The global footprint of persistent extra-tropical precipitation anomalies:

1856 - 2003

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Abstract

The major North American droughts and pluvials of the instrumental record are shown to be part of a larger, global pattern of low frequency precipitation 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. The opposite precipitation pattern occurs during the ‘wet’ 1990s. Examination of these major historical extratropical droughts/pluvials reveals a hemispherically and, in the extratropics, a zonally symmetric pattern consistent with forcing from the tropics.

Ensembles of model simulations forced by observed SSTs globally (GOGA) and only within the tropical Pacific (POGA-ML) were both able to capture the hemispheric and zonal symmetry of persistent extratropical drought/wetness regimes since 1856. This strongly suggests that these droughts/pluvials were SST forced, primarily by the persistence of cool/warm SST anomalies in the tropical Pacific. Indian Ocean SST forcing is required to capture the droughts in central-east Africa. Over Europe, the modeled low frequency precipitation signal is unrealistically ENSO dominated as the model does not faithfully reproduce the low frequency NAO variability. Overall, the global pattern of persistent precipitation anomalies appears to be a low frequency version of interannual ENSO-forced variability. Examination of the recent 1998 to 2003 period of drought in western North America reveals a similar global hydroclimatic ‘footprint’ with the exception of wet in southern South America and continued dry in the Sahel. In this 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.
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 West since 1998 (Woodhouse and Overpeck 1998; Fye et al. 2003; Cole et al. 2002; Seager et al. 2005b; Herweijer et al. 2005). 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 stretched from North America to Asia, but the in-phase relationship of historical droughts with North American drought has, until now, been overlooked.

Much recent attention has been focused on understanding the nature, extent and forcing of drought in the Western United States (Hoerling and Kumar 2003; Schubert et al. 2004a; Fye et al. 2004; Seager et al. 2005b; Herweijer et al. 2005). Persistently cold tropical Pacific sea surface temperature (SST) anomalies have co-occurred with each major North American drought since the mid nineteenth century (Cole et al. 2002, Fye et al. 2004; Seager et al. 2005b; Herweijer et al. 2005). 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. 2005a). 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. 2005b; Huang et al., 2005b; Herweijer 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, 2005b, Robinson 2005). The existence of this mechanism suggests that drought over North America appears as part of a larger, global pattern of mid-latitude drought. Conversely, multi-year wet regimes in North America are likely accompanied by wet conditions throughout much of the mid-latitudes.

Here we examine the global hydroclimatic context of the major North American moisture regimes\(^\dagger\) of the past 150 years. Using historical precipitation we make the case that each of these dry/wet events can be considered as part of a global, hemispherically symmetric hydroclimatic regime. To demonstrate the extent to which these hemispherically-symmetric droughts/pluvials are tropically-forced, two ensembles of simulations with an atmosphere general circulation model (AGCM) were generated: the first 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 North American droughts/pluvials since the mid nineteenth century along with the observed coincident dry/wet conditions in a number of subtropical and mid-latitude regions of the world, including much of Europe and central Asia in the northern hemisphere, and southern south America and western Australia in the southern hemisphere. Furthermore we will demonstrate that this pattern is largely captured when the forcing is limited to the tropical Pacific region. We will also show that the spatial pattern of extreme and persistent precipitation regimes is a low frequency component of the large-scale climate variability associated with the El Niño Southern Oscillation (ENSO). Finally, we will examine how similar and/or different the global context of the recent 1998 to 2003 North American drought is to its predecessors.

\(^\dagger\)Here we use the dictionary definition of *regime*: ‘the characteristic behavior or orderly procedure of a natural phenomenon or process’ (Webster’s Ninth New Collegiate Dictionary) and do not mean to imply a nonlinear process.
2 Synchronous large-scale extratropical droughts and pluvials

2.1 Observed History

The global context of six periods of severe and prolonged hydroclimate in North America is examined: the droughts of the 1850s-1860s, 1870s, 1890s, 1930s and 1950s, and the wet 1990s (Fye et al. 2004). The average observed SST anomaly for each interval of persistent drought/wetness is shown in Figure 1. The SST data (Rayner et al. 2003; Kaplan et al. 1998) is that used to force the model experiments outlined in Section 2.2 (for details see Seager et al. 2005b; Herweijer et al. 2005). Each of the dry/wet episodes coincides with the persistence of anomalously cool/warm tropical Pacific SSTs. A cool Indian Ocean, typical of La Niña conditions, accompanies all the droughts and a warm Indian Ocean accompanies the 1990s pluvial. During the 1930s and 1950s droughts, while the tropical Pacific was cool, the North Atlantic Ocean was warm which has been suggested in model studies as important for simulating the Dust Bowl drought (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 cool. (This is also true when the global mean warming trend is removed.)

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 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. Persistent drought in North America is consistently accompanied by extra-tropical drought in the South American region encompassing north and central Argentina, Uruguay and southern Brazil. This in phase relationship between low-frequency drought/wetness in the Americas is further highlighted by the high correlation ($r = 0.57$ at $p < 0.01$) between the 6yr low-pass filtered precipitation anomalies averaged over the southwestern United States ($25^\circ N - 35^\circ N; 95^\circ W - 120^\circ W$) and over Uruguay and the Pampas in Argentina ($35^\circ S - 45^\circ S; 50^\circ W - 65^\circ W$) since 1900 (Figure 3).

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). The 1930s are an exception. Western Australia also tends to be dry during these times, with the 1930s again being an exception. Tropical land regions including central
America, tropical South America, North Africa including the Sahel, 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. The opposite pattern - a dominantly wet extratropical moisture regime - is observed during the 1990s. Precipitation over North East 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.

In southern South America, Europe and East Africa the precipitation reductions amount to approximately 10% of the mean annual precipitation, with slightly greater deficits of up to 20% in the Southwest United States. Whilst these percentage reductions are small they are sufficient to cause hydrological drought.

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

### 2.2 Modeled History

We employ two climate model experiments: the first forces an atmosphere general circulation model (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-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. (2005b) [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.

Figure 4 shows averages of the modeled precipitation anomalies for the POGA-ML model as for 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 (or mid-latitude wetness during the 1990s). Each period of
modeled 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 drought in the South American region of north and central Argentina, Uruguay and southern Brazil. The POGA-ML model does less well in capturing the observed western Australian droughts. Wetter than normal conditions are simulated in tropical South America, the Sahel, South Africa, and the southern Mediterranean, as observed. The largescale precipitation pattern of the ‘wet’ 1990s is similarly captured, with the notable exception that the model produces drought over Australia that did not occur.

Including the forcing from the global ocean generally gives a comparable picture (Figure 5). 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 6). During the 1930s the Indian Ocean SST anomalies are muted, as is the corresponding east-central African drought in both the model and in Nature.

A potential flaw of the GOGA experiment concerns the impact of specified SSTs on annular mode variability, and the associated component of extratropical precipitation variability (e.g. Hurrell 1995; Hurrell 2003). Annular modes are internal atmospheric modes that drive extratropical SST anomalies (e.g. Seager et al. 2000; Visbeck et al. 2003). A long-standing question has been the extent to which anomalous extratropical 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 extratropical 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 (Barsugli and Battisti 1998; Bretherton and Battisti 2000). 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. 2005a, Mariotti et al. 2005). A multivariate regression of the GHCN precipitation anomalies onto the 6yr 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 December through March months 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 (Figures 6b and 6d) 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 the winter NAO index was persistently negative (Hurrell 1996), a factor that may explain the observed wet central and southern Europe (Figure 2). Similarly, the 1990s witnessed a persistently positive winter NAO index (Hurrell 1996) which explains the observed dryness in central and southern Europe, and wetness in northwestern Europe. 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 misses these NAO-related variations in the 1930s and 1990s. 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. This adds 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 (see also Mariotti et al. 2005).

The complication in Europe aside, the GOGA and POGA-ML models do an impressive job at capturing the largescale footprint of the persistent drought and wetness regimes of the last 150 years. Fur-
thermore, the similarity of the POGA-ML and GOGA models suggests that the component of persistent extra-tropical drought/wetness that is SST forced, is forced from the tropical Pacific - a La Niña-like or El Niño-like tropical Pacific.

3 The low frequency ENSO/mid-latitude drought signal

By regressing the GHCN precipitation data onto the 6yr low-pass filtered NINO 3‡ index (Kaplan et al. 2003) we can directly isolate the precipitation variability that arises as part of the low frequency ENSO signal (Figure 7a). This is done for the December through May months (the months of greatest NINO3 variability) from 1857 to 2004. The corresponding correlation coefficients are shown in Figure 7b. Analagous figures of the 6yr high pass filtered case, representative of interannual ENSO variability, are also shown (Figures 7c and 7d). 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. A correlation coefficient of 0.16 is required for significance at the 95% level. Low pass filtering the data necessitates a higher degree of correlation for statistical significance. Due to the limited length of the observational record, only the extratropical 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-extratropical 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 southern hemisphere mid-latitudes (Figure 7f). 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

‡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°W - 150°W, 5°N - 5°S)
both sampling error and a sizable 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 east Africa, southern India, Sri Lanka, and parts of western Australia. Noticeably, low frequency precipitation variability in the north-east Brazil region (Figure 2) does not always fit in to this pattern of global hemispheric and zonal symmetry (Figure 7). Precipitation in this region is strongly influenced by the meridional gradient of tropical Atlantic SST (e.g. Servain et al. 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 Cavalcanti 2001, Giannini et al. 2002). As both ENSO and tropical Atlantic variability (TAV) add up to force precipitation anomalies in north-east Brazil, variability local to the tropical Atlantic can at times disrupt the hemispherically symmetric pattern.

Correlating the low frequency (i.e. 6yr low pass filtered) precipitation variability in the southwestern United States (25°N-40°N; 95°W-120°W) with the low frequency precipitation variability over the rest of the world produces a near-identical pattern (Figure 8) to the low-frequency ENSO pattern (Figure 7d). However, over North America, regression on the southwest United States precipitation index produces the same sign precipitation anomalies across the U.S. whereas regression on low pass filtered NINO3 produces a north-south dipole. In general, the persistent droughts affected the entire U.S. Although the models, which capture the all U.S. pattern, indicate that the droughts are fundamentally forced from the tropical Pacific, this comparison suggests that, within the tropical Pacific Ocean, more than just the low frequency evolution of the equatorial east Pacific SSTs is responsible. This detail aside, the model results confirm that the ENSO phenomena play a fundamental role in forcing persistent extra-tropical droughts and pluvials.
4 The recent 1998 - 2003 drought

The period since 1998 marks the most recent occurrence of multi-year drought in North America. Drought conditions continue to persist in parts of the Northern Rocky Mountains and the Pacific Northwest today (summer 2005), but were interrupted in the central Midwest and the Pacific coast in early 2004 and late 2004 respectively. As such, we will focus on the 1998 to 2003 period of widespread drought in western North America. Does this event also look akin to the global hydroclimatic footprint of low frequency ENSO variability?

Figure 9 shows the observed SSTA, along with the observed and modeled precipitation anomalies averaged from 1998 to 2003. As for the earlier droughts, the east-central tropical Pacific is anomalously cool. Everywhere else, SSTs are anomalously warm consistent with the global warming trend relative to the 1856-2004 mean. Extra-tropical drought occurred in western North America and southern and central Europe, but unlike each of the preceding persistent droughts since the 1850s, southern South America was anomalously wet (see also Figure 3). Liebmann et al. (2004) also note a recent positive trend in South American precipitation centered over southern Brazil which they relate to a positive trend in SST in the nearby Atlantic Ocean, although not causally. Both the GOGA and the POGA-ML models correctly simulate a dry western North America and a dry southern Europe and central Asia. The GOGA model has a dry southern South America consistent with the expected hemispherically symmetric response to a La Niña-like tropical Pacific, yet inconsistent with Nature. In contrast, the POGA-ML model correctly makes southern South America wet during this period, 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 wetness of southern South America during the most recent mid-latitude drought regime is not explained by the behavior of the dominant mode of Southern Hemisphere atmosphere circulation, the Southern Annular Mode (SAM). The SAM is often defined as the leading mode of 700mb heights south of 20°S and describes a basically zonal mean oscillation of mass between the mid-latitudes and the polar 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 10a 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 10a) is essentially the same as that associated with La Niña (Figure 7a). Like La Niña, the SAM tends to make southern South America dry. In the 1998-2003 period the SAM was positive (Figure 10b), 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 behavior of the SAM during southern summer (not shown), confirming dominance of ENSO-forcing of the SAM.

The other obvious difference between the global footprint of the most recent drought and its 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 is 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.

In summary, southern South America and the Sahel aside, the most recent 1998 through 2003 drought pattern displays a similar global footprint to the five preceeding major mid-latitude droughts of the instrumental era. 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.

5 Conclusion

Analysis of historical station precipitation data indicates that each major North American drought and pluvial of the last 150yrs appears as part of a larger, global pattern of low frequency precipitation variability. There is a clear hemispherically and, in the extratropics, zonally symmetric component to this variability, such that when the tropical eastern Pacific and tropical troposphere are cooler than normal, much
of the midlatitudes are warm and dry. This feature is related to a low frequency realization of the TMME mechanism described in detail by Seager et al. (2003, 2005a, 2005b). During persistent La Niña-like conditions, the subtropical jets weaken and move poleward, alter the meridional and vertical propagation of transient eddies and cause an anomalous eddy-driven mean meridional circulation (MMC) that results in a tendency for descent and drying at all longitudes of the mid latitudes. Zonal asymmetries arise due to Rossby wave propagation from the cooler tropical Pacific, which regionally enhance or diminish the tendency for mid-latitude drought. In particular, regions of enhanced and in-phase extratropical drought include western North America and southern South America, each under the downstream influence of Rossby wave propagation from the tropical Pacific. The opposite response - contemporaneous multi-year wet episodes - occur in these extratropical regions when El Niño-like conditions persist.

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 features of persistent mid-latitude drought/wetness since 1856 including the hemispheric symmetry and the zonal symmetry in the extratropics. The implication is that, as demonstrated for the western North American sector (Schubert et al. 2004; Seager et al. 2005b; Herweijer et al. 2005), the major extratropical droughts/pluvials of this period are primarily forced by tropical Pacific SSTs. In particular, sustained La Niña-like/El Niño-like conditions correspond to persistent drought/wetness in western North America, southern South America (Uruguay, southern Brazil and north and central Argentina), and much of Europe, as observed. Contemporaneous drought/wetness in western Australia also occurs in Nature, 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 South America, the Sahel) and over North Africa, and South Africa. North-east 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 (1998 to 2003), warming of all surface waters outside of the east-central tropical Pacific appears to have interrupted this global pattern. In particular, the drought in North America is no longer mirrored in southern south America while the Sahel has remained dry. In these cases the persistent extratropical precipitation anomalies cannot be explained by the persistent La
Niña-like state during 1998 and 2002. 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.

Our findings imply that atmospheric circulation changes associated with decadal ENSO-like climate variability are largely responsible for inducing the long term interhemispheric extratropical drought and wetness regimes of the instrumental record. There is a strong spatial similarity to the hydroclimatic response to interannual ENSO-like climatic variability. With regard to climatic implications for the greenhouse future, were the tropical Pacific to become more La Niña-like (Cane 2005), persistent drought is likely to become increasingly widespread across the extratropical regions sensitive to tropical Pacific SST variability (in particular western North America, southern South America and central and eastern Northern Europe). In today’s globalized economy, such coordinated drought in several agriculturally productive regions of the world could have a profound social and economic impact.

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Regression onto Dec-Mar NAO index

Regression onto Dec-Mar NINO3 index

Figure 6: Multivariate regression of the observed GHCN 4°x4° gridded station data precipitation anomaly onto the 6yr 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.
a. GHCN 6yr low pass filtered  

b. Correlation  

c. GHCN 6yr high pass filtered  

d. Correlation  

e. POGA-ML 6yr low pass filtered  

f. Correlation  

Figure 7: The Dec-May GHCN precipitation anomaly regressed onto the (a) 6yr low-pass, or (c) 6yr high pass filtered Kaplan NINO 3 index. The corresponding correlation coefficients are shown in panels (b) and (d). The Dec-May POGA-ML precipitation anomaly regressed onto the low pass filtered Kaplan NINO 3 index (e) and the respective correlation coefficients (f). Each calculated over the period from 1857 to 2004.
Figure 8: The correlation between the 6yr low-pass filtered GHCN precipitation data averaged over the southwestern United States (25°N - 40°N; 95°W - 120°W) and the rest of the world. Refers to the period from 1900-2004.
Figure 9: The 1998-2003 event: observed SST anomalies (top left); observed GHCN precipitation anomalies (top right); modeled precipitation anomalies. SSTA in units of K, and precipitation anomalies in units of mm/month. All anomalies are relative to the 1856 to 2004 mean.
a. GPCP Regression onto SAM index post 1979

Figure 10: (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.