On the Role of SST Forcing in the 2011 and 2012 Extreme U.S. Heat and Drought: A Study in Contrasts

HAILAN WANG

SIEGFRIED SCHUBERT AND RANDAL KOSTER
Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland

YOO-GEUN HAM
Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, and Goddard Earth Sciences Technology and Research Studies and Investigations, Universities Space Research Association, Greenbelt, Maryland

MAX SUAREZ
Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland

(Manuscript received 26 April 2013, in final form 26 January 2014)

ABSTRACT

This study compares the extreme heat and drought that developed over the United States in 2011 and 2012 with a focus on the role of sea surface temperature (SST) forcing. Experiments with the NASA Goddard Earth Observing System, version 5 (GEOS-5), atmospheric general circulation model show that the winter/spring response over the United States to the Pacific SST is remarkably similar for the two years despite substantial differences in the tropical Pacific SST. As such, the pronounced winter and early spring temperature differences between the two years (warmth confined to the south in 2011 and covering much of the continent in 2012) primarily reflect differences in the contributions from the Atlantic and Indian Oceans, with both acting to cool the east and upper Midwest during 2011, while during 2012 the Indian Ocean reinforced the Pacific-driven, continental-wide warming and the Atlantic played a less important role. During late spring and summer of 2011, the tropical Pacific SST forced a continued warming and drying over the southern United States, though considerably weaker than observed. Nevertheless, the observed 2011 anomalies fall well within the model's intraensemble spread. In contrast, the observed rapid development of intense heat and drying over the central United States during June and July 2012 falls on the margins of the model's intraensemble spread, with the response to the SST giving little indication that 2012 would produce record-breaking precipitation deficits and heat. A diagnosis of the 2012 observed circulation anomalies shows that the most extreme heat and drought was tied to the development of a stationary Rossby wave and an associated anomalous upper-tropospheric high maintained by weather transients.

1. Introduction

Throughout its history, the United States has experienced numerous droughts and heat waves, and these have caused extensive human suffering and enormous economic loss. The last few decades have seen significant advances in our understanding of large-scale controls on these droughts. In particular, it is now well known that certain spatial patterns of sea surface temperature (SST) are conducive to generating precipitation deficits or meteorological droughts over much of the continent. Examples of such SST patterns include those associated with the El Niño–Southern Oscillation (ENSO) on seasonal-to-interannual time scales and those associated with the Pacific decadal oscillation (PDO) and the

Corresponding author address: Siegfried Schubert, Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, NASA/GSFC Code 610.1, Greenbelt, MD 20771.
E-mail: siegfried.d.schubert@nasa.gov

DOI: 10.1175/JHM-D-13-069.1

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Atlantic multidecadal oscillation (AMO) on decadal and longer time scales.

The impacts of these SST patterns over the United States and the physical mechanisms by which they act have been extensively studied using observations (e.g., Ting and Wang 1997; Nigam et al. 2011; Hu and Feng 2012; Dai 2013) and atmospheric general circulation model (AGCM) simulations (e.g., Hoerling and Kumar 2003; Schubert et al. 2004a,b; Seager et al. 2005; Wang et al. 2010). An important finding from such studies is that ENSO and the PDO in their cold phases, and the AMO in its warm phase, produce a tendency for drought conditions over the United States, with the Pacific playing the dominant role (e.g., Mo et al. 2009; Schubert et al. 2009). In addition, the impact of SST anomalies over the United States varies substantially from region to region. While droughts over the southern Great Plains and southwestern United States are significantly promoted by certain tropical SST anomalies and appear to have some predictability on seasonal time scales, the droughts over the northern Great Plains are more strongly determined by atmospheric internal variability and appear to be less predictable (Hoerling et al. 2009).

While certain SST patterns can be important in initiating drought and determining the timing of the drought, sustaining and/or amplifying droughts over the United States involves other factors such as local soil moisture feedback and random atmospheric internal variability (e.g., Koster et al. 2003; Ferguson et al. 2010). For example, a month with low precipitation leads to a drier-than-average soil, which in turn can lead to lower-than-average evaporation, which may lead to continued low precipitation. Such feedback between the land and atmosphere plays an important role in the development and continuation of droughts over the United States, particularly during the warm season and over the central part of the country (Koster et al. 2006). There is also evidence that extended droughts can lead to heat waves in the following months (Mueller and Seneviratne 2012).

Recently, the United States again experienced severe drought and heat events. Drought and heat waves encompassed the southern United States (especially Texas) and northern Mexico during the summer of 2011 (e.g., Seager et al. 2014), while during the summer of 2012, intense drought and heat anomalies were seen in the central Great Plains (e.g., Hoerling et al. 2014). Figure 1 shows the air temperature at two meters $T_{2m}$ from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al. 2011) and precipitation and surface soil wetness anomalies from MERRA-Land (Reichle et al. 2011; Reichle 2012). The stippling indicates regions where the amplitude of the anomalies exceeds two standard deviations.

1 This is the degree of saturation in the top 2 cm of the soil (values range from 0 to 1).

2 MERRA-Land is a land-only replay of the MERRA-Land model component, with the precipitation forcing based on merging a gauge-based data product from the NOAA Climate Prediction Center with MERRA precipitation, using an updated version of the NASA GEOS-5 catchment land surface model.
the real-world anomalies reasonably well, the modeled values also reflect various model assumptions affecting soil moisture persistence. Figure 1 shows that during 2011, the drought over the United States was primarily over the southern Great Plains—a region characterized by strong surface warming anomalies (Fig. 1c) and by severe deficits in precipitation (Fig. 1i) and surface soil wetness (Fig. 1o). During the preceding winter, while there were cooling anomalies over the majority of the United States (Fig. 1a), the precipitation (Fig. 1g) and surface soil wetness (Fig. 1m) anomalies showed some indications of dry conditions along the southern and southeastern United States. Such dry anomalies were enhanced in the spring (Figs. 1h,n), apparently facilitating the development of the drought that reached its maximum strength during June and July (Figs. 1c,i,o). By comparison, the 2012 summer drought and heat wave mainly occurred over the central Great Plains (Figs. 1f,l,r). In contrast with 2011, the preceding winter and early spring were unusually warm over much of the continent (Figs. 1d,e), especially during March 2012, when numerous records were set (Dole et al. 2014). The abnormally warm surface condition in the preceding cold seasons led to the presence of very little snow during the winter and spring, though this was largely confined to the western and northern United States, outside our region of interest. The central U.S. soil moisture anomalies preceding the summer drought (Figs. 1p,q) gave little indication of what was to come, with average moisture conditions in April (during which precipitation anomalies in the central and upper Great Plains were indeed positive) and dry conditions only developing in May (individual months not shown).

The substantial differences in the record heat and drought that developed over the United States during 2011 and 2012 offer an important opportunity to assess further the differing roles of SST forcing in the development of such extreme events. The 2011 and 2012 U.S. droughts were accompanied by SST anomalies that had important similarities as well as some differences. Figure 2 shows that La Niña conditions existed in the tropical Pacific during the winter of 2010/11 (Fig. 2a) and that these gradually decayed during the spring and summer (Figs. 2b,c), though with somewhat of a recovery to colder conditions going into the winter of 2012 (Fig. 2d); La Niña conditions decayed quickly after that (Figs. 2e–g). [The ENSO–Multivariate ENSO (Wolter and Timlin 2011), PDO (Zhang et al. 1997), and AMO (Enfield et al. 2001) indices were...
obtained from www.esrl.noaa.gov/psd/enso/mei/table.html, http://jisao.washington.edu/pdo/PDO.latest, and www.esrl.noaa.gov/psd/data/correlation/amon.us.data, respectively.] Thus, whereas the summer of 2011 still showed some remnants of the La Niña with cold anomalies over the central tropical Pacific, these remnants were largely gone during the summer of 2012, with the eastern tropical Pacific showing signs of a developing warm event. A feature common to both summers was a cold PDO (Fig. 2h), while the summer of 2012 was also characterized by a substantial warm AMO, though the main warm anomalies in the North Atlantic are largely confined to the far northwestern Atlantic (Fig. 2i). We note that some of the largest differences in the SST between the two years occurred in the Southern Hemisphere.

The objective of this study is to investigate the roles played by SST forcing in the evolution of the 2011 and 2012 U.S. summer droughts. We include an analysis of SST impacts on temperature and precipitation during the preceding winter and spring, with the idea that the influence of winter and spring anomalies can perhaps persist into the warm season via mechanisms involving land processes and land–atmosphere feedback. The analysis is based primarily on a series of AGCM experiments designed to isolate the impacts of SST anomalies in different ocean basins. The AGCM used in this study is the National Aeronautics and Space Administration Goddard Earth Observing System, version 5 (GEOS-5), as documented by Rienecker et al. (2008).

The paper is organized as follows. The description of the observational (reanalysis) data, the GEOS-5 AGCM, and the model experiments are given in section 2. Section 3 presents the results from a suite of AGCM experiments as well as from some limited simulations with the atmosphere–ocean coupled version of the GEOS-5 model. The discussion and conclusions are provided in section 4.

2. Model experiments

a. Reanalysis

The reanalysis data consist of 3-hourly and monthly MERRA (Rienecker et al. 2011) and MERRA-Land data (Reichle et al. 2011; Reichle 2012) for the period January 1979–August 2012. The MERRA data are used primarily to describe the atmospheric circulation. Overall, as discussed in Rienecker et al. (2011), MERRA is an improvement over the previous generation of reanalyses and is in many aspects comparable to the other new reanalyses such as the Interim European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim) (Dee et al. 2011) and the National Oceanic and Atmospheric Administration Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010). There are, however, still substantial uncertainties and differences between these new reanalyses in poorly constrained quantities such as precipitation and surface fluxes. Here we use the precipitation (and surface soil wetness) fields from MERRA-Land in which case the precipitation estimates are, by construction, consistent with Global Precipitation Climatology Project (GPCP) observations (Huffman et al. 2009).

b. The GEOS-5 model

The GEOS-5 AGCM (Rienecker et al. 2008; Molod et al. 2012) employs the finite-volume dynamics of Lin et al. (2004) and various moist physics packages, described in Bacmeister et al. (2006), including a modified form of the relaxed Arakawa–Schubert convection scheme (Molod et al. 2006), and the catchment land surface model (Koster et al. 2000). Molod et al. (2012) show that GEOS-5 AGCM simulation results generally agree well with observational estimates of basic climate variables such as the seasonal mean wind, temperature, and height fields. Relevant to this study, the GEOS-5 AGCM deficiencies during boreal summer include a dry bias and associated warm bias over the U.S. Great Plains, along with weaker-than-observed upper-tropospheric zonal wind and transients in the Northern Hemisphere (NH) middle latitudes. We mitigate the effects of such biases by focusing our analyses on anomalies and percentiles; the reader is nevertheless advised to keep the biases in mind when interpreting our results. We will point out certain implications of the dry bias for the interpretation of our results in subsequent sections.

We will also show some limited results from the coupled GEOS-5 atmosphere–ocean general circulation model (AOGCM) seasonal forecasts. With the AOGCM (Vernieres et al. 2012), SST fields are not prescribed but are rather provided by the Modular Ocean Model, version 4 (MOM4) (Griffies et al. 2005).

c. The GEOS-5 AGCM experiments

Most of our results in this study are derived from a series of GEOS-5 AGCM (Rienecker et al. 2008) experiments forced with prescribed SST. The experiments consist of simulations covering the period January 1979–August 2012, as well as shorter-term AGCM experiments for the years 2011 and 2012. All of the AGCM experiments were run at 1° latitude–longitude horizontal resolution with 72 vertical levels.

The GEOS-5 simulations over the period January 1979–February 20103 (referred to hereafter as our

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3 We note that these runs were actually started in 1870, so there is no memory of the initial conditions for the recent decades.
baseline simulations) were forced with monthly SST and ice fraction data obtained from Hurrell et al. (2008), which are available up to March 2010. For the period from March 2010 to present, the GEOS-5 simulations were forced with the NOAA Optimum Interpolation (OI) weekly SST, version 2 (Reynolds et al. 2002). The use of different SST and ice fraction products over different periods in our AGCM runs does not notably affect our results (not shown). The baseline simulations consist of 12 members, among which 10 use Goddard Chemistry Aerosol Radiation and Transport (GOCART) aerosols and 2 use parameterized (PCHEM) aerosols. Again, the use of different aerosol fields does not noticeably affect the monthly means of the variables examined here.

Numerous short-term GEOS-5 AGCM experiments were performed for both 2011 and 2012. One experiment consists of a 20-member ensemble initialized in November of the previous year (2010 or 2011) and forced with global observed SST anomalies. These ensembles were then repeated several times, using climatological SSTs (from the period 1980–2010) everywhere but in selected regions of interest; in separate ensembles, we prescribed observed SSTs only in (i) the tropical Pacific (30°S–25°N), (ii) the North Pacific (25°–65°N), (iii) the tropical Atlantic (30°S–25°N), (iv) the North Atlantic (25°–65°N), and (v) the tropical Indian Ocean (30°S–25°N). Another set of short-term experiments (also initialized in November but run only through March of the next year) have a less refined spatial decomposition focusing on the wintertime response to SST in just the three major ocean basins: the Pacific (30°S–65°N), the Atlantic (30°S–65°N), and the Indian Ocean (30°S–25°N).

For these shorter simulations, the atmospheric and land initial conditions were taken from November of different years of the baseline runs. The early start date provides the spinup time needed to avoid any transient adjustments that the model might make in response to the initialization. Spinup issues are further alleviated by taking initial conditions from the baseline simulations rather than from observational data such as MERRA, helping us to isolate better the SST impacts on simulated drought. The 20 ensemble members in a given experiment differ from each other only in their atmospheric and land initial conditions. To construct a useful climatology for the short-term experiments (to allow the computation of anomalies for 2011 and 2012), we also performed a set of AGCM runs for each year from 1980 through 2010, with two members per year. The atmospheric and land initial conditions for these runs were made with soil moisture feedback disabled—see text.

**Table 1.** List of the main characteristics of the various GEOS-5 AGCM simulations. The model was run at 1° latitude × 1.25° longitude resolution with 72 vertical levels. Further details of the simulations can be found in the text.

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<td>Same as 2</td>
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* Additional global SST runs were made with soil moisture feedback disabled—see text.
** Note that since the baseline restart files were only saved once per month and the dates vary from year to year, the exact dates during November of the initial conditions vary.
3. Results

a. The response to global SST forcing

We begin by evaluating how well the 2011 and 2012 heat waves and droughts are represented in the baseline simulations forced with the observed global SSTs. Our comparison begins with a look at the ensemble means. The ensemble average reduces the unforced atmospheric internal variability and highlights those signals forced by the SSTs. Comparisons between MERRA and the model simulations must therefore be made with the understanding that the observational estimates are themselves a mix of forced (by SST) and unforced variability—that is, that the signals contained in the ensemble means will be, by their very nature, smoothed out and potentially less extreme than those seen in the observations. To address this, we also examine the model’s intraensemble variability.

Figure 3 shows the 12-member ensemble mean results of the baseline model simulations. One of the most striking aspects of the comparison with MERRA/MERRA-Land (Fig. 1) is that the model reproduces the pronounced differences between the two winters discussed earlier, with 2012 showing a continental-wide warming, while during 2011 the warming (if any) was confined to the Gulf States (Figs. 3a,d). The model also reproduces the main features of the anomalies during the spring (April/May) of 2011 characterized by enhanced warming and drying in the southern Great Plains and the southeast (Figs. 3b,h,n). It, however, failed to capture the relatively strong warming and drying that occurred over the central United States during the spring of 2012 (Figs. 3c,k,q), showing instead only a weak warming and weak and mixed precipitation signal in that region. The results during summer are generally less accurate than for winter or spring. In particular, the ensemble mean does not reproduce the intensification of the heat and precipitation deficits over Texas during the summer of 2011, showing primarily a northward expansion of the warming signal (Fig. 3c), with little in the way of precipitation deficits (Fig. 3i), and modest soil wetness deficits covering much of the central part of the country (Fig. 3o). The ensemble mean of the simulations also does not reproduce the observed intense heat and record-breaking precipitation deficits (and associated soil wetness anomalies) that developed over the central Great Plains in 2012 during late spring and summer: the ensemble mean shows only relatively weak warming confined to the western United States and southern plains in June and July (Fig. 3f), together with weak precipitation and soil wetness anomalies (Figs. 3l and 3r, respectively).

Figure 4 shows the January–August time series of $T_{2m}$, precipitation, and surface soil wetness anomalies for 32 individual ensemble members (12 baseline and the 20 forced by global SST) and the observations (MERRA and MERRA-Land) averaged over the southern Great Plains in 2011 (Figs. 4a–c) and central Great Plains in 2012 (Figs. 4d–f). For 2011, with the exception of summertime precipitation, the observational estimates generally fall within the spread of the ensemble members. In contrast, during 2012, the observed spring and summer anomalies of all three variables tend to be further out at the margins of the model spread. The soil wetness anomalies illustrate the key differences between the two years. During 2011 (Fig. 4c), most ensemble members show drying (an indication of a strong SST influence in the southern Great Plains), with the observations falling well within the relatively large
ensemble spread. During 2012 (Fig. 4f), the model shows relatively weak drying (on average) over the central Great Plains and overall less spread in the ensemble with most members clustered around zero, but with a few ensemble members showing relatively strong drying (in fact, two are comparable to MERRA-Land) developing in spring and summer. The strongest impact of SST in 2012 over the central Great Plains is on the temperature during winter and spring (Fig. 4d).

As already mentioned, the free-running AGCM does have a dry bias over the Great Plains, so some of the differences with respect to MERRA/MERRA-Land may simply reflect that model deficiency. To minimize that problem, we present the anomalies as percentiles (relative to each dataset’s underlying distribution) in Fig. 5. In terms of percentiles, the observational estimates generally do fall well within the model spread for the summer of 2011 (Figs. 5a–c), but they remain on the margins of the model spread for the summer of 2012 (Figs. 5d–f). This suggests that the 2012 summer anomalies reflect a very extreme and rare event that was unlikely to have been strongly induced by SST distributions. We nevertheless acknowledge the possibility that model error associated with missing land–atmospheric feedback could contribute to the lack of an SST impact during 2012.

b. The response to regional SST forcing

In view of the stronger impact of the SST on U.S. surface temperature (compared with precipitation), our analysis of the roles of the different ocean basins will focus primarily on how they influence temperature. We will begin with an examination of the different SST forcing of the 2011 and 2012 cold seasons and then turn to the late spring and summer seasons. We note that the below model-based assessment of the impact of the different ocean basins is something that is difficult to
obtain from observations owing to the correlated nature of the variability in the different ocean basins.

1) WINTER/EARLY SPRING (JFM)

Figure 6 shows the ensemble mean results of two sets (for 2011 and 2012) of 20 AGCM simulations initialized the previous November. The results (Figs. 6a,b) confirm what we saw with our baseline AGCM runs for January–March (JFM): the largest positive surface temperature anomalies are confined to the southern United States during 2011, and they span the continental United States and parts of Canada during 2012. The 250-hPa height anomalies (Figs. 6c,d) also show distinct differences over the United States. A weak positive height anomaly extends from the Pacific eastward across the southern United States during 2011, and a substantially stronger positive height anomaly covers much of the United States during 2012, with the latter being part of a large positive anomaly that extends from the United States northeastward into northern Europe. Overall, the height anomalies during 2012 appear to be a combination of a positive North Atlantic Oscillation (NAO) and a Pacific–North American (PNA)-like wave response. In contrast, during 2011, the anomalies over the North Atlantic resemble those of a negative NAO, while over the Pacific there is a strong tropical response, with weaker and smaller-scale north–south oriented anomalies in the North Pacific/North American region. The observed (MERRA) 250-hPa height anomalies (Figs. 6e,f) show substantial similarities to the ensemble mean responses, especially in the tropical and subtropical Pacific, presumably reflecting the response to the cold tropical Pacific SST anomalies. Surprisingly, there is also a substantial similarity in the northern extratropics. Notably, this includes the positive height anomalies extending from the North Pacific eastward across the southern United States and the negative height anomalies in the North Atlantic during 2011, and the strong positive height anomalies over North America and Europe (with negative anomalies to the south) during 2012. There are, of course, differences that presumably reflect the part of the variability not forced by SST, including the strong negative anomaly in the North Pacific during 2012.
Figure 7 shows the results from the additional 20-member ensembles in which the AGCM was forced with SSTs from individual (Pacific, Atlantic, and Indian) ocean basins, with climatological SST elsewhere. A key result is the remarkable similarity between years in the U.S. surface temperature response to the Pacific SST (Figs. 7a,d), with warming encompassing the entire U.S. continent during both years. The height responses (Figs. 7g,j) are also quite similar over the United States, despite a much stronger response over the Pacific during 2011. We must therefore look to the other oceans to explain the differences over the United States between the two years. In particular, we see that the Atlantic (Fig. 7b) and Indian (Fig. 7c) Ocean SST distributions act to confine the positive surface temperature anomalies to the southern Great Plains during 2011 since they both induce negative surface temperature anomalies over the northern Great Plains and the eastern United States. These effects are associated with negative NAO-like responses to the SST in both oceans (Figs. 7h,i), which, together with the response to the Pacific, combine to produce the

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4 Results for the Indian Ocean are based on 30 ensemble members. We note that while the anomalies shown differ little from those based on 20 ensemble members, they were in the latter case not significant over the United States at the 5% level.
negative NAO-like response shown in Fig. 6c. In contrast, during 2012 the Indian Ocean acts to reinforce the warming from the Pacific (Fig. 7f) and the Atlantic Ocean, while still inducing negative temperature anomalies over the eastern United States, plays a less important role (Fig. 7e). In this case, the generally positive height anomalies shown in Fig. 6d stretching from the United States into northern Europe are primarily the result of more wavelike responses to the Pacific, Indian, and, to a lesser extent, Atlantic Ocean SST (Figs. 7j–l) that combine to produce a more zonally extended anomaly.

We note that the above temperature responses over the United States are remarkably linear in the sense that the sum of the responses to the individual ocean basins are a good approximation to the response to the global SST fields (not shown). We now turn to an analysis of the warm season.

2) LATE SPRING AND SUMMER

We saw in section 3a that the impact of SST during spring and summer is rather modest, though stronger for surface temperature than for other variables, and stronger for 2011 than for 2012. Here we dissect that modest impact on surface temperature over the United States into contributions from the different ocean basins, with a particular focus on the impacts of the Pacific and Atlantic Oceans—the key contributors to U.S. drought during the warm season, as determined from previous studies (e.g., Schubert et al. 2004b; McCabe et al. 2004; Seager et al. 2005; Mo et al. 2009; Schubert et al. 2009). The results are based on several additional sets of 20 simulations for 2011 and 2012 (initialized in the middle of the previous November) in which the SST anomalies are specified globally (in the control ensemble) or confined to the tropical Pacific, North Pacific, tropical Atlantic, North Atlantic, and tropical Indian Ocean, with climatological SST elsewhere (see Table 1).

Figure 8 shows the results for 2011. Consistent with the baseline simulations (Fig. 3), the response to global SST anomalies (Figs. 8a,b) shows surface warming anomalies over the southern United States during April and May. The warming anomalies expand northward into the central Great Plains and subsequently expand to occupy much of the United States in June and July. The responses to the regional SST anomalies indicate that the surface warming anomalies over the southern United States are mainly forced by the SST anomalies in the tropical Pacific. The North Pacific has little impact. The contribution from the tropical Atlantic is the main driver behind the surface warming anomalies over the central and northern United States during June and July,
with some contribution also from the North Atlantic. There is little impact from the Indian Ocean SST (Figs. 8k, l).

Figure 9 is the same as Fig. 8, but for 2012. The surface temperature responses to global SST anomalies are again generally consistent with those in the baseline simulations (Fig. 3). We note that for April/May, when there do appear to be some differences in the spatial distribution of the anomalies between the 20-member ensemble and the 12 baseline simulations (in particular, the spatially more extensive positive anomalies that extend across the central United States in the baseline simulations), these apparent differences involve values that are not significant at the 5% level.

Looking at the impacts of the individual ocean basins during the spring and summer of 2012, we find that the tropical Pacific (Figs. 9c, d) plays a key role in defining the southern U.S. temperature anomalies, whereas the tropical Atlantic (Figs. 9g, h) tends to impact the northern half of the country. In contrast, the North Atlantic (Figs. 9i, j) impacts the eastern seaboard in spring and the western United States in summer. The North Pacific (Figs. 9e, f) and the Indian Ocean (Figs. 9k, l) show generally smaller impacts, though during April/May the Indian Ocean appears to produce a significant warming over the western part of the country. One final note regarding Figs. 8 and 9 concerns the linearity of the results (i.e., the extent to which the results from the individual ocean basin experiments add up to those from the global SST experiment). Here we find that the results are again (as we found for the winter cases) quite linear for 2011, but less so for 2012 (not shown). The latter appears to be a consequence of the overall weaker impact of SST on U.S. temperature during the spring and summer of 2012, suggesting that many more ensemble members than produced here may be required to accurately estimate the more subtle balance of contributions from the various ocean basins during that year.

Figure 10a summarizes the impacts of the regional SST anomalies on $T_{2m}$ averaged over the southern Great Plains from January to August of 2011. The results highlight the important role of the tropical Pacific in forcing surface warming over that region in early 2011, as well as during the first half of the summer. During the summer, the SST anomalies in the tropical Atlantic also act to warm the region. These results further emphasize that the development of the 2011 heat wave was driven by SST anomalies in both the Pacific and Atlantic, with the different timing of the impacts acting to extend the warm conditions throughout
the warm season. Figure 10b is the same as Fig. 10a, but for the central Great Plains during 2012. As in early 2011, the tropical Pacific SST during 2012 contributed to surface warming over the southern United States during the winter and early spring, whereas the tropical Atlantic contributed to a weak surface warming over the central United States during the latter half of the summer.

In summary, the timing of the impacts of the ocean basins on U.S. temperature anomalies is similar in the two years. We have already seen (Fig. 7) that the cold season response to SST is linked to large-scale changes in the stationary waves, with the response to the Pacific associated with a PNA-like response and the response to the Atlantic resembling a NAO-like structure. During the summer the warming and drying over the United States associated with the Atlantic (and Pacific) SST tends to be associated with more of a zonally symmetric response in the upper-tropospheric height field (e.g., Schubert et al. 2002; Kumar et al. 2003) as well as a low-level response that impacts the moisture transported from the Gulf of Mexico (e.g., Schubert et al. 2009; Wang et al. 2010; Hoerling et al. 2014). In this case, we do indeed find ensemble mean upper-level height anomalies in the baseline simulations that have a distinct zonally symmetric character during June and July of both years, though only 2011 (in particular, June of that year) has a substantial anomaly (southerly) in the low-level winds in the southern Great Plains consistent with a moisture flux divergence in that region (results not shown).

While the Pacific produced a predilection for warming over the United States during both years and while the Atlantic appears to be instrumental in continuing the warming over the central Great Plains in summer, the SSTs by themselves do not explain the development of the extremes, especially the sudden development of the 2012 heat wave and drought. In the following, we look at the processes involved in the development of the 2012 heat wave and drought in more detail, with an eye toward identifying potential connections between the 2011 and 2012 events.

c. Are the 2011 and 2012 summer heat and drought events connected?

In assessing potential links between the 2011 and 2012 events, we focus in particular on determining if persistence of the 2011 dry soil conditions into 2012 contributed to the development of the 2012 drought. We also look more directly at the physical processes involved in the forcing and maintenance of the atmospheric circulation anomalies that developed during the 2012 summer.

1) ROLE OF SOIL MOISTURE

The evolution of the soil wetness anomalies in Fig. 1 gives little indication that the dry conditions that developed in May and June 2012 are a continuation of preexisting dry soil conditions (see also Hoerling et al. 2014). In fact, the first four months of 2012 had near-normal, if not slightly above normal, rainfall in the central and upper Great Plains, and soil wetness was near normal going into April, with the exception of a region in the upper Midwest that could have played a role in the subsequent development of anomalies in May. Figure 11 addresses this possibility, showing results from a suite of seasonal forecasts with the GEOS-5 coupled model initialized in early May, June, and July2 2012. For these runs, the atmosphere is initialized from MERRA, the ocean

5 The actual start dates for the ensemble members are as follows. For the early May starts, the initial conditions are on 11, 16, 21, and 26 April and 1 and 6 May, with 1 May having five members. For the early June starts, the initial states are on 11, 16, 21, 26, and 31 May, with the 31 May starts having seven members. For the early July starts, the initial conditions are on 10, 15, 20, 25, and 30 June, with seven members on 30 June.
from the GEOS-5 ocean analysis (Vernieres et al. 2012), and the land from an offline calculation in which the land model is forced with observation-based meteorological forcing, including precipitation fields tied to rain gauge measurements. We note that the catchment land surface model, a state-of-the-art treatment of large-scale land surface energy and water processes, utilizes soil moisture prognostic variables with an inherent memory of a few weeks to a couple of months (Wang et al. 2009), allowing for subsequent impacts on temperature and precipitation (Guo et al. 2012).

While the forecasts starting in May do predict warm anomalies for July in the Great Plains (Fig. 11a) (extending northwestward into Canada), any sense of the severity of the 2012 event is not predicted until the next set of forecasts, which start in June (Fig. 11b). The forecasts starting in early July finally pick up on the breadth of the event (Fig. 11c). The forecasted signal is even less clear for precipitation (Figs. 11e–h). While the forecasts starting in May and June predict small precipitation deficits for July over parts of the Great Plains (Figs. 11e,f), only the forecasts starting in early July (Fig. 11g) capture the full strength of the precipitation deficits. If dry soil moisture conditions from 2011 (Fig. 1) persisting into 2012 did contribute significantly to the 2012 drought, we would expect the forecasts (which take advantage of such information) to capture this. The overall sense of the forecast results, however, is that, while the dry conditions perhaps contributed in some way to the development of the July temperature anomalies, they did not contribute significantly to the initiation of the severe record-breaking precipitation deficits of that summer.

The above results, however, must be tempered by the fact that the GEOS-5 model has a dry bias over the Great Plains, so we could be underestimating the role of soil moisture deficits. With the dry bias, there may be little room for further drying of the soil and subsequent feedback on the precipitation. Some sense of the impact of the land is given in Fig. 12, which shows the evolution of 2012 conditions in two different ensemble members. One member (ensemble 6) is shown because it comes into spring with extremely warm March conditions (Fig. 12a) rivaling those found in MERRA, though these conditions are quickly dissipated in the following months (Fig. 12b), with little support from dry land conditions (Figs. 12m–o) or subsequent precipitation deficits (Figs. 12g–i). This simulation’s behavior supports the idea that the extremely warm March in nature did not have a major impact on the subsequent development of the summer extremes. The other member (ensemble 4) shows substantial soil wetness deficits in March over the west and Midwest (Fig. 12p) that are subsequently amplified and expanded to include much of the central United States (Fig. 12q). This late spring amplification of the soil wetness anomalies is associated with a precipitation deficit that developed over the central and northern part of the country during April/May (Fig. 12k). Those soil wetness deficits are similar in magnitude to those found in nature (as estimated from MERRA-Land, Fig. 1).
and (together with the precipitation deficits) continue into June and July (Figs. 12l,r).

The effect of soil moisture feedback on 2012 conditions was addressed further with some additional AGCM experiments (not shown). In these experiments, the soil moisture feedback was artificially disabled—the seasonal cycle of climatological soil moisture (obtained by averaging 3-hourly soil moisture from a set of short-term hindcast runs for years 1980–2010) was continuously prescribed at the land surface. These experiments, when compared to those with interactive land, show that soil moisture feedback is critical for amplifying the SST-forced warm summer surface temperature anomalies during both years. The effect of the feedback on precipitation, however, is significantly less.

2) DEVELOPMENT AND MAINTENANCE OF THE 2012 SUMMER ANOMALIES

The development of the April/May precipitation deficits over the central and northern Great Plains in ensemble member 4 (Fig. 12) is found to be associated with the development of a stationary Rossby wave (not shown). Schubert et al. (2011) show that such waves have played a key role in the development of some of the most extreme heat waves and droughts over the United States. In this subsection, we take a closer look at the evolution and maintenance of the atmospheric circulation anomalies associated with the 2012 event to assess whether such waves also played a role here.

Figure 13 shows the evolution of the daily $T_{2m}$ and precipitation anomalies over the United States together with the (10-day running mean) evolution of the upper-level meridional wind and height field. The longitude–time Hovmöller diagrams (values averaged between $34^\circ$ and $46^\circ$N) show considerable week-to-week variability in the evolution of both $T_{2m}$ (Fig. 13a) and precipitation (Fig. 13b). The most intense and persistent positive anomalies in $T_{2m}$ developed over the central United States in mid-June, lasting well into August. This was accompanied by sustained precipitation deficits that lasted into late August (Fig. 13b). The wind and height anomalies (Figs. 13c,d) also show rather unorganized variability on weekly time scales with the signature of a well-defined wave train that propagates eastward from the Pacific impacting the central United States in the second half of June and with some evidence of a phase locking and persistence of the wave resulting in positive height anomalies over the central United States throughout July. A second wave train develops during August, producing negative height anomalies over the United States, that appears linked with negative temperature anomalies and an alleviation of the central U.S. precipitation deficits in late August.

The above results are consistent with an important role for summertime Rossby waves in the development and evolution of the main precipitation and temperature anomalies over the central Great Plains during the summer of 2012. This is further bolstered by the results of a stationary wave model diagnosis (not shown), indicating that the positive height anomalies over the United States are maintained by submonthly (primarily vorticity) transients, the primary forcing of summertime stationary Rossby waves (Schubert et al. 2011). One therefore gets the impression of an unfolding of a series...
of events during the summer of 2012 that are primarily driven by internal atmospheric dynamics, which together produced one of the most severe droughts on record over the central United States. In fact, Hoerling et al. (2014) concluded that the drought was the result of “a sequence of unfortunate events.” While our results are generally in agreement with that assessment, Fig. 14 suggests that the sequence of events may have developed in a large-scale environment favoring a predilection for warm temperatures and precipitation deficits. That environment consists of weak but positive height anomalies that extend around the globe in the middle latitudes of both hemispheres (Fig. 14a). The similarity between the MERRA anomalies and the baseline model response (Fig. 14b) suggests that they are largely SST forced. Furthermore, the global nature of the response suggests the possibility of simultaneous drought in various regions—for example, it makes the fact that the Eurasian grain belt also suffered from drought and heat during that summer somewhat less of a coincidence.

Coming back to the comparison with 2011, we note that the same type of zonally symmetric response occurred in the model for that summer, though slightly shifted to the south compared with 2012 (not shown). That response was in this case, however, not reflected in the observations (MERRA), which suggests a substantial contribution from internally generated atmospheric variability that appears to have, in part, masked the SST-forced signal.

4. Discussion and conclusions

The United States experienced record-breaking drought and heat during both 2011 and 2012. The location and overall evolution of the temperature and precipitation anomalies in the two years, however, show
substantial differences. The 2011 anomalies largely reflect what is now a generally well-understood response to cold tropical Pacific (La Niña) SSTs primarily in the southern Great Plains (especially Texas and northern Mexico; e.g., Seager et al. 2014). In contrast, the 2012 anomalies were rather atypical, with unusual warmth spanning the entire continent during the winter and early spring, followed by a rapid development of record-breaking precipitation deficits and extreme temperatures over the central Great Plains—a region believed not to be strongly affected by remote SST forcing during the warm season.

GEOS-5 AGCM simulations forced with observed SSTs are consistent with observations for 2011, with the ensemble mean showing warming and drying generally confined to the south for the first half of the year. Although the intensification of the drought and heat over Texas during the summer of 2011 was not captured in the ensemble mean and thus appears not to be forced by SST, the observed summertime temperature and precipitation extremes fell within the spread of the model’s ensemble. The model also generally reproduced the unusual 2012 winter and early spring warmth that extended across much of the continent. The ensemble mean, however, failed to reproduce the rapid development of intense heat and drying over the central United States during June and July 2012, with the observed anomalies falling on the margins of the model’s intraensemble spread.

The above model results were analyzed further by performing additional experiments in which the prescription of observed SSTs was confined to individual ocean basins or subbasins, with climatological SSTs prescribed elsewhere. These results showed that during the cold season the Pacific SSTs produce a general warming over the United States that is remarkably similar for the two years, despite the near absence of La Niña conditions during 2012; this indicates that the SSTs associated with a negative Pacific decadal oscillation (common to both years) played a key role during both cold seasons. We found also that the pronounced temperature differences between the two years (warmth confined to the south in 2011 as opposed to covering much of the continent in 2012) primarily reflect differences in the contributions from the Atlantic and Indian Oceans: during 2011, both basins acted to cool the east and upper Midwest, whereas during 2012, the Indian Ocean reinforced the Pacific-driven continental-wide warming, and the Atlantic Ocean’s contribution was less important. These results are not inconsistent with the Hoerling et al. (2004) study, which found that a warm Indian Ocean forces a positive polarity of the NAO. Such an impact from the Indian Ocean, however, does not appear in all models. For example, Seager et al. (2014) found that neither Community Climate Model, version 3 (CCM3), nor ECHAM4.5 showed a significant impact on the NAO from the SST forcing in the winter of 2010/11, suggesting that the occurrence of the negative NAO during that winter was, instead, largely an example of unforced internal atmospheric variability.

The response over the United States to Atlantic SST anomalies is consistent with the impacts found over the eastern United States by Lim and Schubert (2011). Our results are also not inconsistent with the study of Dole et al. (2014), who found that the March 2012 heat anomaly, in particular, was the result of enhanced northward transport of warm air from the Gulf of Mexico, part of a global teleconnection pattern forced by tropical heating associated with La Niña SST anomalies and a strong Madden–Julian oscillation (MJO). We indeed find that some of our ensemble members have the most intense heating anomalies in March (not shown), indicating that internal atmospheric variability...
did play an important role, though our results show that the Indian Ocean contributed as well. Whether the Pacific Ocean’s contribution is associated with La Niña or the negative PDO may be largely an issue of definition. The importance of a cold tropical Pacific for forcing North American drought has been established in numerous studies (e.g., Schubert et al. 2009). However, pinpointing the precise aspects of Pacific SST that truly matter for the United States will require additional research. A framework for carrying out such an analysis was recently developed by Shin et al. (2010) based on AGCM simulations forced with localized SST patches. Their analysis, which focused on tropical SST forcing of North American drought, identified a substantial sensitivity to SST in the central and eastern tropical Pacific Ocean as well as the Gulf of Mexico/Caribbean Sea.

During late spring and early summer of both years the tropical Pacific forces heat and drought conditions over the southern Great Plains; this is followed in both years by a northward expansion of a modest warming in midsummer tied primarily to forcing from the Atlantic. This seasonality in response to the Pacific and Atlantic SSTs reflects the seasonal changes in the mean flow—the Pacific Ocean modifies stationary waves in late spring and early summer, whereas the Atlantic (and Pacific) SST affect the inflow of moisture from the Gulf of Mexico during mid and late summer. Schubert et al. (2009) and Wang et al. (2010) found that such seasonality in the responses to Pacific and Atlantic SSTs can be expected even with a seasonally unvarying SST forcing, indicating that the changes largely reflect the dependence of the SST response on seasonal changes in mean stationary waves, low-level winds, and so on.

There is little evidence from the model simulations to suggest that the development of the 2012 extreme summer heat and drought in the central Great Plains was significantly promoted by antecedent dry soil conditions, say from the preceding year of drought. Nevertheless, the experiments in which we disabled soil moisture feedback suggest that, once drought conditions developed in 2012, land–atmosphere feedbacks contributed substantially to the intensity of the heat. Any impacts of feedback on the precipitation deficits were much smaller.

A diagnosis of the observed summer circulation anomalies over the United States shows that the most extreme heat and drought during late June and July 2012 was associated with the development of an anomalous upper-tropospheric high over the central and northern United States, and this was linked to the development of a Rossby wave and maintained by weather transients. Overall, our results regarding the rapid development of the 2012 summer drought provide additional support to the multimodel analysis of this event by Hoerling et al. (2014), indicating that atmospheric internal variability was the basic cause and that any contribution from SST forcing was rather small. We should emphasize that our results indicate that the intensity of the 2011 summer drought conditions over the southern Great Plains region was also strongly tied to internal atmospheric variability, consistent with the findings of Seager et al. (2014). This highlights the importance of atmospheric variability in the development of the most extreme short-term drought and heat wave events in general over the United States (e.g., the role of Rossby waves, Schubert et al. 2011), though we would argue that it played a greater role in 2012 than in 2011.

Finally, we need to emphasize that all of our conclusions regarding the relative importance of atmospheric variability are made with the caveat that model deficiencies (e.g., the dry bias of the GEOS-5 AGCM over the Great Plains) may contribute to an underestimation of the impact of other factors, especially the contribution of land feedbacks that could be very important in amplifying even a weak SST-forced signal in the precipitation.

Acknowledgments. This study was supported by the NOAA Modeling, Analysis, Predictions and Projections (MAPP) program and the NASA Modeling, Analysis and Prediction (MAP) program. YGH was funded in part by the Korea Meteorological Administration Research and Development Program under Grant CATER 2012-3041.

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