Great Plains Drought in Simulations of the Twentieth Century

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ABSTRACT

In the Great Plains region, water resource planners are curious to learn about how climate change may influence precipitation variability and the occurrence of future long-term drought. Coupled global climate models (CGCMs) have been widely used to predict future climate change, but before these climate projections are to be trusted, the ability of the models to simulate the present day climate must be assessed. This study evaluates the ability of three of the the CGCMs that participated in the Intergovernmental Panel on Climate Changes (IPCCs) Fourth Assessment Report to simulate Great Plains drought with the same frequency and intensity as was observed during the twentieth-century. The three models are: the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Model version 2.0 (CM2.0), the NCAR Community Climate System Model version 3 (CCSM3), and the Hadley Centre Coupled Atmosphere-Ocean General Circulation Model version 3 (HadCM3).

Results indicate that the models have some difficulty capturing the climatology of the hydrologic cycle of the Great Plains. The magnitude of the seasonal variations in the hydrologic cycle are too extreme in CM 2.0 and HadCM3, where both models overestimate the amplitude of the annual cycles of precipitation, evapotranspiration and runoff. CCSM3 does not accurately capture the seasonal cycle of the hydrologic cycle of the Great Plains, as precipitation, evapotranspiration and runoff all experience unrealistic decreases between the months of July and August.

All three models do simulate at least one long-term drought period for the Great Plains region during their representations of twentieth-century climate, but the frequency of occurrence of long-term droughts is underestimated by the models, especially CM 2.0. Also, multi-year droughts produced by the models have magnitudes and spatial scales similar to
those observed during the twentieth-century.

The relative roles of external forcing from the tropical Pacific and local feedbacks between the land surface and the atmosphere in the initiation and perpetuation of Great Plains drought in each model are also investigated. Cool, La Niña-like conditions in the tropical Pacific are associated with long-term drought conditions over the Great Plains in CM 2.0 and HadCM3. There appears to be no systematic relationship between tropical Pacific SST variability and Great Plains drought in CCSM3.

In CCSM3, local contributions to precipitation via evapotranspiration dominate the variability of precipitation over the Great Plains. Land-atmosphere feedbacks may cause precipitation anomalies to lock into place in this model, thereby perpetuating drought conditions. On the other hand, in HadCM3, the land surface and the atmosphere are relatively decoupled, indicating that large-scale forcing mechanisms are what lead to persistent drought conditions in this model.
1. Introduction

The risk of future long-term drought is one of the biggest concerns facing the Great Plains region of the United States (30°-50°N and 95°-105°W). Droughts have serious social, economic, and environmental consequences and can negatively impact surface and groundwater supplies, water quality, agriculture and rangeland productivity, natural ecosystems, and recreation (Kallis 2008). The Great Plains region is expected to become increasingly vulnerable to drought as the demand for water increases due to enhanced agricultural production and growing populations, and water continues to be pumped unsustainably from the Ogallala Aquifer (Jacobs et al. 2000). Reminders of the devastation associated with the Dust Bowl drought of the 1930s and the 1950s southwest drought lead water managers to ask how future climate change may influence precipitation over the Great Plains region.

Coupled global climate models (CGCMs) are often employed to help predict future climate change. A recent study by Seager et al. (2007) uses the CGCMs that participated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) to show that the western portion of the United States, including the Great Plains, may become increasingly arid in the future. While CGCMs are an important tool for understanding possible future climate change, our limited understanding of the complex climate system and the factors that influence precipitation variability makes assessing the accuracy of the CGCMs projections a challenge.

One way to evaluate the CGCMs performance is to compare their simulations of the variations in twentieth-century climate with observations. The ability of the models to realistically simulate the observed climate can be considered a measure of their capability
for projecting the future. In this context, we evaluate the ability of three of the CGCMs used in the AR4 IPCC report to simulate long-term Great Plains drought with the same frequency and intensity as was observed during the twentieth-century. The three CGCMs chosen are: the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model - version 2.0 (CM2.0), the National Center for Atmospheric Research (NCAR) Community Climate System Model - version 3.0 (CCSM3), and the United Kingdom Met Office (UKMO) Hadley Center Climate Model - Version 3 (HadCM3).

To successfully simulate long-term drought, the models must not only capture the observed low-frequency variability in Great Plains precipitation; they must also accurately represent the processes that cause and maintain the droughts. While considerable effort has been made to understand the causes of long-term Great Plains droughts, the processes involved have not yet been fully established. Observational and modeling studies alike point to several variations of the climate system that are correlated with drought conditions over the Great Plains (Borchert 1950; Namias 1960; Borchert 1971; Namias 1983; Oglesby 1991; Ting and Wang 1997; Ropelewski and Halpert 1986; Trenberth and Branstator 1992; Livezey and Smith 1999). These include, but are not limited to: variations in sea surface temperature (SST) patterns in the North Pacific, Indian Ocean, subtropical Atlantic, and tropical Pacific; changes in storm tracks; and changes in the strength and position of the Bermuda High. Studies also indicate that land-atmosphere feedbacks play an important role in the initiation and persistence of long-term droughts over the Great Plains region (Namias 1991; Oglesby and Erickson 1989; Schubert et al. 2004a, 2008).

While these factors may all contribute to dryness over the Great Plains in some ways, for reasons discussed below it appears that two primary mechanisms cause Great Plains
precipitation anomalies to persist for long periods of time. These are: 1) variations in tropical Pacific SSTs and, 2) land-atmosphere interactions that involve feedbacks between soil moisture and rainfall.

Recently, modeling studies that use atmospheric global circulation models (AGCMs), forced with historic time series of global SSTs have implicated cool, La Niña-like conditions in the tropical Pacific as the primary cause of Great Plains drought during the twentieth-century (Schubert et al. 2004a,b; Seager et al. 2005, 2007; Cook et al. 2007; Seager et al. 2008). Similar modeling studies have also shown that the three long-term droughts that occurred in the mid-to-late nineteenth century were also forced by variations tropical Pacific SSTs (Herweijer et al. 2006). These studies point to a number of different ways in which tropical Pacific SSTs are linked to changes in North American precipitation. For example, Seager et al. (2005) have found that changes in tropical Pacific SSTs are associated with changes in the subtropical jets which affect the propagation of transient eddies, leading to changes in the eddy-driven mean meridional circulation (MMC). When cool conditions are present in the tropical Pacific, changes in the MMC can result in enhanced subsidence over the Great Plains, thereby triggering drought.

SST fluctuations in other ocean basins, such as warm conditions in the Indian Ocean (Hoerling and Kumar 2003; Lau et al. 2005, 2006) and warm conditions in the tropical Atlantic (Schubert et al. 2004b; Sutton and Hodson 2005; McCabe et al. 2008) have also been linked to Great Plains drought, but the degree to which these conditions matter appears to vary from case to case.

Land-atmosphere interactions and feedbacks between soil moisture and rainfall have also been shown to contribute to drought conditions over the Great Plains. Studies that highlight
the importance of soil moisture conditions in the generation and perpetuation of precipitation anomalies include those of Namias (1991); Findell and Eltahir (1997); Eltahir (1998); Schubert et al. (2004a); Pal and Eltahir (2001); Koster et al. (2004, 2003, 2006); Guo et al. (2006). Land-atmosphere interactions influence Great Plains precipitation by regulating the amount of water that is fluxed into the atmosphere via evapotranspiration (precipitation recycling). In addition, soil moisture can impact precipitation indirectly, by affecting boundary layer characteristics and atmospheric stability. Some studies suggest that soil-moisture rainfall feedbacks may act as a bridging mechanism between cool-season precipitation anomalies, resulting from SST forcing, and warm-season precipitation anomalies (Seager et al. 2005; Cook et al. 2007). Koster et al. (2000) and Schubert et al. (2008) argue that in the Great Plains region, precipitation is particularly sensitive to changes in soil moisture conditions, especially during the warm months.

The present study addresses the following questions: 1) How well do the three CGCMs simulate the climatology of the hydrologic cycle of the Great Plains? 2) Do the CGCMs simulate long-term Great Plains droughts with the same frequency and intensity as was observed during the twentieth-century? 3) What mechanisms influence the simulated long-term droughts, and are they the same as observed?

The structure of this paper is as follows. Section 2 describes the models and data sets used in this study. In Section 3 we provide a definition for long-term drought. In Section 4, the simulated climatology of the hydrologic cycle of the Great Plains from each model is compared against observations. Section 5 examines the ability of the models to realistically represent the frequency and variability of long-term Great Plains drought. In Section 6 the influence of tropical Pacific SST anomalies and land-atmosphere interactions on the
simulated droughts is investigated.

2. Data and Methodology

a. Models

As mentioned above, this study utilizes the Climate of the 20th Century integrations performed with CM 2.0, CCSM3, and HadCM3, which were used in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007). These simulations were obtained from the World Climate Research Programmes (WCRPs) Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl et al. 2007) multimodel dataset, which can be found at http://www-pcmdi.llnl.gov. Although simulations of twentieth-century climate are available from 21 different modeling groups, we restrict our analysis to just three of them. Table 1 summarizes some basic properties of the models.

The twentieth-century climate simulations produced for the AR4 IPCC report were initialized from preindustrial control runs in which the atmospheric content of trace gases and solar irradiance were representative of the late nineteenth century (Meehl et al. 2007). The simulations also made use of historical time series of observed 20th Century atmospheric greenhouse gas concentrations, sulfate aerosol direct effects, and volcanic and solar forcings. Multiple integrations of twentieth-century climate were performed with each of the three models, and differ only in their initial conditions as determined by the preindustrial control run of each model (Table 1).
b. Data Sets

The data sets used to evaluate the CGCM simulations come from many different sources. Descriptions of the data sets can be found in Table 2.

Simulated precipitation is compared with the CRU TS 2.1 observational data set produced by the Climate Research Unit (CRU) at the University of East Anglia, United Kingdom (Mitchell and Jones 2005). CRU TS 2.1 is a gridded data set that covers the global land surface at a 0.5° × 0.5° resolution for the period 1901-2002 and was developed from station data.

Downwelling shortwave radiation is compared with data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project obtained from the NOAA CDC website¹ (Kalnay et al. 1996). The NCEP/NCAR reanalysis (hereafter NCEP reanalysis) extends from January 1948 - present and has global coverage with horizontal resolution of 2.5° × 2.5° latitude/longitude with data available on 17 levels.

For SST data analysis, we use the United Kingdom Met Office (UKMO) Hadley Centre Sea Ice and SST data set (HadISST, Rayner et al. 2003) which has 1° × 1° resolution and spans from 1870 - present.

Observations of hydrologic variables such as soil moisture and evapotranspiration are scarce. It is particularly difficult to find long-term data records (i.e. records longer than a few decades) for these variables over the Great Plains region (Robock et al. 2000). Without observations, it is not possible to make direct estimates of the relationships between precip-

¹http://www.cdc.noaa.gov/cdc/reamalysis/reamalysis.shtml
itation, evapotranspiration and soil moisture over the Great Plains region during the two most devastating droughts of the twentieth-century (the 1930s and 1950s). To get around this problem, we use output from a hydrologic modeling study performed by Andreadis et al. (2005) (hereafter, AEA). The AEA study simulated historical soil moisture, evapotranspiration and runoff over the contiguous United States for the period 1920-2003 at 0.5° × 0.5° spatial resolution using the Variable Infiltration Capacity (VIC) Macroscopic Hydrologic Model (Liang et al. 1994, 1996; Cherkauer and Lettenmaier 2003). AEA accomplishes this by forcing the VIC model with observed precipitation and near-surface meteorology for the twentieth century to estimate soil moisture, runoff and evapotranspiration rates. Results from the AEA study will be used as a proxy for direct observations, but they are not truth and should be treated with caution.

c. Methodology

This study defines the Great Plains of the United States, as the area that lies between 30° - 50°N and 95° - 105°W (Similar to that of (Schubert et al. 2004a)). All time series analyses in this study are based on area-weighted averages within this domain. In Section 4 of this paper, the seasonal cycle of hydrologic variables such as precipitation are compared between the models and observations. The climatological values used in this section are computed from the entire time period of the modeled and observational records. For the models, the climatological values are created from the ensemble mean, not for each individual run. In Sections 5 and 6, anomalies of precipitation, SSTs, evapotranspiration and soil moisture are examined. Anomalies are calculated relative to the entire time series, and
for the models anomalies are calculated based on each individual models climatology and not the climatology discussed in Section 4. It should be noted though, that the climatology does not differ widely between model integrations.

3. A Definition of long-term Drought

One of the more interesting challenges that we faced in this research was settling on a definition for what we mean by long-term drought. In the scientific literature there are a number of different definitions of drought. Some are based only on precipitation deficits, some on the supply of surface and subsurface water, others on sustained soil moisture deficits, and still others involve the overall health of the surface vegetation cover (Wilhite and Glantz 1985; Heim 2002). Common to all definitions is that droughts originate from a deficiency in precipitation. For this reason we choose to define long-term drought simply in terms of sustained precipitation deficits. Specifically, we define a long-term drought as a period during which annual precipitation is abnormally low for at least 80 percent of the years during a minimum of seven years (e.g. anomalously low precipitation during 6 out of 7 years, 7 out of 8 years etc.). We further require that any positive precipitation anomalies that occur during the long-term drought period must not exceed one standard deviation above the mean. This simple definition does capture both the 1930s and 1950s droughts from the annual time series of Great Plains precipitation (Fig. 2; drought periods are shaded). Specifics of these droughts will be discussed in Section 5.
4. Climatology of the Hydrologic Cycle of the Great Plains

The first step to assessing the usefulness of the models is to investigate how well they represent the climatology of the Great Plains hydrologic cycle. If the models do not accurately capture the annual cycles of variables such as precipitation and evaporation, their usefulness in studies that require an investigation of the variability about the seasonal mean is questionable. A discussion of the ability of some of the IPCC models to represent the climatology of Great Plains precipitation can also be found in Ruiz-Barradas and Nigam (2006).

Fig. 1 compares the climatology of the hydrologic cycle of the Great Plains between the observations and the models using time series plots of the annual cycles (12 month climatology) of precipitation, evapotranspiration, and soil moisture. The observed annual cycle of Great Plains precipitation shows marked seasonality, with minimum precipitation rates occurring in January (0.6 mm day\(^{-1}\)) and maximum precipitation rates occurring in June (2.7 mm day\(^{-1}\))(Fig. 1). The time series also exhibits a slightly bimodal pattern with a second weaker maximum in precipitation occurring in September (2.1 mm day\(^{-1}\)). Total annual precipitation for the Great Plains region averages 1.54 mm day\(^{-1}\) with the amplitude of the seasonal cycle reaching approximately 2.1 mm day\(^{-1}\) (Table 3). It therefore appears that the annual cycle of Great Plains precipitation can be divided into two distinct seasons, a wet-season that extends from April-September, and a non-active or a dry season that extends from October-March.

In the models, the annual cycle of Great Plains precipitation also shows large seasonal
variations, with minimum precipitation occurring in winter and maximum precipitation occurring in early summer (Fig. 1). All three models tend to overestimate precipitation rates between November and March, possibly due to poor representation of the surface topography which leads to a weakening of the rainshadow effect of the Rocky Mountains. Both CM 2.0 and HadCM3 also overestimate precipitation rates throughout the remainder of the seasonal cycle where maximum precipitation in CM 2.0 is almost twice that observed. CCSM3, on the other hand, has difficulty capturing the timing of the seasonal cycle of Great Plains precipitation. In late summer, CCSM3 experiences what could be considered a seasonal drought, in which precipitation drops dramatically between June and August, to rates that are below 1 mm day\(^{-1}\). Of the three models, only CM 2.0 captures the secondary maximum in precipitation that occurs in September, although the drop in precipitation that occurs between June and August in CM 2.0 is much more dramatic than observed. All of the models overestimate mean annual precipitation rates for the Great Plains region, as well as the overall amplitude of the seasonal cycle (Table 3).

Much like precipitation, the annual cycle of evapotranspiration averaged over the Great Plains region experiences large seasonal variations (Fig. 1b). Minimum evapotranspiration rates occur in fall and winter when both water and energy availability (measured here as the short wave radiative flux) at the surface are limited (Fig. 1a and c). Evapotranspiration rates then increase in spring and summer when both water and energy at the surface increase. Throughout the entire seasonal cycle, both CM 2.0 and HadCM3 overestimate evapotranspiration rates, compared to the observations. The seasonal drought in precipitation that is seen in CCSM3 in the late summer can be found in the evapotranspiration time series as well. Again, reductions in the amount of water at the surface may account for these
reductions in evapotranspiration.

Mean annual climatological total column soil moisture content is shown in Table 3. Total column soil moisture content varies quite dramatically among the CGCMs and VIC soil model. For example, average soil moisture content in HadCM3 is more than three times what is observed, while total column soil moisture content in CM 2.0 is only one quarter of what is observed. These variations may be due to differences in the total depth of the soil column and the water holding capacity of the soils in each model. Fig. 1d shows the time series for the annual cycle of Great Plains soil moisture content. The mean annual climatological values from Table 3 have been removed, so that the timing of the seasonal cycle and the magnitude of the seasonal variations in soil moisture can be more easily compared among the models.

Seasonal variations in total column soil moisture are determined by the seasonal differences between precipitation and evapotranspiration at the surface. In all of the models, soil moisture content increases from late fall to early spring, when precipitation exceeds evapotranspiration (Fig. 1d). During the summer, soil moisture content decreases when evapotranspiration exceeds precipitation. The amplitude of the seasonal cycle of soil moisture is largest in HadCM3, for which soil moisture content varies between spring and fall by 103 mm and it is smallest in CCSM3, for which soil moisture content varies by only 23 mm. The amplitudes of the seasonal cycle of soil moisture are comparable between the observations and CM 2.0. Large differences in soil moisture between the models may not be physically based, but rather a product of how subsurface processes are parametrized.

In general, the three models capture the broad features of the hydrologic cycle of the Great Plains, but each model exhibits some difficulty in representing the timing and magnitude of
the seasonal variations in precipitation, evapotranspiration and soil moisture. In the next section, the ability of the CGCMs to represent long-term drought is evaluated.

5. Long-Term Drought

Time series plots of annual mean Great Plains precipitation anomalies for the observations and one integration from each of the three models are shown in Fig. 2. (Due to space constraints, we cannot show the time series plots from all of the model integrations, but they can be found in McCrary (2008)) These figures demonstrate that precipitation over the Great Plains region is highly variable, even in the annual mean time series. Great Plains precipitation tends to be more variable in the models than in the observations, as seen by the standard deviation values given in Table 4. This is especially true for CM 2.0, for which standard deviation values are almost two thirds larger than in the observations.

Following the definition of drought outlined in Section , the long-term drought periods found in each time series are highlighted in Fig. 2. These drought periods, and the long-term droughts found in the simulations not shown in Fig. 2, are described in Table 5. These are fully coupled GCM integrations that are forced only by time series of observed greenhouse gas concentrations, sulfate aerosols, and volcanic eruptions. This implies that, for each model integration, not only are the atmospheric conditions unique, but so are the oceanic and land surface conditions. Therefore, it is not expected that the timing of any long-term droughts in the models will coincide with the observed timing. Also, it is expected that the timing of the long-term droughts in each individual model integration (from the same model) will be different. That being said, what we are looking to see is if the characteristics of Great
Plains droughts in the models are similar to those observed.

Three long-term droughts stand out in the observed precipitation time series. The first and weakest drought occurred 1907-1913. During this period, negative precipitation anomalies occurred only in the Great Plains region of the United States; rainfall reductions were largest over southeastern Texas and Oklahoma (Fig. 3a). The second drought extended from 1929-1940. This drought is commonly referred to as the Dust Bowl, because it was accompanied by severe dust storms. While precipitation reductions covered most of the United States during this time period, the central and northern parts of the Great Plains were most heavily impacted (Fig. 3b). The third and final long-term drought of the 20th century occurred during 1947-1956. It had a larger impact on the southern Plains than either of the two previous droughts (Fig. 3c). This drought also exhibits the canonical pattern of drought that is expected from tropical Pacific SST forcing (Seager et al. 2008). This will be discussed in the next section.

In each simulation of twentieth-century climate, the Great Plains region experienced at least one long-term drought period, with some integrations having up to three or four long-term droughts (Table 5). Table 5 also shows that the simulated long-term droughts lasted from 6 years up to 20 years, with most persisting for 7-11 years. This range is similar to that seen during the real twentieth-century. Since the model integrations span over a longer time period than the observational record, Fig. 4 shows the number of long-term droughts that occurred per century from each realization of the twentieth-century. From the figure it appears that the models (especially CM 2.0) tend to underestimate the frequency of occurrence of long-term droughts compared to what was observed. In fact, of all thirteen model integrations considered in this study, only two integration’s from CCSM3
have three long-term droughts per century occurring over the Great Plains region, matching the observations.

The spatial patterns of the simulated long-term droughts are shown in Fig. 3d-m. In general, the simulated droughts exhibit spatial patterns similar to those observed during the twentieth-century. In many of the simulated droughts, the southern half of the Great Plains region is more heavily impacted than the northern half, as in the observed 1950s drought (Fig. 3e, f, j). In some cases, a simulated Great Plains drought extends over most of North America, as in 1930s Dust Bowl drought (Fig. 3g and l). In other cases, drought is restricted to only the Great Plains region, as was observed for the 1907-1913 drought (Fig. 3h and k). For spatial patterns of the simulated droughts not shown in Fig. 3, see McCrary (2008).

Considering that the models tend to underestimate the frequency of occurrence of long-term droughts over the Great Plains, we can then ask the question, what is the likelihood that these persistent dry periods occurred just by chance, given the random and highly variable nature of precipitation? We can also ask if there is an external forcing or memory in the system that causes negative precipitation anomalies to persist over the Great Plains? To investigate these questions, Relative Frequency Distribution (RFD, von Storch and Zwiers 2001, p.19) histograms for the length of wet and dry events in the annual mean precipitation time series are shown (Fig. 5). The RFD histograms are created by binning precipitation by the number of consecutive years with abnormally low or high precipitation and normalizing each bin by total number of dry or wet events that occur during the time series. Results from all the integrations are included in the figure. In the observed RFD histogram, three dry events persisted for 5 years, accounting for 11% of the total dry distribution, while one wet event persisted for 7 years and accounts for approximately 4% of the total wet
distribution. From the RFD histograms of the models, it appears that the long-term dry and wet events that occur in the simulations account for less of the total distribution than observed. To explore whether or not these persistent dry and wet events could potentially occur this frequently just by chance, consider a simple experiment in which the persistence that exists in an idealized time series, of annual mean Great Plains precipitation anomalies is examined. In this idealized time series, only two outcomes are possible at each time step: precipitation anomalies can either be positive (wetter than average) or negative (drier than average), and the two outcomes are mutually exclusive. This implies that there is no memory in the precipitation time series and that precipitation is not being externally and persistently forced. Defined in this way, the idealized precipitation time series can be considered equivalent to a sequence of coin flips, such that the probability of getting a wetter than average year is equal to the probability of getting a drier than average year, i.e.,

\[ P\{wet\} = P\{dry\} = \frac{1}{2} \]  \hspace{1cm} (1)

The probability that \( n \) consecutive years will be positive (or negative) in the idealized time series is then

\[ P\{n\} = P^n\{dry\} = \frac{1}{2^n}. \]  \hspace{1cm} (2)

This concept can be used to create an idealized Probability Distribution Function (PDF) for the lengths of consecutive dry and wet events. The idealized PDF demonstrates how frequently long-term dry events and long-term wet events are expected to occur by chance. The idealized curve is shown on each RFD histogram in Fig. 5. The RFD histograms
indicate how precipitation events are organized in the models and the observations, while the idealized PDF shows what is expected from a random series of independent events. Any persistent dry or wet periods in the RFD histograms that exceed the idealized curve may indicate some memory or forcing in the system that allows precipitation events to persist over these periods of time. In the observations (Fig. 5a) precipitation events that persist for four years or less occur as frequently or less frequently than would be expected just by chance. Precipitation events that persist for five years or longer, on the other hand, clearly stand above the idealized PDF, indicating that during the observed twentieth-century, long lasting wet and dry events occurred more frequently than expected just by chance. This suggests a possible forcing or feedback with precipitation that increases the persistence of droughts and pluvials. The model RFD histograms, on the other hand, approximately follow the idealized curve. The long-term events that do occur in the models tend to lie on or below the idealized curve. This indicates that, although long-term events do occur in the models, these events do not occur more frequently than would be expected just by chance. In general, the frequency of occurrence of the long-term, continuous, precipitation events in the models falls within the realm of chance. It is possible that the mechanisms that cause precipitation events to persist in the real world, for long periods, such as tropical Pacific SST forcing and land-atmosphere interactions, do not exist or are too weak in the models. The extent to which these processes are absent in the models will allow us to draw conclusions about why the models misrepresent the frequency of occurrence of long-term droughts over the Great Plains.
6. Processes that influence long-term drought

a. Tropical Pacific SSTs

As mentioned in the introduction, recent modeling studies have shown that the twentieth-century long-term Great Plains droughts of the 1930s and 1950s, as well as the three long-term droughts that occurred in the mid-to-late nineteenth-century, were all forced by cool, La Niña-like conditions in the tropical Pacific. Here we compare the SST patterns from the observed droughts with the SST conditions found during the simulated droughts.

Fig. 6 shows the composite SST anomalies from the three observed drought periods along with composite SST anomalies from a subset of the modeled droughts (See McCrary (2008) for composite SST maps of the simulated droughts not shown). To summarize the SST conditions in the tropical Pacific from all of the observed and modeled droughts (identified in Table 5), Fig. 7 shows values for the composite SST anomalies from each drought period averaged over the Nino3 region (5°S - 5°N and 150° - 90°W). The composite maps show that SST patterns during the three observed drought periods were quite varied, but common to all three of the droughts were cool conditions in the tropical Pacific. The magnitude of the SST anomaly was largest during the 1950s and weakest during the 1930s. It has been argued by some that other factors such as land-atmosphere interactions and aerosol loading of the atmosphere due to the dust storms associated with the 1930s drought, may have played an important role in influencing the strength and position of this drought (Cook et al., 2008).

Global SST patterns also vary among the different simulated droughts (Fig. 6d-l). In agreement with the observations, the droughts simulated by both CM 2.0 and HadCM3 are also associated with cool, La Niña-like conditions in the tropical Pacific. These SST
anomalies vary from case to case, but tend to be quite large and negative in CM 2.0 and smaller (closer to zero, but still negative) in HadCM3. In some cases (such as HadCM3 Run 2 1904-1931), cool conditions in the tropical Pacific are displaced slightly to the south, but may still have important implications for precipitation over the Great Plains. In CCSM3, on the other hand, there is little if any systematic relationship between cool conditions in the tropical Pacific and drought. For example, long-term Great Plains droughts are found to be associated with both cool (Fig. 6l) and warm (Fig. 6h) conditions in the tropical Pacific. It is possible that there may be systematic errors in the way that Great Plains precipitation responds to changes in SSTs in this model. It is also possible that the atmospheres response to SST variability and the associated teleconnection patterns are not well represented in CCSM3 (Joseph and Nigam 2006).

To investigate the linear relationship between tropical Pacific SSTs and U.S. precipitation in the observations and the three models we regress United States precipitation on to an index of tropical Pacific SSTs (the monthly SST anomaly averaged over the Nino3 region). Regression maps are shown in Fig. 8.

In the observations, there is a positive and statistically significant relationship between precipitation and tropical Pacific SSTs in the southern portion of the Plains, primarily in the Gulf Coast region. This indicates that cool conditions in the tropical Pacific are associated with dry conditions over the southern portion of the Plains. As for the the three models, CM 2.0 overestimates the strength of the linear relationship between tropical Pacific SSTs and Great Plains precipitation supporting the idea that persistent cool conditions in the tropical Pacific cause long-term droughts in this model. The linear relationship between SSTs and precipitation is also similar to the observations in HadCM3. CCSM3, on the other hand,
greatly underestimates the relationship between tropical Pacific SSTs and precipitation. This supports the idea that there may be systematic errors in the way that Great Plains precipitation responds to tropical Pacific SST variability.

These differences among the models may explain why there is a coherent relationship between tropical Pacific SSTs and drought in CM 2.0 and HadCM3, but not in CCSM3. Another possible cause of long-term drought over the Great Plains in CCSM3 may be the strength of land-atmosphere interactions. This will be discussed in the next section.

b. *Land-atmosphere interactions*

As discussed in the introduction, land-atmosphere interactions play a key role in influencing the magnitude and persistence of Great Plains droughts. To investigate the relationship among the land surface and the atmosphere in each model, we look for linear relationships between precipitation, evapotranspiration, and soil moisture over the Great Plains. Since evapotranspiration is a key mechanism through which the land surface influences the atmosphere above, we expect the coupling between the land-surface and the atmosphere to be strongest during the wet season months (April-September) when the amount of water and energy available at the surface is largest (Fig. 1).

Scatter plots of monthly mean anomalies of Great Plains precipitation, evapotranspiration and soil moisture are shown in Fig. 9. Both the regression and correlation coefficients for each scatter are shown on the figure and denoted by an $a$ and an $r$, respectively. Also, all correlations shown in the figure are statistically significant at the 95% confidence level based on a two-tailed t-test.
In the observations, there exists a positive relationship among precipitation, evapotranspiration and soil moisture. The relationship among these variables is similar in CM 2.0, but stronger than observed in CCSM3, and weaker than observed in HadCM3. In CCSM3, the magnitude of the linear relationship between precipitation and evapotranspiration is almost three times larger than in the observations. Also, precipitation explains much more of the variance in evapotranspiration than is observed. One possible explanation for the tight coupling between these two variables is that much of the precipitation that reaches the surface is immediately re-evaporated into the atmosphere, never having a chance to become part of the soil moisture. Previous studies have shown that the CAM, the atmospheric component of CCSM3, tends to overestimate the amount of light to moderate rainfall that reaches the surface and underestimates the amount of heavy or convective rainfall that reaches the surface (Sun et al. 2006). This light to moderate rainfall is easily intercepted by the vegetation at the surface and tends to be immediately re-evaporated into the atmosphere (DeMott et al. 2007). Immediate re-evaporation of precipitation from the surface can also explain why large changes in precipitation result in only small changes in soil moisture and why large changes in evapotranspiration are also associated with only small changes in soil moisture. It is possible that the strong land-atmosphere coupling in CCSM3 causes precipitation rates over the Great Plains to respond too strongly to small changes in surface conditions thereby promoting drought conditions, but again, long-term drought periods do not occur more frequently than expected just by chance.

In HadCM3, on the other hand, the linear relationship between precipitation and evapotranspiration is only about half as strong as observed, and one fifth as strong as the relationship found in CCSM3. Also, precipitation explains only 6% of the variance in evapotranspiration.
Evapotranspiration in HadCM3. The relationship between soil moisture and evapotranspiration is similarly weak in HadCM3. This points to a lack of interaction between the land surface and the atmosphere in the model. This conclusion is not unique to this study; the GLACE (Global Land-Atmosphere Coupling Experiment) study also found the land surface and atmosphere to be decoupled in HadCM3 (Koster et al. 2004, 2006). Lawrence and Slingo (2005) have studied the land surface of HadCM3 in detail, and they argue that the cause of the weak soil moisture - precipitation feedback in HadAM3 (the atmospheric component of HadCM3) is related to one of two factors: either how the boundary-layer adjusts to changes in surface forcing (i.e., how the boundary layer adjusts to changes in latent and sensible heat fluxes), or how moist convection responds to boundary layer conditions (i.e. the relationship between the stability of the boundary layer and the timing and initiation of moist convection). Whatever the cause, the lack of coupling between the land surface and the atmosphere indicates that land-atmosphere interactions do not play a strong role in influencing Great Plains drought in this model.

Land-atmosphere coupling in CM 2.0 is similar to what is seen from the observations. Precipitation, evapotranspiration, and soil moisture all exhibit positive linear relationships, and local evapotranspiration is clearly linked to precipitation. This suggests that the importance of land-atmosphere interactions in the magnitude and persistence of long-term drought over the Great Plains is similar in CM 2.0 as compared with observations.
7. Concluding Remarks

The present study has sought to evaluate the ability of three of the CGCMs used in the AR4 IPCC report to simulate long-term drought over the Great Plains region of the United States. Our goal has been to determine whether or not the models are credible for use in future drought assessment studies. Assessing the credibility of these models has required examining their ability to represent: 1) the climatology of the hydrologic cycle of the Great Plains; 2) the variability of Great Plains precipitation including the frequency of occurrence of long-term droughts; and 3) the physical processes that cause long-term droughts to occur over the region. Overall, results from this study indicate that the models have difficulty capturing a number of key elements in the climate system that are fundamental for representing long-term Great Plains drought.

Reproducing the climatology of the hydrologic cycle over the Great Plains proved to be a challenge for the models. While the broad features of the annual cycle are captured by the models, e.g., the Great Plains are wet during the warm season and dry during the cold season, the models all experience some problems representing either the timing or the amplitude of the seasonal cycles of precipitation, evapotranspiration and soil moisture. Both CM 2.0 and HadCM3 overestimate the amplitude of the seasonal cycles of precipitation and evapotranspiration, while in CCSM3, both precipitation and evapotranspiration experience large, unrealistic decreases between the months of June and August. In effect, CCSM3 experiences a seasonal drought in the late summer and early fall. The impact that this annual drought has on long-term drought has yet to be investigated in CCSM3, but it is likely that this would have some impact on the way the model handles drought. The
treatment of total column soil moisture has also been shown to vary among the models, possibly due to differences in the depth of the soil column being considered, differences in the hydraulic properties of the soils including texture and porosity, and differences in the root depths of the vegetation in the Great Plains regions. These parameters are prescribed as input to the models and were difficult to diagnose based on the data provided on the PCMDI website.

By defining long-term drought in terms of precipitation deficits alone, we identified a number of long-term drought periods in the observed and simulated Great Plains precipitation time series. While long-term dry events are found to occur in each simulation, a simple probability test indicates that it is possible that the persistent dry events in the models may occur by chance, implying that external forcing mechanisms and internal feedback processes may not be required for long-lasting dry events to occur. Unfortunately, the low sample size of the data inhibits significance testing, but this is one indication that the models have trouble representing long-term drought.

Another area where the models struggle is in how well they represent the two main processes that are believed to cause long-term droughts, namely SST conditions in the tropical Pacific and land-atmosphere interactions. Much like the observations, cool La Niña-like conditions in the tropical Pacific are found to be associated with the simulated droughts in both CM 2.0 and HadCM3, but previous studies have found that these models have trouble representing the frequency of - and the teleconnections associated with the El Niño - Southern Oscillation (ENSO), which is the primary mode of interannual SST variability in the tropics (van Oldenborgh et al. 2005; Joseph and Nigam 2006). So while tropical Pacific SST variability does appear to be correlated with Great Plains drought, these models have
difficulty representing the observed variations in tropical Pacific SSTs, which may influence the frequency or intensity of Great Plains droughts.

In CCSM3, on the other hand, there appears to be no systematic relationship between tropical Pacific SSTs and drought. Great Plains precipitation anomalies, do not appear to be influenced by variations in tropical Pacific SSTs in this model. It is possible that SST conditions in the tropical Atlantic as well as the Indian Ocean are important for the generation of precipitation anomalies over the Great Plains in CCSM3. However the relationship between SST conditions in these ocean basins and Great Plains drought is not well understood in the observed twentieth-century, which makes them difficult to diagnose in the CGCMs.

Land-atmosphere interactions, and the strong coupling between the land surface and the atmosphere found in CCSM3 may also explain the occurrence of long-term droughts in this model. While previous studies have indicated that most of the precipitation that falls to the surface in this model is immediately re-evaporated into the atmosphere (DeMott et al. 2007), diagnosing why land-atmosphere interactions are too strong in CCSM3 proved difficult in this study. This is because evapotranspiration (or latent heat flux) was not defined in terms of where it came from (i.e. the soils, canopy, or transpiration), but rather output as one bulk value. Determining whether or not interception of precipitation by the vegetation cover and immediate re-evaporation into the atmosphere is the source of this strong coupling strength over the Great Plains was therefore not possible without the proper diagnostic tools. We also showed that long-term droughts do not occur more frequently than expected just by chance in CCSM3, therefore the importance of land-atmosphere interactions in the initiation and perpetuation of long-term droughts needs to be further investigated in this model.

This study has also found that in HadCM3, the land surface and the atmosphere appear
to be fairly decoupled, indicating that land-atmosphere feedbacks possibly do not play a significant role in the persistence of drought conditions over the Great Plains in this model. These results are supported by other studies which indicate that misrepresentation of boundary layer processes may account for the lack of interaction between the land surface and the atmosphere in this model (Lawrence and Slingo 2005).

One way to investigate the degree to which land-atmosphere interactions influence long-term drought might be to perform idealized SST experiments where global SSTs are set to the seasonally varying climatology. In these experiments, precipitation will only be influenced by internal atmospheric variability and land-atmosphere feedbacks, thus allowing us to see if long-term drought periods occur in these models without low-frequency variations in SSTs.

Given the difficulty that the models have in representing the climatology of the Great Plains region, the frequency of occurrence of long-term droughts, and the mechanisms known cause long-term droughts over the region it appears that in their current state, the models are not credible for use in future drought assessment studies. Since SST variations in the tropical Pacific are known to be correlated with the observed long-term drought over the Great Plains region, assessment of future drought conditions over this region will need to wait until these models can better represent this key behavior of the climate system. While both CM 2.0 and HadCM3 do appear to accurately capture the relationship between tropical Pacific SSTs and Great Plains precipitation, these models still have trouble accurately capturing ENSO and tropical Pacific SST variability. Misrepresenting the frequency and intensity of ENSO events may be one reason why these models do not capture the observed persistence in Great Plains precipitation.

Also, the models do not currently represent a number of key processes involving in-
Interactions between the land surface and the atmosphere that may be prove important for representing long-term drought. These processes include 1) allowing the surface vegetation cover to respond to changes in moisture at the surface and 2) allowing for enhanced dust transport from the surface to the atmosphere as the surface dries out. These two processes can result in important radiative feedbacks that may act to magnify the original precipitation deficit (Charney et al. 1977; Cook et al. 2008).

Acknowledgments.

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Table 1. Coupled global climate models analyzed in this study.

<table>
<thead>
<tr>
<th>Model</th>
<th>Horizontal Resolution (lat × lon)</th>
<th>Number of Levels</th>
<th>Number of Simulations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM 2.0 GFDL</td>
<td>2.0° × 2.5°</td>
<td>24</td>
<td>3</td>
<td>Delworth et al. (2006)</td>
</tr>
<tr>
<td>NCAR CCSM3</td>
<td>T85 (1.4° × 1.4°)</td>
<td>26</td>
<td>8</td>
<td>Collins et al. (2006)</td>
</tr>
<tr>
<td>UKMO HadCM3</td>
<td>2.0° × 2.5°</td>
<td>24</td>
<td>3</td>
<td>Gordon et al. (2000)</td>
</tr>
</tbody>
</table>
Table 2. Observational data sets used to evaluate the CGCMs in this study.

<table>
<thead>
<tr>
<th>CRU TS 2.1</th>
<th>VIC</th>
<th>NCEP</th>
<th>HadISST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Origin</strong></td>
<td>Station data</td>
<td>Hydrologic model forced with observed precipitation and surface meteorology</td>
<td>Observations and model forecasts</td>
</tr>
<tr>
<td><strong>Resolution</strong> (lat × lon)</td>
<td>0.5° × 0.5°</td>
<td>0.5° × 0.5°</td>
<td>2.5° × 2.5°</td>
</tr>
<tr>
<td><strong>Domain</strong></td>
<td>Global land surface (except Antarctica)</td>
<td>Land surface of continuous United States</td>
<td>Global</td>
</tr>
<tr>
<td><strong>Variables</strong></td>
<td>Precipitation</td>
<td>Evapotranspiration, soil moisture</td>
<td>short wave forcing</td>
</tr>
</tbody>
</table>
Table 3. Values for the mean and the amplitude of the time series of the annual cycle of precipitation, evapotranspiration, and soil moisture averaged over the Great Plains region for the observations and models as shown in Fig. 1.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Precipitation (mm day(^{-1}))</th>
<th>Evapotranspiration (mm day(^{-1}))</th>
<th>Soil Moisture (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Mean</td>
<td>Amplitude</td>
<td>Annual Mean</td>
</tr>
<tr>
<td>Observations</td>
<td>1.54</td>
<td>2.09</td>
<td>1.39</td>
</tr>
<tr>
<td>CM 2.0</td>
<td>2.38</td>
<td>2.98</td>
<td>1.98</td>
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<tr>
<td>CCSM3</td>
<td>1.62</td>
<td>2.53</td>
<td>1.33</td>
</tr>
<tr>
<td>HadCM3</td>
<td>2.21</td>
<td>2.66</td>
<td>1.77</td>
</tr>
</tbody>
</table>
Table 4. Table of values for the standard deviation of the observed and simulated time series of annual mean Great Plains precipitation anomalies.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Standard Deviation (mm day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>0.024</td>
</tr>
<tr>
<td>CM 2.0</td>
<td>Run 1: 0.288, Run 2: 0.296, Run 3: 0.260</td>
</tr>
<tr>
<td>CCSM3</td>
<td>Run 1: 0.216, Run 2: 0.204, Run 3: 0.217, Run 4: 0.207, Run 5: 0.216, Run 6: 0.208, Run 7: 0.220, Run 9: 0.239</td>
</tr>
<tr>
<td>HadCM3</td>
<td>Run 1: 0.224, Run 2: 0.230</td>
</tr>
</tbody>
</table>
Table 5. Summary of the long-term droughts from the observations and the simulations of the climate of the twentieth-century. Table includes the total number of droughts in each realization of the twentieth-century, the total length of each drought, the years spanned by each drought, and the average precipitation anomalies associated with each drought.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Number of droughts</th>
<th>Length of Drought (years)</th>
<th>Drought Years</th>
<th>Average Anomaly (mm day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations Run 1</td>
<td>3</td>
<td>7</td>
<td>1907-1913</td>
<td>-0.1019</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1929-1940</td>
<td>-0.1575</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1947-1956</td>
<td>-0.1437</td>
</tr>
<tr>
<td>CM 2.0 Run 1</td>
<td>2</td>
<td>7</td>
<td>1865-1871</td>
<td>-0.1737</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1906-1916</td>
<td>-0.2183</td>
</tr>
<tr>
<td>CM 2.0 Run 2</td>
<td>1</td>
<td>7</td>
<td>1883-1889</td>
<td>-0.2602</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1941-1947</td>
<td>-0.1511</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1961-1967</td>
<td>-0.1757</td>
</tr>
<tr>
<td>CM 2.0 Run 3</td>
<td>1</td>
<td>14</td>
<td>1925-1938</td>
<td>-0.2065</td>
</tr>
<tr>
<td>CCSM3 Run 1</td>
<td>3</td>
<td>7</td>
<td>1881-1893</td>
<td>-0.0992</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1923-1930</td>
<td>-0.1992</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>1972-1977</td>
<td>-0.0551</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>1980-1990</td>
<td>-0.1157</td>
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<tr>
<td>CCSM3 Run 2</td>
<td>1</td>
<td>7</td>
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<tr>
<td>CCSM3 Run 3</td>
<td>3</td>
<td>10</td>
<td>1875-1884</td>
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<td></td>
<td></td>
<td></td>
<td>1950-1958</td>
<td>-0.1528</td>
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<td></td>
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<td></td>
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<tr>
<td>CCSM3 Run 4</td>
<td>4</td>
<td>11</td>
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<td></td>
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<td>1920-1925</td>
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<td>1942-1958</td>
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<tr>
<td>CCSM3 Run 5</td>
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<tr>
<td>CCSM3 Run 6</td>
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<td>1911-1917</td>
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<td>1949-1955</td>
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</tr>
<tr>
<td>CCSM3 Run 7</td>
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<td>12</td>
<td>1877-1888</td>
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<td>1924-1931</td>
<td>-0.0481</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1988-1999</td>
<td>-0.1900</td>
</tr>
<tr>
<td>CCSM3 Run 8</td>
<td>2</td>
<td>9</td>
<td>1894-1902</td>
<td>-0.1676</td>
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<tr>
<td></td>
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<td>1923-1928</td>
<td>-0.1365</td>
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<tr>
<td>HadCM3 Run 1</td>
<td>2</td>
<td>7</td>
<td>1925-1931</td>
<td>-0.1368</td>
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<td>1980-1989</td>
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<td>HadCM3 Run 2</td>
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<td>1864-1870</td>
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<td></td>
<td></td>
<td>1980-1991</td>
<td>-0.1539</td>
</tr>
</tbody>
</table>
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1  Time series plots for the annual cycle of Great Plains precipitation in mm day\(^{-1}\) (a), evapotranspiration in mm day\(^{-1}\) (b), short wave radiation flux in W m\(^{-2}\) (c) and seasonal variations of total column soil moisture in mm from the observations (black) and the three models (CM 2.0 - red, CCSM3 - blue, HadCM3 - green).

2  Time series of annual mean Great Plains precipitation anomalies from the observations (a) and one integration from each model: CM 2.0 Run 1 (b), CCSM3 Run 4 (c), HadCM3 Run 2 (d). Units of anomalies are in mm day\(^{-1}\). Time series plots from the other model integrations can be found in McCrary (2008).

3  Composite SST anomalies for a selection of the long-term drought periods identified in Table 5. Results are from the observations (a-c), CM 2.0 (d-f), CCSM3 (g-i), and HadCM3 (j-l).

4  Number of long-term droughts, using the definition from Section 3, found in the annual mean Great Plains precipitation time series from the observations (black) and the twentieth-century climate simulations from CM 2.0 (red), CCSM3 (blue) and HadCM3 (green).
Relative Frequency Distribution histograms for length of wet and dry events that occur in the time series of annual mean Great Plains precipitation anomalies from the observations (a), CM 2.0 (b), CCSM3 (c), and HadCM3 (d). Results from all model simulations are included in the figures. In the histograms, precipitation is binned by the number of consecutive years in a row that exhibit positive or negative anomalies. Also shown on each figure is the idealized PDF described by Equation 2.

Composite SST anomalies associated with the three observed droughts (a-c), and three of the long-term drought periods found in each of the models, CM 2.0 (d-f), CCSM3 (g-i), and HadCM3 (j-l). SST anomalies are in units of °C.

Composite SST conditions averaged over the Nino3 region during the observed and simulated long-term drought periods identified in Table 5. Units are in °C.

Regression maps displaying values for United States precipitation anomalies regressed onto the time series of monthly mean SST anomalies averaged over the Nino3 region. Relationships that are significant at the 95% confidence level are delineated by the black curve. Units are in mm day\(^{-1}\) per standard deviation of the SST index.

Scatter plots of monthly mean anomalies for the Great Plains region for precipitation vs evapotranspiration (left column), precipitation vs. soil moisture (middle column) and soil moisture vs evapotranspiration (right column). Units of all anomalies are in mm month\(^{-1}\). Values shown are only from the wet season months (April-September), when land atmosphere interactions are known to be active.
Fig. 1. Time series plots for the annual cycle of Great Plains precipitation in mm day$^{-1}$ (a), evapotranspiration in mm day$^{-1}$ (b), short wave radiation flux in W m$^{-2}$ (c) and seasonal variations of total column soil moisture in mm from the observations (black) and the three models (CM 2.0 - red, CCSM3 - blue, HadCM3 - green).
Fig. 2. Time series of annual mean Great Plains precipitation anomalies from the observations (a) and one integration from each model: CM 2.0 Run 1 (b), CCSM3 Run 4 (c), HadCM3 Run 2 (d). Units of anomalies are in mm day$^{-1}$. Time series plots from the other model integrations can be found in McCrary (2008).
FIG. 3. Composite SST anomalies for a selection of the long-term drought periods identified in Table 5. Results are from the observations (a-c), CM 2.0 (d-f), CCSM3 (g-i), and HadCM3 (j-l).
Fig. 4. Number of long-term droughts, using the definition from Section 3, found in the annual mean Great Plains precipitation time series from the observations (black) and the twentieth-century climate simulations from CM 2.0 (red), CCSM3 (blue) and HadCM3 (green).
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FIG. 6. Composite SST anomalies associated with the three observed droughts (a-c), and three of the long-term drought periods found in each of the models, CM 2.0 (d-f), CCSM3 (g-i), and HadCM3 (j-l). SST anomalies are in units of °C.
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