Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the Great Plains

Sumant Nigam,[1] Bin Guan,[2] and Alfredo Ruiz-Barradas[1]

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[1] The Great Plains of North America are susceptible to multi-year droughts, such as the 1930s ‘Dust Bowl’. The droughts have been linked to SST variability in the Pacific and Atlantic basins. This observationally rooted analysis shows the SST influence in multi-year droughts and wet episodes over the Great Plains to be significantly more extensive than previously indicated. The remarkable statistical reconstruction of the major hydroclimate episodes attests to the extent of the SST influence in nature, and facilitated evaluation of the basin contributions. We find the Atlantic SSTs to be especially influential in forcing multi-year droughts; often, more than the Pacific ones. The Atlantic Multidecadal Oscillation (AMO), in particular, contributed the most in two of the four reconstructed episodes (Dust Bowl Spring, 1980s fall wetness), accounting for almost half the precipitation signal in each case. The AMO influence on continental precipitation was provided circulation context from analysis of NOAA’s 20th Century Atmospheric Reanalysis. A hypothesis for how the AMO atmospheric circulation anomalies are generated from AMO SSTs is proposed to advance discussion of the influence pathways of the mid-to-high latitude SST anomalies. Our analysis suggests that the La Nina–US Drought paradigm, operative on interannual time scales, has been conferred excessive relevance on decadal time scales in the recent literature. **Citation:** Nigam, S., B. Guan, and A. Ruiz-Barradas (2011), Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the Great Plains, *Geophys. Res. Lett.*, *38*, L16713, doi:10.1029/2011GL048650.

1. Introduction

[2] Sea surface temperatures (SST) exert a significant, and often predictable, influence on climate. Interannual SST variations related to El Nino Southern Oscillation, for instance, impact the Indian summer monsoon to the west [*Rasmussen and Carpenter*, 1983] and the North American hydroclimate to the east [e.g., *Joseph and Nigam*, 2006]. The link between SST and hydroclimate is also manifest on decadal time scales, as in case of droughts. Multi-year droughts such as the 1930s ‘Dust Bowl’ over the Great Plains mark notable excursions of regional hydroclimate, with devastating socio-economic impacts. Multi-year, summertime droughts over North America have been observationally linked to decadal SST variability in the Pacific [*Ting and Wang*, 1997; *Nigam et al.*, 1999; *Barlow et al.*, 2001; *McCabe et al.*, 2004; *White et al.*, 2008] and the Atlantic [*Namias*, 1966; *McCabe et al.*, 2004; *Ruiz-Barradas and Nigam*, 2005; *Wang et al.*, 2006; *Guan*, 2008; *McCabe et al.*, 2008; *Mo et al.*, 2009] but the extent of the SST influence in major 20th century droughts (including basin contributions) remains unevaluated, both statistically and dynamically.

[3] Great Plains droughts are typically simulated using dynamical models of the atmosphere [*Schubert et al.*, 2004; *Seager et al.*, 2005; *Sutton and Hodson*, 2005; *Cook et al.*, 2009; *Schubert et al.*, 2009] which reproduce many aspects of the atmospheric circulation but the simulation of regional hydroclimate (precipitation, evaporation, surface air temperature, etc.) remains challenging [*Ruiz-Barradas and Nigam*, 2005; *Nigam and Ruiz-Barradas*, 2006]. Droughts are more strongly linked with the Pacific than Atlantic SST anomalies in the simulations [e.g., *Schubert et al.*, 2004, Figure 3]; the Pacific influence resulting, largely, from the tropical SST anomalies [*Schubert et al.*, 2004; *Seager et al.*, 2005]. The coordinated modeling experiments of the US CLIVAR Drought Working Group [*Schubert et al.*, 2009] reiterate the primacy of Pacific SSTs in generating North American droughts. The La Nina–US Drought paradigm, operative on interannual timescales, was again found most relevant in context of decadal droughts by these modeling experiments.

[4] In this observationally rooted analysis, we find Atlantic SSTs to play a dominant role in the reconstruction of multi-year droughts and wet episodes over North America – in contrast with the secondary role of this basin in model-based assessments. We show the singular influence of the Atlantic Multidecadal Oscillation (AMO) on 20th century North American hydroclimate, especially during spring and fall (section 3), and propose a mechanism for this influence (section 4). Data sets and the analysis technique are briefly discussed in section 2.

2. Data Sets and Analysis Technique

[5] The SST data comes from the U.K. Met Office’s Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST 1.1) [*Rayner et al.*, 2003]. Precipitation data is from University of East Anglia’s Climate Research Unit (CRU): the high resolution TS3.0 analysis of station data [*Mitchell and Jones*, 2005]. Upper-air meteorological analysis for the full century was obtained from NOAA’s 20th Century Reanalysis (20CR) [*Compo et al.*, 2011], which was developed from short-term forecasts generated from assimilation of synoptic surface/sea-level pressure and monthly SST and sea-ice boundary conditions. The modern period upper-air data comes from NOAA’s NCEP Reanalysis [*Kalnay et al.*, 1996].

[6] The drought reconstruction reported here is rooted in the recent innovative analysis of natural variability and secular trend in the Pacific (and Atlantic) SSTs in the 20th century [*Guan and Nigam*, 2008, hereinafter GN2008]. By

[1]Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA.
[2]Climate Physics Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

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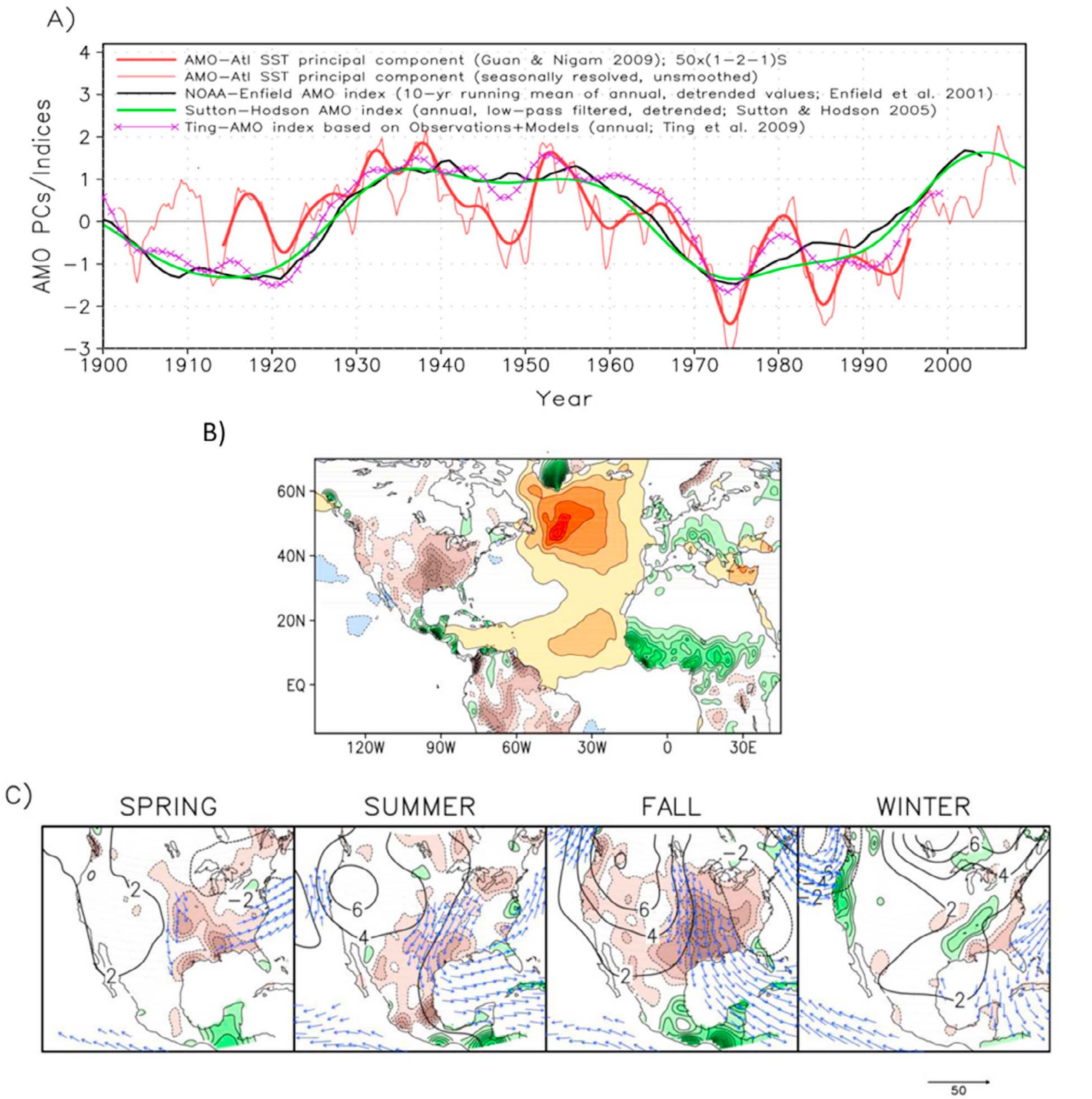

Figure 1. (a) Atlantic Multidecadal Oscillation SST principal component (AMO-*Atl* PC, red) is compared with other AMO indices: NOAA-Enfield (black); Sutton-Hodson (green); and *Ting et al.*'s [2009] index (purple-x). The notable 1970s decadal pulse in the AMO-*Atl* PC is coincident with the Great Salinity Anomaly (see text). The smoothed PC (thick red) is obtained from 50 applications of the 1-2-1 smoother on seasonally-resolved values (thin red); all indices are normalized over the January 1900 – April 2009 period. Smoothed index correlations: (Red, Black) = 0.65; (Red, Green) = 0.69; (Red, Purple) = 0.78. (b) All-season regressions of the smoothed AMO-*Atl* PC on *residual* Atlantic SSTs (see text for definition) are shaded blue-to-red while its *fall*-season regressions on precipitation are shown in brown-to-green colors. SST is contoured at 0.1 C interval and precipitation is shaded/contoured at 0.075 mm/day. (c) AMO's impact on North American *seasonal* hydroclimate: Regressions of smoothed AMO-*Atl* PC on precipitation, and NOAA-20CR's 700 hPa geopotential and surface-300 hPa column stationary moisture flux. Precipitation is plotted as above, height is contoured at 2 m, and the column moisture flux is in blue vectors with the indicated scale (in kg $m^{-1}s^{-1}$), and with values less than 15% of the scale not plotted; zero contours are omitted in all panels. All regressions are for the April 1914 – July 1995 period, the interval over which the thick red curve (Figure 1a) is defined. To preclude aliasing of the nonstationary SST Secular Trend PC in the regressions, its signal in seasonal data was removed prior to regression analysis; smoothing of the AMO-*Atl* PC alters the orthonormal property of the SST PCs, necessitating this preemptive measure.

Table 1. Percentage Contribution of the Pacific and Atlantic SST Principal Components to Great Plains Droughts and Wet Episodes[a]

Hydroclimate Episodes	Canonical ENSO ($ENSO^-$ + $ENSO^+$)	ENSO Non-Canonical ($ENSO^{NC}$)	North Pacific Decadal Var. (PDV^{NP})	SST Secular Trend (Non-stationary)	Atlantic Multidecadal Oscillation (AMO-*Atl*)	Atlantic Nino ($Nino^-$ + $Nino^+$)	Total (From 11 modes)
Dust Bowl Drought (Spring 1931–1939; deficit 0.253)	8			26	**55**	12	92
Dust Bowl Drought (Summer 1931–1939; deficit 0.291)		9		22	12	**31**	82
1950s Drought (Fall 1953–1956; deficit 0.626)	23		**29**		24		78
1980s Wet Period (Fall 1982–1986; surplus 0.687)	14		19		**37**		75

[a]Principal components are defined and displayed by GN2008 and GN2009. Contributions are noted when the reconstructed signal is ≥10% of the observed precipitation anomaly (in mm/day) in the 20° latitude-longitude box (103–83W, 30–50N) covering ~4 million km^2 and outlined in red in Figure 2a (top).

focusing on spatial *and* temporal recurrence, the extended empirical orthogonal function analysis discriminates between interannual and decadal-multidecadal variability, and the non-stationary secular trend – all without any advance filtering (and potential aliasing) of the SST record. The Atlantic SSTs were similarly analyzed but after excluding the influence of Pacific SSTs and the SST secular trend on the Atlantic basin [*Guan and Nigam*, 2009, hereinafter GN2009]. This influence was estimated by multiplying the time-dependent Pacific SST principal components (PCs; including the SST secular trend) with their regressions on contemporaneous Atlantic SST in the full record (1900–2009).

3. Atlantic Multidecadal Oscillation and Its Hydroclimate Impact

3.1. Spatiotemporal Structure

[7] The leading mode of Atlantic SST variability is a multidecadal oscillation focused in the extratropical basin (AMO-*Atl*; GN2009). It differs from its conventional description [*Enfield et al.*, 2001; *Enfield and Cid-Serrano*, 2010] in the western tropical basin where the amplitude is weaker due to the absence of the Pacific's influence (see Figure 5b of GN2009). The seasonally-resolved AMO-*Atl* PC is shown in Figure 1a (thin red) along with other markers of this variability, including a recent one from *Ting et al.* [2009]. Negative decadal pulses reflecting massive discharge of sub-Arctic water into the North Atlantic, as during the Great Salinity Anomaly of 1968–82 [e.g., *Slonosky et al.*, 1997], are evident in the AMO-*Atl* PC (and to an extent in the Ting index) but not in other AMO markers; AMO-*Atl* differs from others in the 1940s–50s too.

[8] The AMO-*Atl*'s SST footprint (Figure 1b) is focused in the northern basin, in the subpolar gyre. The same-sign extension into the Tropics develops a little after the northern lobe attains significant amplitude; AMO evolution is shown by GN2009. The fall-season regressions on land precipitation (Figure 1b) show a general drying over the Americas (except southern Mexico and Central America) but wetter conditions to the east (notably over Sahel). Given AMO's decadal time scales, its warm phase can lead to multi-year droughts over central-eastern United States.

3.2. Seasonal Precipitation Footprints

[9] AMO's impact on North American seasonal precipitation (Figure 1c) is significant in summer and the transitional seasons, with the fall impact being largest (0.4–0.5 mm/day per unit PC amplitude). The AMO's warm phase is associated with precipitation deficits in all three seasons; the absence of offsetting surpluses (or seasonal compensation) makes AMO even more relevant for North American droughts. The overlaid regressions of the 700 hPa geopotential and column stationary moisture flux (from a data set completely independent of CRU precipitation) indicate a strikingly consistent circulation context for the precipitation signal: low-level northerly flow across the central continent and related southward moisture transport. The flow opposes the seasonal southerly flow (including the Great Plains low-level jet in spring) which brings moisture from the Gulf of Mexico into the continental interior [e.g., *Nigam and Ruiz-Barradas*, 2006]. The AMO circulation leads to a precipitation deficit both from reduced moisture transport and the low-level subsidence generated by northerly anomalies [assuming $\beta v \approx f(\partial w/\partial z)$].

[10] The statistical significance of the regressions is assessed via a two-tailed Student's *t*-test at the 5% level using an effective sample size *Ne* ($=N/(1 + 2r_{x,1}r_{y,1} + 2r_{x,2}r_{y,2} + \ldots)$, where *N* is time-series length; $r_{x,1}$, $r_{x,2}\ldots$ are the first, second, …-order autocorrelations for time series *x*, and $r_{y,1}$, $r_{y,2}\ldots$ for time series *y* [*Quenouille*, 1952]) that accounts for serial autocorrelation; stable *Ne* (and thus *t*-test) values are obtained by summing up to the 4th-order. Figures 1b and 1c show regressions where *t*-values (obtained with *Ne*) exceed the theoretical values at the 5% significance level.

3.3. Contribution to 20th Century Droughts and Wet Periods

[11] The observed precipitation deficit during the Dust Bowl (1931–39) and 1950s droughts, and the excess during 1980s are shown in Figure 2a (top). The anomalies are large (often greater than 0.6 mm/day) and coherent, exhibiting subcontinental scale structure. The drought reconstruction is based on linear, seasonal regressions of the SST PCs (7 Pacific, 4 Atlantic) on precipitation in the full record (October 1901 – April 2006). Multiplication of each SST PC with its 'fixed' seasonal precipitation regression pattern, and summing the 11 contributions yields the drought and wetness signals (Figure 2a, middle). A similar strategy was recently used to reconstruct tropical cyclone counts in the Atlantic sector [*Nigam and Guan*, 2010].

[12] The SST-based precipitation reconstruction is remarkable as evident from the close correspondence of the observed and reconstructed structure at both regional and subcontinental scales. The amplitude correspondence is more limited,

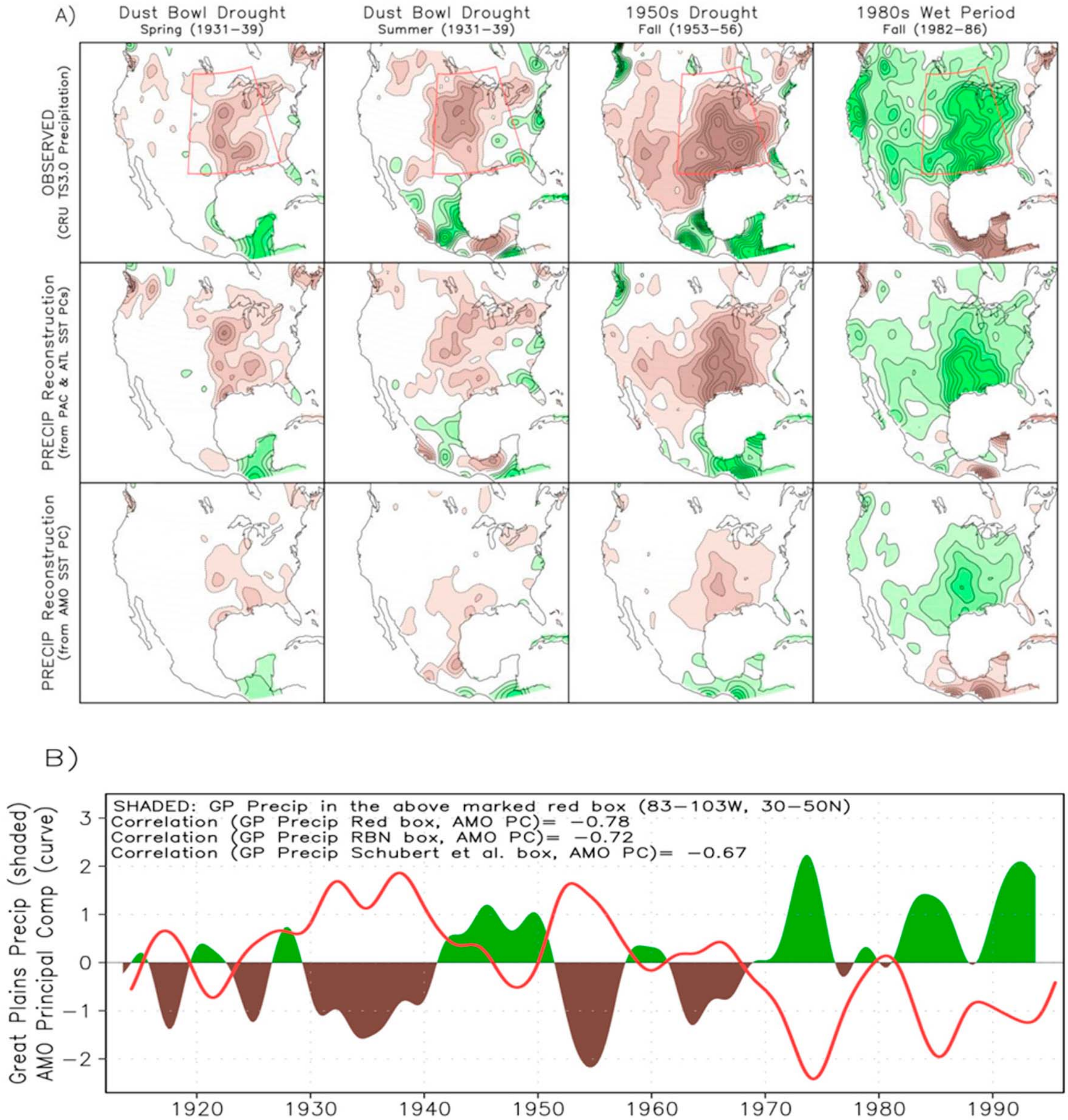

Figure 2. (a) (top) Observed and (middle) reconstructed 20th century Great Plains droughts and wet episodes. Seasonal precipitation regressions of the 7 Pacific and 4 Atlantic SST principal components over the October 1901 – April 2006 period constitute the building blocks of the Dust Bowl (1931–39) spring and summer droughts (first and second column), 1953–56 fall drought (third column), and the 1982–86 fall wet episode (fourth column). (bottom) The AMO-*Atl* contribution to the reconstruction. Contouring, shading, and smoothing of precipitation as in Figure 2, except for the twice as large interval (0.15 mm/day). The 20° wide latitude-longitude box marked in red in the top panels identifies a common impacted region. (b) Average precipitation in the marked red box is plotted along with the AMO-*Atl* SST principal component; both time series are smoothed by 50 applications of the 1-2-1 smoother on seasonal values, and normalized. The AMO-*Atl* curve is identical to that displayed in Figure 1a, and is correlated with the precipitation curve at −0.78; its correlation with other precipitation averages is noted in the legend. RBN box: 100–90W, 35–45N [*Ruiz-Barradas and Nigam*, 2005]; Schubert et al. box: 105–95W, 30–50N [*Schubert et al.*, 2004].

consistent with the potential contribution of other processes, notably, regional and upstream land-surface states and attendant interactions. The AMO contribution itself is shown in Figure 2a (bottom) and is sizeable in the spring and fall episodes. Other significant SST contributions are noted in Table 1: AMO-*Atl* is dominant in Dust Bowl spring and in the 1980s wetness, accounting for 55% and 37% of the observed anomalies, respectively, in the central-eastern continent (~4 million km^2 region outlined in red in Figure 2a (top)). Interestingly, Atlantic Nino contributes the most (31%)

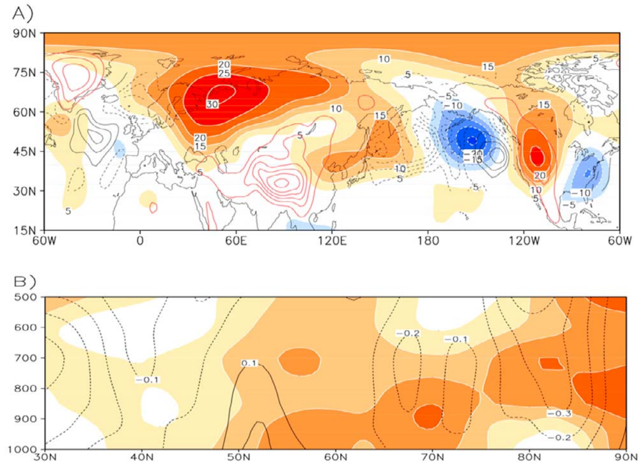

Figure 3. (a) Regressions of the smoothed AMO-*Atl* SST principal component on fall 300 hPa geopotential (shaded and contoured at 5 m interval) and 850 hPa meridional wind variance; the submonthly variance – a marker of stormtrack activity – is contoured over extratropical basins (30–75N) with a 1.5 $m^2\ s^{-2}$ interval in black color. Orography is shown in red contours with a shading threshold/interval of 750 m, after 2 applications of *smth9* on the 2.5° longitude-by-2.0° latitude field. (b) Corresponding regressions on the Atlantic sector (60W–0) averaged temperature (shaded and contoured at 0.1 C interval) and zonal wind (contoured in black at 0.1 m/s interval). Circulation and temperature fields are from NCEP reanalysis, and the regressions for the October 1949 – October 1994 period; the overlapping period of NCEP reanalysis and the smoothed AMO-*Atl* PC (thick red curve in Figure 1a). The zero-contour is omitted in all panels.

during Dust Bowl summer. The Atlantic SSTs are thus very influential in 3 of the 4 hydroclimate episodes, not only at modal resolution, but also in the aggregate. Pacific SSTs are the dominant influence only in the 1950s fall drought, when they account for over 50% of the observed signal.

[13] A compelling view of AMO's influence on Great Plains' hydroclimate is provided by Figure 2b which shows the normalized AMO-*Atl* SST PC (red curve) and central-eastern US precipitation in the 20th century. Their negative correlation (−0.78) indicates an important role for the AMO in Great Plains hydroclimate variability. Together with the role of Atlantic Nino in Dust Bowl summer (noted above), this analysis suggests that, as a basin, the Atlantic is, perhaps, more influential than the Pacific for multi-year Great Plains drought and wetness.

[14] The analysis presented in this study is based on contemporaneous regressions/correlation, yet the inference drawn is that SST variations lead to droughts. The inference is backed up by SST-lead/lag regressions that are not displayed for space reasons. The coherent nascent drought signals in the SST-leading reconstructions (obtained by multiplying the decadal SST PCs with their 1–6 year lagged precipitation regressions; and not shown) support the drawn inference.

4. AMO's Influence Mechanism: A Hypothesis

[15] The AMO influence mechanism is investigated in fall when the hydroclimate impact is strongest (Figure 1c). The impact is produced via circulation anomalies that attenuate moisture transport into the Great Plains and generate low-level subsidence there, as discussed earlier. The 700 hPa anomaly consists of a ridge (trough) over the western (eastern) US (Figure 1c); the origin of this zonal dipole is thus of key interest. The height anomaly has a barotropic structure: the larger-domain 300 hPa analysis shows the US anomaly to be part of a coherent wave pattern stretching from northeast Asia to eastern North America (Figure 3a). How is this wave pattern excited? The immediate source of the wave pattern appears to be in the upstream Pacific basin where stormtrack modulation is stronger than in the Atlantic (Figure 3a), which leads to the related question: How can AMO influence the Pacific stormtrack? A hypothesis follows:

[16] The AMO SSTs warm the lower troposphere in the north Atlantic sector (Figure 3b). The resulting positive $\partial T/\partial y$ will be linked with $-\partial U/\partial z$ (thermal wind balance), or a lower tropospheric easterly anomaly in the northern basin. Zonal wind regressions (Figure 3b) do show an easterly anomaly. We hypothesize that AMO-induced warming of the north Atlantic lower-troposphere and related southeastward displacement of the Atlantic stormtracks, and ensuing interaction of the generated flow anomalies with Greenland and Asian orography is what perturbs the Pacific stormtracks.

[17] The proposed influence mechanism is quite different from that put forward to explain the impact of a somewhat differently defined AMO [*Enfield et al.*, 2001]. When defined without factoring out Pacific's influence on Atlantic SST, AMO has an equally strong SST footprint in the Tropics, especially in the Caribbean Sea region [*Guan and Nigam*, 2009, see Figures 5b–5d], lending its circulation and hydroclimate impact to more canonical interpretation based on the SST-forced response from the Atlantic Warm Pool region [*Wang et al.*, 2006]. The influence mechanism for an AMO with a mid-high latitude SST focus remains to be elucidated; thus the above hypothesis – one developed not by choice but spurred by the structure of the coherent hemispheric wave-pattern (Figure 3a).

5. Concluding Remarks

[18] Droughts (and wet episodes) over the Great Plains have been linked to SST variability in the Pacific and Atlantic basins. The basin influences have however not been fully evaluated, in part, because the SST-forced dynamical models of the atmosphere – a common investigative tool – remain challenged in simulation of regional hydroclimate variability [*Ruiz-Barradas and Nigam*, 2005] for various reasons, including, potentially, the specification of SST anomalies in the models' extratropics [*Kushnir et al.*, 2002].

[19] Here we adopt a statistical approach rooted in innovative spatiotemporal analysis of 20th century SST variations (GN2008; GN2009) and related drought links [*Guan*, 2008], which leads to impressive reconstruction of several major droughts and wet episodes; attesting to the extent of the SST-influence on Great Plains in nature. We find Atlantic SSTs, tropical and extratropical, to be particularly influential; often, more than the Pacific ones, and more than in previous analyses, especially from the SST-forced atmospheric models: AMO is the dominant contributor (~50% of the signal) in the Dust Bowl spring drought and in the 1980s fall wetness (i.e., in 2 of the 4 episodes) while the Atlantic Nino is in another (Dust Bowl summer). As a basin, the

Atlantic is more influential than the Pacific in 3 of the 4 reconstructed episodes (cf. Table 1).

[20] The AMO's influence on continental hydroclimate is provided circulation context from analysis of low-level flow and the column stationary moisture flux, both obtained from NOAA's 20th Century Reanalysis; the modulation of moisture transport was consequential. A hypothesis for how the AMO atmospheric circulation anomalies are generated from AMO SSTs is proposed.

[21] The Atlantic SSTs evidently exert a profound influence on Great Plains hydroclimate on decadal timescales, especially in the transition seasons; an influence not represented in the SST-forced dynamical models of the atmosphere. For instance, *Schubert et al.* [2009] find a cold-Pacific and neutral Atlantic to be significantly more influential for US droughts than a neutral-Pacific and warm-Atlantic (PcAn≫PnAw in their drought modeling experiment nomenclature).

[22] Our analysis suggests that the La Nina–US drought paradigm, operative on interannual time scales, has been conferred excessive relevance on decadal time scales in the recent literature, in part, because dynamical models of the atmosphere are unable to represent the influence of Atlantic SSTs on Great Plains hydroclimate. Regardless, the present analysis is encouraging for the investigation of SST-based decadal drought/wetness predictability.

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B. Guan, Climate Physics Group, Jet Propulsion Laboratory, California Institute of Technology, MS T1714, Pasadena, CA 91109, USA.

S. Nigam and A. Ruiz-Barradas, Department of Atmospheric and Oceanic Science, University of Maryland, 3419 Computer and Space Science Bldg., College Park, MD 20742-2425, USA. (nigam@atmos.umd.edu)