Twentieth-Century Sea Surface Temperature Patterns in the Pacific during Decadal Moisture Regimes over the United States*

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ABSTRACT: Three great moisture anomalies were observed during the twentieth century over the western United States: a pluvial from 1905 to 1917, the Dust Bowl drought (1929–40), and the Southwestern drought of 1946–56. A composite analysis of the concurrent Pacific sea surface temperature (SST) field is used to infer the atmospheric circulation that may have been associated

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with these objectively defined decadal dry and wet periods. The early-twentieth-century pluvial occurred during a 13-yr SST regime with unusually cold water in the northern and northwestern North Pacific and in the eastern North Pacific. This pattern would favor a “Pineapple Express–like” mean storm track into the west. Warm ENSO-like conditions also observed during the pluvial would have favored an enhanced subtropical jet stream into the southwestern United States. The 11-yr Dust Bowl drought occurred during a poorly defined Pacific SST regime, although unusually cold water was present in the far western North Pacific. Weak warm SST conditions were also noted in the extreme northeastern North Pacific. This cold west–warm east SST pattern, although weak for the full 11-yr interval, may have contributed to positive atmospheric geopotential heights over the western and central United States during the Dust Bowl drought. Cooler SSTs in the eastern equatorial Pacific during some of the Dust Bowl years (e.g., 1934, 1935, 1938, and 1939) suggest a possible La Niña influence. La Niña conditions definitely seemed to have contributed to the 1950s drought, but the most anomalous SSTs for the 11-yr average were observed in the west-central North Pacific. The overall Pacific SST field during the 1946–56 drought was consistent with the cool phase of the Pacific decadal oscillation, and the warm SSTs in the west-central North Pacific would have favored a trough over the central North Pacific and a ridge over western North America in the upper-tropospheric flow.

KEYWORDS: Drought; Tree rings; Sea surface temperatures

1. Introduction

Drought is potentially one of the most devastating climate variations in human terms and one of the most complex and least understood of natural hazards (American Meteorological Society 1997). The geographical position, frequency, and persistence of drought are critical to our society (National Research Council 1998). The most severe droughts of the twentieth century were the Dust Bowl drought of the 1930s and the 1950s Southwestern drought (Figure 1a; Fye et al. 2003).

Over 500+ years of tree-ring-reconstructed summer Palmer Drought Severity Index (PDSI; Cook et al. 1996; Cook et al. 1999) over the central and western United States (Figure 1b) indicate repeated decadal drought as well as episodic wet regimes. The instrumental and reconstructed PDSI data are in close agreement at annual and decadal time scales during the late-nineteenth and early-twentieth centuries (Figures 1a,b). The optimally smoothed instrumental sea surface temperature (SST) data produced by Kaplan et al. (Kaplan et al. 1998) present an opportunity to investigate the warm and cold Pacific sea surface temperature anomalies that co-occurred with the decadal droughts and pluvial (Figure 2). Decadally persistent spatial modes of SSTs may favor certain atmospheric circulation and surface moisture regimes over the United States. The following questions will be investigated. 1) Were decadal moisture regimes over the United States matched by decadal SST regimes over the Pacific? 2) If so, were these SST regimes unusual? 3) Were the SST regimes witnessed during droughts or the pluvial persistent across the time interval of the regime, or were they determined by
a few extreme years? 4) How might the decadal SST regimes be linked via atmospheric circulation to the moisture regimes over the United States?

2. SST forcing of atmospheric circulation

The potential SST forcing of atmospheric circulation and the associated precipitation and temperature anomalies in North America have been intensively studied, and teleconnection patterns have been identified as emanating from both the tropical and extratropical oceans (Horel and Wallace 1981; Yarnal and Diaz
Figure 2. Seasonal mean (DJF) SST anomalies for the three great decadal moisture anomalies of the twentieth century: (a) the early-twentieth-century pluvial, (c) the Dust Bowl drought of the 1930s, and (e) the Southwestern drought of 1946–56. (b), (d), (f) Composites of instrumental summer PDSI for the corresponding years are shown in the right-hand column. (Note the seasonal lead–lag relationship between SST and PDSI). Colors are scaled to the maximum range of values in the respective columns of SST and PDSI.
1986; Palmer and Brankovic 1989; Livezey et al. 1997; Mantua et al. 1997; Cole and Cook 1998; Hoerling and Kumar 2003). These studies suggest that regional drought and wetness anomalies across North America may be caused, in part, by SST-forced atmospheric circulation regimes. Namias (Namias and Cayan 1981; Namias 1986), in particular, was a proponent of Pacific SST forcing of downstream flow patterns.

Variations in the oceanic thermal structure operate on time scales of an order of magnitude longer than the atmosphere (Namias and Cayan 1981). With this long memory, seasonal SSTs may persist or reemerge interannually and invoke long-term continental moisture regimes that may be potentially predictable (Trenberth 1997). Hoerling and Kumar (Hoerling and Kumar 2003), for example, associate droughts in the United States from 1998 to 2002 with persistent cold SSTs in the eastern Pacific (La Niña conditions) concurrent with warm SSTs in the western Pacific and Indian Oceans.

The tropical Pacific can exert strong control over extratropical circulation in the Northern Hemisphere and on climate over North America via teleconnections (Trenberth 1997). However, climate anomalies over North America can vary under the same tropical SST regime. Both nonlinearity in the thermodynamic control over deep tropical convection and variability in the position of anomalous SSTs reduce predictability of the extratropical response (Hoerling et al. 1997). Extratropical thermal forcing of atmospheric circulation can also have a different structure than thermal forcing from the Tropics (Hoskins and Karoly 1981). Observational and modeling studies are both needed to describe the complex climate response to Pacific SST forcing. In this paper, we apply a few basic empirical principles regarding the mechanisms of SST forcing of atmospheric circulation.

The process of thermal forcing the atmospheric circulation by tropical oceans involves heating of the atmosphere, instability, convective precipitation, latent heat release, and divergent flow in the upper troposphere. The poleward component of this divergent flow is often manifested as the subtropical jet stream and may transfer significant quantities of momentum and moisture into the extratropics. The extratropical response to this influx of energy often involves an extratropical trough poleward of the tropical heat source. Thus, a typical teleconnection pattern involves a strengthened subtropical jet emanating from the vicinity of the heat source into the eastern half of a midlatitude trough. This process can influence the position of wave trains in the Northern Hemisphere in the form of geopotential height and streamfunction anomalies (Trenberth 1997). As an example, intense convection in the intertropical convergence zone (ITCZ) may shift anomalously east and south toward warmer water in an El Niño and move the teleconnected subtropical jet and storm track to a position that impacts southwestern North America. Depending on moisture availability from the Pacific, the Gulf of California, and the Gulf of Mexico, very wet regimes may result in the vicinity of this storm track, but there may be great variability in the strength and location of the storm track. In a La Niña, the most intense ITCZ convection, favoring warmer water, may shift north and west away from the cold water and force a relocation of the storm track (typically into the Pacific Northwest), producing very dry conditions over much of North America (Yarnal and Diaz 1986; Trenberth and
Guillemot 1996). Ensemble modeling studies by Schubert et al. (Schubert et al. 2004a) describe above- (below) normal SSTs in the tropical Pacific as resulting in reduced (enhanced) extratropical heights and above- (below) normal precipitation in the Great Plains.

Surface thermal anomalies over the extratropics may also perturb the westerlies, but these effects are probably subtle and poorly understood (Harman 1991). The best-known perturbation results from the strong winter thermal contrast between a cold eastern Asia and a relatively warm western North Pacific. This results in a large-scale trough in the west-central North Pacific with cyclonic turning of the westerlies. This quasi-stationary feature can anchor wave trains in the downstream flow of the troposphere (Harman 1991). The warm anomalies can stretch the vertical column of the atmosphere via thermal expansion and induce cyclonic torque of the streamflow through the mechanism of absolute vorticity conservation (Smagorinski 1953; Harman 1991). As a result, a trough is often east of the relative midlatitude heat source (Hoskins and Karoly 1981). Cold anomalies can produce the opposite effect and result in an anticyclonic torque. Vorticity conservation can also influence wave amplitude as well as the hemispheric wavenumber (Harman 1991). As a general rule, the extratropical atmosphere responds to a greater meridional temperature gradient with enhanced meridional circulation as heat is shifted poleward. The location of these circulation meanders may adopt an atypical and sometimes recurring position as determined by the location of the thermal gradients (Harman 1991).

3. Data and methods
3.1. U.S. PDSI

The PDSI was used as a measure of the drought and wet episodes described in this study. PDSI is a soil moisture index derived from comparing mean monthly temperature and precipitation data with climatological means in a two-layer hydrological model (Palmer 1965). The PDSI is zero centered with “0” being climatologically “normal” and negative values representing drought and positive values indicating wetness. The index can exceed +4 (extreme wetness) to −4 (extreme drought).

In this study we used the instrumental PDSI developed by Cook et al. (Cook et al. 1996; Cook et al. 1999) to calibrate gridded reconstructions of summer PDSI from climatically sensitive tree-ring chronologies for 500+ years over the United States. The summer PDSIs were interpolated to a 2° × 3° latitude–longitude grid. We used an average of observed PDSI grid points for selected subregions west of the Mississippi River to define the history of decadal droughts and pluvials for the western United States (the entire West is averaged for Figure 1). Summer PDSI (instrumental and reconstructed) integrate a winter/spring/summer moisture signal with a maximum during June–July–August (JJA, hereafter 3-month units will be abbreviated similarly) across the United States. The long memory makes PDSI suitable for comparison with potential ocean–atmosphere forcing from the antecedent winter and spring. We focus on the period after 1900 when instrumental PDSIs are available and when the SSTs improved in observation quantity and quality (Kaplan et al. 1998).
Composite averages of the instrumental summer PDSI data were developed for the major moisture anomalies following the objective procedures used by Fye et al. (Fye et al. 2003). First, the geographical footprints were identified for the three twentieth-century moisture anomalies. The drought footprints for the Dust Bowl and the 1950s drought were identified from the gridded instrumental PDSI data points lying within the boundary of the –1 PDSI value shown in Figures 2d and 2f, respectively. For the pluvial, we used the +1 PDSI contour (Figure 2b). All grid points within these subregions were then averaged into a single annually resolved time series of summer PDSI, and a 10-yr cubic smoothing spline was fit to each regional reconstructed and instrumental time series (Cook and Peters 1981).

To objectively define the exact start and end years of these decadal drought and wetness regimes, a running sum was calculated from each regional time series. The beginning (end) year of a moisture regime was determined when the regime was preceded (followed) by two consecutive years of opposite sign in the cumulative time series. To produce the composite maps shown in this study the instrumental PDSI were averaged at each grid point over the objectively determined time interval and then interpolated spatially using a thin plate spline (Mitasova and Hofierka 1992).

### 3.2. SSTs

The SST data used in this study were taken from 5° × 5° monthly SSTs available from 1856 to 1991 (Kaplan et al. 1998). The method used to fill large data-void areas was optimal smoothing (OS) and was intended to capture large-scale features while sacrificing detail (Kaplan et al. 1998). The input data were primarily merchant ship reports corrected for long-term biases. The anomalies were calculated as departures from the 1951–80 mean at each grid point. The SST dataset is weakest during both world wars and the nineteenth century due to low data availability (Kaplan et al. 1998). Our analyses were restricted to the twentieth century.

The available SST datasets are complicated by poor data coverage and potential biases in the principal measurement methods (bulk sampling with buckets and ship intakes and radiometric measurements from satellites). Quality control and bias correction are a challenge in the production of reliable SST (Hurrell and Trenberth 1999). In this study of large-scale and long-lasting SST and continental moisture regimes, we believe the OS dataset by Kaplan et al. (Kaplan et al. 1998) provides a broad view of the major SST anomaly structures and should be useful for the interpretation of decade-scale, continent-wide drought and wetness regimes after 1900.

We produced decadal SST averages that coincided with the major U.S. moisture anomalies witnessed during the twentieth century. Averages for all seasons (SON, DJF, MAM, and JJA) prior to and concurrent with summer PDSI were computed, but we concentrate on the DJF anomalies when Northern Hemisphere ocean–atmosphere circulation regimes are typically most amplified (Horel and Wallace 1981). Gridded point values of SST were also interpolated using a thin plate spline (Mitasova and Hofierka 1992) to produce the composite SST figures in this study.
4. Results and discussion

4.1. SST regimes associated with twentieth-century U.S. moisture anomalies

The SST regimes concurrent with the three largest decadal moisture regimes over the United States during the twentieth century are shown in Figure 2. Spatial patterns similar to the Dust Bowl and 1950s decadal droughts (northern plains and the Southwest) have been identified with rotated principal component analyses of reconstructed and instrumental PDSI from 1700 to 1978 and from 1895 to 1980, respectively (Cook et al. 1999; Karl and Koscielny 1982). The large-scale, long-term nature of the decadal PDSI anomalies suggest a possible influence of SST regimes on atmospheric circulation over North America (Figure 2).

The early-twentieth-century pluvial (Figure 2b) extended across the western United States from Canada to Mexico. The strong wet area in the Wyoming–Montana area is especially noteworthy. The SST regime associated with the early 1900s western pluvial consists of unusually cold water across the far North Pacific, through the Gulf of Alaska, and along the west coast of North America (Figure 2a). The western North Atlantic was also relatively cool. Weaker anomalies were also present across the Pacific during this 13-yr interval, including a relatively warm eastern and cool western equatorial Pacific consistent with recurrent El Niño conditions (Figure 2a).

The Dust Bowl drought of 1929–40 was most intense over the northern Rocky Mountains and northern Great Plains, but this 12-yr drought affected most of the contiguous United States (Figure 2d). The strongest SST anomaly during the Dust Bowl period occurred in the far western North Pacific, which was cold throughout most of the Dust Bowl. A warm anomaly is also evident in the southeastern Pacific (Figure 2c) but is in a data-poor area.

The 11-yr Southwestern drought of the 1950s was focused over New Mexico and Texas, although incipient drought conditions affected most of the United States. Cool SSTs off the west coast of North America extended north to the Gulf of Alaska during the 1946–56 drought, and relatively warm SSTs were present in the western and central North Pacific (Figure 2e). The warm western North Pacific contrasts sharply with SSTs witnessed during the pluvial (Figure 2a) and the Dust Bowl (Figure 2c). The eastern equatorial Pacific was also slightly cool during the 1946–56 drought, suggesting that La Niña conditions may have contributed to this decadal drought.

4.2. The early-twentieth-century pluvial

The 13-yr mean SST map is compared with the SST means for each individual year of the early-twentieth-century pluvial (1905–17) in Figure 3. The instrumental PDSI time series averaged over the region of the western United States influenced by the pluvial is also presented (Figure 3b). All SST maps are shown for the antecedent DJF season. Considerable variability is seen in the SST maps for each year from 1905 to 1917, but a cold anomaly was present off the North American west coast in 9 of 13 yr during the pluvial. A cold anomaly in the Gulf of Alaska is present in all but two of the pluvial years. The weak warm conditions observed in
Figure 3. (a) Winter (DJF) SST anomalies during the 13-yr early-twentieth-century pluvial (1905–17). (b) The average instrumental summer PDSI time series over the pluvial region of the western United States (black), and a 10-yr smoothing spline (red). (c)–(o) The winter (DJF) SST average for each year concurrent with the early-twentieth-century pluvial.
the eastern equatorial Pacific during this 13-yr period (Figure 3a) were primarily
the result of just five warm years (1905, 1906, 1912, 1914, and 1915; Figure 3),
and cold conditions occurred in this region in 1909, 1910, 1911, 1916, and 1917
(Figure 3). In fact, the driest years of the pluvial occurred in 1910, 1911, and 1917
(Figure 3b), consistent with La Niña forcing of drought over the southwestern
United States.

To indicate the magnitude of the SST anomalies witnessed for the 13-yr pluvial,
t tests were performed at each grid point comparing the 1905–17 SST mean with
the SST average for all remaining years from 1896 to 1991 (Figure 4a). These tests
were performed for both the winter (DJF) and spring (MAM) SST seasons
antecedent to the summer PDSI (Figure 4), and the results highlight the importance
of SST anomalies in the northern North Pacific, the SST gradient in the far western
North Pacific, the cool SSTs in the east-central North Pacific, and in fact, the weak
warm SSTs in the ENSO region.

The early-twentieth-century pluvial predates upper-air data, so descriptions of
atmospheric circulation associated with this moisture anomaly are not available.
However, the strong meridional SST gradient in the North Pacific (cold north,
warm central North Pacific; Figure 3a) present in most years of the pluvial may
have contributed to strong anticyclonic flow in the central North Pacific and a polar
jet stream forced southeast toward the California coast that resulted in a long-wave
trough with its axis located in the vicinity of the West Coast. Once over land, the
polar jet stream would tend to curve toward the northeast and the intermontane
region. These key North Pacific SST patterns were unusual when compared with
normal conditions (Figure 4a), and would be consistent with a ‘‘Pineapple
Express–like’’ circulation pattern in which the mean storm track is directed from
the southwest to the northeast into the West Coast and Rockies where PDSI values
were wettest during this regime (Figure 2b).

Two shorter wet episodes occurred over the western United States from 1941 to
1945 (Figure 5b) and from 1978 to 1987 (Figure 5d). The Pacific SSTs were
averaged during these two shorter wet episodes for comparison with the early-
twentieth-century pluvial. The SST fields during these two episodes were
dominated by warm El Niño–like conditions in the equatorial eastern Pacific
(Figures 5a,c), and included some of the largest El Niño events of the twentieth
century. The warm SSTs off western North America during 1941–45 and 1978–87
also contrast strongly with the early-twentieth-century pluvial (Figure 2a).

Correlation analysis was also used to identify regions of the Pacific where winter
and spring SSTs were related to drought and wetness over the pluvial region of the
western United States. Summer PDSIs were averaged for all grid points under the
pluvial footprint, and that regional time series was then correlated with the gridded
SST data from 1896 to 1991. The correlation coefficients are mapped in Figures 6a
and 6b and indicate a weak association between the interannual variability of
summer PDSI over the pluvial region of the west and SSTs in the central and
eastern equatorial Pacific. There is also some weak correlation with SSTs in the far
western North Pacific, but the SST patterns associated with a Pineapple Express–
like circulation regime (e.g., Figures 2a and 3a) are not strongly evident in the
correlation maps (Figures 6a,b).

The results in Figures 3, 4, 5, and 6 suggest that at least two long-term SST

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regimes in the Pacific have been associated with decade-long wet episodes over the western United States. The early-twentieth-century pluvial (1905–17) was associated with an SST pattern typical of the Pineapple Express, with weak and inconsistent SST anomalies in the equatorial Pacific. However, the Pacific SSTs during two shorter wet episodes (1941–45 and 1978–87) were dominated by warm

**Figure 4.** Plotted $p$ values from Student’s $t$ tests comparing seasonal SST means during each moisture regime with the mean of all years, at each grid point. (a) The $p$ values for winter (DJF) of the pluvial, 1904–17. (b) Same as (a) but for the spring (MAM). (c) The $p$ values for winter (DJF) of the Dust Bowl years, 1929–40. (d) Same as (c) but for the spring (MAM). (e) The $p$ values for winter (DJF) of the Southwestern drought years, 1946–56. (f) Same as (e) but for the spring (MAM).
El Niño–like conditions in the eastern equatorial Pacific, and by warm SSTs off western North America, in strong contrast with the early-twentieth-century pluvial. When a composite map of SSTs is calculated for just the eight wettest years of the early-twentieth-century pluvial (i.e., 1905, 1906, 1907, 1908, 1909, 1914, 1915, 1916; see Figure 3b) warm conditions in the equatorial Pacific are more pronounced, but the North Pacific Pineapple Express SST anomalies are also enhanced (not shown).

4.3. The Dust Bowl drought

The 12-yr winter mean SST map (1929–40) is compared with the winter SST means for each year of the Dust Bowl drought (Figure 7). Warm SST conditions in the northeast North Pacific and cool conditions in the northwest North Pacific were evident in most years (Figures 7c–n). The strongest DJF SST anomalies during the Dust Bowl era were observed in 1931 and 1940 (Figures 7e,n). The four strongest
years of drought were 1931, 1934, 1936, and 1940 according to instrumental PDSI (Figure 7b) and all occurred during warm SST conditions in the eastern North Pacific and cold conditions in the western and central North Pacific (Figures 7e,h,j,n). Overall, the tropical Pacific SST anomalies during the Dust Bowl were rather weak. The most robust feature during the 1929–40 period appears to be the cold anomaly in the northwestern North Pacific, the only large area where the $t$ tests indicate unusual SSTs (Figure 4c). The correlation between the interannual variability of summer PDSI over the Dust Bowl region and Pacific SSTs are also very weak (Figure 6c,d), but do suggest some support for the role of warm (cool) SSTs in the northeastern (northwestern) North Pacific during Dust Bowl–like droughts.

The atmospheric circulation associated with the Dust Bowl drought is believed to have included above-normal 500-mb geopotential heights in the central United

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**Figure 6.** The Pearson correlation coefficient between the gridded SSTs and summer PDSI (averaged for the geographical region of each moisture anomaly) from 1896 to 1991. (a) Correlation coefficient for the pluvial winter (DJF). (b) Same as (a) but for the spring (MAM). (c) Correlation coefficient for the Dust Bowl winter (DJF). (d) Same as (c) but for the spring (MAM). (e) Correlation coefficient for the Southwest drought winter (DJF). (f) Same as (e) but for the spring (MAM).
Figure 7. SST anomalies during the Dust Bowl drought of the 1930s. (a) The mean winter (DJF) SST anomalies for the 12 Dust Bowl years (1929–40). (b) The average instrumental summer PDSI time series over the Dust Bowl region (black), and a 10-yr smoothing spline (red). (c)–(n) The winter SST average for each year during the Dust Bowl.
States, below-normal heights in the northwestern United States, and higher-than-normal heights in the North Pacific south of the Aleutians (Chang and Wallace 1987). Consistent with the higher pressure in the central United States, drought in the plains is also often accompanied by stronger-than-normal summertime westerlies and more persistent dry flow from the base of the Rockies (Bryson 1966; Trewartha 1981). Schubert et al. (Schubert et al. 2004b) attribute the Dust Bowl circulation pattern for the 1932–38 period to cold tropical Pacific SSTs that lowered geopotential heights in the Tropics and raised heights in the midlatitudes. Schubert et al. (Schubert et al. 2004b) also relate the suppression of moisture flux into the U.S. interior to cyclonic activity in the Gulf of Mexico, a result of anomalously warm Atlantic SSTs.

Two well-known single-year droughts of the central United States occurred in 1980 and 1988, and their respective PDSI maps and associated SST patterns are illustrated in Figures 8a and 8d for comparison with the 12-yr Dust Bowl drought. The 1980 drought (Figure 8b) covered the central United States from Canada to Mexico. Considerable wetness existed in the west (Figure 8b), a pattern seen only in the extreme southwestern United States during the Dust Bowl (Figure 2d). The 1988 drought (Figure 8d) may provide a more reasonable 1-yr analog to the 12-yr Dust Bowl drought (Figure 2d). The 1988 drought covered most of the country, but like the Dust Bowl, was most extreme over the north-central United States while portions of the Southwest were relatively moist (Figures 8d and 2d).

The SST regimes of 1980 and 1988 (Figures 8a,c) contain similarities to the SST regimes witnessed during the Dust Bowl drought (Figure 2c) with respect to anomalously warm water in the eastern North Pacific and a cold anomaly in the western and north-central North Pacific. Like the 12-yr Dust Bowl, these single-year SST regimes were also most anomalous during the MAM season (not shown). These similarities in the SST regimes for the Dust Bowl, 1980, and 1988 droughts suggest that similar atmospheric circulation features may have been involved in these droughts.

A long-wave pattern with large-amplitude troughs on the West Coast and the East Coast and a three-cell pattern of anticyclones over the eastern North Pacific, central United States, and western Atlantic were identified by Namias (Namias 1982) as factors in the 1980 drought. This circulation pattern was supported by cold water in the central North Pacific (Namias 1982). During the drought in 1936, strong anticyclones similarly dominated the North Pacific and Atlantic (Namias 1980), and we note some similarity in the SST patterns of 1936 (Figure 7j) and 1980 (Figure 8a; i.e., the cold central and warm eastern North Pacific).

The 1988 drought has been attributed to short episodes of strong anticyclones in the Great Plains region that started in April 1988 and culminated in a very strong and persistent anticyclone in that area starting in June 1988 (Chen and Newman 1998). The prominent wet area in the Southwest in 1988 (Figure 8d) corresponded with average to mild wetness over most of the Southwest during the Dust Bowl (Figure 2d). Ropelewski (Ropelewski 1988) associated this wet pattern with the strong El Niño of 1987 and early 1988. Others have attributed the 1988 drought to cold water in the eastern tropical Pacific that appeared in June 1988 and continued through the summer (Trenberth and Branstator 1992; Ting and Wang 1997). The composite SST map for DJF of 1988 (Figure 8c) indicates warm waters in the
eastern equatorial Pacific. However, cold SSTs quickly developed in the extreme eastern equatorial Pacific and were prominent through July and August 1988 (not shown).

The timing of the strongest SST regimes may have played an important role in the development and severity of drought over the Great Plains during the Dust Bowl. In our analysis, SST averages during the spring season (MAM, not shown) were the most anomalous of the three seasons antecedent to the summer PDSI of the Dust Bowl, 1980, and 1988 droughts. Precipitation in the continental interior of the United States is typically greatest in May and June (Trewartha 1981). A midcontinental anticyclone tends to develop over the central United States from mid-June to late August and typically suppresses rainfall over a large area along an axis from Wisconsin to West Texas. Early development of anticyclonic flow and suppression of the normal May–June rains in the Great Plains may be a critical

Figure 8. The mean winter SST anomalies during the drought years of (a) 1980 and (c) 1988, and (b), (d) the corresponding summer instrumental PDSI.
factor for drought initiation. Namias (Namias 1960) noted that dry springs tend to be followed by hot dry summers over the U.S. Great Plains. The 1988 drought began with anomalous atmospheric circulation in April, May, and June (Trenberth and Branstator 1992). The SST anomalies witnessed during the Dust Bowl (cold central and warm eastern North Pacific), though relatively weak for the full 12-yr event (Figures 2b and 4c), were most extreme during the spring season and did occur during the four most severe years of drought. This North Pacific SST regime would have favored anticyclonic flow and drought over central North America during what would normally be the wettest time of the year. The correlation between the interannual variability of summer PDSI averaged over the Dust Bowl region and Pacific SSTs are very weak, but do offer some support for a cold central and warm western North Pacific during northern plains droughts (Figures 6c,d).

4.4. The Southwestern drought of the 1950s

The mean winter SST regime for the 11 yr (1946–56) of the Southwestern drought indicates weak cool SST conditions over most of the tropical and eastern North Pacific and a warm anomaly in the west and central North Pacific (Figure 9a). This SST regime strongly resembles the cool phase of the Pacific decadal oscillation (PDO), which reached its lowest (coldest) values during the 1950s drought (Mantua et al. 1997). Relatively cool waters in the eastern equatorial Pacific were prevalent in 8 of the 11 individual years (Figures 9c–m). The most intense cold anomaly in the equatorial Pacific (DJF of 1955–56; Figure 9m) preceded the summer drought of 1956, the worst year of drought during this decade (PDSI time series; Figure 9b). A warm SST anomaly in the west and central North Pacific also appeared in at least 8 of the 11 yr of this regime, including 1956.

Anomalously cold water in the equatorial Pacific during the boreal winter suggests an ENSO influence on the 1950s drought (e.g., Philander 1989). The correlation analyses between Pacific SSTs and the interannual variability of summer PDSI over the region impacted by the 1950s drought strongly supports this inference (Figures 6e,f). However, the \( t \) tests do not indicate that SSTs were particularly unusual in the equatorial Pacific during the 11-yr period of this drought (Figures 4e,f). Instead, the warm SSTs in the western North Pacific and in the western Atlantic appear to have been most anomalous over the decade (Figures 9a and 4e).

The warm SST anomaly in the west-central North Pacific would have favored development of an upper-level trough over the east-central North Pacific, northward diversion of the polar jet into the Gulf of Alaska and western North America, and an upper-level ridge over the intermontane and southwest region (e.g., Yarnal and Diaz 1986). Upper-air data available starting in 1948 [the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis; more information available online at http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl] confirm this suggested flow pattern. Composite 500-mb geopotential height anomalies for DJF (not shown) of the 1949–56 period indicate strong positive anomalies (ridging) in the central North Pacific concurrent and downstream of the warm SST anomaly, followed by negative anomalies (troughing) on the west coast of North America, and positive
anomalies from the Southwest to New England. Composite analyses of the driest years of this drought (1953–56; Figure 9b) during the growing season (MAMJJA) agree with the DJF anomalous geopotential height pattern, but with increased amplitude in the flow pattern, especially the anticyclonic flow along an axis from

Figure 9. (a) Winter SST anomalies (DJF) during the 11-yr Southwestern drought of the 1940s–50s. (b) The average instrumental PDSI time series over the region of the Southwestern drought (black), and a 10-yr smoothing spline (red). (c)–(m) The winter (DJF) SST average for each year of the Southwestern drought.
Alaska to New Mexico. This circulation pattern may have helped sustain the drought conditions in 1952, 1953, and 1954 (Figures 9i,j,k) when La Niña conditions were absent, but the warm SST anomaly remained in place in the west-central North Pacific.

5. Discussion and conclusions

This empirical study has examined the potential relationship between seasonal SST regimes and decade-long moisture anomalies over the United States. The early-twentieth-century pluvial lasted at least 13 yr and was focused over the intermontane west. Concurrent mean SSTs show unusually cold water in the northern and northwestern North Pacific, and in the eastern North Pacific. This pattern would favor a Pineapple Express–like mean storm track that would account for the wet conditions in the west. Warm ENSO-like conditions also observed during the pluvial would also have favored an enhanced subtropical jet stream into the Southwestern portion of the pluvial region. Comparison of the pluvial mean SST field with more recent SST fields of wet episodes in the western United States (1941–45, 1978–87) reveals a very different SST field in the North Pacific, and suggests these more recent multiyear wet episodes were related to prolonged or recurring El Niño conditions. These results suggest that all three (1904–17, 1941–45, 1978–87) wet regimes over the western United States may have been associated with El Niño conditions while a contrasting SST regime in the North Pacific may have prolonged and intensified the wet conditions of the 1904–17 pluvial.

The 1930s Dust Bowl was focused in the central and northern plains, extending to the northwestern United States. The winter and spring SSTs observed during the Dust Bowl were very weak, but included warm water in the northeastern North Pacific and cold water in the western North Pacific. This may have favored anticyclonic conditions and drought over central North America during the spring and summer. Tropical SSTs were variable during the Dust Bowl, but cold La Niña conditions, when present, may have contributed to this drought.

The Southwestern drought of the 1950s has been linked with cold conditions in the eastern equatorial Pacific and warm water in the western and central North Pacific, the classic pattern identified with the cold phase of the PDO. The warm anomaly in the western and central North Pacific during the 11 yr of this drought may have helped perpetuate the dry conditions by forcing the polar jet into the Gulf of Alaska, and favoring downstream ridge development over the western United States.

These results indicate that decade-long moisture regimes of the twentieth century over the United States may be associated with recurring Pacific SST regimes and associated circulation patterns (Namias 1986). However, the SST anomalies do not appear to have been as persistent as the concurrent droughts over the United States. Once initiated, these decadal droughts must have been perpetuated, in part, by surface feedback processes on a year-to-year basis (see, e.g., Palmer 1965; Charney 1975; Madden 1977; Namias 1978; Namias 1982; Chang and Wallace 1987; Trenberth et al. 1988; Pal and Eltahir 2001; Cole et al. 2002; Schubert et al. 2004b).

The SST field during the Dust Bowl was weak and poorly defined. The apparent lack of a distinctive Pacific SST pattern suggests that the Dust Bowl drought may have arisen from a random sequence of dry years with multiple causes. We have
not investigated SSTs over the Atlantic or Indian Oceans, but McCabe et al. (McCabe et al. 2004) note widespread drought over the northern plains and Rockies during the concurrent warm phases of the PDO and Atlantic multidecadal oscillation (AMO). Although weak, the average Pacific SSTs in Figure 2c were consistent with a warm PDO phase, but further research will be needed to examine the possible role of Atlantic SSTs during the Dust Bowl and other decadal moisture regimes over the United States.

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