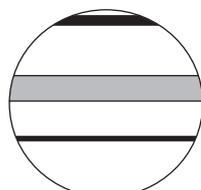


# North American droughts of the mid to late nineteenth century: a history, simulation and implication for Mediaeval drought

Celine Herweijer,\* Richard Seager and Edward R. Cook

(Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades NY 10964, USA)

Received 1 March 2004; revised manuscript accepted 15 December 2005



A  
HOLOCENE  
RESEARCH  
PAPER

**Abstract:** Unlike the major droughts of the twentieth century that are readily identified in the instrumental record, similar events in the nineteenth century have to be identified using a combination of proxy data, historical accounts and a sparse collection of early instrumental records. In the USA, three distinct periods of widespread and persistent drought stand out in these records for the latter half of the nineteenth century: 1856–1865, 1870–1877 and 1890–1896. Each of these events is shown to coincide with the existence of an anomalously cool, La Niña-like tropical Pacific. To examine the physical mechanisms behind these droughts two ensembles of simulations with an atmosphere general circulation model (AGCM) were generated: the first forces an AGCM with the observed history of Sea Surface Temperatures (SSTs) everywhere from 1856 to 2001 (the GOGA experiment), the second forces the AGCM only with tropical Pacific SSTs, being coupled to a two-layer entraining mixed layer (ML) ocean elsewhere (the POGA-ML experiment). Owing to a sparsity of instrumental precipitation data at this time, proxy evidence from tree rings is used as verification. A comparison of modelled soil moisture with tree-ring reconstructions of the Palmer Drought Severity Index (PDSI), a proxy for soil moisture, from the North American Drought Atlas is made. Both the POGA-ML and GOGA ensemble means capture the three multi-year droughts of the mid to late nineteenth century, indicating that the droughts were SST forced. The similarity of the POGA-ML and GOGA simulations implies that the component of each drought signal that is forced by the SST is driven ultimately by the La Niña-like tropical Pacific. The global atmosphere–ocean context of each of the mid to late-nineteenth century droughts reveals a zonally and hemispherically symmetric pattern consistent with forcing from the tropics. In addition, Rossby wave propagation from the cooler equatorial Pacific amplifies dry conditions over the USA. Finally, using published coral data for the last millennium to reconstruct a NINO 3.4 history, the modern-day relationship between NINO 3.4 and North American drought is applied to recreate two of the severest Mediaeval ‘drought epochs’ in the western USA. The large-scale spatial similarity to the Drought Atlas data demonstrates the potential link between a colder eastern equatorial Pacific and the persistent North American droughts of the Mediaeval period.

**Key words:** Drought, La Niña, North America, megadrought, Mediaeval climate anomaly.

## Introduction

Drought is a recurring major natural hazard that has dogged civilizations through time and remains the ‘world’s costliest natural disaster’, with damages in the USA alone reaching US\$6–8 billion annually (Wilhite, 2000). Headlines telling of ‘drought’, ‘wildfires’ and ‘water-shortages’ have become a staple, yet unwelcome, feature of many a North American summer. When drought conditions persist for a number of years and spread across vast areas, these impacts become devastating.

The instrumental record gives evidence of multiyear to decadal drought and wetness regimes punctuating the climate of the last century over the central and western USA. The two

major long-lasting droughts of the 1930s and 1950s covered large areas of the interior and southern states and have long served as paradigms for the social and economic cost of sustained drought in the USA. Both had severe environmental and social impacts, in the Great Plains and southwest, respectively. During the Dust Bowl period of the 1930s, drought conditions gripped the Plains for as much as a decade, ‘black blizzards’ swept from Texas to the Dakotas and red snow was seen falling in New England. More than a quarter million ‘dust-bowlers’ headed west (Worster, 1985) to leave behind the depressed economy, drought and exhausted soils of the Plains. Drought conditions returned in the 1950s, which, unlike the 1930s, was in general a time of growth and stability for many Americans. Nonetheless, in the southwest, drought and soaring temperatures devastated the region’s agriculture and economy. Today, the American southwest has

\*Author for correspondence: (email: celineh@ldeo.columbia.edu)

been ravaged by 6 years of drought that in the last few months has abated, yet the experience of the 1930s and 1950s cautions against concluding it is over.

These events are not unique to the twentieth century. Severe and extensive decadal- to multidecadal-length droughts in the West punctuated the nineteenth century (Muhs and Holliday, 1995; Woodhouse and Overpeck, 1998; Fye *et al.*, 2003). Cook and Krusic (2004) have recently constructed a North American Drought Atlas using hundreds of tree-ring records, which shows that the present multiyear drought in the western USA pales in comparison with a 'Mediaeval Megadrought' that occurred from AD 900 to AD 1300. This drought reconstruction also shows an abrupt shift to wetter conditions after AD 1300, coinciding with the 'Little Ice Age', a time of globally cooler temperatures, and a return to more drought-prone conditions beginning in the nineteenth century.

Little attention has been paid to the drought history of the USA during the nineteenth century. The cultural environment of the interior states changed significantly over the course of this century, as Native Americans were displaced by European settlers who moved west across the country, made their homes, ploughed the land and began new processes of water management. In this study we focus on the period of 'Incipience' (Worster, 1985) from the mid to the late nineteenth century, the first period of economic and agricultural intensification of the western USA that began with the Mormon migration into Utah in 1847. This period was characterized by a general dependence on local skills and resources, with isolated communities vulnerable to the swings of nature. Palaeoclimate and early historical records can be used to provide hydroclimatic evidence at this time when the keeping of instrumental records ranged from sparse to non-existent in the drought-prone regions of the central and western states. Using a combination of proxy, historical and instrumental data, we will show three distinct periods of widespread and persistent drought that stand out in these records for the latter half of the nineteenth century: 1856–1865, 1870–1877 and 1890–1896.

Several recent studies have developed the notion that large-scale extra-tropical drought events are linked to variations of the coupled tropical climate system (Trenberth *et al.*, 1998; Cole *et al.*, 2002; Hoerling and Kumar, 2003; Schubert *et al.*, 2004; Seager *et al.*, 2005). It is well known that changes in the configuration of tropical SSTs on interannual timescales can strongly influence extratropical precipitation: during La Niña winters there is reduced precipitation across much of the northern subtropics and mid-latitudes, with large deficits in particular in the southwest USA, extending into the Great Plains (Trenberth and Branstator, 1992; Trenberth and Guillemot, 1996; Cole *et al.*, 2002; Seager *et al.*, 2004). On longer timescales, the notion of tropical forcing of extratropical drought has recently been advanced by two separate simulations of the major US droughts of the twentieth century in an ensemble of climate model simulations forced by the time history of observed SST (Schubert *et al.*, 2004; Seager *et al.*, 2005). In both studies, persistent drought conditions in the Great Plains (and also the Southwest in Seager *et al.*, 2005) were primarily influenced by the tropical part of the SST forcing, with a tendency for drought when the tropical Pacific SSTs are cold.

In this paper we shall identify and investigate the major mid to late-nineteenth century multiyear US droughts using observations, palaeoclimate tree-ring data and numerical climate models. Observational data and coral records will be used to show that each of these events coincided with an anomalously cool, La Niña-like tropical Pacific ocean. We will use an atmospheric model forced by observed SSTs to

investigate the relative role of tropical Pacific and global SST anomalies in forcing the predictable components of persistent US drought events. A gridded tree-ring reconstruction of Palmer Drought Severity Index (the North American Drought Atlas PDSI data, Cook and Krusic, 2004) is used to verify the modelled soil moisture anomalies.

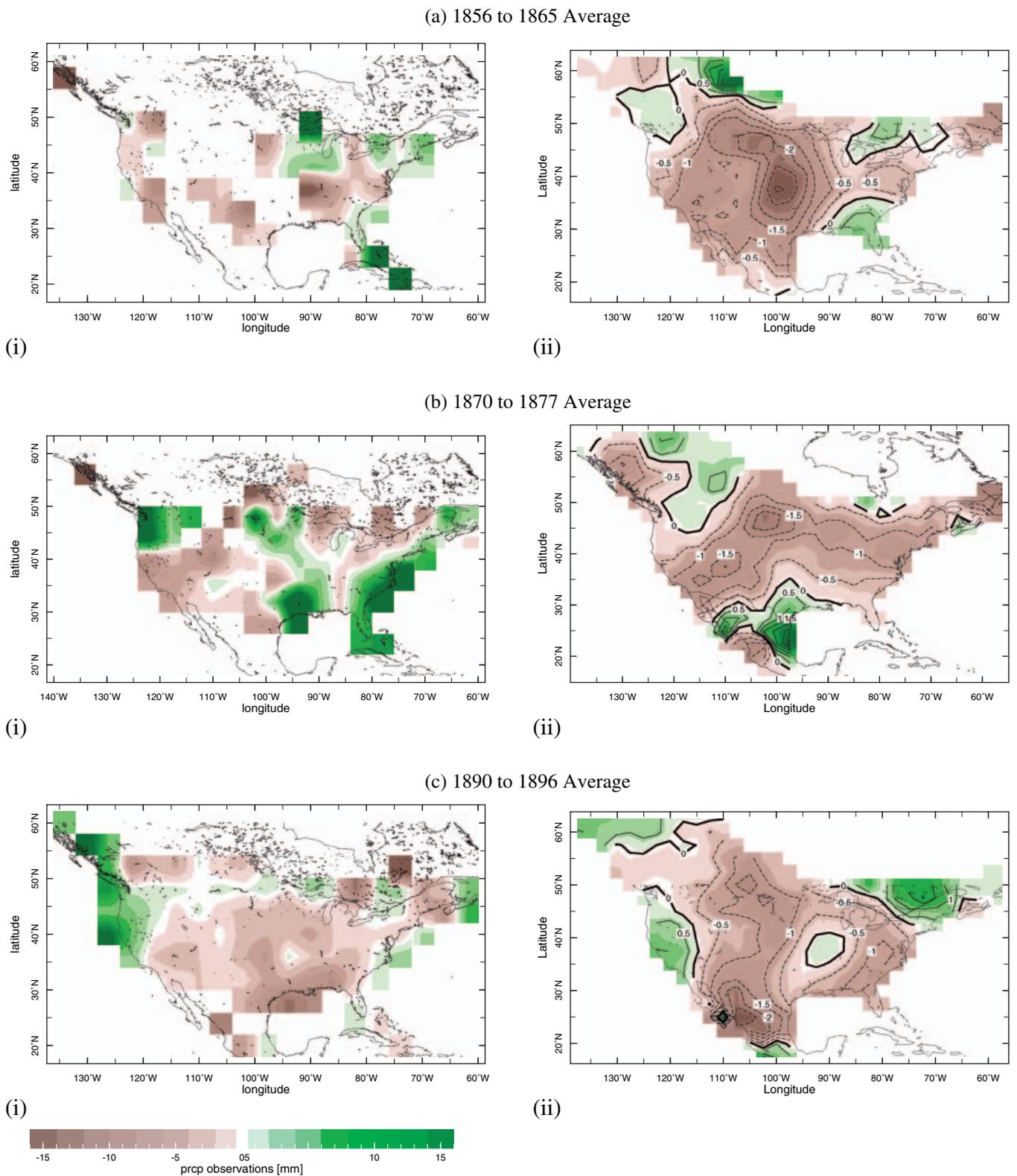
We will propose that each of the three multiyear US droughts of the mid to late nineteenth century identified by the Drought Atlas PDSI data is forced by SSTs – primarily tropical Pacific La Niña-like SSTs. In the next section we diagnose the mid to late-nineteenth century drought events using historical and proxy evidence. In the third section we will outline the existing evidence for a link between La Niña and persistent North American drought and present instrumental and proxy evidence of La Niña-like conditions during the major nineteenth-century US droughts. We will then describe the model arrangements and simulation. In the following section we will analyse the modelled history of mid- to late-nineteenth century US droughts, including verification with tree-ring PDSI data, and examine the global atmosphere–ocean context of these droughts to elucidate the underlying physical mechanisms. The final section presents an extrapolation of the modern-day relationship between La Niña and North American drought back over the last millennium, using coral proxy records as input, and tree-ring PDSI as verification. Conclusions follow.

## Identification of persistent droughts of the mid to late nineteenth century

Unlike the major droughts of the twentieth century that are readily identified in the instrumental record, similar events in the nineteenth century may be identified using a combination of proxy data, historical accounts and a sparse collection of early instrumental records. Gridded PDSI data have previously been used to examine patterns of US drought in this period (Cole *et al.*, 2002; Fye *et al.*, 2003). Here, we make the case that three distinct periods of widespread and persistent drought stand out in proxy, historical and early instrumental records for the latter half of the nineteenth century: 1856–1865, 1870–1877 and 1890–1896.

### Diagnosis of the 'Civil War' drought (1856–1865)

A major persistent drought near 1860 can be identified in a number of historical and proxy records from the Great Plains and southwest regions. Drought-like conditions were reported in Kansas newspapers, which continued to mention the severity of the 1860s ('Civil War') drought several decades later (Bark, 1978). Historical accounts from early explorers in the Great Plains and southwest note blowing sand and dune reactivation at this time (Muhs and Holliday, 1995). Regional-scale aeolian sand depositional events in western Nebraska and Idaho have been dated at  $150 \pm 20$  yr BP (Forman and Pierson, 2003). Temperature and precipitation records from early meteorological stations and US Army Forts in the Great Plains also indicate a severe 1860s drought (Ludlum, 1971; Mock, 1991). Station precipitation data from the Global Historical Climate Network (GHCN) exist for this period but must be interpreted with caution because of the scarcity of records west of the Appalachian Mountains. Nonetheless, a composite of the 1856–1865 precipitation anomaly over the USA taken from the GHCN station data, binned into boxes of four degrees of latitude and longitude, does show evidence of the Civil War drought, with drier than normal conditions over the entire Plains and southwest where data are available (Figure 1a (i)).



**Figure 1** Evidence of the mid- to late- nineteenth century North American droughts: (i) the observed GHCN  $4^{\circ} \times 4^{\circ}$  gridded station data precipitation anomaly (mm/month); (ii) tree ring reconstructed summer PDSI from the North American Drought Atlas. (a) 1856 to 1865 average, (b) 1870 to 1877 average, and (c) 1890 to 1896 average

A collection of dendroclimatological studies also point to a widespread severe and prolonged drought in the late 1850s and early 1860s. Tree-ring records flanking the Great Plains show a period of drought equalling or surpassing the intensity of the 1930s drought (Stockton and Meko, 1983, Meko *et al.*, 1995). In south Texas, tree-ring records rank the decade centred at 1860 as the driest since 1698 (Stahle and Cleaveland, 1988). Blasing *et al.* (1988), in a study in the Texas–Oklahoma–

Kansas region, found the 1860s drought to be the most severe in the last 231 years. Dendroclimatological evidence for the Civil War drought is also seen for the entire southwest (Stockton and Meko, 1975; Meko *et al.*, 1995) and even as far west as eastern California (Hardman and Reil, 1936).

The recent ‘North American Drought Atlas’ of Cook and Krusic (2004) provides 286 annual tree-ring drought reconstructions on a  $2.5^{\circ}$  by  $2.5^{\circ}$  gridded network of summer Palmer

Drought Severity Index (PDSI) (Palmer, 1965) data, which extend as far back as 1 BC at some locations. It is the most complete tree-ring derived annual meteorological drought reconstruction available for North America today. Given the sparsity of instrumental station data in the mid nineteenth century, the North American Drought Atlas data provide us with our 'best guess' of the magnitude, severity and extent of the Civil War drought event. The 1856 through 1865 period in the PDSI record stands out as a widespread and severe drought covering most of the continental USA and centred on the Great Plains region (Figure 1a (ii)) where it is unsurpassed by any of the region's droughts over the last two centuries.

### Other large-scale multiyear droughts

Two further late-nineteenth century droughts that were widespread and persistent stand out in historical and proxy records from the USA: 1870–1877 and 1890–1896. For the 1870s interval, evidence for long-lasting drought conditions includes records from early meteorological stations and forts in the Great Plains (Mock, 1991) and Rocky Mountains (Bradley, 1976), historical accounts of aeolian activity in Kansas (Muhs and Holliday, 1995), and various tree-ring drought reconstructions from the Great Plains (Fritts, 1983, Stahle *et al.*, 1985), and western USA (Fritts, 1965; Haston and Michaelson, 1997). A composite of the GHCN  $4^\circ \times 4^\circ$  binned station data of anomalous precipitation for this period shows drier than normal conditions in the southwest reaching across to the Rockies, and in the central Plains states of Kansas and Oklahoma (Figure 1b (i)). The North American Drought Atlas PDSI data for the same interval show dry conditions, but less severe than for the Civil War drought event, centred in the northern Plains and southwest, and reaching eastwards to the Great Lakes and northeast regions (Figure 1b (ii)).

Published evidence for widespread multiyear dry conditions in the USA also exists for the early 1890s, including historical documents and early meteorological records from the Plains (Ludlum, 1971; Bradley, 1976, Mock, 1991), historical accounts of aeolian activity in eastern and central Colorado (Muhs and Holliday, 1995), dendroclimatic data from the eastern and western margins of the Great Plains (Stockton and Meko, 1983, Meko, 1992), the corn belt of Iowa and Illinois (Blasing and Duvick, 1984), the southern Plains (Stahle *et al.*, 1985) and the southwest (D'Arrigo and Jacoby, 1992; Meko *et al.*, 1995). Figure 1c (i) and (ii) show the 1890 to 1896 average of the GHCN  $4^\circ \times 4^\circ$  binned station data of anomalous precipitation and of the North American Drought Atlas PDSI data. The coverage of the GHCN precipitation data is much higher than for the two preceding mid- to late-nineteenth century droughts, and comparison with the PDSI data shows a considerably closer match. Both indicate widespread dry conditions throughout much of the contiguous USA, with drought centred over the entire Great Plains and southern USA whilst the west coast experienced wetter than normal conditions. The 1870s and 1890s droughts were less severe than the Civil War drought in the Great Plains region.

## Links between persistent North American drought and La Niña

### Background

Recent studies have claimed that a persistent anomalously cool tropical Pacific can provide the steady atmospheric forcing necessary for major North American drought (Trenberth *et al.*, 1988; Trenberth and Branstator, 1992; Hoerling and Kumar, 2003; Schubert *et al.*, 2004; Huang *et al.*, 2005; Seager *et al.*,

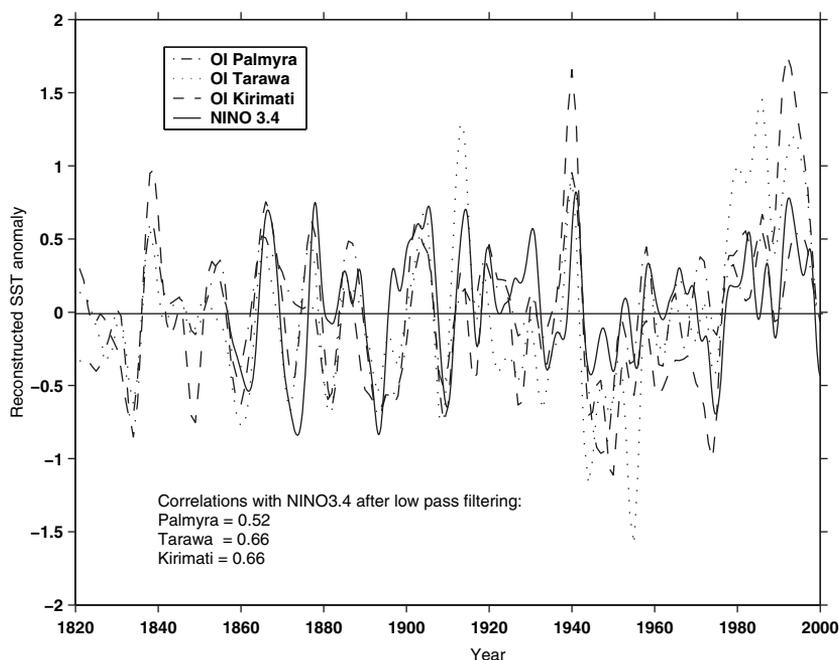
2005). Typically, ENSO-related precipitation anomalies in the extratropics have been explained in terms of teleconnections, ie, tropically forced large-scale Rossby wavetrains (eg, Wester, 1981; Horel and Wallace, 1981, Hoskins and Karoly, 1981, Sardeshmukh and Hoskins, 1988; Trenberth *et al.*, 1998), and changes in storm tracks (Wang and Ting, 2000). Recent work by Seager *et al.* (2003, 2004) describes a mechanism of Tropical Modulation of Mid-latitude Eddies (TMME) that helps explain the strong hemispherically and zonally symmetric components of observed ENSO-related extratropical precipitation anomalies on interannual timescales. The TMME mechanism causes decreased mid-latitude precipitation during La Niña as the subtropical jets weaken and move poleward, altering the meridional and vertical propagation of transient eddies and resulting in an anomalous eddy-driven mean meridional (MMC) circulation that causes descent and drying at mid latitudes (Seager *et al.*, 2004).

With regard to North American drought, the zonally symmetric TMME mechanism is particularly relevant: Seager *et al.* (2005) and Schubert *et al.* (2004) show a zonally and hemispherically symmetric component to the simulated droughts of the twentieth century, supportive of a tropical origin for the persistent dry conditions. It is argued that the TMME mechanism works year-round and is partly responsible for descent over the Plains and southwest during the simulated twentieth-century US droughts (Seager *et al.*, 2005). However, to explain the observed regional departures from symmetry requires reference to stationary waves, ie, teleconnections. For example, during La Niña, tropical Pacific SST anomalies can cause atmospheric heating anomalies in the tropics that initiate a Rossby wavetrain into the extratropics. This, in turn, causes an anomalous strengthening of the western lobe of the North Pacific high, weakens the Aleutian low and leads to a northward-shifted stronger and narrower band of westerlies over North America. The main areas of anomalous descent and suppressed precipitation associated with the La Niña-related stationary wave propagation are over the western USA and across the southern USA (Seager *et al.*, 2004).

Drought in the Great Plains is most often associated with reduced rainfall in the summer wet season (Schubert *et al.*, 2004; Seager *et al.*, 2005) but the ENSO-related SST anomalies typically peak during the winter and spring. It may be that a soil moisture–atmosphere interaction introduces memory into the hydrologic cycle (Oglesby and Erickson, 1989; Namias, 1991; Zeng *et al.*, 1999; Schubert *et al.*, 2004;), and allows for persistence of ENSO-related soil moisture anomalies into the summer months. On the other hand, Seager *et al.* (2005) suggested that, while a soil moisture feedback could be important in the season to season persistence of modelled twentieth-century North American droughts, summertime tropical Pacific SST anomalies, though small, do also force summertime circulation anomalies that induce drought.

### State of the Tropical Pacific during late-nineteenth century multiyear droughts

Analysis of mid- to late-nineteenth century instrumental and proxy records from the tropical Pacific reveal prolonged La Niña-like conditions during each of the persistent droughts: 1856–1865, 1870–1877 and 1890–1896. This is clearly shown by the the mid- to late-nineteenth century time series of the observed NINO 3.4 index from the extended optimally interpolated MOHSST5 data set (Kaplan *et al.*, 2003) and the reconstructed SST anomaly derived from three optimally interpolated coral records located in the NINO 3.4 region (Figure 2). (NINO 3.4 is an index that measures the strength of an ENSO event: it is the SST averaged over a region in the



**Figure 2** The six-year low pass filtered time series of the observed NINO 3.4 index from the optimally interpolated MOHSST5 data set (Kaplan *et al.*, 2003) and the reconstructed SST anomaly derived from three optimally interpolated coral records located in the NINO 3.4 region (Palmyra, Tarawa and Kirimati)

east-central equatorial Pacific ( $120^{\circ}\text{W}$ – $170^{\circ}\text{W}$ ,  $5^{\circ}\text{N}$ – $5^{\circ}\text{S}$ .) Interannual variability has been removed from the records by subjecting the data to a six-year low pass filter. Composites of the unfiltered observed SST anomaly for each of these intervals of persistent drought are shown in Figure 3. The SST data are those used to force the model simulations described in the following section. Each of the three major persistent US droughts of the mid to late nineteenth century coincided with the existence of an anomalously cool, La Niña-like tropical Pacific.

## The AGCM simulations and model verification

Here we employ two experiments described by Seager *et al.* (2005): the first forces an atmosphere general circulation model (AGCM) with the observed history of SSTs everywhere from 1856 to 2001, the second forces the AGCM only with tropical Pacific SSTs, being coupled to a two-layer entraining mixed layer (ML) ocean elsewhere.

The AGCM used for these experiments is the National Center for Atmospheric Research (NCAR) Climate Community Model 3 (CCM3) described by Kiehl *et al.* (1998). It has T42 resolution and 18 levels in the vertical, and has ‘state-of-the-art’ physical parameterizations. Comparison of the model and observational fields, including precipitation, is discussed in Hack *et al.* (1998) and Hurrell *et al.* (1998). In the Global Ocean and Atmosphere (GOGA) experiments the AGCM uses observed SSTs as a lower boundary condition. Two data sets have been blended to create the global SST history from 1856 to 2001. For the tropical Pacific ( $20^{\circ}\text{N}$ – $20^{\circ}\text{S}$ ) we use the data set of Kaplan *et al.* (1998) from 1856 to 2001. Elsewhere we use Kaplan data where available from 1856 to 1870, and after 1870 we use the HadISST global data set (Rayner *et al.*, 2003). Between 1856 and 1870, climatological SSTs are used where Kaplan data are not available.

For the Pacific Ocean Global Atmosphere (POGA) set of experiments, the AGCM is coupled to a ML model outside of

the tropical Pacific region. The ML model is a two-layer model with a variable depth surface layer that exchanges mass and heat with the uniform depth layer beneath. The ‘q-flux’ formulation of Russell *et al.* (1985) is used, which primarily accounts for the horizontal heat transport in each layer, and also for modelled surface flux errors (see Seager *et al.*, 2005 for further details). SSTs are only specified within the tropical Pacific region, using the Kaplan data, with SSTs elsewhere computed using the ocean ML model.

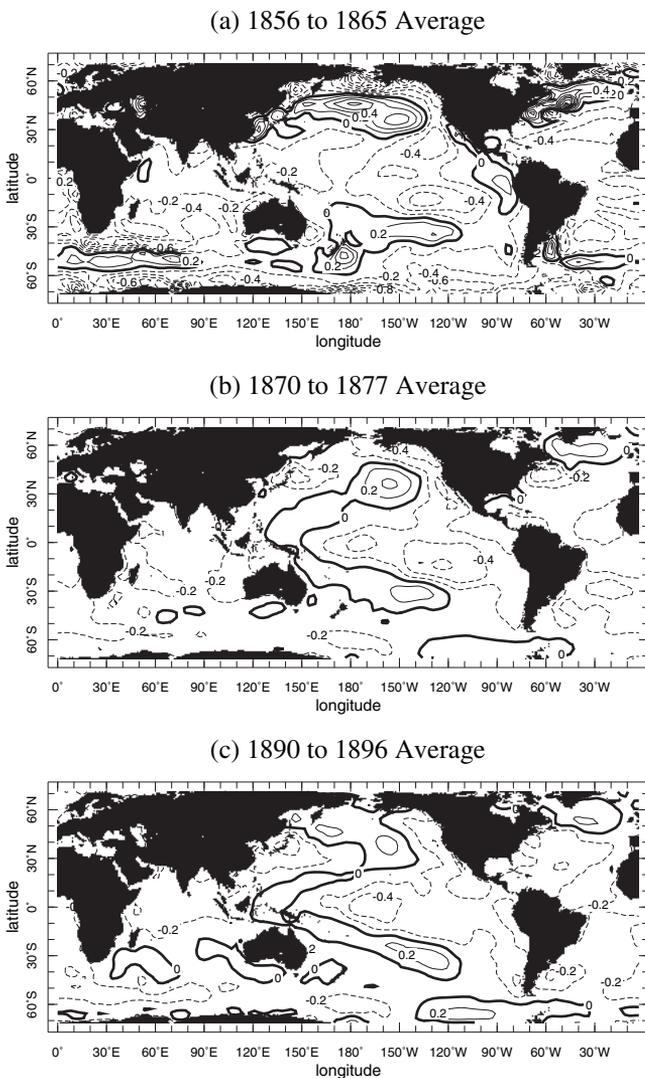
In both the GOGA and POGA-ML experiments a 16-member ensemble of integrations has been generated using a different initial condition on 1 January 1856 for each run. We will focus on the ensemble mean, the average of the 16 individual runs, which represents the part of the climate variability forced by observed SSTs.

## Model results

Here we assess the ability of the SST-forced AGCM simulations to capture the major mid- to late-nineteenth century droughts in the USA. The extent to which the ensemble means of the climate model are able to simulate the observed drought intervals is a test of whether the dry conditions are SST-forced, and of the relative role of the tropical Pacific alone. Because of a sparsity of instrumental precipitation data at this time, proxy evidence from tree rings will be used as verification. A comparison of modelled soil moisture with PDSI data (a proxy for soil moisture) from the North American Drought Atlas is made. A recent study by Dai *et al.* (2004) indicates that PDSI is significantly correlated with observed soil moisture content within the top 1 m of soil depth. Modelled anomalies are calculated as differences from the 1856–2001 climatology.

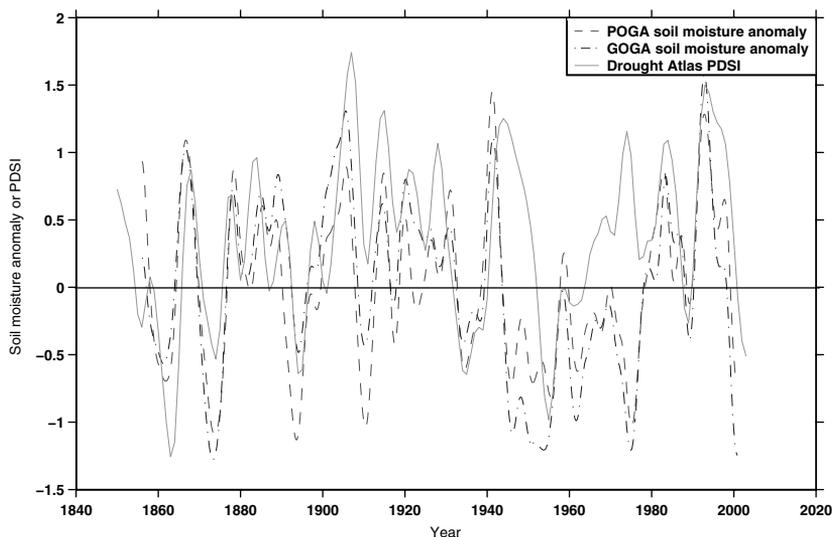
### Late-nineteenth century drought forced by SST

We define a climatic area for the ‘Great Plains’ extending from  $110^{\circ}\text{W}$  to  $90^{\circ}\text{W}$  and  $30^{\circ}\text{N}$  to  $50^{\circ}\text{N}$ , the same as in Seager *et al.* (2005). Figure 4 shows a time series of the standardized



**Figure 3** Observed SST anomalies during the mid- to late-nineteenth century North American droughts: (a) 1856 to 1865 average, (b) 1870 to 1877 average and (c) 1890 to 1896 average. Temperature units are K. The SST field is that used in the GOGA ensemble mean

Drought Atlas PDSI and the standardized soil moisture anomalies from the POGA-ML and GOGA model ensemble means from 1856 to 2001 for this area. The modelled soil



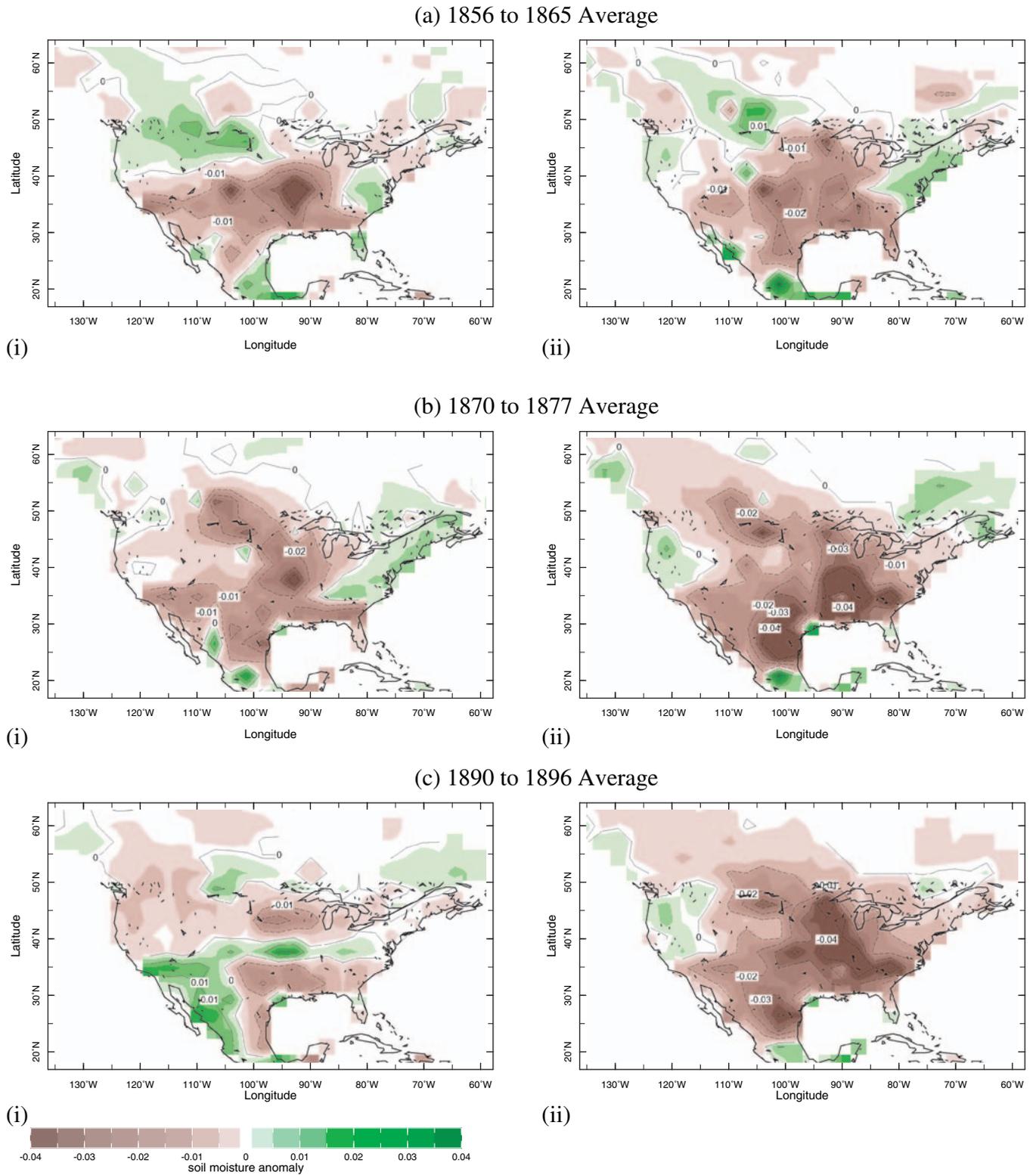
**Figure 4** The Drought Atlas PDSI and the soil moisture anomalies from the POGA-ML and GOGA model ensemble means over the Great Plains (110°W–90°W, 30°N–50°N) for the 1856 to 2001 period. All data have been standardized and six-year low pass filtered

moisture anomalies refer to the upper 1 m of soil, representative of the tree root zone. The observed and model data have both been smoothed by a six-year low pass filter to retain variability on timescales longer than just under a decade.

Both models capture the three observed major Great Plains droughts of the mid to late nineteenth century, and the wetter spells in between. Much of the twentieth century variability in the Great Plains is also reproduced, with the exception of the period between the late 1940s and the mid 1970s. The POGA-ML and GOGA soil moisture time series are very similar, implying that the component of the Great Plains drought signal that is forced by the SST is driven by the SST anomalies within the tropical Pacific. SST anomalies from other regions may still play an important part in contributing to drought in the Plains, but are a remote response to tropical Pacific variability. A comparison of modelled and observed Great Plains precipitation anomalies in these model simulations show consistent results (Seager *et al.*, 2005).

In the mid to late nineteenth century, both models underestimate the severity and length of the Civil War drought and overestimate the severity of the 1870s drought. The POGA-ML simulation of the 1890s Great Plains drought is overestimated in length and severity, while the GOGA model captures this event well. For the entire model history, the correlation coefficients between modelled soil moisture anomaly and PDSI in the Plains for the POGA-ML and GOGA simulations, respectively, are 0.40 and 0.42 ( $p < 0.01$ ). For the nineteenth century alone (1856 through 1900) the correlation coefficients between PDSI and modelled soil moisture are 0.46 (POGA) and 0.55 (GOGA) ( $p < 0.01$ ). The high skill at reproducing Plains drought variability in the mid to late nineteenth century suggests that drought conditions are highly SST-forced during this period.

Figure 5a–c shows maps of the GOGA and POGA-ML model ensemble mean soil moisture anomalies for the Civil War, 1870s and 1890s droughts, respectively. In the PDSI reconstructions, between 1856 and 1865 the entire USA, with the exception of Florida, experienced drought, with the driest conditions centred on the Great Plains (Figure 1a (ii)). The POGA-ML and GOGA model ensemble means (Figure 5a) capture this widespread drought, and the increased severity over the Plains. The POGA-ML model unrealistically extends the drought into Florida, while both models make the northeast and northwest wet where they should be dry. In spite of these errors, both models simulate the general features of the



**Figure 5** Modeled mid- to late-nineteenth century North American droughts: (i) GOGA ensemble mean; (ii) POGA-ML ensemble mean. (a) 1856 to 1865 average, (b) 1870 to 1877 average, and (c) 1890 to 1896 average. The variable shown is volumetric soil moisture, and hence unitless

Civil War drought, implying that this drought was forced by SSTs, and in particular by moderate yet persistent La Niña-like conditions in the tropical Pacific (Figure 3a).

The drought from 1870 to 1877 also stretched from the west to the east coast of the USA, with the most severe conditions located in the northern Plains and southwest, followed by the Lakes region and far northeast (Figure 1b (ii)). The model ensemble means both produce this major drought, with the locations of maximum drought in the northern Plains and southwest as in Nature (Figure 5b). However, they also

produce a serious drought in the southern Plains and northern Mexico that is not in the tree-ring reconstruction. Nonetheless, the ability of the models to capture many of the large-scale features of this drought suggests that it was also forced by La Niña conditions (Figure 3b), weaker than during the Civil War drought interval but consistent with a weaker drought in the USA.

The final multiyear drought of the nineteenth century, the 1890 to 1896 drought, also covered much of the USA (Figure 1c). Drought stretched across the entire Plains and into

northern Mexico. The Lakes, East coast and Florida were also dry, while wetter than normal conditions occurred along the west coast. Both models capture the observed drought in the northern and southern Plains (Figure 5c). In general, however, the POGA-ML model does a better job at reproducing the large-scale features of the proxy-derived PDSI composite, including a dry southwest and a wetter than normal west coast. The observed SST anomalies show weak La Niña conditions during the 1890s drought, similar in magnitude to the 1870s event (Figure 3c).

Next, having established that the model successfully simulates the history of multiyear Great Plains drought in the mid to late nineteenth century, and that these events were forced mainly from the tropical Pacific, we will identify the large-scale atmosphere and ocean setting that underlies each of these droughts.

### Physical mechanisms linking tropical Pacific SSTs and persistent US drought

#### *Seasonality of the drought signal*

The seasonality of drought in the US Great Plains in the 1930s and 1950s is variable, but there was a clear summer wet season deficit in rainfall (Seager *et al.*, 2005). The modelled mid- to late-nineteenth century droughts involved a substantial reduction in precipitation throughout the year. Generally for the POGA-ML and GOGA models, the largest precipitation deficit in the Plains coincided with the largest negative SST anomaly in the NINO 3.4 region, that is autumn to spring (not shown). The GHCN binned station data implicate solely the springtime months as being responsible for the droughts (not shown), but the sparsity of data in the Plains region at this time reduces the value of this comparison.

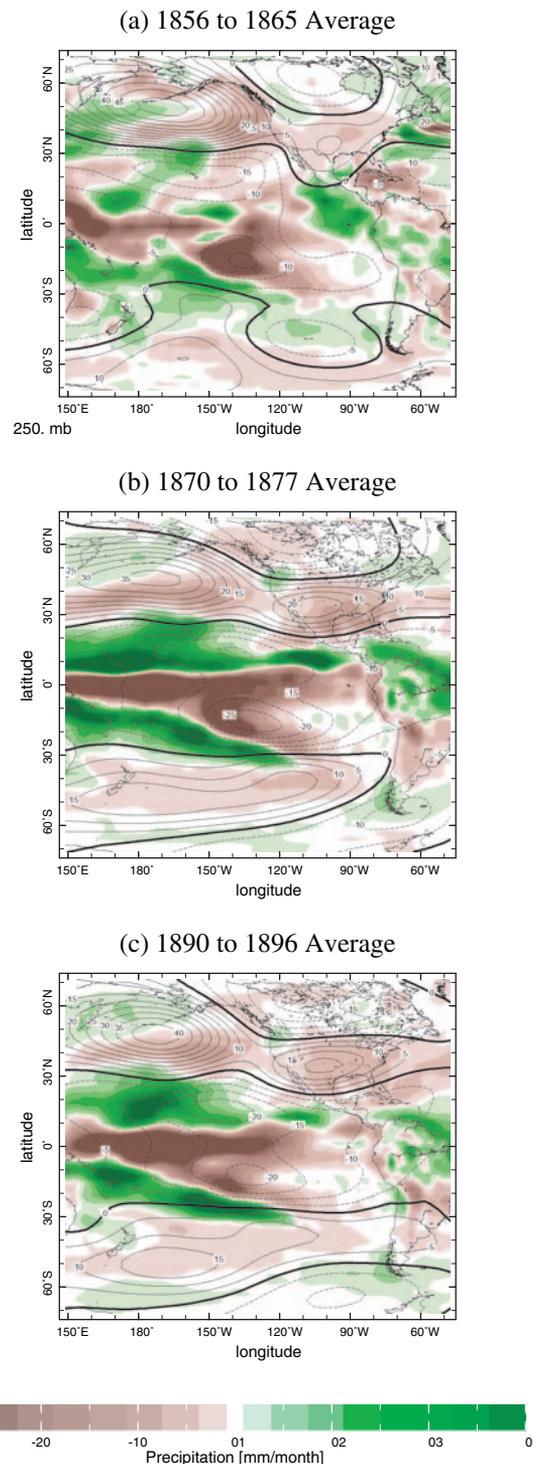
#### *Global atmosphere–ocean context of the droughts*

Here we examine the large-scale patterns of surface temperature, precipitation and tropospheric circulation associated with the mid- to late-nineteenth century droughts. We focus on the December–May half year, the months over which the modelled nineteenth-century Great Plains drought signal is strongest. Because of the time-integrating effect of soil moisture feedbacks, the influences of winter December–May precipitation reductions are bridged into the summer PDSI reductions (ie, Seager *et al.*, 2005a).

The global surface temperature anomalies during each of the mid- to late-nineteenth century droughts in the GOGA model, detrended to account for the globally cooler world at this time, are shown in Figure 3. In each case we see the classic La Niña pattern of a cool tropical Pacific, cool along the west coast of the Americas and a warm mid-latitude North Pacific. By design, the POGA-ML model has the same cool tropical Pacific, yet unlike the GOGA ‘La Niña-like’ extratropics, the North Pacific is cool, the tropical Atlantic is warm and the Indian Ocean unchanged (not shown). These POGA-ML SST anomalies outside of the tropical Pacific are as expected from tropical Pacific forcing of extratropical atmospheric circulation and surface flux anomalies (Alexander *et al.*, 2002). Given that the two ensembles have very different extra-tropical surface temperature signatures, yet both capture the large-scale features of the droughts, we must conclude that the atmospheric forcing that promoted these droughts originated from the La Niña-like tropical Pacific SST anomalies at the time that were common to both ensembles.

Next we focus on the POGA-ML model to identify the physical mechanisms underlying the droughts. The Pacific-wide December–May POGA-ML model ensemble mean precipitation anomalies and 200 mb geopotential height

anomalies for the drought periods, relative to the period from 1856 to 2000, are shown in Figure 6. Again, these quantities were detrended to remove the global warming signal. Drier than normal conditions in the central equatorial Pacific accompany the US drought in each case. Dry conditions also exist throughout much of the mid-latitudes, with below normal rainfall in mid-latitude South America and central Europe (not shown). According to the GHCN binned station precipitation



**Figure 6** Modelled POGA-ML precipitation anomalies (colours) and detrended 200 mb height anomalies (contours) for the December through May half-year of the mid- to late-nineteenth century North American droughts: (a) 1856 to 1865 average, (b) 1870 to 1877 average, and (c) 1890 to 1896 average. Precipitation is in mm/month, geopotential height is in m

data central Europe was dry at this time (not shown), but data are lacking for the South American region of concern.

During each of the mid- to late-nineteenth century droughts, the upper tropospheric geopotential heights are lowered in the tropics consistent with cooling at these latitudes (Figure 6, contours). Over North America, and more generally in the mid-latitudes of the Northern Hemisphere and Southern Hemisphere of the POGA-ML model, the geopotential heights are raised consistent with mid-latitude warming, as explained in Seager *et al.* (2003). The change in the geopotential heights indicates a weakening and poleward movement of the subtropical jets, which influences the propagation of transient eddies causing anomalous eddy-driven descent, warming and reduced precipitation in mid-latitudes (Seager *et al.*, 2004, 2005). It is also clear from the upper tropospheric height anomalies that Rossby waves propagate eastwards and polewards from the area of cooler waters and reduced precipitation in the central Pacific. The combined effects place high pressure aloft over the southern and western USA, which will tend to induce descent below.

#### Explaining the precipitation anomaly over North America

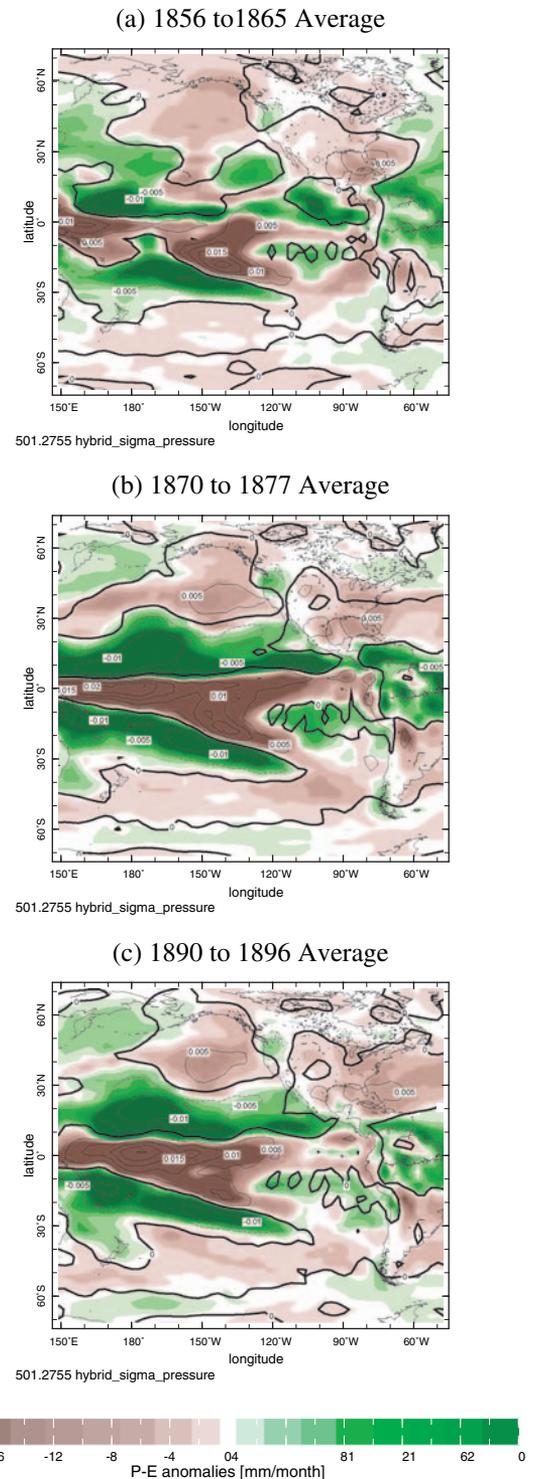
Two necessary ingredients for precipitation are a moisture source and upward motion. Anomalous drying occurs where there is low-level moisture divergence and/or anomalous subsidence. Here we analyse the anomalous precipitation ( $P$ ) minus evaporation ( $E$ ) during the Civil War drought period, a term equal to the vertically integrated atmospheric moisture convergence via the mean and eddy flow, and the anomalous vertical motion field at 500 mb.  $P - E$  is also equivalent to the sum of soil moisture tendency and drainage. As before, we focus on the December–May half year.

During the Civil War, 1870s and 1890s droughts  $P - E$  was reduced, indicative of anomalous moisture divergence, over large regions of the mid-latitudes, including the southern and interior USA. (Figure 7). The tropical Pacific  $P - E$  anomalies show a northward shift of the Intertropical Convergence Zone (ITCZ) in the 1870s and 1890s droughts, analogous to interannual La Niña conditions. Comparing Figures 6 and 7, the regions of anomalous descent are also those of reduced precipitation. Seager *et al.* (2004) argue that it is the anomalous subsidence that drives the anomalous precipitation. Both models show anomalous ascent in the Pacific Northwest consistent with the modelled (Figure 6) and observed (Figure 1b) wetness at the time. Only the GOGA model simulates anomalous ascent and, wetter than normal conditions, over the far Southeast, in agreement with the PDSI data for this time.

The anomalous descent in the North American region, which causes reduced precipitation, is closely related to the upper level highs. It is strongest on the eastern flanks of these highs where northerly upper tropospheric flow produces a tendency for sinking motion through Sverdrup balance. The anomalous highs extend to the surface and cold low-level advection on the eastern flanks will also induce descent. The match is nowhere near perfect, though, because anomalous momentum fluxes can also drive regional ascent and descent (see Seager *et al.*, 2004).

## An extrapolation exercise: La Niña and North American droughts of the last millennium

Here we present a simple statistical experiment to demonstrate the link between tropical Pacific SST and North American



**Figure 7** Modelled POGA-ML precipitation ( $P$ ) minus evaporation ( $E$ ) anomalies (colours) and 500 mb vertical velocity anomalies (contours) for the December through May half-year of the mid- to late-nineteenth century North American droughts: (a) 1856 to 1865 average, (b) 1870 to 1877 average and (c) 1890 to 1896 average.  $P - E$  units are in mm/month, vertical velocity is in Pa/s

drought over the last millennium. The modern-day relationship between instrumental NINO 3.4 and North American PDSI is used to extrapolate back to periods of the last millennium where windows of coral-reconstructed tropical Pacific SSTA exist. Cobb *et al.*'s (2003) coral oxygen isotopic records from the island of Palmyra in the east-central tropical Pacific are used. Palmyra corals are sensitive recorders of regional-scale ENSO activity, with the modern coral record from this site sharing 72% of its interannual variance with the NINO 3.4

index (Cobb *et al.*, 2003). A reconstructed NINO 3.4 timeseries is derived from the modern coral record at Palmyra. We perform a regression of the annual  $\delta^{18}\text{O}$  anomaly data on like averages of the Kaplan *et al.* (2003) NINO 3.4 data (NINO3.4<sub>mod</sub>) for the length of the modern coral record (1886 to 1998). A 30-yr high pass filter has been applied to the coral data ( $\delta^{18}_{\text{coral}}\text{O}$ ) to remove the apparent warming trend since the 1970s recorded by the modern coral but not mirrored to the same extent in the instrumental record. We use the linear model:

$$\delta^{18}_{\text{coral}}\text{O anomaly} = a\text{NINO3.4}_{\text{mod}} + \varepsilon \quad (1)$$

where  $a$  is constant and  $\varepsilon$  is the error in the relationship. The  $\delta^{18}\text{O}/\text{NINO}$  3.4 slope ( $a$ ) for the modern Palmyra coral is  $-0.13\%/^{\circ}\text{C}$  ( $p < 0.01$ ). The mean observational error ( $\sqrt{\langle \varepsilon^2 \rangle}$ ), where angled brackets denote time averaging, is equal to 0.01%. As formulated,  $\varepsilon$  represents the error in the NINO 3.4 reconstruction by means of  $\delta^{18}\text{O}$  due to proxy measurement and age model uncertainty, error in our assumption that coral vital effects are constant in time, and the error in the assumption that local seawater  $\delta^{18}\text{O}$  (ie, sea surface salinity, SSS) varies in concert with NINO 3.4. With regard to the latter, Cobb *et al.* (2003) show that on interannual timescales, SST exerts the dominant influence ( $\sim 75\%$ ) on coral  $\delta^{18}\text{O}$  at Palmyra, and that SST and SSS variability are tightly correlated on interannual timescales in directions that compound each other in the coral  $\delta^{18}\text{O}$  record.

Using this modern-day relationship between coral  $\delta^{18}\text{O}$  and NINO 3.4 we reconstruct NINO 3.4 from the fossil corals at Palmyra (NINO3.4<sub>rec</sub>). A further statistical relationship is established by regressing the normalized North American Drought Atlas tree-ring PDSI record (PDSI<sub>mod</sub>) onto the normalized coral reconstructed NINO 3.4 index for the length of the modern coral record (ie,  $\text{PDSI}_{\text{mod}}^{(x,y)} = a_2^{(x,y)}\text{NINO3.4}_{\text{mod}} + b^{(x,y)}$ ). A similar regression is performed using the POGA-ML modelled soil moisture anomalies in place of the PDSI. This regression will isolate the drought response directly related to the tropical Pacific part of the ENSO forcing. We then use these statistical relationships to estimate the past patterns of North American soil moisture or PDSI during periods when a coral reconstructed NINO 3.4 history exists (ie,  $\text{PDSI}_{\text{rec}}^{(x,y)} = a_2^{(x,y)}\text{NINO3.4}_{\text{rec}} + b^{(x,y)}$ ). The reconstructed normalized PDSI/soil moisture anomaly maps were subsequently multiplied by the variance of each data set to obtain realistic amplitude reconstructions. Finally, the North American drought atlas PDSI data of Cook and Krusic (2004) is used to verify whether this simple statistical model forced only by an index of ENSO variability can to first order reproduce the large-scale patterns of North American drought captured by the tree-ring data.

There are two underlying assumptions for this simple exercise: first, the tropical–mid-latitude ENSO teleconnection was the same in the past as in the present; second, the reconstruction of a NINO 3.4 history from the fossil corals demands the assumption that spatial patterns of ENSO have not changed significantly over the last 1000 years. With regard to the first point, it has been suggested that the pattern of the North American precipitation response to ENSO events has changed over time (Cole and Cook, 1998; Diaz *et al.*, 2001; and Cole *et al.*, 2002). This pattern is controlled by tropical forcing of extratropical circulation anomalies and could be altered by changes in the pattern of tropical convection or the mean atmospheric flow. We do not expect either to have changed enough to significantly alter the response patterns. The relationship between NINO 3.4 and the coral oxygen isotope values at Palmyra, an island on the fringe of the cold tongue

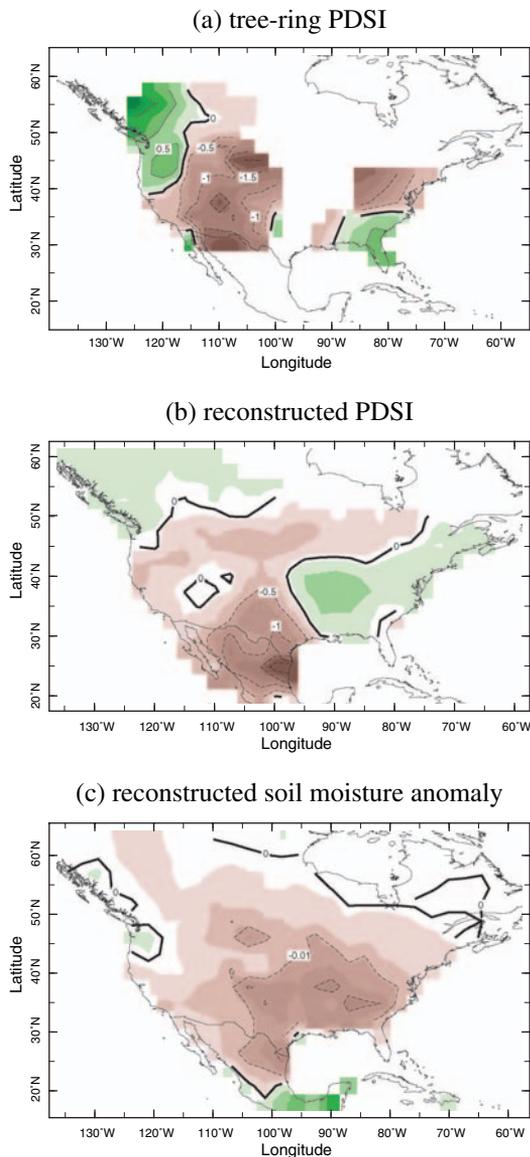
region, may also not have remained stationary while the mean climate changed, yet the sign of the relationship is unlikely to have reversed. Despite these limitations, this exercise provides us with a simple test of whether we can use the observed modern-day relationship between La Niña and North American drought to identify a tropical Pacific origin to the North American hydroclimate of the past millennium.

To first order, proxy-evidence from tree rings, lake levels, lake sediments, fire scars and aeolian depositional features point to a drier Plains and southwest between AD 800 and AD 1400 (Swetnam, 1993; Stine, 1994; Forman *et al.*, 1995; Muhs *et al.*, 1996; Dean, 1997; Laird *et al.*, 1996, 1998; Woodhouse and Overpeck, 1998; Fritz *et al.*, 2000; Forman *et al.*, 2001; Cook *et al.*, 2004; Yuan *et al.* 2004), and a wetter period in the ‘Little Ice Age’ (LIA) from AD 1400 until the 1800s (except for the major late-sixteenth century drought). The recent drought atlas PDSI data of Cook and Krusic (2004) give us our ‘best guess’ of the spatial pattern of drought at these times. Palmyra fossil coral records exist for windows of the tenth and twelfth century coincident with two of the driest epochs of the Mediaeval Climate Anomaly (MCA) in Western North America as identified by Cook *et al.* (2004). Following the method outlined above, widespread persistent drought from AD 934 to 944 is recreated from the reconstructed NINO 3.4 conditions at the time (Figure 8). Using the modern-day NINO 3.4–PDSI relationship, the pattern of North American drought is closest to that shown by the tree-rings: a ‘bipolar’ pattern with a dry west and southwest, and a wet eastern USA (Figure 8a and b). Regressing the POGA-ML modelled soil moisture anomaly data onto NINO 3.4 for the modern day (1886 to 1998) gives the more familiar one sign relationship between ENSO and North American hydroclimate, and thus is unable to recreate the bipolar nature of the AD 934–944 drought. A similar result is found for the 1167–1178 drought (Figure 9). The wettest epochs of the LIA in the western USA as defined by Cook *et al.* (2004) are similarly captured using this simple statistical approach (not shown).

It is possible that the PDSI–NINO 3.4 regression contains an element of surface moisture variability over North America that is fortuitously correlated with ENSO and appears in the regression pattern, but arises from other processes. North American monsoon variability produces a bipolar-like signature on interannual timescales (Higgins *et al.*, 1999; Higgins and Shi, 2001) and may be a contributing factor. Cole and Cook (1998) also identify the existence of such a bipolar ENSO–North American drought relationship in the instrumental and tree-ring PDSI record, and demonstrate the non-stationarity of the relationship since the late nineteenth century. This feature and its physical significance will be the subject of an ongoing investigation. Suffice to say that persistent La Niña-like conditions during the MCA appear implicated in the chronic drought in western North America at that time, but that other processes, possibly including the variability of the North American monsoon, are likely also involved.

## Conclusions

The USA experienced three major multiyear droughts during the latter half of the nineteenth century: 1856–1865, 1870–1877 and 1890–1896. Historical accounts, early instrumental data and an extensive network of gridded tree-ring data have been used to identify the existence, extent and severity of these events. In each case, drought stretched across the USA, with the severest conditions gripping the Plains and southwest for

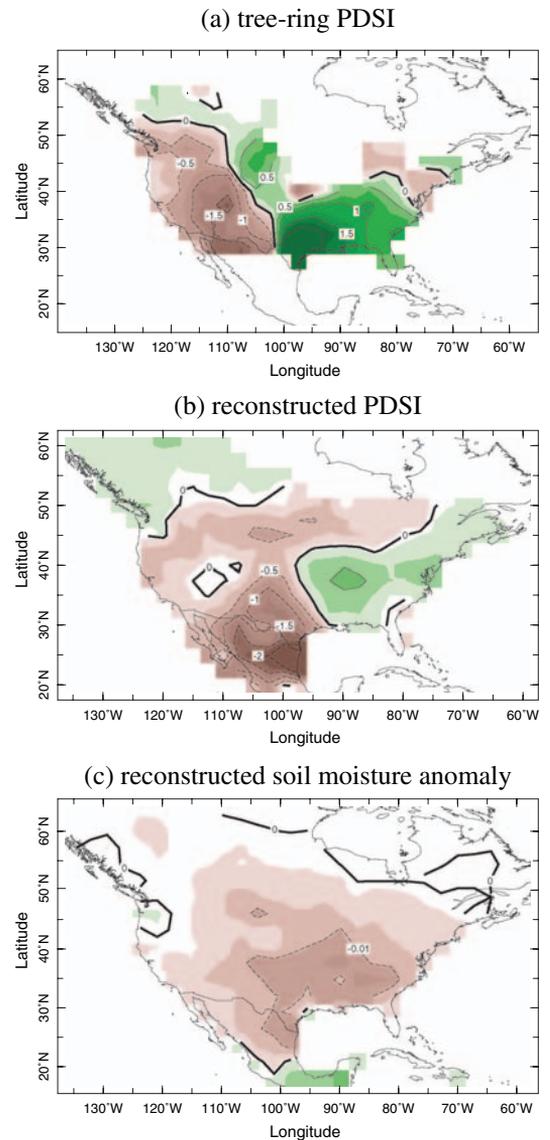


**Figure 8** The AD 934–944 drought: (a) tree-ring reconstructed summer PDSI from the North American Drought Atlas; (b) reconstructed PDSI using the fossil coral-derived NINO 3.4 history; (c) reconstructed top soil moisture anomaly using the coral derived NINO 3.4 history. PDSI and volumetric soil moisture are both unitless

many years at a time. Undoubtedly these events devastated the small, self-dependent and often isolated farming communities in the area at the time. The 1856–1865 ‘Civil War’ drought, in particular, is likely to have had a profound ecological and cultural impact on the interior USA, with the persistence and severity of drought conditions in the Plains surpassing those of the infamous 1930s Dust Bowl drought.

Concurrent with each of the major US droughts of the mid to late to nineteenth century, early instrumental and coral-derived proxy records show evidence for prolonged La Niña conditions. Model ensemble simulations forced with both global SSTs (GOGA) and tropical Pacific SSTs alone (POGA-ML) were both able to capture the long-term droughts over the USA since 1856.

Both the GOGA and the POGA-ML models do an impressive job at capturing the droughts of the mid- to late-nineteenth century, and the wetter spells between, when verified against gridded PDSI reconstructions from tree rings (Cook and Krusic, 2004). In agreement with the conclusions of Schubert *et al.* (2004) and Seager *et al.* (2005), the implication



**Figure 9** The AD 1167–1178 drought: (a) tree-ring reconstructed summer PDSI from the North American Drought Atlas; (b) reconstructed PDSI using the fossil coral-derived NINO 3.4 history; (c) reconstructed top soil moisture anomaly using the coral derived NINO 3.4 history. PDSI and volumetric soil moisture are both unitless

is that these widespread and persistent drought events are SST forced, primarily from the tropical Pacific. It is found that the correlation between modelled and observed soil moisture variability in the Plains region decreases from the nineteenth century to the twentieth century, indicative of drought conditions that are more SST forced in the earlier period. In the twentieth century, internal atmospheric variability and/or external forcing (ie, anthropogenic changes in land use and/or atmospheric composition or solar variability) had a larger influence on the drought variability in the Plains.

Drought conditions during the Civil War, 1870s and 1890s droughts were not restricted to the summer months, but existed year round, with a large signal in the winter and spring months when the tropical Pacific SST anomalies were strongest. In line with the notion of forcing from the tropics, a zonally and hemispherically symmetric pattern is observed. As explained by Seager *et al.* (2005), this pattern is a lower frequency realization of the interannual mechanism of subtropical jet, transient eddy, mean meridional circulation interaction that works throughout the year and promotes descent in

mid-latitudes when the tropical Pacific is cool. In addition, Rossby wave propagation from the cooler equatorial Pacific amplifies the dry conditions over the USA. A soil moisture-atmosphere feedback may allow drought conditions to persist into the summer months (Schubert *et al.*, 2004) but was not examined here.

Our results, as well as those of Schubert *et al.* (2004) and Seager *et al.* (2005), point to the central role of persistent forcing from an anomalously cool tropical Pacific in causing the major modern-day droughts in the USA. This suggests that knowledge of the variability of the tropical Pacific climate in the past may tell us something about the longer-term drought history of North America, an assumption that we test. A coral-derived SST record from Palmyra Island in the ENSO sensitive NINO 3.4 region (cf. Cobb *et al.*, 2003) is used to reconstruct a history of NINO 3.4 for several windows over the last millennium. Using the modern-day relationship between NINO 3.4 and surface moisture (PDSI or modelled soil moisture anomaly) over North America, we are able to recreate two of the severest Mediaeval 'drought epochs' in the western USA, as identified by Cook *et al.* (2004). In both instances, the large-scale features of the 'coral reconstructed' Mediaeval droughts are, albeit with some error, consistent with the tree-ring data from the North American Drought Atlas (Cook and Krusic, 2004). As such, we demonstrate the potential linkage between a colder eastern equatorial Pacific and persistent North American drought over the last 1000 years. With regard to the forcing that has led the tropical Pacific to become more La Niña-like or El-Niño like, it has been suggested that irradiance variations resulting from both solar and volcanic forcing may provide the key (Mann *et al.*, 2005). In this case, increased irradiance corresponds to a colder eastern equatorial Pacific and, by extension, increased drought occurrence in North America and other mid-latitude continental regions.

## Acknowledgements

We wish to thank Mark Cane and Yochanan Kushnir for useful discussions on this topic. Many thanks also to Naomi Naik for performing the model simulations, and also to Jennifer Velez and Alexey Kaplan. CH was supported by a NASA Earth Systems Science Fellowship NNG04GQ55H and NSF Grant ATM-0347009. RS was supported by NOAA Grant NAO30-AR4320179 and NSF Grant ATM-0347009. ERC was supported by NOAA CICAR Grant NAO30AR4320179. The model data for the GOGA and POGA-ML simulations can be found at: <http://kage.ideo.columbia.edu/expert/SOURCES/.LDEO/.ClimateGroup/.PROJECTS/.CCM3/>

## References

- Alexander, M.A., Blade, I., Newman, M., Lanzante, J.R., Lau, N. and Scott, J.D. 2002: The atmospheric bridge: the influence of ENSO teleconnections on air-sea interaction over the global ocean. *Journal of Climate* 15, 2205–231.
- Bark, L.D. 1978: History of American drought. In Rosenberg, N.J., editor, *North American droughts*. Westview Press, 9–23.
- Blasing, T.J. and Duvick, D.N. 1984: Reconstruction of precipitation history in North American corn belt using tree rings. *Nature* 307, 143–45.
- Blasing, T.J., Stahle, D.W. and Duvick, D.N. 1988: Tree ring-based reconstruction of annual precipitation in the south-central U.S. from 1750–1980. *Water Resource Bulletin* 24, 163–71.
- Bradley, R.S. 1976: *Precipitation history of the Rocky Mountain states*. Westview Press, 334 pp.
- Cobb, K.M., Charles, C.D., Cheng, H. and Edwards, R.L. 2003: El Niño/Southern Oscillation and tropical Pacific climate change during the last millennium. *Nature* 424, 271–76.
- Cole, J. and Cook, E.R. 1998: The changing relationship between ENSO variability and moisture balance in the continental United States. *Geophysical Research Letters* 25, 4529–32.
- Cole, J., Overpeck, J.T. and Cook, E.R. 2002: Multi-year La Niña events and persistent drought in the contiguous United States. *Geophysical Research Letters* 29, 1647–50.
- Cook, E.R. and Krusic, P.J. 2004: *North American summer PDSI reconstructions*. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2004-045. NOAA/NGDC Paleoclimatology Program.
- Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M. and Stahle, D.W. 2004: Long term aridity changes in the western United States. *Science* 306, 1015–18.
- Dai, A., Trenberth, K.E. and Qian, T. 2004: A global dataset of palmer drought severity index for 1870–2002: relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology* 5, 1117–130.
- 1992: A tree-ring reconstruction of New Mexico winter precipitation and its relation to El Niño/Southern Oscillation events. In Diaz, H.F. and Markgraf, V., editors, *El Niño: historical and paleoclimatic aspects of the Southern Oscillation*. Cambridge University Press, 243–57.
- Dean, W.E. 1997: Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: evidence from varved lake sediments. *Geology* 25, 331–34.
- Diaz, H., Hoerling, M.P. and Eischeid, J.K. 2001: ENSO variability, teleconnections and climate change. *International Journal of Climatology* 21, 1845–62.
- Forman, S.L. and Pierson, J. 2003: Formation of linear and parabolic dunes on the eastern Snake River Plain, Idaho in the nineteenth century. *Geomorphology* 56, 189–200.
- Forman, S.L., Oglesby, R., Markgraf, V. and Stafford, T. 1995: Paleoclimatic significance of late Quaternary eolian deposition on the Piedmont and High Plains, central United States. *Global and Planetary Change* 11, 35–55.
- Forman, S.L., Oglesby, R. and Webb, S. 2001: Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links. *Global and Planetary Change* 29, 1–29.
- Fritts, H.C. 1965: Tree-ring evidences for climatic changes in western North America. *Monthly Weather Review* 93, 421–43.
- 1983: Tree-ring dating and reconstructed variations in central Plains climate. *Transactions Nebraska Academy of Science* 11, 37–41.
- Fritz, S.C., Ito, E., Yu, Z., Laird, K.R. and Engstrom, D.R. 2000: Hydrologic variation in the Northern Great Plains during the last two millennia. *Quaternary Research* 53, 175–84.
- Fye, F.K., Stahle, D.W. and Cook, E.R. 2003: Paleoclimate analogs to twentieth century moisture regimes across the United States. *Bulletin of the American Meteorological Society* 84, 901–909.
- Hack, J.J., Kiehl, J.T. and Hurrell, J.W. 1998: The hydrologic and thermodynamic characteristics of the NCAR CCM3. *Journal of Climate* 11, 1179–206.
- Hardman, G. and Reil, O.E. 1936: *The relationship between tree-growth and stream runoff in the Truckee River basin, California-Nevada*. University of Nevada Agricultural Experiment Station Bulletin 141, 38 pp. (Available from Nevada Agricultural Experiment Station, University of Nevada, Reno NV 895570107.)
- Haston, L. and Michaelsen, J. 1997: Spatial and temporal variability of southern California precipitation over the last 400 years and relationships to atmospheric circulation patterns. *Journal of Climate* 10, 1836–52.
- Higgins, R.W. and Shi, W. 2001: Intercomparison of the principal modes of interannual and intraseasonal variability of the North American monsoon system. *Journal of Climate* 14, 403–17.
- Higgins, R.W., Chen, Y. and Douglas, A.V. 1999: Interannual variability of the North American warm season precipitation regime. *Journal of Climate* 12, 653–80.
- Hoerling, M.P. and Kumar, A. 2003: The perfect ocean for drought. *Science* 299, 691–99.

- Horel, J.D. and Wallace, J.M. 1981: Planetary scale atmospheric phenomena associated with the Southern Oscillation. *Monthly Weather Review* 109, 813–29.
- Hoskins, B. and Karoly, K. 1981: The steady response of a spherical atmosphere to thermal and orographic forcing. *Journal of the Atmospheric Sciences* 38, 1179–96.
- Huang, H.-P., Seager, R. and Kushnir, Y. 2005: The 1976/77 transition in precipitation over the Americas and the influence of tropical sea surface temperature. *Climate Dynamics* 24, 721–40.
- Hurrell, J.W., Hack, J.J., Boville, B.A., Williamson, D.L. and Kiehl, J.T. 1998: The dynamical simulation of the NCAR Community Climate Model Version3 (CCM3). *Journal of Climate* 11, 1207–36.
- Kaplan, A., Cane, M.A., Kushnir, Y., Clement, A.C., Blumenthal, M.B. and Rajagopalan, B. 1998: Analyses of global sea surface temperature: 1856–1991. *Journal of Geophysical Research* 103, 18567–89.
- Kaplan, A., Cane, M.A. and Kushnir, Y. 2003: Reduced space approach to the optimal analysis interpolation of historical marine observations: accomplishments, difficulties, and prospects. In *Advances in the applications of marine climatology: the dynamic part of the WMO guide to the applications of marine climatology*. WMO/TD-1081, World Meteorological Organization, 199–216.
- Kiehl, J.T., Hack, J.J., Bonan, G.B., Boville, B.A., Williamson, D.L. and Rasch, P.J. 1998: The National Center for Atmospheric Research Community climate model: CCM3. *Journal of Climate* 11, 1131–49.
- Laird, K.R., Fritz, S.C., Grimm, E.C. and Mueller, P.G. 1996: Century-scale paleoclimatic reconstruction from Moon Lake, a closed-basin lake in the northern Great Plains. *Limnology and Oceanography* 41, 890–902.
- Laird, K.R., Fritz, S.C. and Cumming, B.F. 1998: A diatom-based reconstruction of drought intensity, duration, and frequency from Moon Lake, North Dakota: a sub-decadal record of the last 2300 years. *Journal of Paleolimnology* 19, 161–79.
- Ludlum, D.M. 1971: *Weather record book*. Weatherwise, 98 pp.
- Mann, M.E., Cane, M.A., Zebiak, S.E. and Clement, A. 2005: Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *Journal of Climate* 18, 447–56.
- Meko, D. 1992: Spectral properties of tree-ring data in the United States Southwest as related to El Niño/Southern Oscillation. In Diaz, H.F. and Markgraf, V., editors, *El Niño: historical and paleoclimatic aspects of the Southern Oscillation*. Cambridge University Press, 349–75.
- Meko, D., Stockton, C.W. and Boggess, W.R. 1995: The tree-ring record of severe sustained drought. *Water Resource Bulletin* 31, 789–801.
- Mock, C.J. 1991: Drought and precipitation fluctuations in the Great Plains during the late nineteenth century. *Great Plains Research* 1, 26–56.
- Muhs, D.R. and Holliday, V.T. 1995: Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers. *Quaternary Research* 43, 198–208.
- Muhs D.R., Stafford, T.W., Cowherd, S.D., Mahan, S.A., Kihl, R., Maat, P.B., Bush, C.A. and Nehring, J. 1996: Origin of the late Quaternary dune fields of northeastern Colorado. *Geomorphology* 17, 129–149.
- Namias, J. 1991: Spring and summer 1988 drought over the contiguous United States – causes and prediction. *Journal of Climate* 4, 54–65.
- Oglesby, R.J. and Erickson, D.J. 1989: Soil moisture and the persistence of North American drought. *Journal of Climate* 2, 1362–80.
- Palmer, W.C. 1965: *Meteorological drought*. U.S. Department of Commerce Weather Bureau Research Paper 45, 58.
- Rayner, N., Parker, D., Horton, E., Folland, C., Alexander, L., Rowell, D., Kent, E. and Kaplan, A. 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research* 108, 10.1029/2002JD002670.
- Russell, G.L., Miller, J.R. and Tsang, L.-C. 1985: Seasonal oceanic heat transports computed from an atmospheric model. *Dynamics of Atmospheres and Oceans* 9, 253–71.
- Sardeshmukh, P.D. and Hoskins, B.J., 1988: The generation of global rotational flow by steady idealized tropical divergence. *Journal of the Atmospheric Sciences* 45, 1228–51.
- Schubert, S.D., Suarez, M.J., Region, P.J., Koster, R.D. and Bacmeister, J.T. 2004: Causes of long-term drought in the United States Great Plains. *Journal of Climate* 17, 485–503.
- Seager, R., Harnik, N., Kushnir, Y., Robinson, W. and Miller, J. 2003: Mechanisms of hemispherically symmetric climate variability. *Journal of Climate* 16, 2960–78.
- Seager, R., Harnik, N., Robinson, W.A., Kushnir, Y., Ting, M. and Huang, J.V.H.P. 2004: Mechanisms of ENSO-forcing of hemispherically symmetric precipitation variability. *Quarterly Journal of the Royal Meteorological Society* 131, 1501–27.
- Seager, R., Kushnir, Y., Herweijer, C., Naik, N. and Miller, J. 2005: Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000. *Journal of Climate* 18, 4068–91.
- Stahle, D.W. and Cleaveland, M.K. 1988: Texas drought history reconstructed and analyzed from 1698 to 1980. *Journal of Climate* 1, 59–74.
- Stahle, D.W., Cleaveland, M.K. and Hehr, J.G. 1985: A 450-year drought reconstruction for Arkansas, United States. *Nature* 316, 530–32.
- Stine, S. 1994: Extreme and persistent drought in California and Patagonia in medieval time. *Nature* 369, 546–49.
- Stockton, C.W. and Meko, D.M. 1975: A long-term history of drought occurrence in western United States as inferred from tree rings. *Weatherwise* 28, 244–49.
- 1983: Drought recurrence in the Great Plains as reconstructed from long-term tree-ring records. *Journal of Climate Applied Meteorology* 22, 17–29.
- Swetnam T.W. 1993: Fire history and climate change in giant sequoia groves. *Science* 262, 885–89.
- Trenberth, K. and Branstator, G.W. 1992: Issues in establishing causes of the 1988 drought over North America. *Journal of Climate* 5, 159–72.
- Trenberth, K. and Guillemot, C.J. 1996: Physical processes involved in the 1988 drought and 1993 floods in North America. *Journal of Climate* 9, 1288–98.
- Trenberth, K.E., Branstator, W.G. and Arkin, P.A. 1988: Origins of the 1988 North American drought. *Science* 242, 1640–45.
- Trenberth, K., Branstator, G.W., Karoly, D., Kumar, A., Lau, N. and Ropelewski, C. 1998: Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperature. *Journal of Geophysical Research* 103, 14 291–324.
- Wang, H. and Ting, M.-F. 2000: Covariabilities of winter US precipitation and Pacific sea surface temperatures. *Journal of Climate* 13, 3711–19.
- Webster, P.J. 1981: Mechanisms determining the atmospheric response to sea surface temperature anomalies. *Journal of the Atmospheric Sciences* 38, 554–71.
- Wilhite, D.A. 2000: Drought as a natural hazard: concepts and definitions. In Wilhite, D., editor, *Drought: a global assessment*. Routledge, Volume 1, 3–18.
- Woodhouse C.A. and Overpeck, J.T. 1998: 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* 79, 2693–714.
- Worster, D. 1985: *Rivers of empire: water, aridity and the growth of the American West*. Oxford University Press, 61–127.
- Yuan, F.B., Linsey, K., Lund, S.P. and McGeehin, J.P. 2004: A 1200 year record of hydrologic variability in the Sierra Nevada from sediments in Walker Lake, Nevada. *Geochemistry, Geophysics, Geosystems* 5, 1–13.
- Zeng, N., Neelin, J.D., Lau, K.-M. and Tucker, C.J. 1999: Enhancement of interdecadal climate variability in the Sahel by vegetation. *Science* 286, 1537–40.