OM, GFDL-CM2.1 and UKMO-HadCM3 remains the same in the 20th and 21st centuries but increases in the 22nd century.

5. Change and variability of SSTs

Change and variability of the regional precipitation is analyzed in terms of their contemporaneous SST structures.

a. Change

The observed changes in climatological precipitation in the 20th century (Figure 3) are not the only changes in the climate system. Concurrent changes in other climatic variables, such as SSTs, are also evident. Figure 8 (left panels) shows changes in climatological summer SSTs from the first to the second halves of the 20th century in both observations and model simulations. The analysis of observed SSTs indicates that the differences between the 2nd and the 1st halves of the 20th century have the signature of a linear warming trend (or a nonlinear trend as shown in Fig. 13 from Guan and Nigam 2008) with the following features: 1) maximum warming along the midlatitude (20°-50°N) coastal regions in both Pacific and Atlantic Oceans, being largest over the Pacific; 2) maximum tropical coastal warming in the Indian and Atlantic
Oceans; 3) minimum tropical warming in the Pacific Ocean. Models, as it was the case for the changes in precipitation, fail to reproduce those regions of maximum and minimum warming. While CCSM3 favors high latitude (north of 40°N) warming over both Pacific and Atlantic basins, and warming in the tropical Pacific, GFDL-CM2.1 favors maximum warming over the global tropical oceans and cooling over central midlatitudes in the Pacific Ocean. Warming in UKMO-HadCM3 is larger in the Atlantic midlatitudes than in the Pacific, and warming in the tropical Pacific is larger than over the other tropical oceans. Warming in ECHAM5/MPI-OM in the Pacific Ocean is spread from the coastal midlatitudes to the central and eastern Pacific; warming in the tropical Pacific is larger than in the Atlantic and Indian Oceans, with the tropical Atlantic warming appearing in the central basin. Thus, if the observed changes in climatological summer precipitation are driven by the corresponding changes in SSTs, and are consequence of the increase in greenhouse gases in the 20th century, then the failure of the models to properly simulate the changes in SSTs are at the center of the poor simulation of the changes in summer precipitation.

b. Variability

Before attempting to link precipitation variability over the Great Plains with SSTs of the neighboring oceans, a basic examination of the SST variability provides a quick assessment of the capabilities of the models. For that purpose the standard deviation of summer SSTs in the 20th century are displayed in Figure 8 (right panels) in both observations and model simulations. Interannual variability of summer SSTs in observations is the largest in the cold tongue region of the eastern equatorial Pacific (~1K), followed by the midlatitudes of both the western Atlantic (~0.8K) and the central Pacific (~0.8K), and last the eastern equatorial Atlantic (~0.6K). While
the maximum over the equatorial Pacific is associated with ENSO, those in the midlatitudes are ultimately associated with variability of the atmosphere (e.g., due to PNA or NAO). It is interesting to point out that the regions of maximum variability do not coincide with the regions of maximum warming trend (i.e., change in SST seen in the upper left panel in the same Figure 8), except, in the coastal region of the western midlatitude Atlantic and in a lesser degree in the eastern Atlantic. Models tend to overemphasize and misplace variability over the equatorial Pacific as a consequence of the problems they have in simulating ENSO evolution and structure (e.g. van Oldenborgh et al. 2005, and Joseph and Nigam 2006). Variability over the midlatitude oceans is also overestimated and misplaced; it is further to the west and to the north of the position in observations. In consequence the simulated regional and global climates are affected (e.g. Barsugli et al. 2006).

6. SST links of Great Plains Precipitation

The structure of SST anomalies related to low frequency precipitation variability over the Great Plains in the warm-season is obtained by simultaneous correlation of summer global SST anomalies and smoothed summer Great Plains precipitation indices in observations and simulations of the 20th century climate (Figure 9). The summer-only precipitation index is extracted from the smoothed seasonal precipitation index derived from the 1-2-1 binomial filter applied twelve times. Significant SST correlations from observations show a coherent basin-scale structure over the Pacific basin with both tropical and extra-tropical imprints, similar to the Pacific decadal variability pattern; equally important, are correlations over the subtropical and extra-tropical Atlantic basin. The features in both basins, with maximum correlations of 0.3, have been shown to play important roles in generating hydroclimate variability over the Central
Interestingly, the Great Plains also exhibits some connectivity with the Indian Ocean, which may be a reflection of the role that the tropics play in North Pacific interdecadal climate variability (e.g., Deser et al. 2004). The structure and sign of SST correlations with spring precipitation over the Great Plains (not shown) are very similar to those displayed in summer.

In general, all models reasonably capture the negative SST correlation structures over the extra-tropical Pacific and Atlantic Oceans, but the structure of the positive correlations, mainly in the Pacific basin, is more challenging. The broad structure of the positive correlations from the Central Pacific to the Western coast of Mexico seen in observations is absent in CCSM3. The absence of the positive correlations in CCSM3 is mixed also with negative correlations. Similarly GFDL-CM2.1 and UKMO-HadCM3 display a region of negative correlations off the Western coast of Mexico. The correlation structure seen in observations over the Pacific Ocean is best captured by ECHAM5/MPI-OM. On the other hand, the structure of positive correlations over the Caribbean Sea, the Indian Ocean and the northern tropical Atlantic Ocean are reasonably captured by the models, although with a larger magnitude. The structure and sign of SST correlations with spring precipitation in the model simulations (not shown) do not differ by much from those in summer.

Before continuing with the analysis of the projections of the 21st and 22nd centuries, it is necessary to make a stop here to highlight that in observations the regions of maximum summer SST variability in the 20th century (Figure 8, right panels) are not coincident with the regions of maximum correlation between SSTs and the Great Plains summer precipitation (Figure 9). This is not surprising because the correlation structure in observations, with minimum correlations in the equatorial Pacific, rules out a contemporaneous link between summer Great Plains
precipitation variability and ENSO, the latter been highlighted in the standard deviation maps. In
despite of the discrepancies between observations and models, the correlation structure in models
also show the absence of an ENSO link of the GPP variability.

The correlation structure of seasonal SST anomalies associated with the low-frequency
summer precipitation variability over the Great Plains seen in the simulations of the 20th century
climate is altered in the projections of the 21st and 22nd century climates as shown in Figure 10.
The contrasting negative/positive SST correlation structures in both the Pacific and Atlantic
Oceans are practically nonexistent under the rapid increase of CO2 during the 21st century; that
is, the cooling regions in the midlatitude and subtropical regions are being warmed. As revealed
in the right panels, once the CO2 concentrations are stabilized in the 22nd century, the contrasting
negative/positive correlation structures tend to recover towards their conditions in the 20th
century. Similarly, the SST correlations with spring precipitation (not shown) display a decrease
in magnitude in the 21st century and a recovery in the 22nd century, mostly in the negative
correlations in the midlatitude and subtropical regions.

The broad tropical warming stirs the global atmosphere in both observations and model
simulations. The surface tropical warming leads to enhanced 200mb geopotential heights in the
global tropics but reduced heights in the midlatitudes over both hemispheres, as displayed by the
4-model mean in Figure 11, and as shown in Schubert et al. (2004) and Seager et al. (2005). A
ridge, striding the south and east of the U.S. is a feature in the simulations, except in CCSM3 that
has the lowest tropical warming from the models analyzed. As in the case of the midlatitude
negative SST correlations, the reduced heights at midlatitudes are raised during the warming of
the 21st century and reduced back in the 22nd century.
The same sign correlations (i.e. anomalies) over both tropical Pacific and Atlantic basins set up conditions for seasonal anomalous hydroclimatic events during the 21st and 22nd century climates. As mentioned in the introduction if both basins have the same sign, they are still capable of producing extreme hydroclimatic conditions over the Central U.S. (Schubert et al. 2009). This is partially seen in spring where there is an increase in extreme events in the 21st and 22nd centuries as illustrated by the histograms in Figure 5. However, it must not be forgotten that precipitation variability, and so the occurrence of extremes, in the coupled model simulations and projections are not only dependent of the ocean but also on the modeled internal atmospheric variability and land-surface-atmosphere variability as well.

The nature of the differences between the structures of the SST correlations with precipitation variability over the Great Plains is linked to the warming trend driven by the imposed increase in carbon dioxide. This is suggested from those correlations for the 21st century climate but becomes apparent after detrending the data (not shown). After taking the linear trend out from both precipitation indices and SSTs, the correlation patterns that emerge in the 21st century loose the generalized positive correlations and look more like those in the 20th and 22nd centuries. The change in magnitude of the correlations in the 21st century reaches the range 0.1-0.2 in absolute value especially over the midlatitudes of the Pacific Ocean, except in the GFDL-CM2.1 model5 whose changes occur in the tropical latitudes of both Pacific and Atlantic oceans. On the other hand, the structures of the SST correlations in the 20th and 22nd centuries do not change as much as in the 21st century in the models. However, the effect of extracting the trend for the 20th century is way larger in observations than in the model simulations. Changes in observations, after detrending the precipitation indices and SSTs, are in the range 0.08-0.12 in
absolute value but in the range 0.04-0.06 in the models. More important is the fact that the warming seen in the deep tropical Atlantic in the 20\textsuperscript{th} century disappears in observations but not in simulations; similarly the warming displayed in the Indian Ocean is reduced but remains almost without change in the model simulations.

It is significant that coupled models can capture, albeit imperfectly, the links of summer precipitation over the Great Plains with SSTs over the Pacific and Atlantic oceans. As mentioned in the Introduction, such links have been established in observations and atmospheric models forced with observed or idealized SSTs. However, deficiencies in the coupled models to capture ENSO variability (e.g. Joseph and Nigam 2006, Merryfield 2006), Pacific Decadal variability (e.g. Furtado et al. 2009) and tropical Atlantic variability (e.g. Breugem et al. 2006) may be preventing them from better portraying those links. In addition while the warm-season precipitation variability over the Great Plains in the models is related to SST anomalies over both Pacific and Atlantic basins, as observations indicate, overactive land-surface-atmosphere interactions in those models may be preventing them from a better simulation of the observed precipitation variability (Ruiz-Barradas and Nigam 2005, 2006).

7. Concluding Remarks

The present study has analyzed climatological spring and summer precipitation over North America, precipitation variability over the Great Plains and its summer SST links from observations, simulations of the 20\textsuperscript{th} century climate and projections of the 21\textsuperscript{st} and 22\textsuperscript{nd} century climates under the A1B scenario. Under this scenario, carbon dioxide increases rapidly in the 21\textsuperscript{st} century until it reaches almost twice its initial value at the end of the century to remain at this

\footnote{In fact, the Great Plains precipitation index from the GFDL-CM2.1 model is the only one among the precipitation indices from the four models analyzed here that has a negative trend in the 21\textsuperscript{st} century.}
point during the 22nd century.

- The dry West and humid East conditions observed in the United States in spring and summer cannot be accurately simulated by the models. Opposite of what is observed, models tend to produce wetter springs over the Western U.S. and wetter summers over the Central U.S. However, all four of the models simulate reasonably well the spring maximum over the U.S. Pacific Northwest and its subsequent disappearance in summer. Models are also relatively successful in simulating the increase in precipitation over Mexico especially over the Western coast, from spring to summer; however, they fail to do so over the Eastern coast.

- The projected changes in spring precipitation for the 21st century including a wetter North-Central U.S., a drier Southwestern U.S., and a drier Southeastern Mexico chime in with the observed tendencies in spring precipitation in the second half of the 20th century. However, the projected changes in summer for the 21st century find little support from the observed tendencies in summer precipitation in the second half of the 20th century. The projected changes in climatological precipitation are accompanied with changes in the occurrence of extreme seasonal events over the Central Great Plains. That is, projected springs in the 21st and 22nd centuries will be wetter as compared to those in the 20th century, with an increase in wet springs in the 1 to 2 mm day\(^{-1}\) range. Interestingly, this subset of four models portrays remarkably well the results drawn from the complete set of 21 models used in the IPCC AR4 report (2007).

- The observed changes in climatological precipitation are associated with characteristic SST structures seen as the footprint of global warming. The coastal
regions of the midlatitude Pacific and Atlantic oceans suffer the largest warming with no important changes along the equator. The change in summer SSTs in the 20th century climate simulations are deficient; the GFDL-CM2.1 model is the only one that has cooling rather than warming over the midlatitude oceans!

- Precipitation variability over the U.S., as portrayed by seasonal standard deviation, experiences its largest values throughout the Central region of U.S., that is, over the Great Plains (100°W-90°W, 35°N-45°N). Spring and summer standard deviations over this region in the 20th century are captured with some difficulties by the models. While the UKMO-HadCM3 model has a distribution of seasonal events close to observations, ECHAM5/MPI-OM and GFDL-CM2.1 models have the largest spring and summer variability as a result of extreme seasonal events. On the other hand all models project an increase in spring precipitation variability in the 21st century and, except for CCSM3, the models project an additional increase of spring variability for the 22nd century. Projected summer precipitation variability lacks coherence among the models.

- Models have difficulties in simulating long-term droughts and pluvial events over the Great Plains. Simulations of the 20th century climate tend to underestimate the observed number of droughty events, and overestimate the number of pluvial events. Events from the projections of the 21st and 22nd century climates do not show consistency among the four models.

- Climate models can portray, with varied degrees of success, the SST links of summer Great Plains precipitation seen in observations and atmospheric model simulations forced with historical SSTs. Pluvial events in observations are
associated with SST features in the Pacific that resemble those from the Pacific
decadal pattern with positive anomalies at tropical and subtropical latitudes closing
over the Western coasts of Mexico and the U.S., and negative anomalies over the
central mid-latitudes. Atlantic SST features include positive SST anomalies over the
tropics, including the Gulf of Mexico, and negative SST anomalies over the central
mid-latitudes. The SST features are reversed for droughty events. All models
capture the observed SST structures in the central mid-latitudes of the Pacific and
Atlantic Oceans, but have some problems with the broad SST structure in the
tropical and subtropical Pacific and the confined SST structure in the deep tropical
Atlantic. The most successful is the ECHAM5/MPI-OM model, while the less one
is the CCSM3 model. Interestingly, the positive SST correlations in the deep
tropical Atlantic are related to the linear trend in observations but not in the models.

- Here it is important to highlight that the SST correlation structures seen in both
observations and simulations of the 20th century climate lacks of an equatorial
ENSO footprint. This is in spite of the exaggerated variability along the equatorial
Pacific in the simulations. Maximum SST variability in observations and
simulations cover similar regions of the equatorial Pacific and northern hemisphere
midlatitude oceans but the magnitude in the simulations is much larger than in
observations.

- The contrasting positive and negative SST structures in both Pacific and Atlantic
oceans, which are associated with summer precipitation variability over the Great
Plains in the 20th century, are almost removed in the projections of the 21st century
and are recovered, to some extent, in the 22nd century. This is due to the generalized
increased warming in the 21st century and its subsequent stabilization in the 22nd century. That is, the linear trend obscures the contrasting SST structures in both Pacific and Atlantic oceans.

- The surface warming in the tropics associated with the summer precipitation variability over Central U.S. in simulations of the 20th century climate is associated with raised geopotential heights at 200 mb in the global tropics and decreased heights at the midlatitudes of both hemispheres. Among the models CCSM3 has the weakest tropical response. The atmospheric response is similar to that identified in observations and atmospheric simulations forced with historical SSTs. The linear trend, as in the case of the SSTs, conceals the midlatitude decrease in heights in the 21st century and does little in the 20th and 22nd centuries.

In summary, one can see more consistent simulations and projections in spring than in summer over North America, particularly over the Central United States. Previous findings have shown that summer precipitation variability over the Great Plains imposes a challenge for state-of-the-art climate models because many of them prioritize local land-surface-atmosphere interactions over remote SST-moisture flux convergence interactions at interannual-to-larger scales, which is at odds with observations. However, and in spite of those deficiencies, and others involving global teleconnections, the climate models seem to possess the mechanisms that link summer precipitation variability over the Central U.S. with the oceans. Thus, it must be a priority to have those interactions right in climate models in order to improve simulations of summer precipitation variability over the Central U.S.
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References


Figure Captions

**Figure 1.** Spring (MAM, left column) and summer (JJA, right column) precipitation climatology during the 20th century (1901-1999) in observations and coupled model simulations. a)-b) CRUTS2.1, c)-d) CCSM3, e)-f) GFDLCM2.1, g)-h) UKMO-HadCM3, i)-j) ECHAM5/MPI-OM. Contour interval is 1 mm day$^{-1}$ and shading is for values equal or larger than 2 mm day$^{-1}$.

**Figure 2.** Differences between the 21st century projections (2001-2099) and 20th century simulations (1901-1999) of spring (left column) and summer (middle column) precipitation climatologies, and between the 22nd century projections (2101-2199) and the 20th century simulations of summer precipitation climatologies (right column). a)-c) CCSM3, d)-f) GFDL-CM2.1, g)-i) UKMO-HadCM3, j)-l) ECHAM/MPI-OM. Contour interval is 0.3 mm day$^{-1}$, and dark/light shading denotes positive/negative differences larger than |±0.3| mm day$^{-1}$. Shaded differences are significant according a 1-tail t-student test at the 0.10 level.

**Figure 3.** Precipitation changes from 4-model mean projections and simulations. Changes from models CCSM3, GFDL-CM2.1, UKMO-HadCM3 and ECHAM/MPI-OM were used for the 4-model mean that were re-gridded to a 1.5°×1.5° grid. Changes are with respect to the 20th century seasons (1901-1999). Changes in a) spring, b) summer of the 21st century (2001-2099), c) summer of the 22nd century (2101-2199). Changes are given in percent units of the fractional changes with a contour interval of 5%. Dark/light shading denotes positive/negative changes larger than |±5|%.

**Figure 4.** Differences between the 2nd (1951-1999) and 1st (1901-1950) halves in the 20th century of climatological spring (left column) and summer (right column) precipitation from observations and coupled model simulations. a)-b) CRUTS2.1, c)-d) CCSM3, e)-f) GFDLCM2.1, g)-h) UKMO-HadCM3, i)-j) ECHAM5/MPI-OM. Contour interval is 0.1 mm day$^{-1}$.
1, and dark/light shading denotes positive/negative differences larger than $|\pm 0.1| \text{ mm day}^{-1}$. Note that the contour interval and the threshold of the shading are one third of those in Figure 2. Shaded differences are significant according a 1-tail t-student test at the 0.10 level.

**Figure 5.** Histogram of precipitation events over the Great Plains (100°W-90°W, 35°N-45°N) as portrayed by the seasonal Great Plain precipitation index in observations and coupled model simulations of the 20th century (1901-1999), and projections of the 21st (2001-2099) and 22nd (2101-2199) centuries in spring (left column) and summer (right column). a)-b) CCSM3, c)-d) GFDL-CM2.1, e)-f) UKMO-HadCM3, g)-h) ECHAM5/MPI-OM. Histograms of the simulations of the 20th century anomalies are plotted with a thick short dashed line with open circles, projections of the 21st century anomalies are plotted with a thin continuous line with open triangles, and projections of the 22nd century anomalies are plotted with a thin continuous line with plus signs; seasonal anomalies used to create the indices of these histograms are with respect to climatologies of their corresponding century. For comparison purposes, the histogram from the observed CRUTS2.1 index has been plotted as a thick continuous line with filled circles in all panels, and the projections of the 22nd century seasonal anomalies, calculated with respect to the corresponding simulated 20th century seasonal climatologies, are plotted with a thin dash-dot line with multiplication signs. The x-axis represents the anomalous events by categories of 0.5 mm day$^{-1}$ and the y-axis shows the number of seasons (springs or summers) that a given category of anomalies occurs.

**Figure 6.** Smoothed seasonal Great Plains precipitation and PDSI indices (100°W-90°W, 35°N-45°N) during the 20th century (1901-1999). Precipitation index is from CRUTS2.1 and PDSI from Dai’s data set. The seasonal indices have been smoothed using a 1-2-1 binomial filter applied 12 times, and have a correlation on 0.84 after the smoothing. The simultaneous
correlation between the seasonal indices goes from 0.54 without filtering to 0.92 when applying the filter 50 times. Precipitation leads PDSI by two seasons.

**Figure 7.** Histograms of total droughty (left panels) and pluvial (right panels) spring-summer-fall events over the Great Plains (100ºW-90ºW, 35ºN-45ºN) in observations and simulations of the 20th century climate, and projections of the 21st and 22nd climates. Events are tallied from smoothed precipitation indices (1-2-1 binomial filter applied 12 times) when the mean spring-summer-fall anomaly exceeds in absolute value one standard deviation of the smoothed index. The total number of events comprises multi-year events (when the exceeding anomaly stays for at least 2 consecutive years) and single year events. Histograms from the models are organized as follows: a) - b) CCSM3, c) - d) GFDL-CM2.1, e) - f) UKMO-HadCM3, and g) - h) ECHAM5/MPI-OM. The histogram from the observed precipitation data set CRUTS2.1 is marked by the black square in each panel, and the corresponding to the simulations and projections from the models are given by the grey bars above their corresponding labels marking the century.

**Figure 8.** Differences between the 2nd (1951-1999) and 1st (1901-1950) halves in the 20th century of climatological summer SSTs (left column) and standard deviation of summer SSTs in the 20th century (1901-1999, right column) from observations and coupled model simulations. a)-b) Observed Hadley Centre’s, c)-d) CCSM3, e)-f) GFDLCM2.1, g)-h) UKMO-HadCM3, i)-j) ECHAM5/MPI-OM. Contour interval is 0.2 K, and dark/light shading denotes positive/negative differences larger than ±0.2 K. Shaded differences are significant according a 1-tail t-student test at the 0.10 level.

**Figure 9.** Simultaneous summer SST correlations of the smoothed Great Plains precipitation index in observations and coupled model simulations during the 20th century (1901-1999).
Unsmoothed summer SST anomalies are correlated with summer Great Plains indices (100ºW-90ºW, 35ºN-45ºN) extracted after the all-season precipitation indices have been smoothed 12 times via the 1-2-1 filter. a) Observed Hadley SSTs and CRUTS2.1 precipitation index, b) CCSM3, c) GFDL-CM2.1, d) UKMO-HadCM3, e) ECHAM5/MPI-OM. Contour interval is 0.1, and dark/light shading denotes positive/negative correlations larger than |±0.1|. A 2-tail t-student test at the 0.05/0.10 level indicates significant correlations equal or larger than 0.19/0.17.

**Figure 10.** Simultaneous summer SST correlations of the smoothed Great Plains precipitation index in projections of the 21st (2001-2099, left column) and 22nd (2101-2199, right column) centuries. Unsmoothed summer SST anomalies are correlated with summer Great Plains indices extracted after the all-season precipitation indices have been smoothed 12 times via the 1-2-1 filter. a)-b) CCSM3, c-d)) GFDL-CM2.1, e)-f) UKMO-HadCM3, g)-h) ECHAM5/MPI-OM. Contour interval is 0.1, and dark/light shading denotes positive/negative correlations larger than |±0.1|. A 2-tail t-student test at the 0.05/0.10 level indicates significant correlations equal or larger than 0.19/0.17. Anomalies in the indices and SSTs are with respect to the climatologies of the corresponding centuries.

**Figure 11.** Summer regressions of smoothed Great Plains precipitation indices on geopotential height anomalies at 200mb from 4-model mean projections and simulations. Models CCSM3, GFDL-CM2.1, UKMO-HadCM3 and ECHAM/MPI-OM were used for the 4-model mean that were re-gridded to a common 1.5º×1.5º grid. a) 20th century (1901-1999), b) 21st century (2001-2099), c) 22nd century (2101-2199). Contour interval is 3m, and dark/light shading denotes positive/negative anomalies larger than |±3|m. All four models show similar structures to the 4-model mean with CCSM3 having the weakest tropical response among the models.
Figure 1. Spring (MAM, left column) and summer (JJA, right column) precipitation climatology during the 20th century (1901-1999) in observations and coupled model simulations. a)-b) CRUTS2.1, c)-d) CCSM3, e)-f) GFDLCM2.1, g)-h) UKMO-HadCM3, i)-j) ECHAM5/MPI-OM. Contour interval is 1 mm day$^{-1}$ and shading is for values equal or larger than 2 mm day$^{-1}$. 
Figure 2. Differences between the 21st century projections (2001-2099) and 20th century simulations (1901-1999) of spring (left column) and summer (middle column) precipitation climatologies, and between the 22nd century projections (2101-2199) and the 20th century simulations of summer precipitation climatologies (right column). a)-c) CCSM3, d)-f) GFDL-CM2.1, g)-i) UKMO-HadCM3, j)-l) ECHAM/MPI-OM. Contour interval is 0.3 mm day$^{-1}$, and dark/light shading denotes positive/negative differences larger than $\pm 0.3$ mm day$^{-1}$. Shaded differences are significant according a 1-tail t-student test at the 0.10 level.
Figure 3. Precipitation changes from 4-model mean projections and simulations. Changes from models CCSM3, GFDL-CM2.1, UKMO-HadCM3 and ECHAM/MPI-OM were used for the 4-model mean that were re-gridded to a 1.5°×1.5° grid. Changes are with respect to the 20th century seasons (1901-1999). Changes in a) spring, b) summer of the 21st century (2001-2099), c) summer of the 22nd century (2101-2199). Changes are given in percent units of the fractional changes with a contour interval of 5%. Dark/light shading denotes positive/negative changes larger than ±5%. 
Figure 4. Differences between the 2nd (1951-1999) and 1st (1901-1950) halves in the 20th century of climatological spring (left column) and summer (right column) precipitation from observations and coupled model simulations. a)-b) CRUTS2.1, c)-d) CCSM3, e)-f) GFDLCM2.1, g)-h) UKMO-HadCM3, i)-j) ECHAM5/MPI-OM. Contour interval is 0.1 mm day$^{-1}$, and dark/light shading denotes positive/negative differences larger than $|\pm 0.1|$ mm day$^{-1}$. Note that the contour interval and the threshold of the shading are one third of those in Figure 2. Shaded differences are significant according a 1-tail t-student test at the 0.10 level.
Figure 5. Histogram of precipitation events over the Great Plains (100ºW-90ºW, 35ºN-45ºN) as portrayed by the seasonal Great Plain precipitation index in observations and coupled model simulations of the 20th century (1901-1999), and projections of the 21st (2001-2099) and 22nd (2101-2199) centuries in spring (left column) and summer (right column). a)-b) CCSM3, c)-d) GFDL-CM2.1, e)-f) UKMO-HadCM3, g)-h) ECHAM5/MPI-OM. Histograms of the simulations of the 20th century anomalies are plotted with a thick short dashed line with open circles, projections of the 21st century anomalies are plotted with a thin continuous line with open triangles, and projections of the 22nd century anomalies are plotted with a thin continuous line with plus signs; seasonal anomalies used to create the indices of these histograms are with respect to climatologies of their corresponding century. For comparison purposes, the histogram from the observed CRUTS2.1 index has been plotted as a thick continuous line with filled circles in all panels, and the projections of the 22nd century seasonal anomalies, calculated with respect to the corresponding simulated 20th century seasonal climatologies are plotted with a thin dash-dot line with multiplication signs. The x-axis represents the anomalous events by categories of 0.5 mm day$^{-1}$ and the y-axis shows the number of seasons (springs or summers) that a given category of anomalies occurs.
Figure 6. Smoothed seasonal Great Plains precipitation and PDSI indices (100°W-90°W, 35°N-45°N) during the 20th century (1901-1999). Precipitation index is from CRUTS2.1 and PDSI from Dai’s data set. The seasonal indices have been smoothed using a 1-2-1 binomial filter applied 12 times, and have a correlation on 0.84 after the smoothing. The simultaneous correlation between the seasonal indices goes from 0.54 without filtering to 0.92 when applying the filter 50 times. Precipitation leads PDSI by two seasons.
Figure 7. Histograms of total droughty (left panels) and pluvial (right panels) spring-summer-fall events over the Great Plains (100ºW-90ºW, 35ºN-45ºN) in observations and simulations of the 20\textsuperscript{th} century climate, and projections of the 21\textsuperscript{st} and 22\textsuperscript{nd} climates. Events are tallied from smoothed precipitation indices (1-2-1 binomial filter applied twelve times) when the mean spring-summer-fall anomaly exceeds in absolute value one standard deviation of the smoothed index. The total number of events comprises multi-year events (when the exceeding anomaly stays for at least 2 consecutive years) and single year events. Histograms from the models are organized as follows: a) - b) CCSM3, c) - d) GFDL-CM2.1, e) - f) UKMO-HadCM3, and g) - h) ECHAM5/MPI-OM. The histogram from the observed precipitation data set CRUTS2.1 is marked by the black square in each panel, and the corresponding to the simulations and projections from the models are given by the grey bars above their corresponding labels marking the century.
Figure 8. Differences between the 2nd (1951-1999) and 1st (1901-1950) halves in the 20th century of climatological summer SSTs (left column) and standard deviation of summer SSTs in the 20th century (1901-1999, right column) from observations and coupled model simulations. a)-b) Observed Hadley Centre’s, c)-d) CCSM3, e)-f) GFDLCM2.1, g)-h) UKMO-HadCM3, i)-j) ECHAM5/MPI-OM. Contour interval is 0.2 K, and dark/light shading denotes positive/negative differences larger than ±0.2 K. Shaded differences are significant according to a 1-tail t-student test at the 0.10 level.
Figure 9. Simultaneous summer SST correlations of the smoothed Great Plains precipitation index in observations and coupled model simulations during the 20th century (1901-1999). Unsmoothed summer SST anomalies are correlated with summer Great Plains indices (100°W-90°W, 35°N-45°N) extracted after the all-season precipitation indices have been smoothed 12 times via the 1-2-1 filter. a) Observed Hadley SSTs and CRUTS2.1 precipitation index, b) CCSM3, c) GFDL-CM2.1, d) UKMO-HadCM3, e) ECHAM5/MPI-OM. Contour interval is 0.1, and dark/light shading denotes positive/negative correlations larger than ±0.1. A 2-tail t-student test at the 0.05/0.10 level indicates significant correlations equal or larger than 0.19/0.17.
Figure 10. Simultaneous summer SST correlations of the smoothed Great Plains precipitation index in projections of the 21st (2001-2099, left column) and 22nd (2101-2199, right column) centuries. Unsmoothed summer SST anomalies are correlated with summer Great Plains indices extracted after the all-season precipitation indices have been smoothed 12 times via the 1-2-1 filter. a)-b) CCSM3, c-d) GFDL-CM2.1, e)-f) UKMO-HadCM3, g)-h) ECHAM5/MPI-OM. Contour interval is 0.1, and dark/light shading denotes positive/negative correlations larger than ±0.1. A 2-tail t-student test at the 0.05/0.10 level indicates significant correlations equal or larger than 0.19/0.17. Anomalies in the indices and SSTs are with respect to the climatologies of the corresponding centuries.
Figure 11. Summer regressions of smoothed Great Plains precipitation indices on geopotential height anomalies at 200mb from 4-model mean projections and simulations. Models CCSM3, GFDL-CM2.1, UKMO-HadCM3 and ECHAM/MPI-OM were used for the 4-model mean that were re-gridded to a common 1.5°×1.5° grid. a) 20th century (1901-1999), b) 21st century (2001-2099), c) 22nd century (2101-2199). Contour interval is 3m, and dark/light shading denotes positive/negative anomalies larger than ±3m. All four models show similar structures to the 4-model mean with CCSM3 having the weakest tropical response among the models.
Table 1. Basic details of the models analyzed: name, horizontal and vertical resolution of the atmospheric model, years of integration for the historical 20th century climate simulation (20C3M), and the projected climate for the 21st and 22nd centuries (A1B), and the ensemble member used in the analysis.

<table>
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<th>Model’s acronym</th>
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Table 2. Spring standard deviation of precipitation over the Great Plains in observations and climate simulations of the 20th century, and climate projections of the 21st and 22nd century. Units are mm day⁻¹.

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Table 3. Summer standard deviation of precipitation over the Great Plains in observations and climate simulations of the 20\textsuperscript{th} century, and climate projections of the 21\textsuperscript{st} and 22\textsuperscript{nd} century; units are mm day\textsuperscript{-1}.

<table>
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