Would Advance Knowledge of 1930s SSTs Have Allowed Prediction of the Dust Bowl Drought?*

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ABSTRACT

Could the Dust Bowl drought of the 1930s have been predicted in advance if the SST anomalies of the 1930s had been foreknown? Ensembles of model simulations forced with historical observed SSTs in the global ocean, and also separately in the tropical Pacific and Atlantic Oceans, are compared with an ensemble begun in January 1929 with modeled atmosphere and land initial conditions and integrated through the 1930s with climatological SSTs. The ensemble with climatological SSTs produces values for the precipitation averaged over 1932–39 that are not statistically different from model climatology. In contrast, the ensembles with global SST forcing produce a drought centered in the central plains and southwestern North America that is clearly separated from the model climatology. Both the tropical Pacific and northern tropical Atlantic SST anomalies produce a statistically significant model drought in this region. The modeled drought has a spatial pattern that is different from the observed drought, which was instead centered in the central and northern plains and also impacted the northern Rocky Mountain states but not northeastern Mexico. The model error in extending the Dust Bowl drought too far south is attributed to an incorrect response of the model to warm subtropical North Atlantic SST anomalies. The model error in the northern states cannot be attributed to an incorrect response to tropical SST anomalies. The model also fails to reproduce the strong surface air warming across most of the continent during the 1930s. In contrast, the modeled patterns of precipitation reduction and surface air temperature warming during the 1950s drought are more realistic. Tree-ring records show that the Dust Bowl pattern of drought has occurred before, suggesting that while the extensive human-induced land surface degradation and dust aerosol loading of the 1930s drought may have played an important role in generating the observed drought pattern, natural processes, possibly including land interactions, are capable of generating droughts centered to the north of the main ENSO teleconnection region. Despite this caveat, advance knowledge of tropical SSTs alone would have allowed a high-confidence prediction of a multiyear and severe drought, but one centered too far south and without strong cross-continental warming.

1. Introduction

The Dust Bowl drought of the 1930s was one of the worst environmental disasters of the twentieth century anywhere in the world. Drought affected the plains and prairies from the Gulf of Mexico up into Canada and also the northern Rocky Mountain states and Pacific Northwest. The drought lasted from at least 1932 to 1939 with little respite. In the preceding decades, during a long period of average or above-average rainfall, the plains had been converted from a region of prairie grass and ranching to wheat farming. When drought struck in the 1930s the wheat lacked the natural resistance of prairie grass and died exposing bare earth and leading to the horrific dust storms so characteristic of that decade and not seen on the same scale before or after (Chepil 1957; Worster 1979). Three million plains people left their farms during the 1930s and the outmigration to other states probably was in excess of half a million (Worster 1979), numbers only equalled in the United States by the impact of Hurricane Katrina in 2005 (e.g., International Medical Corps 2006).

Recently three papers (Schubert et al. 2004a,b; Seager et al. 2005) have used simulations with atmosphere

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models forced by observed sea surface temperatures (SSTs) to claim that the Dust Bowl drought was forced by small variations of tropical SSTs. In addition, Seager et al. (2005) and Herweijer et al. (2006) have used model simulations to claim that the 1950s Southwest drought and three serious multiyear droughts in the mid-to-late nineteenth century were forced by persistent La Niña–like conditions in the tropical Pacific. Seager (2007) and Hoerling and Kumar (2003) also claim that the 1998–2002 period of the most recent drought (which is ongoing at the time of writing) was similarly forced.

If these claims are true then it should be possible to predict droughts over western North America if the tropical SSTs could be known in advance. Whether that could translate into real drought prediction is currently not known because studies of tropical SST predictability beyond the interannual time scale are in their infancy (Karspeck et al. 2004; Seager et al. 2004). Here we address the more limited question of atmospheric predictability given known SSTs and ask the question: If in 1929 we had known what the SSTs were going to be in the 1930s could we have predicted drought during the 1930s and with what certainty and errors in spatial pattern and amplitude?

To answer this question we will use ensemble model simulations that variously specify SSTs globally and by ocean basin and region. These include our ensembles with global SSTs and tropical Pacific–only SSTs that have been reported on in prior work and a new ensemble with only tropical Atlantic SSTs specified. In addition we have generated another new ensemble that is initialized with model-generated land and atmosphere states in January 1929 and integrated from 1929 to 1940 with the global SST specified to be that of the climatology known in 1929 (i.e., climatological SST for 1856–1929). The first set of ensembles therefore contains climate variability that arises from internal atmospheric processes (interacting with land and, in some simulations, with a mixed layer ocean) plus that which is forced by the imposed SST variations. The new ensemble contains only internal atmospheric variability interacting with land and the memory of the atmosphere and land state in January 1929.

Here we will compare these ensembles to determine if advance knowledge of the SST leads to a prediction of drought that is statistically significantly different from that which could have been obtained from initial conditions and atmosphere–land processes alone. This result will be used to assess the extent to which the Dust Bowl drought was SST forced. We will also examine whether the observed Dust Bowl drought can be reproduced in the model through a combination of SST forcing and internal variability and assess whether there are consistent biases in the model's response to SST forcing that could be potentially corrected. We will demonstrate that the spatial pattern of the Dust Bowl drought differs to an important extent from the canonical pattern of droughts forced by tropical SSTs. Hence, we will also examine millennium long tree-ring records to show how unusual this pattern is and that the only prior analogs to this pattern fell within the Medieval period of intensified aridity (Cook et al. 2004). This work expands on our prior work by examining the relative roles of the tropical Pacific and Atlantic Oceans and internal variability in creating drought, by examining surface air temperature anomalies as well as precipitation, and by considering the issue of predictability through the examination of model ensemble spread as well as the ensemble mean.

2. Data and models

We use precipitation and temperature from the Global Historical Climatology Network (GHCN; Peterson and Vose 1997) for ground truth. Many commonly used definitions of drought [e.g., hydrological drought and agricultural drought as in Wilhite (2000) and Keyantash and Dracup (2002) and references therein] depend on precipitation minus evaporation (or evapotranspiration) since this is the net flux of water substance at the surface and impacts soil moisture, groundwater recharge, runoff, and streamflow. However, reliable data for evaporation and soil moisture are not available. Evaporation depends on soil moisture and atmospheric humidity, which itself depends in part on atmospheric temperature. The Palmer drought severity index (PDSI) is a commonly used measure of drought (Palmer 1965) and is calculated from a simple land surface model using precipitation and temperature variations alone as inputs. Since the land surface model used in the PDSI calculation is simpler than in typical climate models, and because the PDSI calculation ignores variations in radiation and computes evaporation in a highly parameterized manner, we do not compute PDSI for the model. Instead, in the absence of direct observations of soil moisture and evaporation, we compare the model to observations of precipitation and surface air temperature.

The atmosphere model used here is the Community Climate Model version 3 (CCM3) of the National Center for Atmospheric Research (NCAR) run at T42 resolution with 18 vertical levels (Kiehl et al. 1998). The model simulations are as follows:

1) A 16-member ensemble from 1856 to 2005, each with different initial conditions, with global SST forcing. This is the Global Ocean Global Atmosphere (GOGA) ensemble.
2) A 16-member ensemble from 1856 to 2005 with tropical Pacific (20°S–20°N) SSTs specified and SSTs elsewhere computed using a two-layer ocean model in which the top layer is the mixed layer and has a specified seasonally varying depth (derived from observations) and that exchanges heat and mass with the lower layer. Neglected ocean heat transport is accounted for by specified "q-fluxes" in each layer such that the climatological model temperatures in the two layers remain close to those observed. Details can be found in Seager et al. (2005). This is the Pacific Ocean Global Atmosphere–Mixed Layer (POGA-ML) ensemble.
3) A 16-member ensemble from 1856 to 2005 with tropical Pacific (20°S–20°N) SSTs specified and climatological SSTs elsewhere. This is the Pacific Ocean Global Atmosphere (POGA) ensemble.
4) An 8-member ensemble from 1856 to 2005 with specified SSTs in the tropical Atlantic (30°S–30°N) with climatological SSTs specified everywhere else. This is the Tropical Atlantic Global Atmosphere (TAGA) ensemble.
5) A 16-member ensemble from 1929 to 1940 with climatological (average of 1856–1928) SSTs specified everywhere. The 16 ensemble members begin on 1 January 1929 with the atmospheric and land states taken from the 16 GOGA runs on that date. This is the Climatological Ocean Global Atmosphere (COGA) ensemble.[1]

The SST data uses the Kaplan dataset (Kaplan et al. 1998) everywhere from 1856 to 1870 and in the tropical Pacific until 2005 and the Hadley Centre Sea Ice and SST (HadISST) dataset (Rayner et al. 2003) outside the tropical Pacific from 1870 to 2005. All model results shown are relative to their 1856–1928 climatology to mimic a forecast in 1929 based on known future SSTs. For the COGA ensemble, which begins in 1929, anomalies are computed relative to the 1856–1928 climatology from the GOGA run. The use of the 1856–1928 period to compute the climatology poses some problems over North America where for many areas, especially in the West, data coverage is sparse before the late nineteenth century. Most results were recalculated using a 1900–28 base climatology and this difference does not effect our conclusions.

To examine prior analogs of the Dust Bowl we use an update (provided by Dr. E. Cook 2007, personal communication) of the gridded tree-ring records in the North American drought atlas (Cook and Krusic 2004; Cook et al. 2004). The update uses the same analysis methods described earlier but has a larger number of tree records especially before AD 1300. We also examined sea level pressure data for the 1930s but found major differences between the COADS and Kaplan data (Kaplan et al. 1998), on the one hand, and the Hadley Centre data (Allan and Ansell 2006), on the other, and these results are not presented here.

3. Comparison of spatial patterns of observations and ensemble means of precipitation

We will focus on the core period of the Dust Bowl, 1932–39. The near-global SST anomaly for this period (relative to the 1856–1928 climatology), which it is claimed drove the drought, is shown in Fig. 1: a weak La Niña–like state prevailed during the 1930s together with a warm Atlantic Ocean. The North Pacific SST anomalies are, however, not typical of La Niña–like conditions being warm along the coast of North America and cold in the interior, conditions more typical of El Niños.

In Fig. 2 we compare the observed precipitation anomaly, averaged over all months for the core period of the Dust Bowl, 1932–39, to that simulated in the five ensembles, focusing on the ensemble mean. For such large ensembles averaging over the ensemble members greatly reduces the internal variability that is uncorrelated from one member to another and leaves the part that is common to all members: the part forced by the imposed SSTs.

The observed precipitation reduction covered most of the United States with the exception of parts of the Southwest and Northeast and also included parts of northern Mexico and the Canadian Prairies. The center of the precipitation reduction was in the central and northern Great Plains. Positive precipitation anomalies occurred in southern Mexico and Central America, the Caribbean region, and southwestern and eastern Canada. The GOGA ensemble mean (with global SST forcing) precipitation reduction also covers most of the United States but, erroneously, does not make the Pacific Northwest or Great Lakes area dry. Also erroneously, the GOGA ensemble mean produces a stronger drought in the Southwest and extends deeper into

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[1] The information in the atmospheric initial condition will be lost within days to weeks, while the memory of the land surface initial condition is expected to be lost within a season to a year. Initialization of the COGA ensemble with the GOGA land and atmosphere state on 1 January 1929 was done to mimic a forecast and not from any expectation that the initial conditions will impact the decadal prediction.

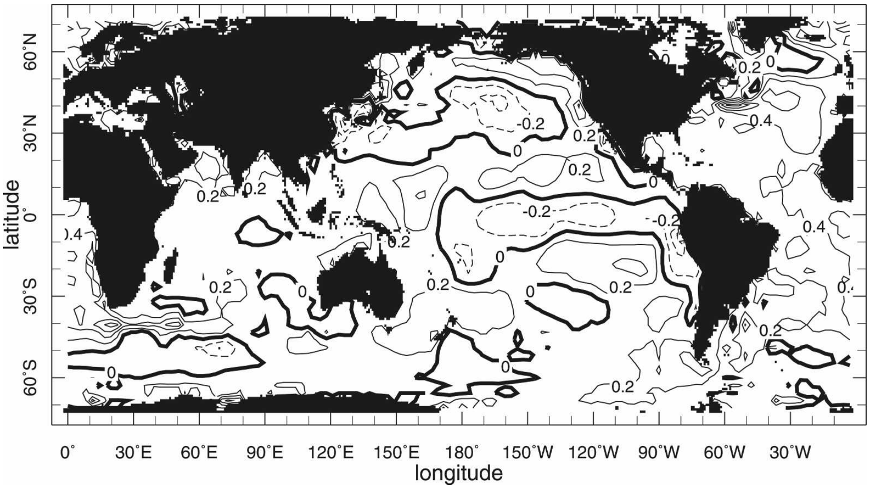

FIG. 1. The observed SST anomaly (K) during the Dust Bowl (1932–39) relative to an 1856–1928 climatology. Observations are from the Kaplan (tropical Pacific) and HadISST datasets. The contour interval is 0.1 K.

Mexico than was observed. The GOGA ensemble mean correctly makes southwestern and eastern Canada, Central America, and the Caribbean wet.

The cold tropical Pacific and warm tropical Atlantic SST anomalies both produce dry conditions in the central and southern plains and much of the American West (taken to mean the area west of 90°W from northern Mexico to the U.S.–Canada border) with wetter conditions to the north and south. The POGA ensemble mean is more realistic than the POGA-ML mean. This is because the latter creates cold SSTs in the subtropical North Atlantic as a response to La Niña, which itself causes wet conditions over western North America (a negative feedback; Seager 2007).

In contrast to the models with historical SST forcing, the COGA ensemble mean, which uses the atmosphere and land initial conditions from January 1929 but climatological SSTs from then until 1940, produces only weak and incoherent precipitation anomalies over North America. [The COGA ensemble mean does actually produce a weak La Niña–like signal that we attribute to the difference in precipitation climatology produced using climatological SSTs and that is produced using historical SSTs. Over North America, El Niño events produce a larger precipitation anomaly than same-sized La Niña events and hence a simulation with climatological SSTs will produce a drier western North America than a simulation with historical SSTs (see, e.g., Bulic and Brankovic 2007)].

This comparison indicates that, according to this model and consistent with the model of Schubert et al. (2004a) and Schubert et al. (2004b), an SST-forced drought driven by precipitation reduction occurred in the 1930s although the modeled drought was centered and extended too far south, and did not include the Pacific Northwest or Great Lakes regions. Despite these errors it is clear that a forecast of the 1930s with advance SST information would have yielded a prediction of drought to impact much of western North America whereas a forecast based on atmosphere and land initial conditions in 1929 would have predicted no coherent or large anomaly. The predicted drought would have been of the magnitude of the three prior (mid-to-late nineteenth century) droughts in the instrumental period as can be seen from Seager et al. (2005) and Herweijer et al. (2006).

4. Comparison of ensemble means and spreads of area-averaged indices

Figure 3 compares the ensemble means and spreads of the precipitation reduction averaged over three areas: 1) The Great Plains (30°–50°N, 110°–90°W), 2) the Southwest (25°–40°N, 125°–100°W), and 3) the West (all land areas west of 90°W between 25° and 50°N). The data is plotted for the GOGA, POGA, TAGA, and COGA ensembles and the observed value is plotted as an asterisk. The mean and the upper and lower quartiles of the ensemble are indicated by the box, and the "whiskers" around each box indicate the range of the ensemble. If the boxes of two ensembles do not overlap then no more than a quarter of the members of each ensemble are overlapped by some members of the other ensemble.

For the Great Plains (GP) region the modeled precipitation anomaly with global SST forcing (GOGA) is

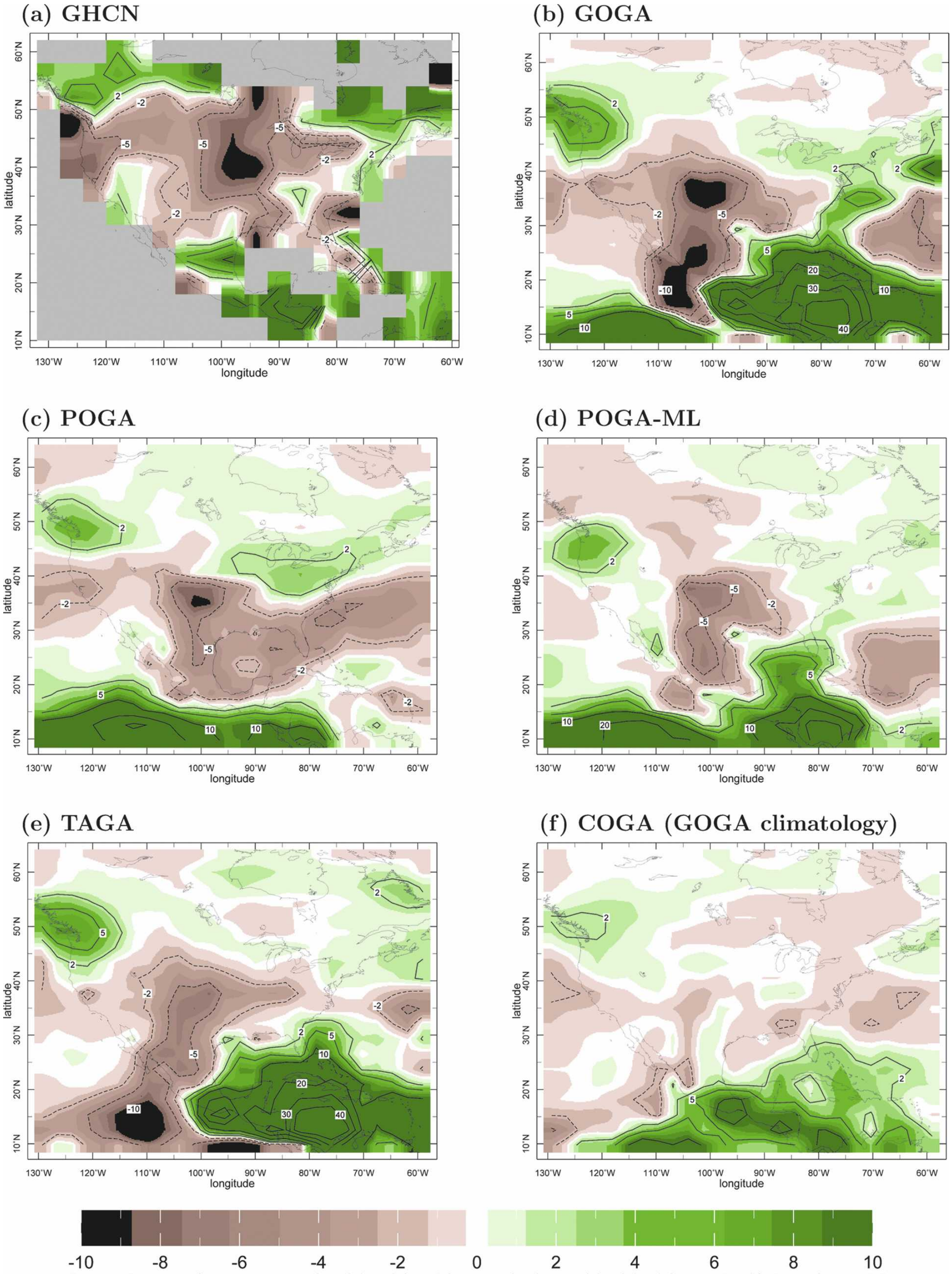

FIG. 2. The (a) observed and (b)–(f) modeled precipitation anomalies (mm month^{-1}) during the Dust Bowl (1932–39) relative to an 1856–1928 climatology. Observations are from GHCN. The modeled values are ensemble means from the ensembles with (b) global SST forcing (GOGA), (c) tropical Pacific forcing (POGA), (d) tropical Pacific forcing and a mixed layer ocean elsewhere (POGA-ML), (e) tropical Atlantic forcing (TAGA), and (f) with land and atmosphere initialized in January 1929 from the GOGA run and integrated forward with the 1856–1928 climatological SST (COGA). The uneven contour interval is given at the base of the figure.

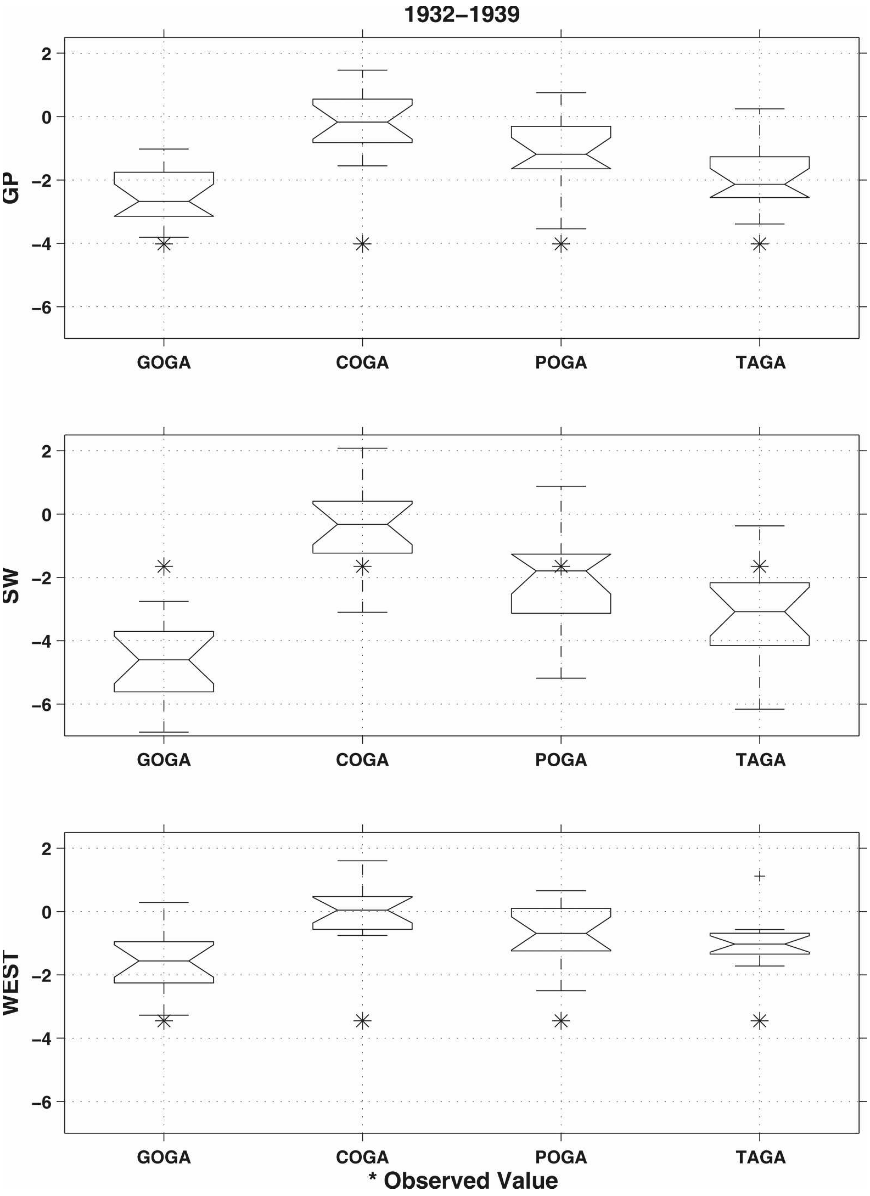

FIG. 3. The lower quartile, median, and upper quartile (shown by the box) and the lower and upper ranges (shown by the whiskers extending below and above the boxes) of precipitation (mm month^{-1}) for the model ensembles for GOGA, COGA, POGA, and TAGA for (top) the Great Plains region, (middle) the Southwest, and (bottom) the entire West. (See text for geographical limits of regions.) The observed value is shown as an asterisk.

negative for all 16 ensemble members. However, the ensemble mean, and even the driest ensemble member, are not as dry as the observations. More than three quarters of the POGA and TAGA ensemble members, and the ensemble mean, are also dry. For the Southwest (SW) region all GOGA ensemble members are dry and the model seriously overstates the drying in this region. The TAGA ensemble has all members, and the POGA ensemble has all members but one, dry in this region. For the West as a whole, the GOGA, POGA, and TAGA ensembles are overall dry (but with some wet members for GOGA and POGA) and with the ensemble means and driest members falling short of the observed dryness. The warmth of the subtropical North Atlantic in the TAGA ensemble dries all regions, contributing about equally with the tropical Pacific in all three.

In contrast, the ensemble with only initial condition

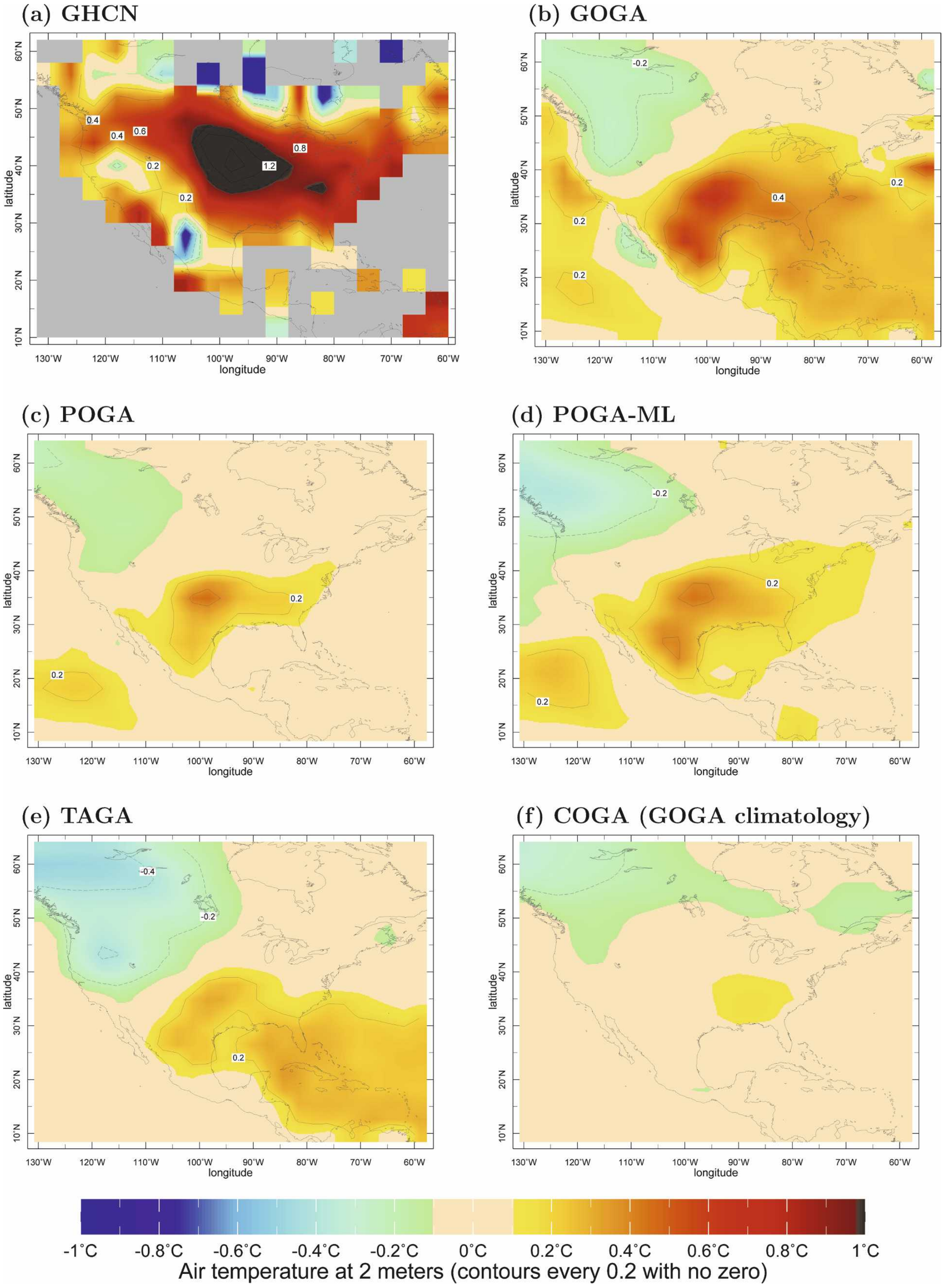

FIG. 4. Same as Fig. 2, but for temperature. The contour interval is 0.2 K.

information and climatological SSTs has precipitation anomalies for the 1930s that are not bounded away from the climatological normal. Taken together these model results indicate that advance knowledge of 1930s SSTs would have allowed a confident prediction of an impending drought in the West but of one that was centered too far to the Southwest and weaker than observed. The most successful prediction would require knowledge of both tropical Pacific and tropical Atlantic SSTs.

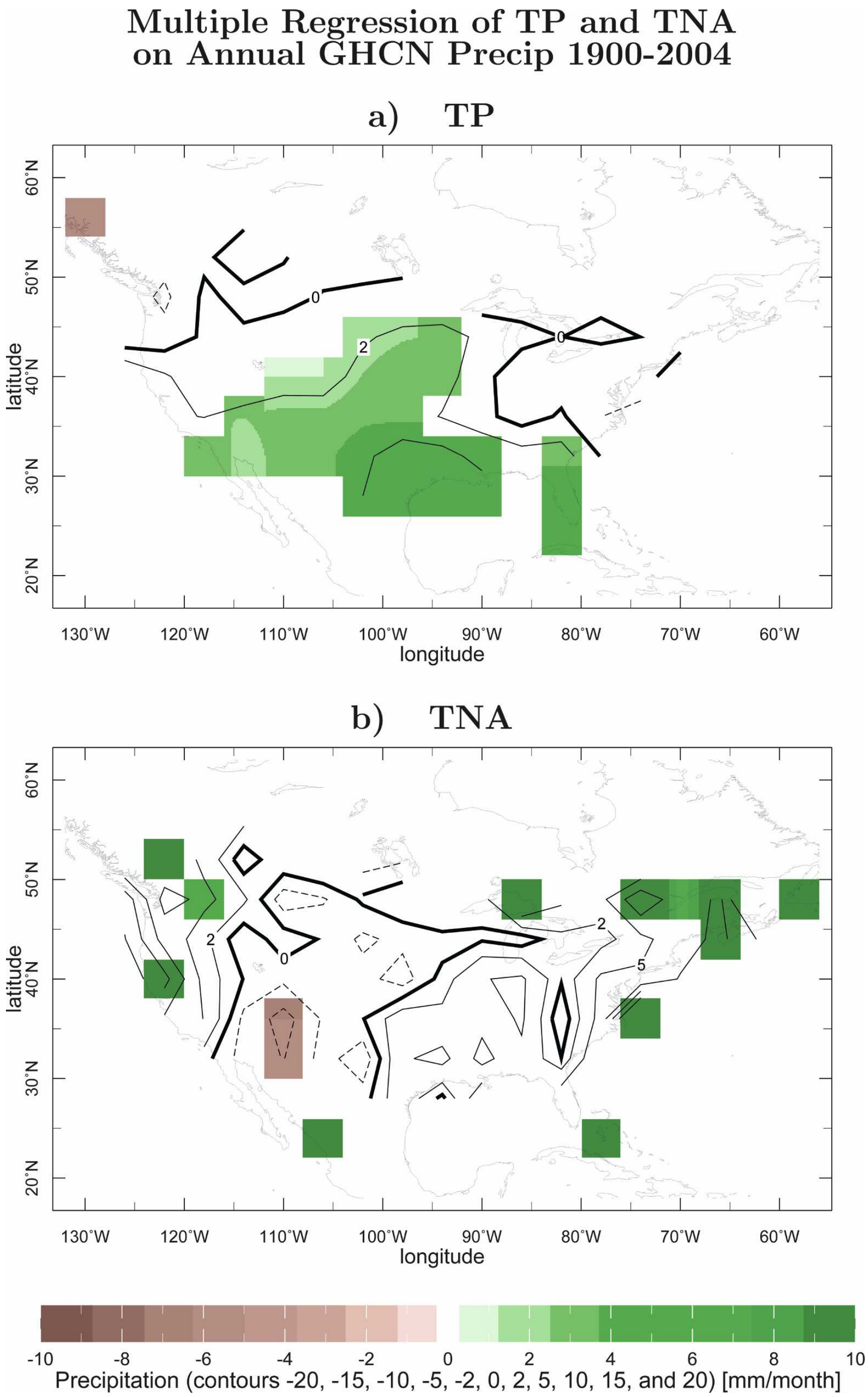

FIG. 5. Multiple regression of observed precipitation on indices of TP and TNA SST anomalies. Shaded areas are significant at the 5% level. Units are mm month^{-1} per std dev of the SST index and the contour interval is uneven and listed at the bottom of the figure.

5. Comparison of observations and ensemble means of temperature

From the point of view of users of water resources the amount of water in the soil, rivers, and streams is more important than precipitation alone (Wilhite 2000). The water potentially available as a resource depends on precipitation (P) minus evaporative loss (E) from the surface. Evaporative loss depends on many factors including the moisture in the ground and plants and on the temperature of the air above. However, evaporation is not independent of precipitation. If all else is equal, a lesser precipitation drives soil moisture down so evaporation goes down, acting as a negative feedback on $P - E$. But, in the process, more of the net radiation at the surface has to be balanced by sensible heat loss instead of latent heat loss and the surface warms to accomplish this. Surface warming drives atmospheric warming but a warmer atmosphere can hold more moisture so this increases evaporative demand. As such, temperature variations can follow precipitation variations, but it is also possible that temperature variations could force changes in soil moisture, even independent of changes in precipitation.

Figure 4 shows the observed and ensemble means of surface air temperature for 1932–39. The observations are quite remarkable, showing warm anomalies of up to a degree Celsius across most of the continent centered on the central and northern plains. This pattern of warmth is missed by all the model ensemble means forced by observed SSTs, which instead show modest warming centered in the southern plains and the Southwest. The ensemble mean with climatological SSTs shows only the weak effect of ignoring the rectified effects of ENSO variability.

The spatial patterns of both observed and modeled warmth closely track the patterns of precipitation reduction. This is consistent with the warmth being a consequence of reduced precipitation and the error in the modeled pattern of temperature anomaly being caused by the error in the precipitation simulation. (The only exception to this relationship occurs in parts of Oregon, Idaho, and Montana where modeled dry conditions went along, erroneously, with cooler temperatures.) Even though the temperature responds to precipitation, the inability of the ensemble means to warm across the northern United States and into the Canadian Prairies will presumably lead to a failure to predict declines in soil moisture there that will exacerbate those induced by errors in the modeled precipitation reduction.

6. Are differences between the modeled and observed Dust Bowl drought caused by systematic errors in the model response to SST anomalies?

The differences between the modeled and observed drought could be caused by systematic errors in how the model responds to tropical SST anomalies. To look at this we performed a multiple regression analysis between the precipitation and temperature fields and indices of the tropical Pacific (TP; SST anomaly between 5°S–5°N and 180°–90°W) and the tropical North Atlantic (TNA; all Atlantic Ocean points between the equator and 30°N) SSTs. This analysis was performed for the period from 1900 to 2000 (data coverage over North America is incomplete prior to 1900). Multiple regression is chosen to identify the impacts of the Pacific and the Atlantic acting alone acknowledging that this will only identify the dominant linear relation between SST, precipitation, and surface air temperature and not identify any weaker nonlinear relationship.

a. Modeled and observed precipitation response to tropical SST anomalies

Figure 5 shows the multiple regression of observed annual mean GHCN precipitation on the observed TP and TNA SST indices. The observed Pacific pattern is familiar with a warm tropical Pacific going along with wet conditions over most of the United States and extending into Mexico and with dry conditions in the coastal area northwest of Washington State and British Columbia, and to a much lesser extent, in central Canada and northeastern North America. Most of the wet region is statistically significant at the 5% level. The observed tropical Atlantic pattern shows a weak relationship between warm Atlantic SSTs, with dry in western North America and wet in eastern North America and the Pacific Northwest, but the relationships are not significant at the 5% level. The modeled relationships, as represented by the GOGA ensemble mean, are shown in Fig. 6. The Pacific pattern is quite realistic but too strong in northeastern Mexico and erroneously extends west into the Northeast. The modeled Atlantic pattern overemphasizes the relationship between warm SSTs and the dry region in western North America and extends this dry region too far into eastern North America. The modeled relationships are highly statistically significant.[2]

The differences between the modeled and observed precipitation anomalies in the northern United States and southwestern Canada during the Dust Bowl drought cannot be explained in terms of differences between the modeled and observed responses to tropical SST anomalies. The modeled Dust Bowl drought

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[2] The weakness of the observed relationship between precipitation over North America and tropical Atlantic SST anomalies may be in part because the latter vary slowly, on a multidecadal time scale (Kushnir 1994) and therefore there are few realizations of changes in Atlantic SSTs in the observed record. The modeled relationship can be stronger because of the multiple realizations. Seager (2007) has claimed a relationship between a dry southwest and a warm subtropical North Atlantic on interannual time scales for the post-1979 period.

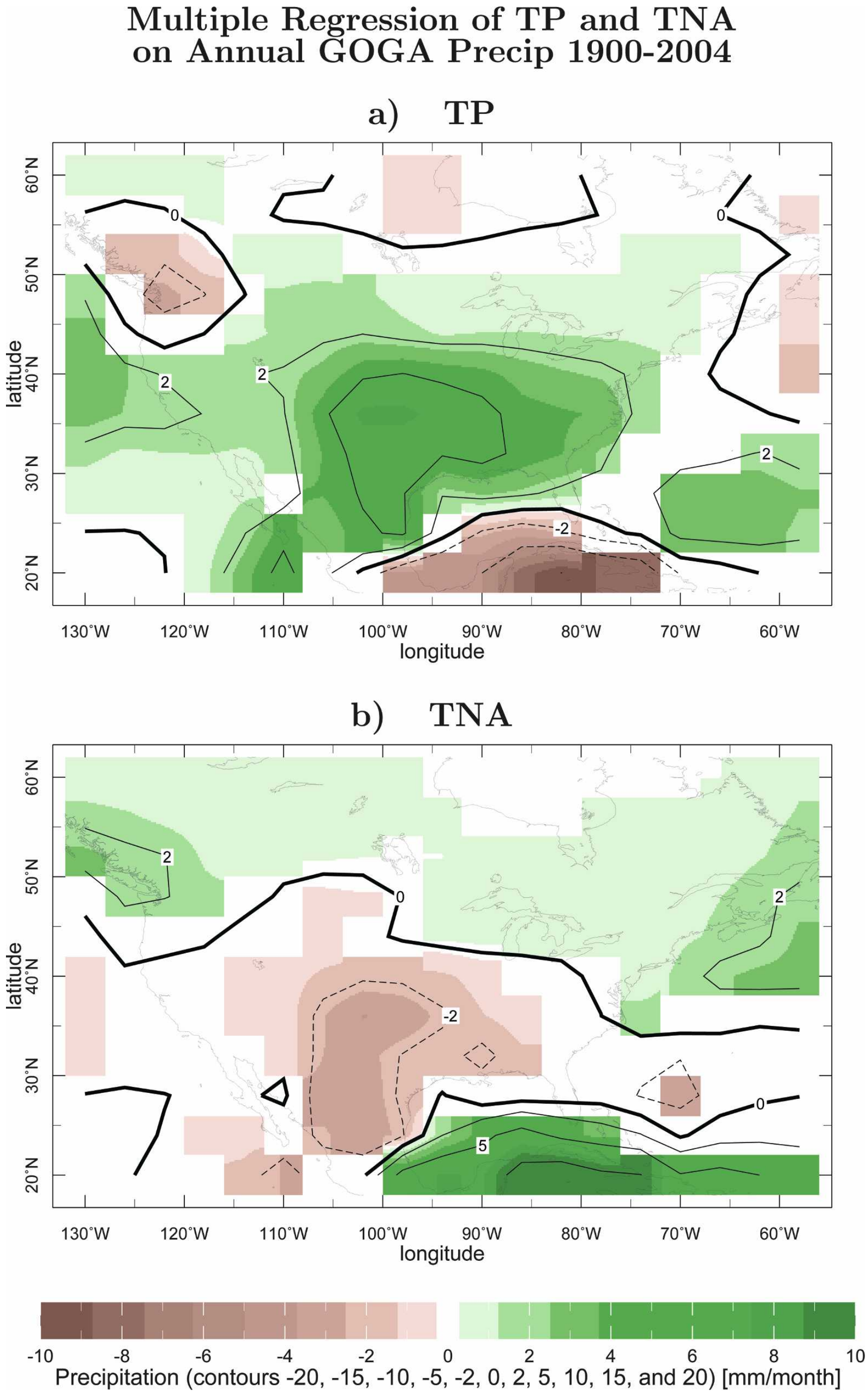


FIG. 6. Same as Fig. 5, but for the GOGA ensemble mean.

accords closely to the modeled and observed pattern of precipitation anomalies forced by tropical SST anomalies. Neither a cold tropical Pacific nor a warm subtropical North Atlantic are systematically related to dry conditions centered in the central and northern plains and extending into the Pacific Northwest.

In contrast, the overlong strong modeled Dust Bowl in the southern plains and northern Mexico can be explained in part by systematic errors of the model. The modeled pattern of precipitation response to Pacific SST anomalies extends unrealistically far south into Mexico. Also, the model responds to warm subtropical North Atlantic SST anomalies with drying in the southern plains and northern Mexico, which the observations

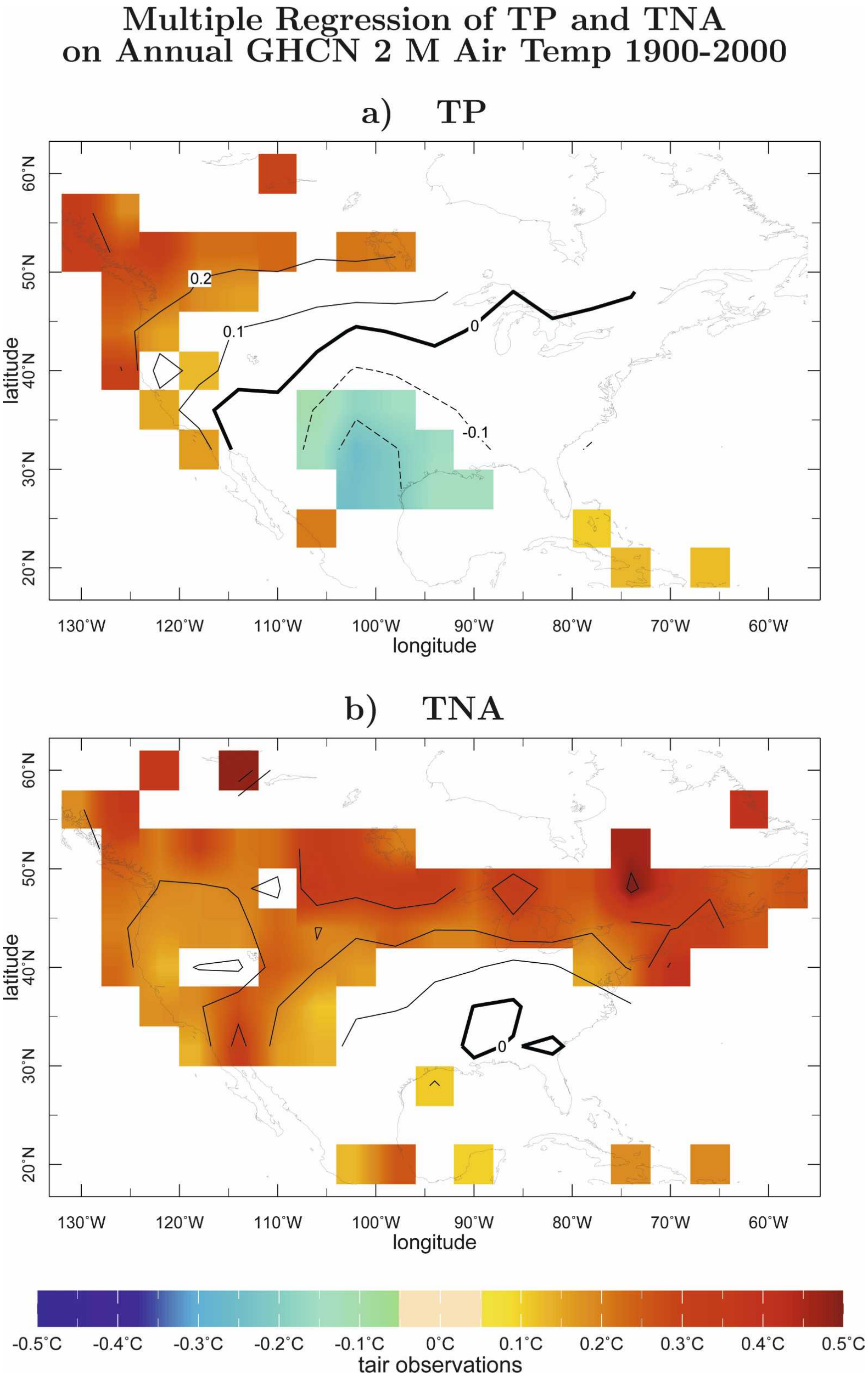


Fig. 7. Same as Fig. 5, but observed surface air temperature. Units are K per std dev of the SST index and the contour interval is 0.1 K.

do not support. Hence, systematic errors of the model response to tropical SST anomalies can explain why the modeled Dust Bowl drought is too strong in the southern plains and northern Mexico, but cannot explain why the modeled drought did not extend far enough north and west.

b. *Modeled and observed temperature response to tropical SST anomalies*

Figures 7 and 8 show the multiple regression of surface air temperature on the tropical Pacific and tropical Atlantic SST indices for observations and the model,

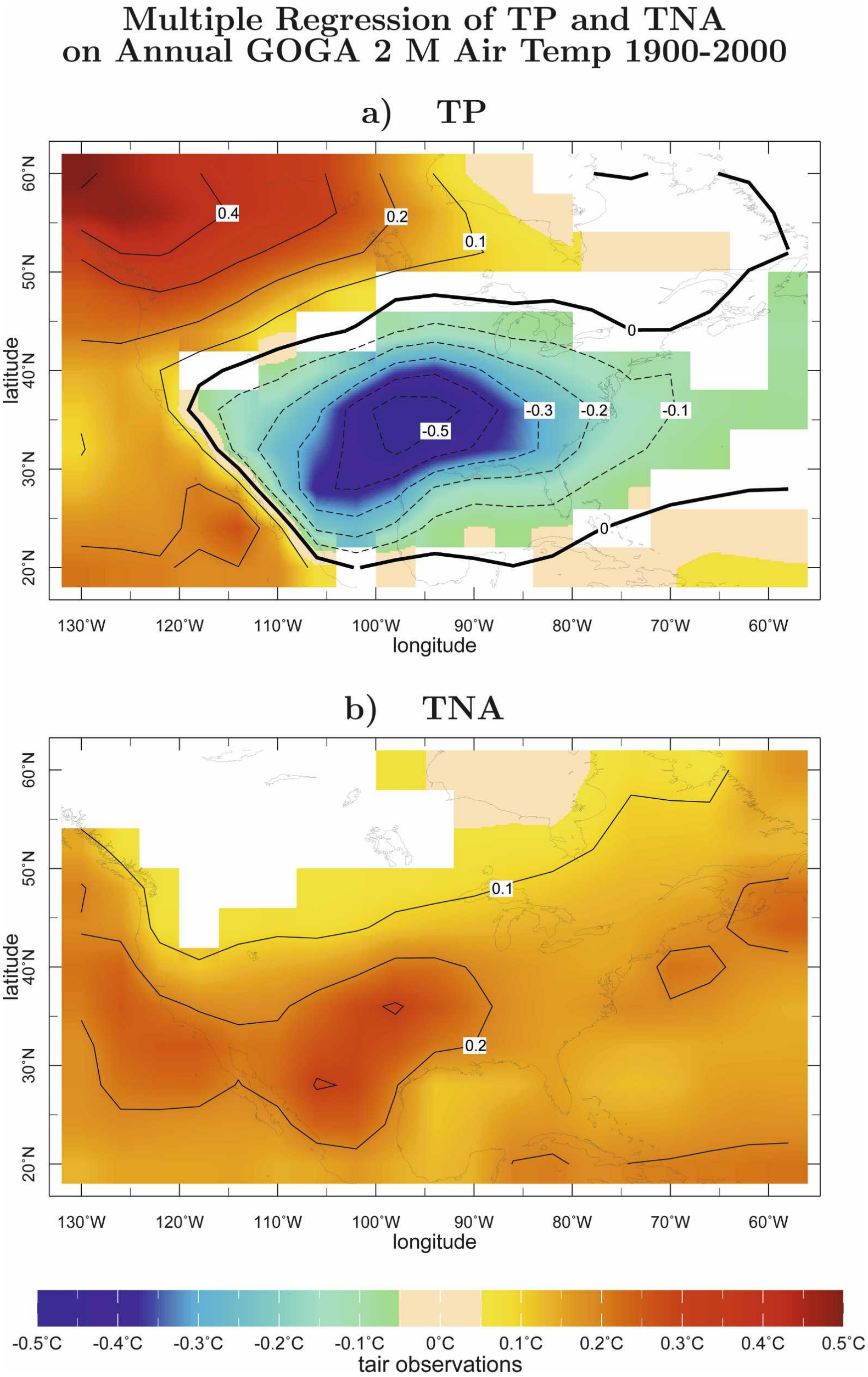


FIG. 8. Same as Fig. 7, but for the GOGA ensemble mean.

respectively. The observations show that, associated with a warm tropical Pacific, there is a clear minimum of surface air temperature over the southern United States and northeastern Mexico and warm temperatures to the north and west. Much of this pattern is statistically significant at the 5% level. Cold temperatures are collocated with increased precipitation (and vice versa) as expected from surface energy budget considerations: when precipitation is high a higher proportion of surface absorbed solar radiation is balanced by latent heat loss, which allows for lower surface temperature than when more of the balancing is done by sensible heat loss and longwave radiation.

The observed Atlantic pattern shows warm and statistically significant, surface air temperature across North America especially in the north. It also shows warming across much of the tropics and northern midlatitudes (not shown) and appears to reflect an externally forced signal of which the Atlantic warming is just part rather than a pattern of climate variability forced from the Atlantic.

The modeled Pacific pattern of the surface air temperature anomaly is very similar in spatial structure to that observed but has greater amplitude and is highly statistically significant. The modeled Atlantic pattern shows maximum, and statistically significant, warming in the southern regions, where the model dries in response to warm Atlantic SST anomalies, rather than in the north as observed. Unlike the observed pattern, the modeled pattern appears to be a direct response to the Atlantic SST anomalies. This difference again suggests that the model may be overestimating the influence of the Atlantic on North American climate.

The observed surface air temperature of the 1930s was warm across the northwestern United States and southern Canada, the plains, and much of the eastern United States, broadly following the region where it was dry. A strong relationship between precipitation reduction and warm surface air temperature could therefore explain the observed warming. Also, by this reasoning, the model fails to produce warming in the northern region because it makes this area wet not dry. At the same time the model erroneously creates warm anomalies centered in the southern plains and northeastern Mexico because that is where it places the maximum precipitation reduction.

c. Canonical responses to tropical SST anomalies in comparison to the pattern of the Dust Bowl drought

By comparing the panels in Figs. 5–8 it is clear that the model reasonably reproduces the temperature and precipitation response over North America to tropical Pacific SST anomalies and that this involves a maximum precipitation reduction in the Southwest with associated warming. The model also produces substantial drying in the southern plains and northeast Mexico, and associated warming, in response to warm subtropical North Atlantic SST anomalies, but the observations do not show such a relationship. Hence, the observed Dust Bowl drought, with a center in the central and northern plains and dry across the northern mountain states of the United States and the Pacific Northwest does not accord to a canonical pattern of precipitation forced by tropical SSTs: the southern portion of this drought can be attributed to SST forcing by the concurrent multiyear La Niña but the portion in the northwest cannot. As noted earlier, the overestimate of intensity of the modeled Dust Bowl drought in the southern plains and northern Mexico is attributable to model error. Errors in the temperature simulations are consistent with being the result of errors in the precipitation simulation.

7. Can we explain the observed Dust Bowl drought as a mix of SST-forced drought plus internal atmosphere variability?

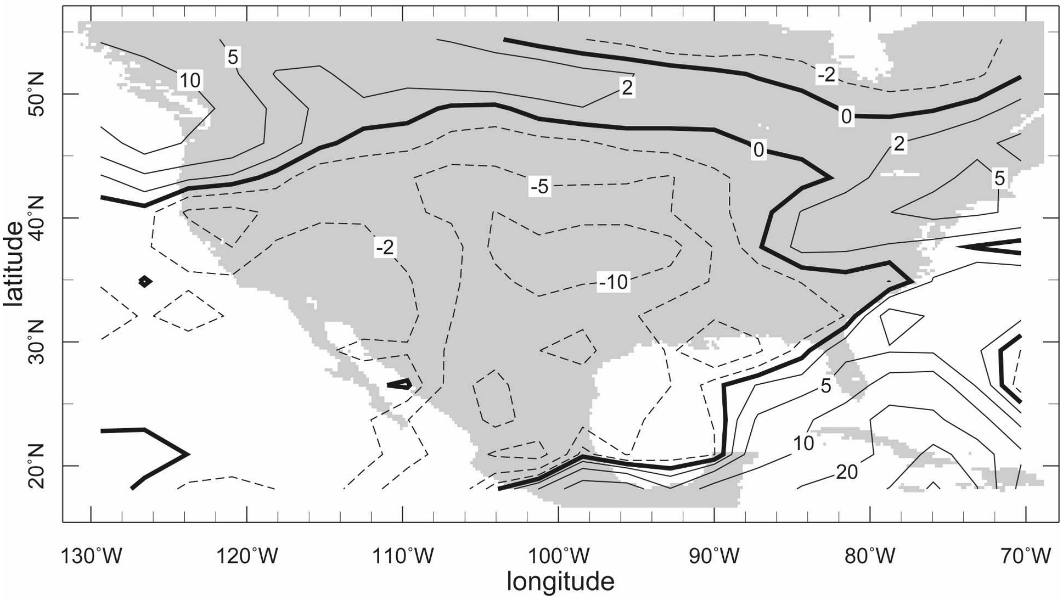
There is considerable variation among the ensemble members between the spatial pattern of precipitation reduction in the 1930s. Some patterns are more realistic than others. For example, in GOGA ensemble member 1, the precipitation reduction was located farther north than in the ensemble mean and extended across the northern mountains states of the United States and into the Pacific Northwest, which is more akin than the ensemble mean to the observed pattern (Fig. 9). In this case a fortuitous coincidence of SST-forced signal and internal atmosphere–land variability produced a drought that was stronger to the north and west of the canonical SST-forced signal.

It is possible that the actual Dust Bowl drought also arose in this way, through a mix of SST forcing and internal variability. However, Fig. 9 also shows that, even though the northwestern parts of the United States were dry in GOGA 1, the observed warm anomaly is not simulated. The arrangement in GOGA 1 is also unusual in that, on both interannual and multiyear time scales, precipitation and temperature are anticorrelated across North America in both the model and observations (not shown). Thus, not even this ensemble member correctly reproduced the widespread drying and warming of the observed Dust Bowl drought.

Does the model's failure to create the observed pattern of precipitation anomalies during the 1930s arise from systematic errors in the patterns of variability, including variability that is not SST forced? Figure 10 shows the variance of the observed annual mean precipitation and that from one ensemble member (GOGA 1) of the GOGA ensemble. We chose a single ensemble member to compare to observations because the variance of the ensemble mean is the same as the variance of the SST-forced precipitation variability whereas the variance of a single ensemble member combines the variance due to both internal atmospheric variability and SST forcing, as in nature. The patterns are similar having maxima in the southeast and northwest (where the climatological precipitation are also

GOGA 1 1932-1939 (wrt 1856-1928)

a) Precipitation



b) Air Temperature

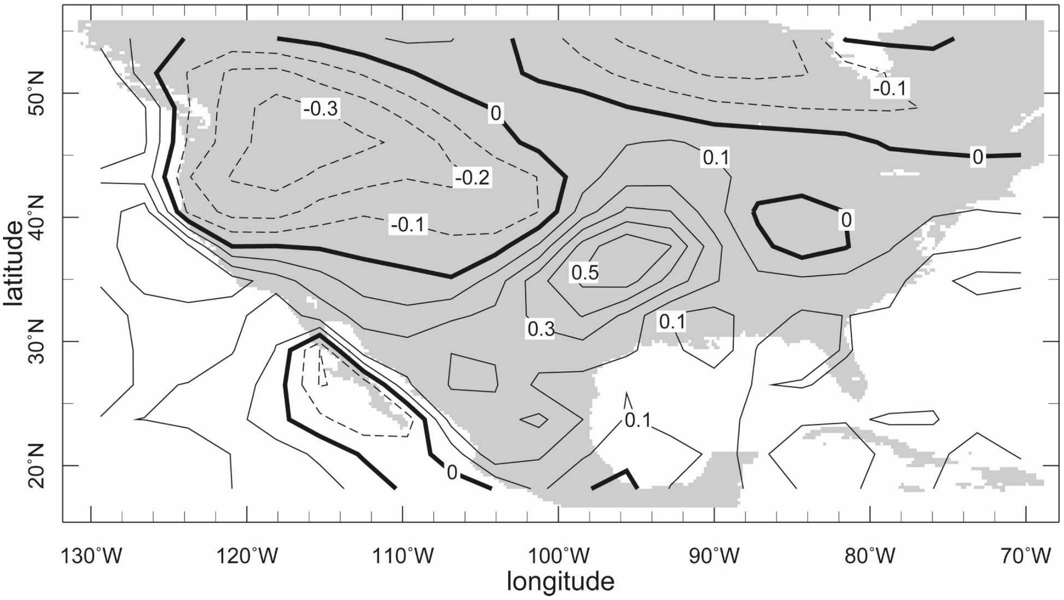


FIG. 9. The (a) precipitation and (b) temperature anomaly for 1932–39 (relative to an 1856–1928 climatology) for the first member (GOGA 1) of the GOGA ensemble. Contours are spaced in (a) at ±2, 5, 10, 20, 30, and 40 mm month^{-1} and in (b) at 0.1 K.

maxima) and lower values in the interior northwest and the southwest. Clearly the model does not fail to produce a dry 1930s in the northwest because it underestimates the variability of precipitation in that region.

8. A brief comparison to the 1950s drought

Another way of determining if the model's errors in the simulation of the Dust Bowl drought was the result of a systematic bias, either in the precipitation patterns

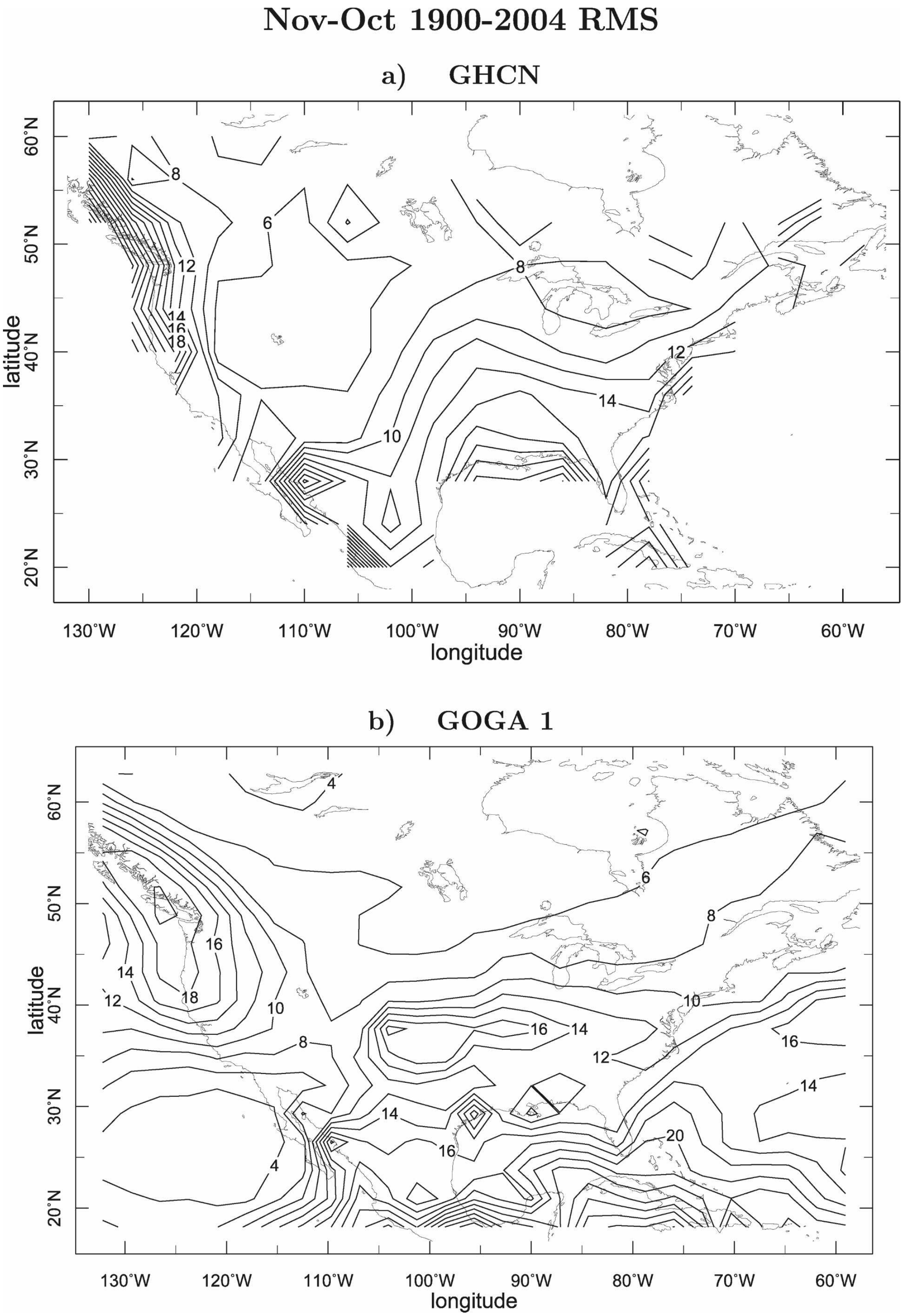


FIG. 10. The std dev of annual mean precipitation (defined on a November–October year) in (a) observations and (b) one member (GOGA 1) of the GOGA ensemble, both evaluated over 1900–2004. The contour interval is 2 mm month^{-1}.

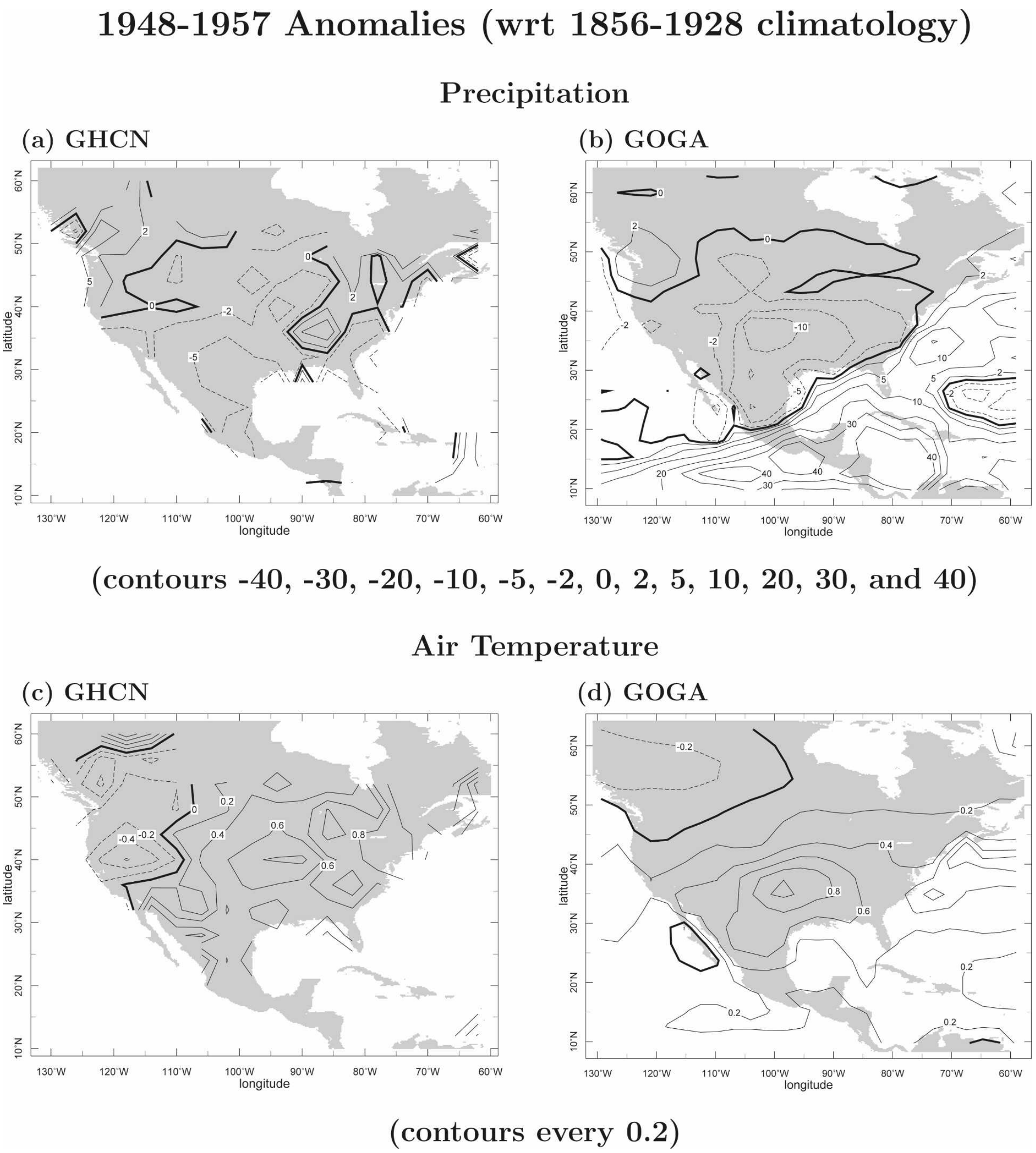


FIG. 11. The (left) observed and (right) modeled with the GOGA ensemble mean (top) precipitation and (bottom) temperature for the 1950s drought (1948–57) relative to the 1856–1928 climatology. Units are mm month^{-1} and Kelvin and the contour intervals are listed beneath each panel.

and/or in the temperature response to precipitation reductions is to contrast the 1930s with another drought. Figure 11 shows the observed and GOGA modeled precipitation and surface air temperature anomaly for the drought that ran from 1948 to 1957 and that was associated with a cold tropical Pacific and a warm tropical Atlantic (Seager et al. 2005). In this case the observed precipitation reduction was centered in the Southwest and Mexico while the northwest was either wet or only modestly dry. This pattern is quite close to the typical La Niña–related pattern, consistent with the SSTs during that period (Seager et al. 2005). Not surprisingly, in that the model quite faithfully reproduces the canonical response to tropical Pacific SSTs, the modeled pattern over North America was quite similar to observations but with the drought intensified in northern Mexico by the concurrent warm subtropical North Atlantic SSTs.

The observed surface air temperature anomalies during the 1950s drought were much smaller than during the 1930s drought, even comparing places with precipitation anomalies of more than 5 mm month^{-1} in both droughts. Unlike the 1930s drought the modeled pattern and amplitude of temperature anomaly during the

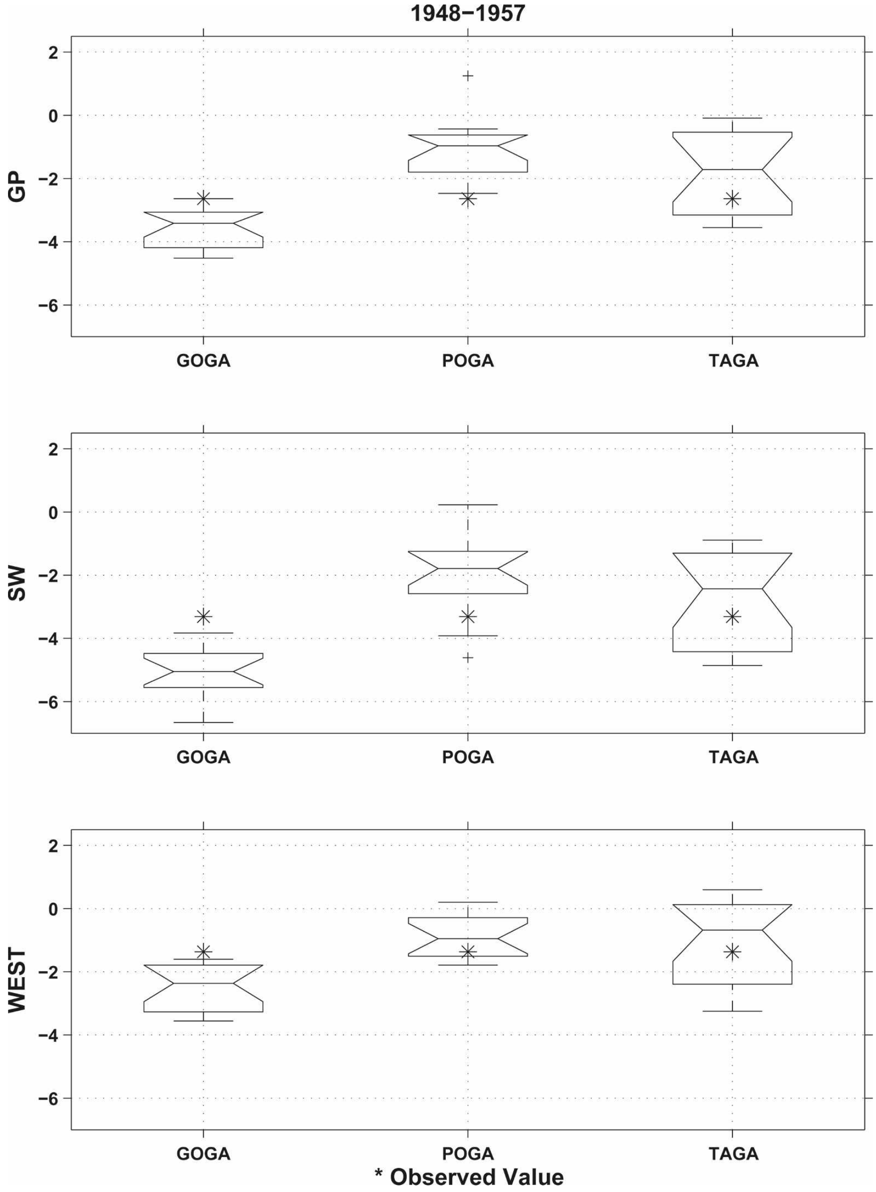


FIG. 12. Same as Fig. 3 (with the exception of an analog to the COGA ensemble), but for the 1948–57 drought. The observed value is shown as an asterisk.

1950s drought is reasonable. This comparison suggests that the model does not systematically underestimate the temperature response to precipitation reductions.

The improved skill modeling the 1950s drought relative to the Dust Bowl drought is also seen in Fig. 12, which follows the same format as Fig. 3 for the 1930s and shows the model ensemble means and spreads of precipitation for the plains, Southwest, and the entire West together with the observed anomaly, again relative to 1856–1928 climatologies. For the GOGA, POGA, and TAGA ensembles the modeled precipitation values are similar in absolute size and relative amplitude to the modeled values during the 1930s, as expected if they reflect the typical model response to SST anomalies. But in the 1950s case, the modeled Southwest drying, while still too strong, was not overestimated by as much as during the 1930s. The observed plains drying was weaker in the 1950s than in the 1930s and now sits at the dry end of the GOGA ensemble.

The five other multiyear droughts of the instrumental period had patterns of precipitation reduction (for the twentieth-century droughts) or tree-ring reconstructed PDSI (for the nineteenth-century droughts) centered in southwestern North America, more akin than the Dust

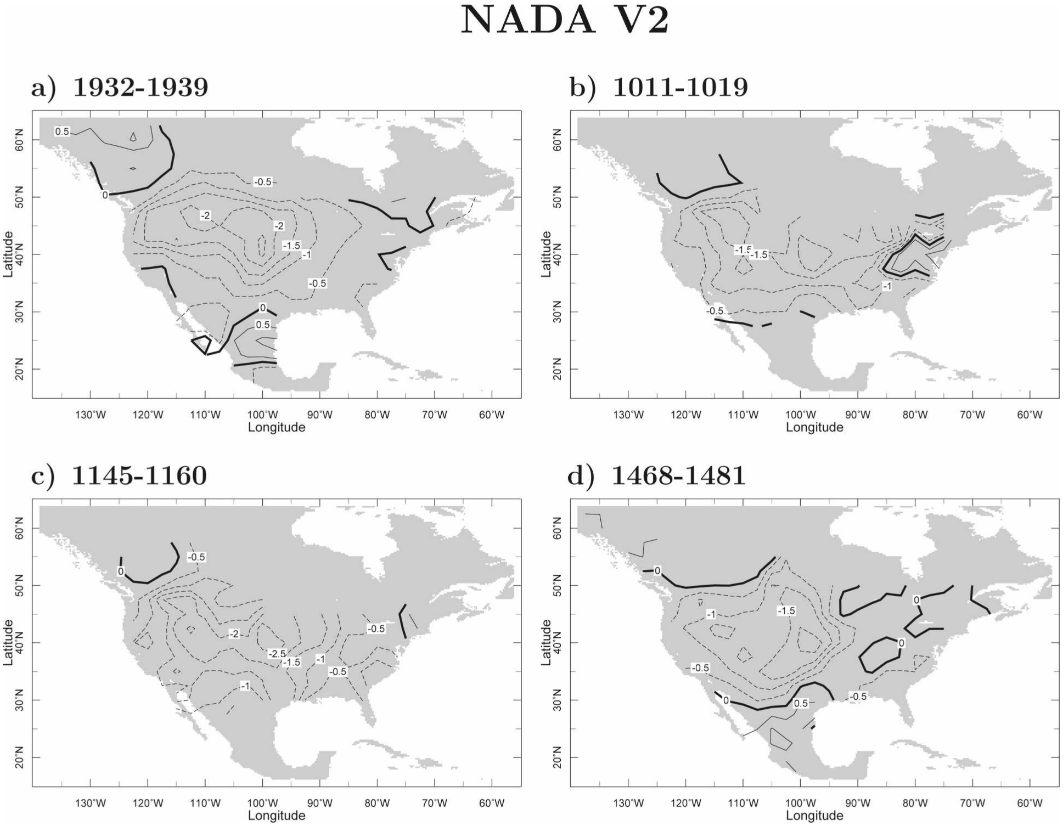


FIG. 13. The tree-ring-reconstructed summer PDSI for (a) the Dust Bowl drought and (b)–(d) three prior droughts in the last millennium that had similar northern-centered patterns and without strong drought in the Southwest or Mexico. The data is from the updated version of the North American drought atlas of Cook and Krusic (2004).

Bowl drought to the canonical patterns of tropical SST forcing of drought seen in observations and the model (Seager et al. 2005; Herweijer et al. 2006; Seager 2007). The northwestward reach of the Dust Bowl drought did not occur in the multiyear average of the precipitation or PDSI anomaly for these other droughts.

9. Was the Dust Bowl drought unique?

So is the inability of the model to reproduce the spatial pattern of the Dust Bowl drought related to this being a unique event? To assess this we need to look beyond the instrumental record. Fye et al. (2003) searched for Dust Bowl analogs in tree-ring records for the post–AD 1500 period. Here we build on that work by examining the tree-ring reconstructions of summer PDSI for AD 1000 to the present using a state-of-the-art dendroclimatological network that includes more records than the drought atlas of Cook and Krusic (2004) especially in the period before AD 1300.

We computed the anomaly correlation (AC; Wilks 1995) between the 1932–39 tree-ring PDSI and the 6-yr low-pass-filtered PDSI for the period from AD 1000 to 2003 using all available data between 20° and 60°N. The AC for the 1932–39 period, not surprisingly, reached nearly 1 and was above 0.5 throughout the decade. We therefore looked for other times when the AC was above 0.5 for at least 8 continuous years but finding none we used a threshold of 0.4 and found four periods within the last thousand years. In addition, time series of PDSI in the Great Plains, Southwest, and Pacific Northwest were examined to identify periods when drought impacted both the plains and Pacific Northwest and, to a lesser extent or not at all, the Southwest.

Three periods identified by the AC analysis were corroborated by the time series results while one other did not have a dry northwest and was discarded. These three are shown in Fig. 13 together with the tree-ring reconstruction of the summer PDSI for 1932–39. The 1930s pattern clearly shows a northern centered drought extending into the northwest but not impacting the Southwest and northern Mexico. [It should be noted that summer PDSI depends in part on antecedent (winter) precipitation and is not a measure of summer climate alone.] Of the three analogs, the second, from AD 1145 to 1160 is in the middle of one of the great medieval megadroughts and created a drier climate from the Mexican border into Canada with a center well to the north of the region with strongest connections to the Pacific Ocean. The third occurred in the late Medieval period (AD 1468–81) and, thanks to the inclusion now of data from Mexico, has a pattern across North America quite reminiscent of the Dust Bowl (see also Stahle et al. 2007). The earliest one (AD 1011–19) is within a period with little data outside of the United States and is a northern centered drought that also impacted the Southwest more strongly than the Dust Bowl.

The anomaly correlation threshold has to be lowered to 0.3 to find any additional Dust Bowl analogs. This method does not confirm that any of the post AD 1500 droughts identified by Fye et al. (2003) are Dust Bowl analogs unless we lower the anomaly correlation threshold to 0.28 in which case just the 1855–65 drought appears. Consequently, it appears that droughts with patterns akin to the Dust Bowl occurred, but were still rare during the Medieval period and that no more droughts with that pattern occurred until the 1930s drought itself.

These comparisons suggest that the pattern of the Dust Bowl drought was not unprecedented. Unfortunately, we do not know what SST patterns accompanied any of these medieval droughts. It is reasonable to assume that human-induced land surface degradation played little role in these prior droughts and therefore it is also reasonable to assume that a northern-centered drought can arise from natural forced and free climate variability and change, including possible vegetation climate interaction, although very rarely.

10. Discussion and conclusions

During the 1930s, eastern and central tropical Pacific SSTs were persistently negative and no El Niños occurred. North Atlantic SSTs were also persistently warm. Had these future SSTs been known ahead of time in 1929 the ensemble mean of the model simulations with global SST forcing would have predicted a multiyear drought of the amplitude seen in the earlier nineteenth-century droughts and most strongly impacting the southwestern United States and northern Mexico but also impacting the central plains. The predicted drought would have missed the extension of the drought into the northern Rocky Mountain states and into the Pacific Northwest and the less dry conditions in the Southwest. The model would also have predicted warm surface air temperature anomalies in the region of precipitation reduction.

Comparison to a parallel ensemble prediction using the initial conditions for land and atmosphere in January 1929, but climatological (1856–1928) SSTs thereafter makes clear that in the absence of SST anomalies the predicted precipitation in the plains, Southwest, and entire West would not have been distinguishable from climatology. In contrast, in the plains and Southwest, the addition of global SST forcing leads to a prediction in which all ensemble members were dry, and all but one member for the area of the entire West. The prediction of a serious drought impacting large regions of the West could, therefore, have been assigned high confidence. Both tropical Pacific and Atlantic SST anomalies contributed.

This hypothetical drought prediction would have been of limited success because of differences in the modeled and observed patterns. The modeled drought corresponded to the typical patterns forced by tropical Pacific and Atlantic SST anomalies, which have centers in the southern regions of North America. The Pacific-related pattern is quite realistic compared to observations, but the model responds to a warm subtropical North Atlantic by drying the southern plains and northeast Mexico, a pattern for which there is no firm observational support. This model response, which is potentially a systematic error that could be accounted for, helps explain why the modeled Dust Bowl drought was too intense in these southern regions. The model error in the northern Rocky Mountain states and northwest cannot be explained in terms of systematic errors of the model response to SST anomalies. It is also not yet possible to explain the dry, hot conditions in that region in terms of internal variability since no ensemble member produced a pattern of precipitation reduction, and hot conditions, during the 1930s that extended into the northwest. Therefore, that particular feature of the Dust Bowl drought, which has not been seen in other droughts of the instrumental period, could not have been anticipated.

This leaves the question of why in the 1930s, unlike other droughts, dry and hot conditions extended from the southern plains into the northwest. It is clear that the southern portion of the drought was SST forced with the observations suggesting a dominance of the tropical Pacific but the model drought also responding to the tropical Atlantic. If the northwest portion of the drought was also SST forced then the response of this model to SST anomalies is, in some ways, in error. The precipitation response of the model to tropical Pacific SST anomalies, however, appears realistic. The model response to tropical Atlantic SST anomalies appears overly strong but this possible error cannot account for the missing northwest drought. Therefore either 1) something can happen that moves the circulation response to tropical Pacific SST anomalies northward or 2) the model is responding incorrectly to SST anomalies outside of the tropical Pacific and Atlantic Oceans. We are unaware of what could cause a northward shift in the forced circulation response and in the only other published simulation of the 1930s (Schubert et al. 2004a,b) the modeled drought is also too far to the south. Two other GCMs, the Geophysical Fluid Dynamics Laboratory model (M. Hoerling 2007, personal communication) and the Goddard Institute for Space Studies model (R. Miller 2007, personal communication) also produce Dust Bowl droughts centered in the Southwest. If the differences in modeled and observed pattern of drought were caused by an incorrect response to SST anomalies, all four of these models would have to have the same error. The alternative is that the northwestern part of the Dust Bowl drought was not directly SST forced.

If the differences are not caused by systematic errors in the model response to SST anomalies then two possibilities come to mind. First, the Dust Bowl drought could have combined an SST-forced part in its southern part and a coincident drought due to internal variability in the northwest. In that case the fact that no model ensemble produced a drought like this is simply because the ensembles we have used do not adequately sample the range of internal variability. The second possibility is that the Dust Bowl drought pattern was influenced by other factors that made the Dust Bowl a unique drought in the historical record: the land surface degradation, dust storms, heavy aerosol loading, and the impact these could have had on land surface hydrology, radiation, circulation, and precipitation. Conversion of even withered grass to bare soil could reduce soil water-holding capacity, increase runoff, and reduce soil moisture causing increased temperature. Furthermore, although there is no evidence yet that the dust aerosol loading of the 1930s altered the local hydroclimate, dust aerosols have been claimed to influence precipitation in other regions of the world (Rosenfeld et al. 2001; Miller et al. 2004).

The scale of land surface degradation and dust aerosol loading during the 1930s was not seen in any prior or subsequent historical droughts and their impact deserves to be evaluated. However, tree-ring records show at least three prior droughts that were centered to the north of the canonical response to tropical SST anomalies and had similarities to the Dust Bowl pattern. All of these three occurred during the Medieval period. These droughts would not have been influenced by human-induced land surface degradation, but there is geomorphological evidence of dune activity throughout the plains and into the Rocky Mountain foothills throughout the Medieval period [see Forman et al. (2001) for a compilation and review of studies] so land surface–vegetation–atmosphere interactions could have played a role in these earlier Dust Bowl–like droughts, too. However, despite the unknown importance of land interactions, the central fact remains that the persistently cold central and eastern tropical Pacific SSTs, and possibly the warm subtropical North Atlantic SSTs, of the 1930s forced a serious drought over parts of North America. This reality motivates efforts to determine if those SST anomalies are themselves predicable.

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REFERENCES

Allan, R. J., and T. J. Ansell, 2006: A new globally complete monthly historical mean sea level pressure dataset (HadSLP2): 1850–2004. *J. Climate,* **19,** 2717–2742.

Bulic, I. H., and C. Brankovic, 2007: ENSO-forcing of the northern hemisphere climate in a large ensemble of model simulations based on a very long SST record. *Climate Dyn.,* **28,** 231–254.

Chepil, W. S., 1957: Dust Bowl: Causes and effects. *J. Soil Water Conserv.,* **12,** 108–111.

Cook, E. R., and P. J. Krusic, 2004: North American summer PDSI reconstructions. Tech. Rep. 2004-045, IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series, Boulder, CO.

——, C. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle, 2004: Long-term aridity changes in the western United States. *Science,* **306,** 1015–1018.

Forman, S., R. Oglesby, and R. S. Webb, 2001: Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: Megadroughts and climate links. *Global Planet. Change,* **29,** 1–29.

Fye, F. K., D. W. Stahle, and E. R. Cook, 2003: Paleoclimatic analogs to twentieth-century moisture regimes across the United States. *Bull. Amer. Meteor. Soc.,* **84,** 901–909.

Herweijer, C., R. Seager, and E. R. Cook, 2006: North American droughts of the mid to late nineteenth century: A history, simulation and implications for Medieval drought. *Holocene,* **16,** 159–171.

Hoerling, M. P., and A. Kumar, 2003: The perfect ocean for drought. *Science,* **299,** 691–694.

International Medical Corps, 2006: *Displaced in America. Health*

Status among Internally Displaced Persons in Louisiana and Mississippi Travel Trailer Parks: A Global Perspective. International Medical Corps, 39 pp.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan, 1998: Analyses of global sea surface temperature: 1856–1991. *J. Geophys. Res.,* **103,** 18 567–18 589.

Karspeck, A., R. Seager, and M. A. Cane, 2004: Predictability of tropical Pacific decadal variability in an intermediate model. *J. Climate,* **17,** 2842–2850.

Keyantash, J., and J. A. Dracup, 2002: The quantification of drought: An evaluation of drought indices. *Bull. Amer. Meteor. Soc.,* **83,** 1167–1180.

Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Bovile, D. L. Williamson, and P. J. Rasch, 1998: The National Center for Atmospheric Research Community Climate Model: CCM3. *J. Climate,* **11,** 1131–1149.

Kushnir, Y., 1994: Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *J. Climate,* **7,** 141–157.

Miller, R. L., I. Tegen, and J. Perlwitz, 2004: Surface radiative forcing by dust aerosols and the hydrologic cycle. *J. Geophys. Res.,* **109,** D04203, doi:10.1029/2003JD004085.

Palmer, W. C., 1965: Meteorological drought. Tech. Rep., U.S. Weather Bureau, Research Paper 45, 58 pp.

Peterson, T. C., and R. S. Vose, 1997: An overview of the global historical climatology network temperature database. *Bull. Amer. Meteor. Soc.,* **78,** 2837–2849.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L.V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.,* **108,** 4407, doi:10.1029/2002JD002670.

Rosenfeld, D., Y. Rudich, and R. Lahav, 2001: Desert dust suppressing precipitation: A possible desertification feedback loop. *Proc. Natl. Acad. Sci. USA,* **98,** 5975–5980.

Schubert, S. D., M. J. Suarez, P. J. Region, R. D. Koster, and J. T. Bacmeister, 2004a: On the cause of the 1930s Dust Bowl. *Science,* **303,** 1855–1859.

——, ——, ——, ——, and ——, 2004b: Causes of long-term drought in the U.S. Great Plains. *J. Climate,* **17,** 485–503.

Seager, R., 2007: The turn-of-the-century North American drought: Dynamics, global context, and prior analogs. *J. Climate,* **20,** 5527–5552.

——, A. Karspeck, M. Cane, Y. Kushnir, A. Giannini, A. Kaplan, B. Kerman, and J. Velez, 2004: Predicting Pacific decadal variability. *Earth Climate: The Ocean–Atmosphere Interaction,* C. Wang, S.-P. Xie, and J. A. Carton, Eds., Amer. Geophys. Union, 115–130.

——, Y. Kushnir, C. Herweijer, N. Naik, and J. Velez, 2005: Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000. *J. Climate,* **18,** 4068–4091.

Stahle, D. W., F. K. Fye, E. R. Cook, and R. D. Griffin, 2007: Tree ring reconstructed megadroughts over North America since AD 1300. *Climatic Change,* **83,** 133–149.

Wilhite, D. A., 2000: Drought as a natural hazard: Concepts and definitions. *Drought: A Global Assessment,* D. A. Wilhite, Ed., Routledge, 3–18.

Wilks, D. S., 1995: *Statistical Methods in the Atmospheric Sciences.* Academic Press, 467 pp.

Worster, D., 1979: *Dust Bowl: The Southern Plains in the 1930s.* Oxford University Press, 277 pp.