The global footprint of persistent extra-tropical drought in the instrumental era

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ABSTRACT: The major North American droughts as per instrumental records are shown to be part of a larger, global pattern of low-frequency drought variability. Drought in western North America during the 1850s–1860s, 1870s, 1890s, 1930s and 1950s, is shown to coincide with the occurrence of prolonged dry spells in parts of Europe, southern South America and western Australia. Tropical land regions are mostly wet during these periods, with the exception of central east Africa, southern India and Sri Lanka, which are dry. The recent 1998–2003 period of drought in western North America reveals a similar global hydroclimatic ‘footprint’ with the exception of a wet southern South America and continued dry conditions in the Sahel. Common to each of the six droughts is the persistence of anomalously cool east central tropical Pacific sea surface temperatures (SSTs). For the 1998–2003 case, the warming of SSTs everywhere outside of the east central tropical Pacific may be influencing precipitation and masking the influence of persistent precipitation anomalies driven from the tropical Pacific alone. In general, examination of these major historical extra-tropical droughts reveals a hemispherically and, in the extra-tropics, a zonally symmetric pattern consistent with forcing from the Tropics.

1. Introduction

Multi-year droughts are a devastating, complex and staggeringly expensive natural hazard. In North America, the most severe multi-year droughts of the last 150 years were the ‘Civil War’ drought (1856–1865), the 1870s and 1890s droughts, the infamous Dust Bowl drought of the 1930s, the late 1940s–mid 1950s southwestern drought and the present-day drought that has gripped the western United States (Hoerling and Kumar, 2003; Fye et al., 2003; Herweijer et al., 2006; Seager et al., 2005a). In the southern part of South America, in a semi-arid area that encompasses the Andean foothills, the Sierra Cordoba and the Pampas in Argentina, along with Uruguay and southern Brazil, extended dry spells have also been noted in the 1930s and 1950s (Mechoso and Iribarren, 1992; Scian and Donnari, 1997; Robertson and Mechoso, 1998; Compagnucci et al., 2002), and inferred from tree-ring data in the 1860s and 1870s (Villalba et al., 1998). In addition, widespread drought conditions have been documented over much of central and eastern northern Europe during the 1860s (Hulme and Jones, 1994), 1890s, 1930s and the late 1940s/early 1950s (Briffa et al., 1994) and over the European part of the Former Soviet Union (FSU) during the 1890s and 1930s (Meshcherskaya and Blazhevich, 1997). Hoerling and Kumar (2003) noted that the most recent drought (which began in 1998) stretched from North America to Asia, but the in-phase relationship of global historical droughts with North American drought has, until now, been overlooked.

Much recent attention has been focussed on understanding the nature, extent and forcing of drought in the western United States (Hoerling and Kumar, 2003; Fye et al., 2004; Schubert et al., 2004a; Herweijer et al., 2005; Seager et al., 2005a). Cole et al. (2002) and Fye et al. (2004) noted that persistently cold tropical Pacific sea surface temperature (SST) anomalies have co-occurred with the major North American droughts since the mid-nineteenth century. It is well known that on interannual timescales, La Niña winters are characterized by reduced precipitation over much of the northern subtropics and mid-latitudes, particularly over western North
America (Trenberth and Branstator, 1992; Trenberth and Guillemot, 1996; Cole et al., 2002; Seager et al., 2005b). Recently, it has also been demonstrated that over longer timescales, a persistently cool tropical Pacific can provide the steady atmospheric forcing necessary for North American drought: each persistent North American drought since the 1850s has been simulated in an ensemble of climate model simulations forced by the observed history of tropical Pacific SSTs alone (Seager et al., 2005a; Herweijer et al., 2005; Huang et al., 2005). In the extratropics, alongside zonal asymmetries produced by Rossby wave propagation from the cooler equatorial Pacific, a zonally and hemispherically symmetric component to the forcing is observed. This pattern is a lower frequency realization of the subtropical jet – transient eddy – mean meridional circulation interaction mechanism (the Tropical Modulation of Mid-latitude Eddies, TMME, mechanism) that works throughout the year to promote eddy-driven descent in mid-latitudes when the tropical Pacific is cool (Seager et al., 2003, 2005a,b; Robinson, 2005). The existence of this mechanism suggests that drought over North America should appear as part of a larger, global pattern of mid-latitude drought. However, whether such a global pattern of persistent extra-tropical drought occurs in nature has thus far not been demonstrated.

Here we extend this recent work, which was largely focussed on North American drought, and examine the global hydroclimatic context of the major extra-tropical drought regimes (Here we use the dictionary definition of regime: ‘the characteristic behaviour or orderly procedure of a natural phenomenon or process’ (Webster’s Ninth New Collegiate Dictionary) and do not mean to imply a non-linear process) of the past 150 years. Using historical precipitation data, and proxy data for the earliest drought, we make the case that each of the famous North American dry events can be considered as part of a global, hemispherically symmetric hydroclimatic regime. To demonstrate the extent to which these hemispherically symmetric droughts are tropically forced, and to identify regions in which SSTs from outside the tropical Pacific play an important role, the two ensembles of simulations with an atmosphere general circulation model (AGCM) that have been previously analysed by the authors are further examined. The first ensemble forces an atmospheric model with observed SSTs everywhere; the second forces the atmosphere model only with tropical Pacific SSTs. We will show that the models simulate each of the major multi-year extra-tropical drought regimes since the mid-nineteenth century, including the observed coincident dryness in much of Europe and central Asia and western North America in the northern hemisphere, and southern South America in the southern hemisphere. The hydroclimatic regime throughout the global tropics includes wet conditions in the Sahel, and drought in central east Africa, features that are also captured by the models. Meanwhile, the coincident droughts in western Australia are less well captured by the models. Furthermore, we will demonstrate that this global hydroclimatic pattern is largely reproduced when the forcing is limited to the tropical Pacific region. We will also show that the spatial pattern of extreme and persistent drought is a low-frequency component of the large-scale climate variability associated with the El Niño southern oscillation (ENSO).

2. Synchronous large-scale extra-tropical droughts
2.1. Observed history
The global context of six well-known periods of severe and prolonged drought in North America is examined: the droughts of the 1850s–1860s, 1870s, 1890s, 1930s and 1950s (Fye et al., 2004) and the recent drought from 1998 to 2003 (The period since 1998 marks the most recent occurrence of multi-year drought in North America. Drought conditions returned to the Northern Rocky Mountains and the Pacific northwest as of Autumn 2005, but were interrupted in the central mid-west and the Pacific coast in early 2004 and late 2004 respectively. As such, we focus here on the 1998–2003 period of widespread drought in western North America).

2.1.1. SSTs
The average observed SST anomaly for each interval of persistent drought is shown in Figure 1. The SST data (Kaplan et al., 1998; Rayner et al., 2003) is that used to force the model experiments outlined in Section 2.2 (for details see Herweijer et al., 2005; Seager et al., 2005a). Each of the dry episodes coincides with the persistence of anomalously cool tropical Pacific SSTs. A cool Indian Ocean, typical of La Niña conditions, accompanies each drought with the notable exception of the most recent event. For the 1998–2003 period, SSTs everywhere outside of the tropical Pacific are anomalously warm, consistent with the global warming trend relative to the 1856–2004 mean. During the 1930s and 1950s droughts, while the tropical Pacific was cool, the north Atlantic Ocean was warm. Such a warm north Atlantic has been suggested to be important for simulating the Dust Bowl drought in several recent model studies (Schubert et al., 2004b; Sutton and Hodson, 2005). While that is possible, it is noteworthy that during the three nineteenth century droughts, the north Atlantic was not notably warmer than the Pacific.

2.1.2. Station precipitation data
Averages of the global precipitation anomaly from the Global Historical Climate Network (GHCN) data-set (described by Eischeid et al., 1991) for each of these drought events are shown in Figure 2. The station data is binned into boxes of four degrees of latitude and longitude and must be interpreted with caution in the mid-nineteenth century as data is scarce outside of Europe. The recent drought aside, persistent drought in North America is consistently accompanied by extra-tropical drought in the South American region encompassing north and central Argentina, Uruguay and
Figure 1. Observed SST anomalies during selected major North American drought regimes of the instrumental period. Temperature units are K. The SST field is that used in the GOGA ensemble mean. (N.B. The POGA-ML model is only forced by tropical Pacific SSTs between 20° N and 20° S). All anomalies are relative to the 1856–2004 mean.

There is a clear tendency for drought to occur over large parts of Europe at the same time there is drought in North America (Figure 2). In the 1998–2003 case, dry conditions are restricted to southern and central Europe. The 1930s are a clear exception, with most of Europe recording wetter than normal conditions. Australia tends to be dry in the west during these times and wet in the east, with the 1930s again being an exception when the entire continent was dry and the most recent pattern being indistinct. Tropical land regions including central America, tropical South America, north Africa including the Sahel (except for the recent drought), southern Africa, the maritime continent and eastern Australia (except for the 1930s) are mostly wet during these persistent mid-latitude dry spells. In contrast, equatorial east Africa (Tanzania, Kenya and Somalia), and the region encompassing southernmost India and Sri Lanka, are consistently dry during mid-latitude droughts. Precipitation over northeast Brazil is greatly influenced by both tropical Atlantic SSTs and tropical Pacific SSTs (Hastenrath and Heller, 1977; Moura and Shukla, 1981) and does not fall easily into the global pattern.

Apart from southern South America, the obvious difference between the global footprint of the most recent drought and its nineteenth and twentieth century predecessors is the Sahel. Precipitation here does respond to ENSO (Giannini et al., 2003), and the persistent La Niñas of the 1930s and 1950s could be responsible for wet conditions during this time, but there has also been a multidecadal drying since the middle of the century, that has been related to warming of the tropical oceans (Giannini et al., 2003). Consequently, the Sahel has been dry during the most recent mid-latitude drought regime, unlike during prior regimes.
For the entire instrumental period, precipitation reductions during the persistent drought regimes amount to approximately 10% of the mean annual precipitation, with slightly greater deficits of up to 20% in the southwest United States. While these percentage reductions are small they are persistent and sufficient to cause hydrological drought.

2.1.3. Historical and proxy data

Beyond North America, Europe and parts of the Indian subcontinent, the GHCN instrumental record for the late-to mid-nineteenth century droughts becomes increasingly sparse. The global footprint of these drought regimes can be reconstructed further using historical references and proxy indicators. For the southern South America region, evidence from tree-ring data (Villalba et al., 1998) and stream flow data (Preito et al., 1999) point to drier than normal conditions in the late 1850s to early 1860s, the 1870s and the early 1890s. To the north, tree ring records from the Amazonian floodplains indicate wetter than normal conditions at these times (Schoengart et al., 2004), while Allan and D’Arrigo (1999), as an extension to the study by Quinn (1993), register a lack of El Niño related northeast Brazil droughts or ‘Secas’ in the 1860s (Quinn and Neal, 1992). Drought in Europe, though fairly well represented by the GHCN data, is further

Figure 2. The observed Global Historical Climatological Network (GHCN) 4° x 4° gridded station data precipitation anomaly (mm/month) for selected major North American drought regimes of the instrumental period. All anomalies are relative to the 1856–2004 mean.
documented in the 1860s by Hulme and Jones (1994), by Casty et al. (2005) gridded precipitation reconstructions for the European Alps during the 1860s and 1890s, and by tree-ring reconstructions from the eastern Mediterranean during the late 1850s, the 1870s and the 1890s (Touchan et al., 2005). Each of the aforementioned reconstructions conforms to the global hydroclimatic pattern of the succeeding twentieth century drought regimes.

The proxy-derived hydroclimatic signature of the mid-to late-nineteenth century droughts on the African continent is more complicated. In North Africa, 1856–1865 is characterized by a mixed occurrence of low and high Nile River discharge levels (Riehl et al., 1979; Evans, 1990; Quinn, 1993), with the late 1850s marked by El Niño-related lowstands, which are absent in the early 1860s. The 1870s and early 1890s in the Nile records are more characteristic of a La Niña-like response, with both periods recording a consistent lack of El Niño-related lowstands (Quinn, 1993). Further south, historical accounts and lake level reconstructions from equatorial east Africa indicate lower water levels in the early-to mid-nineteenth century, followed by, in most cases, steadily rising levels in the following one to two decades (Sieger, 1887, 1888 (as referenced by Walsh and Musa, 1994); Owen and Crossley, 1989; Nicholson, 1998, 1999, 2001; Nicholson and Yin, 2001; Verschuren, 2001). However, the resolution and the complexity of interpreting these historical lake level records, hinders their interpretation on the multi-year timescales required here. In southern Africa, a region characteristically wet during most of the identified extra-tropical drought events, missionary documents from the Kalahari region (Endfield and Nash, 2002; Nash and Endfield, 2002), climate chronologies from the former Cape Province of South Africa (Lindesay and Vogel, 1990), and semi-quantitative southern African rainfall timeseries from Nicholson (2001) each indicate a dry late 1850s to early 1860s. Meanwhile, the 1870s and 1890s are both wet (Lindesay and Vogel, 1990; Nicholson, 2001), equivalent to a La Niña rainfall signal in this region. In summary, the historical and proxy evidence from northern and southern Africa display a mixed signal during the 1860s, whilst the 1870s and 1890s periods share the African hydroclimatic footprint of subsequent instrumental global drought regimes more convincingly.

The hemispherically symmetric nature of these drought regimes implicates the notion of forcing from the tropics, a hypothesis that we now test.

2.2. Unravelling the role of SST forcing: a modelling approach

2.2.1. Climate model simulations

The set-up of the model experiments is akin to several previous studies that have examined the cause and nature of drought in North America (cf Herweijer et al., 2005; Seager et al., 2005a). Here we extend that work by examining the global precipitation response to SST forcing. Two climate model experiments are employed: the first forces an AGCM with the observed history of SSTs everywhere from 1856 to 2004 (the Global Ocean Global Atmosphere, (GOGA), model), the second forces the AGCM only with tropical Pacific SSTs (between 20°N and 20°S), being coupled to a two-layer entraining mixed layer (ML) ocean elsewhere (the Pacific Ocean Global Atmosphere, POGA-ML, model). A 16-member ensemble was performed for each experiment. The SST data is a combination of that of Kaplan et al. (1998) and the HadISST global dataset (Rayner et al., 2003). Further details of these simulations can be found in Seager et al. (2005a) [see also Herweijer et al., 2005 and Huang et al., 2005]. The AGCM used is the National Center for Atmospheric Research (NCAR) Climate Community Model 3 (CCM3) described in detail by Kiehl et al. (1998). We focus on the ensemble mean of each experiment-the part of the climate variability that is SST forced.

2.2.2. POGA-ML model-data comparison

Figure 4 shows averages of the modelled precipitation anomalies from the POGA-ML model for the selected major North American drought regimes, as shown in Figure 2. With forcing only from the tropical Pacific surface ocean, the model is able to simulate much of the observed pattern of mid-latitude drought. Each period of modelled North American drought is accompanied by drought over much of Europe extending into central Asia (a region with limited observational coverage before the 1960s), and, with the notable exception of the recent period, drought in the South American region of north and central Argentina, Uruguay and southern Brazil. For the 1998–2003 period, the POGA-ML model correctly makes southern South America wet, in contrast to creating droughts during the five previous instrumental drought regimes. However, the spread in the ensembles over this period (not shown) is too large to conclude that the wetness in this region is forced by tropical Pacific SSTs. The POGA-ML model does less well in capturing the observed western Australian droughts. Wetter than
normal conditions are simulated in central America, the Sahel (except for the recent period, as explained in Section 2.1), south Africa, and the southern Mediterranean, as observed.

2.2.3. GOGA model-data comparison

Including the forcing from the global ocean generally gives a comparable picture (Figure 5). It is noted that for the 1998–2003 period, wet anomalies are more frequent than dry anomalies in most places—representative of the rather clear global mean global warming signal. As for the POGA-ML experiment, the western Australian droughts are poorly simulated. SSTs from outside the tropical Pacific are required to capture the droughts in equatorial east Africa, consistent with prior work on the impact of Indian Ocean SSTs (Goddard and Graham, 1999). Here, cooler SSTs and diminished convective heating in the west central Indian Ocean leads to anomalous moisture flux divergence and reduced rainfall over equatorial east Africa. These findings are consistent with ours, in that the observed central east African droughts are only captured when forcing from a cool west central Indian ocean is included (i.e. in the GOGA model, Figure 5). During the 1930s the Indian Ocean SST anomalies are muted, as is the corresponding east central African drought in both the model and in the observations. Similarly, during the 1998–2003 period the Indian Ocean, like all surface waters outside of the cool eastern tropical Pacific, is anomalously warm and the model does not produce a drought while the observed record was itself indistinct.
A potential flaw of the GOGA experiment concerns the impact of specified SSTs on annular mode variability, and the associated component of extra-tropical precipitation variability (e.g. Hurrell, 1995; Hurrell et al., 2003). Annular modes are internal atmospheric modes that drive extra-tropical SST anomalies (e.g. Seager et al., 2000; Visbeck et al., 2003). A long-standing question has been the extent to which anomalous extra-tropical SSTs feed back to affect the atmosphere (e.g. Rodwell et al., 1999; Robinson, 2000; Kushnir et al., 2002). It has been shown that AGCMs forced with observed SST anomalies can reproduce the annular mode behaviour that induced these extra-tropical SST anomalies (Rodwell et al., 1999). However, almost by construction, the surface flux anomalies are the wrong sign—i.e. out of the ocean in a region where the annular mode makes the SST warm and the flux should in reality be into the ocean. As such, it is unclear whether the atmospheric response represents a real response to the SST anomalies, or whether it is an artifact of the misrepresentation of the atmosphere-ocean coupling in the model (Barsugli and Battisti, 1998; Bretherton and Battisti, 2000), with the potential to introduce errors in the precipitation signal. If, as argued by Hoerling et al. (2001), annular mode variability is forced from the tropical oceans, the AGCM experiments presented here may be able to simulate the observed changes. On the other hand, if annular mode variability is driven primarily by internal atmospheric variability, or if it responds to external factors such as changing atmospheric trace gas composition (Shindell
et al., 1999) that we neglected in the model experiments, it is likely that there is a component of extra-tropical precipitation variability that the models will not capture.

The above factor is likely to be important over the European sector, where precipitation variability is strongly influenced by the North Atlantic oscillation (NAO) (Hurrell, 1995; Dai et al., 1997), and to a lesser extent by the remote tropical Pacific climate (Dai et al., 1997; Merkel and Latif, 2002; Seager et al., 2005b; Mariotti et al., 2005). A multivariate regression of the GHCN precipitation anomalies onto the 6-year low-pass filtered NAO index (Hurrell, 1995) and NINO3 index (Kaplan et al., 2003) highlights the relative impact of low-frequency NAO- and ENSO-related climate variability on this region (Figure 6). This is done for the months of December through March, from 1863 to 1995, corresponding to the NAO index of Hurrell (1996). The correlation between NAO variability and European precipitation is in general higher than for low-frequency ENSO variability (Figure 6(b) and (d)) which is decidedly weak.

Overall, approximately 20% of the low-frequency precipitation variability over Europe is explained by the combined influence of low-frequency ENSO- and NAO-related climate variability. During the mid- to late-1930s, (Hurrell, 1996) the winter NAO index was persistently negative, a factor that may explain the observed wet central and southern Europe at that time (Figure 2). The model does not faithfully reproduce the low-frequency variations of the NAO. As such, the European low-frequency precipitation in the model is ENSO-dominated and creates a spurious drought in the 1930s. Although the relationship between tropical Pacific SSTs and European rainfall is weak the model simulations quite consistently make parts of Europe dry during protracted La Niña-like states. In agreement, parts or nearly all of Europe were struck by drought in the 1850s, 1870s, 1890s and 1950s. The south European and Mediterranean drought

![Figure 6](image-url)

Figure 6. Multivariate regression of the observed GHCN 4° × 4° gridded station data precipitation anomaly onto the 6-year low-pass filtered: (a) NAO index (mm/month/mb); (c) NINO3 index (mm/month/K). Corresponding correlation coefficients are shown in (b) and (d). Correlation coefficients greater than or equal to 0.23 are significant at p < 0.2.
of the 1998–2003 period is reproduced by the models and was also likely forced from the tropics as suggested by Hoerling and Kumar (2003). The results add some support to the contention that, in addition to the NAO influence, and amidst considerable internal variability, there is a modest tropical Pacific SST influence on precipitation in this region (Mariotti et al., 2005).

The wetness of southern South America during the most recent mid-latitude drought regime is clearly very different to the global footprint of the five preceding major mid-latitude droughts since 1856. Liebmann et al. (2004) also note a recent positive trend in South American precipitation centred over southern Brazil, which they relate to a positive trend in SST in the nearby Atlantic Ocean, although not causally. The inability of the GOGA model to capture the observed southern South American wetness could potentially arise, as for the European sector, from the model’s inability to faithfully capture annular mode variability. The southern annular mode (SAM) is often defined as the leading mode of 700 mb heights south of 20°S and describes a basically zonal mean oscillation of mass between the mid-latitudes and the Polar ice cap together with associated changes in winds and temperature, and arises from interactions between transient eddies and the zonal mean flow (L’Heureux and Thompson, 2005, and references therein). As shown by L’Heureux and Thompson (2005), over the post-1979 period, the SAM during southern summer is highly correlated with the inverted index of SSTs in the eastern tropical Pacific Ocean i.e. La Niña conditions excite the positive phase of the SAM.

Figure 7(a) shows the Global Precipitation Climatology Project (GPCP) satellite and station data precipitation regressed on the SAM index, as defined above, using NCEP-NCAR Reanalysis data. This result confirms the link between SAM and ENSO in that the global pattern of precipitation associated with the SAM (Figure 7(a)) is essentially the same as that associated with La Niña.

Figure 7. (a) The monthly mean GPCP v2 satellite-gauge precipitation anomaly regressed onto the SAM index from January 1979 to December 2004. (b) The SAM index from 1998 to 2003.
Like La Niña, the SAM tends to make southern South America dry. In the 1998–2003 period, the SAM was positive (Figure 7(b)), consistent with the coincident La Niña. Therefore the SAM provides no explanatory power beyond ENSO and the wetness in southern South America in recent years must have other causes. For the record, the POGA-ML and GOGA models both reliably produce the post-1979 behaviour of the SAM during southern summer (not shown), confirming dominance of ENSO-forcing of the SAM.

2.2.4. Summary

In summary, the spurious drought in Europe in the 1930s, and the recent wetness in southern South America aside, the GOGA and POGA-ML models do an impressive job at capturing the large-scale footprint of the persistent drought regimes of the last 150 years. Each of the six droughts is marked by the persistence of anomalously cool east central tropical Pacific SSTs, despite differences in the SSTAs of the Indian Ocean, Atlantic Ocean and north Pacific Ocean. The similarity of the POGA-ML and GOGA models cements the contention that the component of persistent extra-tropical drought/wetness that is SST forced, is forced from the tropical Pacific—a La Niña-like tropical Pacific.

3. The low-frequency ENSO/mid-latitude drought signal

By regressing the GHCN precipitation data onto the six-year low-pass filtered NINO 3 (NINO 3 is an index that...
measures the strength of an ENSO event: it is the SST averaged over a region in the eastern equatorial Pacific (90°–150°W, 5°N–5°S) index (Kaplan et al., 2003) we can directly isolate the precipitation variability that arises as part of the low-frequency ENSO signal (Figure 8(a)). This is done for the months of December through May (the months of greatest NINO3 variability) from 1857 to 2004. The corresponding correlation coefficients are shown in Figure 8(b). Analogous figures of the 6-year high-pass filtered case, representative of interannual ENSO variability, are also shown (Figure 8(c) and (d)). For the high-pass filtered case, a correlation coefficient of 0.16 is required for significance at the 95% level. Low-pass filtering of the data necessitates a higher degree of correlation for statistical significance. The pattern of low-frequency ENSO-related precipitation variability is strikingly similar to the interannual case. On interannual timescales, a cold eastern tropical Pacific corresponds to a dry southwestern United States, southern South America (Uruguay, north and central Argentina and southern Brazil), central and eastern Europe, central western Asia, equatorial eastern Africa (Kenya, Tanzania and Somalia), southern India and Sri Lanka, and wet areas in southern Africa, Mediterranean north Africa, eastern Australia, northeast South America and parts of the eastern United States. Due to the limited length of the observational record, only the extra-tropical drought regions in the southwestern United States, southern South America and (marginally) parts of central Europe and central western Asia have correlation coefficients that qualify as statistically significant at the 80% level.

Whilst these correlations are low, the model simulations add weight to the argument that the tropical Pacific-extra-tropical precipitation relationships on multi-year timescales are real: the POGA-ML model produces a pattern of precipitation variations noticeably similar to that observed, but with statistically significant correlations across North America, Europe, Asia as well as in the southern hemisphere mid-latitudes (Figure 8(f)). Lower correlations between tropical Pacific SSTs and precipitation observations are expected because the observations are an incomplete record of a single realization and hence include both sampling error and a sizeable component due to internal atmospheric variability. In contrast, the model simulations near-perfectly isolate the SST-forced component and make clear that, amidst much precipitation variability generated by internal atmospheric variability, tropical Pacific SSTs do have a discernible impact on precipitation across the mid-latitudes.

On the basis of these arguments it seems fair to state that the large-scale relationships between regions of persistent extra-tropical drought/wetness outlined in Section 2, arise as part of a global response to low-frequency ENSO variability. A La Niña-like tropical Pacific on decadal timescales, causes mid-latitude drought in North and South America, as well as drought in much of central Europe, central east Africa, southern India and Sri Lanka, and parts of western Australia. Noticeably, low-frequency precipitation variability in the northeast Brazil region (Figure 2) does not always fit into this pattern of global hemispheric and zonal symmetry (Figure 8). Precipitation in this region is strongly influenced by the meridional gradient of tropical Atlantic SST (e.g. Servain, 1991; Uvo et al., 1998), which is in part controlled by ENSO variability but also has a local Atlantic origin (Saravanan and Chang, 2000; Pezzi and Cavallanti, 2001; Giannini et al., 2004). As both, ENSO and tropical Atlantic variability (TAV), add up to force precipitation anomalies in northeast Brazil, variability local to the tropical Atlantic can at times disrupt the hemispherically symmetric pattern.

4. Conclusions

Analysis of historical station precipitation data indicates that each major North American drought of the last 150 years appears as part of a larger, global pattern of low-frequency precipitation variability. There is a clear hemispherically and, in the extra-tropics, zonally symmetric component to this variability, such that when the tropical eastern Pacific and tropical troposphere are cooler than normal, much of the mid-latitudes are warm and dry. This feature is related to a low-frequency realization of the TMMw mechanism described in detail by Seager et al. (2003, 2005a,b). Zonal asymmetries arise due to Rossby wave propagation from the cooler tropical Pacific, which regionally enhance or diminish the tendency for mid-latitude drought (Seager et al., 2005b). That this global pattern of multi-year extra-tropical drought regimes occurs in nature is demonstrated here for the first time. In particular, regions of enhanced and in-phase extra-tropical drought include western North America and southern South America, each under the downstream influence of Rossby wave propagation from a colder than normal tropical Pacific. Other regions of in-phase drought include western Australia, parts of Europe, and central east Africa, whilst other tropical land regions tend to be wet.

Model ensemble simulations forced by observed SSTs, globally (GOGA), and only from within the tropical Pacific (POGA-ML), were both able to capture the large-scale footprint of the global drought regimes since 1856, including the hemispheric symmetry and the zonal symmetry in the extra-tropics. The implication is that, as demonstrated for the western North American sector (Schubert et al., 2004b; Herweijer et al., 2005; Seager et al., 2005a), the major extra-tropical droughts of this period are primarily forced by tropical Pacific SSTs. In particular, sustained La Niña-like conditions correspond to persistent drought in southern South America (Uruguay, southern Brazil and north and central Argentina), and much of Europe, as observed. Contemporary drought in western Australia also occurs in the observations, but is not captured by the model simulations. In agreement with the instrumental record, rainfall anomalies of the opposite sign occur over most of the tropics (i.e. in particular over tropical central and South
America, the Sahel) and over north Africa, and south Africa. Northeast Brazil, which is influenced by tropical Atlantic SSTs, and eastern Australia, both experience persistent precipitation anomalies but do not fit easily into this pattern, and neither model configurations reliably reproduce the precipitation histories in these regions.

During the most recent North American drought (shown here as 1998–2003), warming of all surface waters outside of the east central tropical Pacific appears to have interrupted this global pattern to some extent. In particular, the drought in North America is no longer mirrored in southern South America while the Sahel has remained dry. This aside, the global pattern of precipitation anomalies for the most recent drought is similar to that during the five prior droughts. The influence of the SAM is ruled out as an explanation for the wetness in southern South America. Rather, the precipitation response to the observed high polarity SAM index is shown to be similar to that of the cold phase of ENSO, both acting to make southern South America dry. A companion study to this one by Seager (2007), which focuses solely on the recent ‘turn-of-the-century drought’, leaves us with a similar conclusion that mid-latitude South America is wet during this recent period, for ‘unexplained reasons’.

Our findings imply that atmospheric circulation changes associated with decadal ENSO-like climate variability are largely responsible for inducing the long-term interhemispheric extra-tropical drought and wetness regimes of the instrumental record. There is a strong spatial similarity to the hydroclimatic response to interannual ENSO-like climatic variability. On the heels of this study, several relevant studies by the authors have been published.

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