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Analysis Links Pacific Decadal Variability to Drought and Streamflow in United States

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The two leading patterns of Pacific decadal sea surface temperature (SST) variability are strongly linked to large-scale patterns of warm-season drought and streamflow in the United States, recent analysis shows. The predictive potential of this link may contribute to the development of warm-season hydroclimate forecasts in the United States. Understanding of low-frequency variations in drought and streamflow would be important for both agriculture and water resources management.

The two leading patterns are what we call the Pacific Decadal Oscillation (PDO) and the North Pacific mode. Their link with drought and streamflow patterns was notably expressed in the 1960s when severe drought in the northeast (the 1962-66 “Northeastern” drought) and exceptional positive SST anomalies in the North Pacific Ocean (Figures 1a, 1b) both occurred. Analysis of upper tropospheric circulation anomalies showed the North Pacific to be a source region of wave activity affecting the drought area in these summers. The anomalous circulation was vertically coherent and opposed the climatological low-level moisture inflow over the eastern United States associated with the western extension of the Bermuda High.

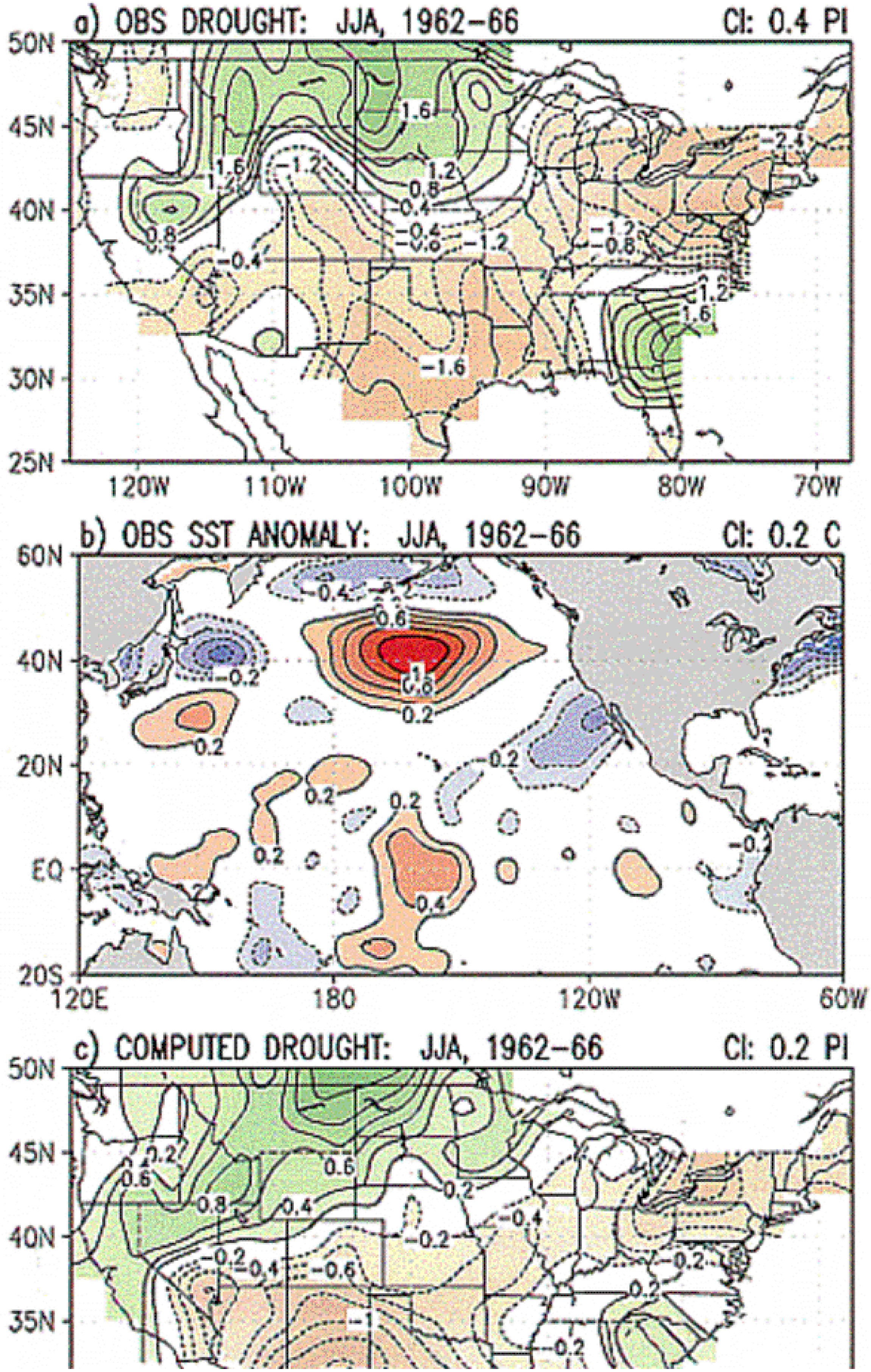
a) OBS DROUGHT: JJA, 1962–66
CI: 0.4 PI
50N
45N
40N
35N
30N
25N
120W
110W
100W
90W
80W
70W
b) OBS SST ANOMALY: JJA, 1962–66
CI: 0.2 C
60N
40N
20N
EQ
20S
120E
180
120W
60W
c) COMPUTED DROUGHT: JJA, 1962–66
CI: 0.2 PI
50N
45N
40N
35N

Fig. 1. a) Observed Palmer Drought Index averaged during June-August 1962-1966. b) Corresponding period sea surface temperature (SST) anomalies. c) Drought signal computed using the SST-drought relationships of the two decadal modes, using half the contour interval of a).

The two decadal patterns, or modes, were extracted, along with the El Niño-Southern Oscillation (ENSO), from a single objective principal component (PC) analysis, yielding a clear distinction between North Pacific and basin-wide decadal variability. SSTs from January 1945 to December 1993 were analyzed in the Pacific basin between 20°S and 60°N latitude; monthly SSTs were also not filtered in time.

Spatial Structure of Modes

The spatial structure of the modes (loading vectors) was determined by allowing regions of greater variance to be more influential (covariance based analysis) and by relaxing the constraint of spatial orthogonality through PC rotation. This method yielded more regional and potentially physical recurrent variability patterns.

The decadal loading vectors and their principal components (time series) are shown in Figure 2. The leading mode from the analysis describes ENSO variability and is not shown. The second mode, accounting for 7.5% of the interannual variance in the displayed domain, is similar to what has been called the “ENSO-like” mode by Zhang et al. [1997]. In our analysis, however, where the decadal modes and ENSO were extracted simultaneously from unfiltered data, this second mode (Figures 2a, b) had less signal in the north central Pacific and in the eastern equatorial Pacific than in Zhang et al.’s analysis, and bore less of a resemblance to ENSO.

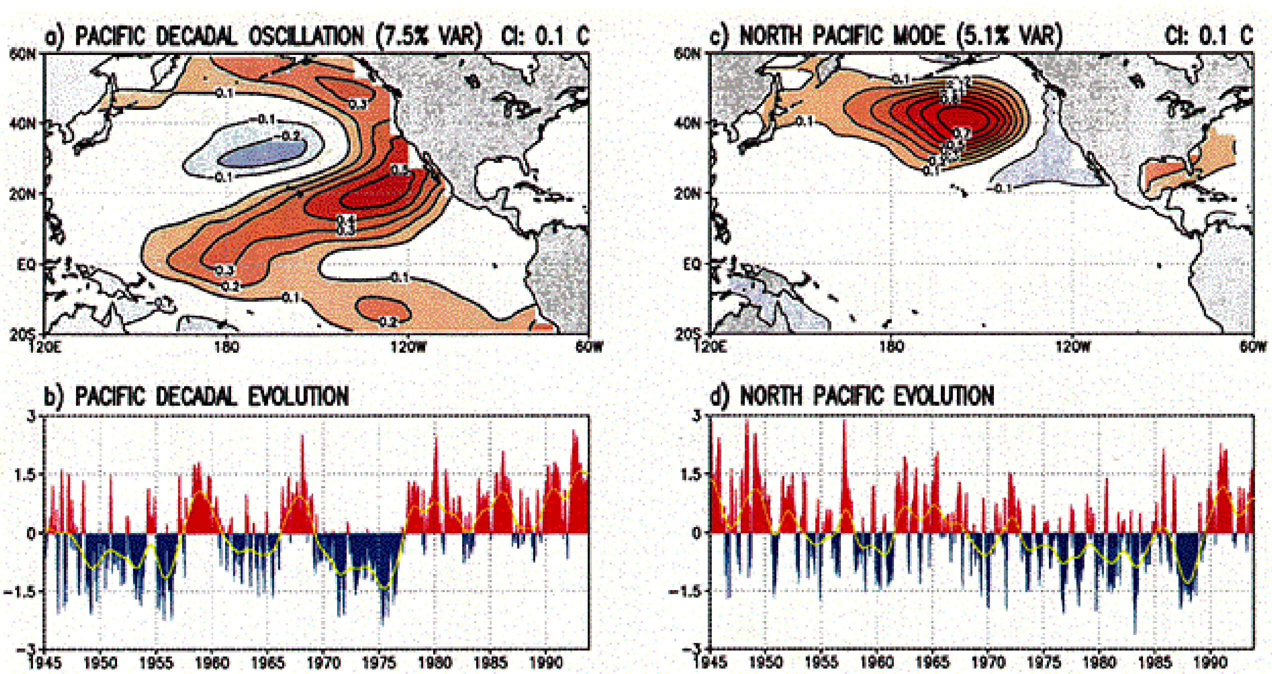

Fig. 2. The two decadal modes of Pacific SST variability during 1945-1993 obtained from rotated principal component analysis. SSTs are from the Comprehensive Ocean Atmosphere Data Set. The Pacific Decadal Oscillation (PDO) and North Pacific loading vectors are shown in a) and c). The associated principal components are shown in b) and d). The superimposed yellow curves represent

heavily smoothed versions of the time series.

It was because of this lack of similarity to ENSO and because of the Pacific-wide structure and notable decadal variations (including striking transitions in 1947 and 1977) that we refer to this mode as the PDO. While broadly similar, our PDO structure differs from Mantua et al.'s [1997] primarily in the North Pacific, likely because of the mixing of modes in their study from unrotated analysis and a more regional domain.

The third mode, the North Pacific mode, accounted for 5.1% of the variance and was in general agreement with previous analyses [e.g., *Zhang et al*., 1996]. As evident from the PC (Figure 2d), this mode exhibits notable variations at both decadal and intraseasonal timescales.

Because of the short duration (49 years) of the analyzed SST record in the context of decadal variability, we ascertained robustness of the leading modes from analysis of a longer-term SST data set, covering 1900-1991. The analysis yielded two modes, the second and the fifth, with considerable similarity to the PDO and North Pacific modes, respectively.

Drought Linkages

Linkage with U.S. hydroclimate fields was determined for the primary growing season, so that societal impact of Pacific decadal variability could be assessed. The June-August covariance between the decadal SST PCS and the drought index and streamflow is shown in Figure 3.

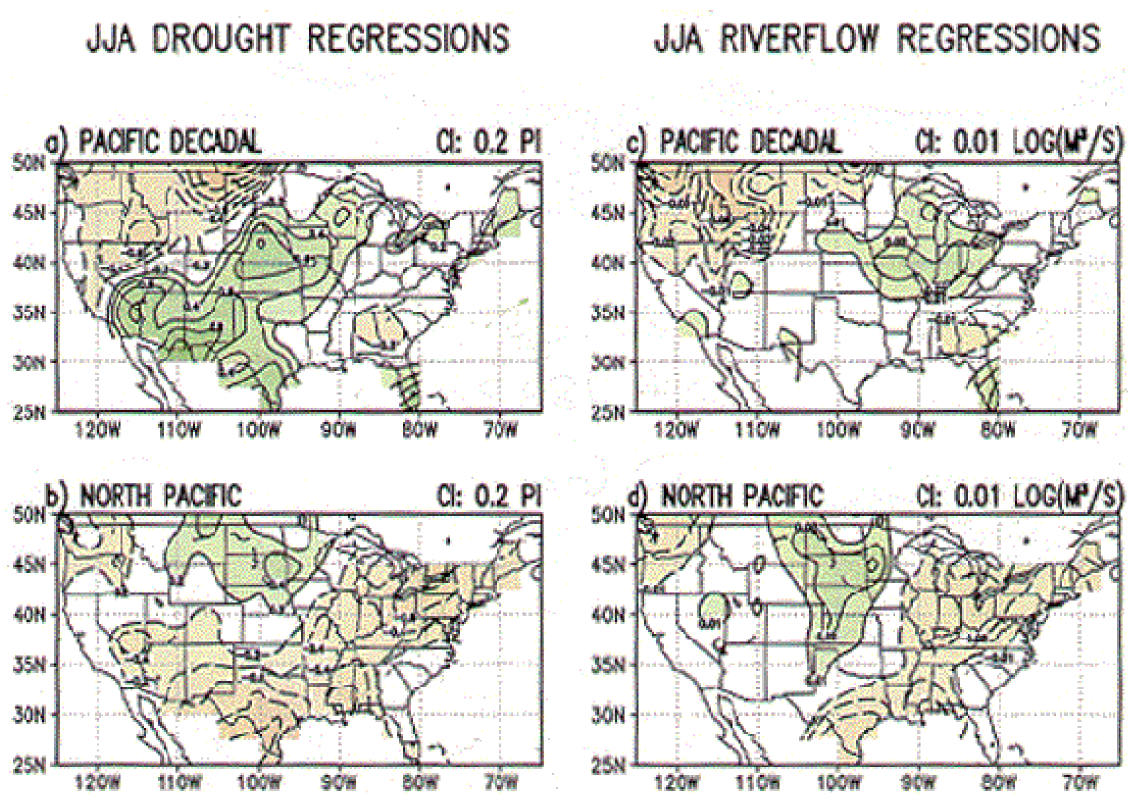

Fig. 3. Drought (a-b) and streamflow (c-d) regressions with the SST principal components of the PDO and North Pacific modes, averaged for June, July, and August (JJA). The drought regressions are in units of the Palmer Drought Index, while streamflow regressions are in the natural logarithm of streamflow, as log(m^3/s). The Palmer Index indicates the

severity of a wet or dry spell, based on a balance between the supply and demand of moisture calculated from a complex relationship involving precipitation and temperature. All computations were performed on the climate division data for Palmer Index and on the station data for streamflow, 1950-1988, and then gridded onto a 2.5° x 2.5° spatial grid. Plots for both variables were made for the period of streamflow data availability (1950-1988); drought data was available for 1945-1993, and results are very similar.

A Palmer Drought Severity Index [*Palmer*, 1965] of less than zero (in browns) represents drought while an index greater than zero (in greens) represents wet conditions; a value of -1.0 is the threshold for drought. Contributions from positive and negative PCS were also separately calculated to verify that the main linkage features have approximately the same structure in both phases of the SST modes (although amplitudes do vary).

That the linkages are largely generated by low-frequency SST variability was also verified by regressing the drought index on heavily smoothed versions of the PCS (see Figures 2b and 2d). Both decadal SST modes have drought linkages with Palmer Index magnitudes of at least 1.0 (comparable to ENSO's).

The statistical field significance of the seasonal drought linkages, computed via a resampling Monte Carlo analysis, was 92% for the PDO and 96% for the North Pacific mode. A rotated principal component analysis of the Palmer Index itself [*Karl and Koscielny*, 1982] yielded highly regionalized patterns, suggesting that the more complex Palmer Index patterns associated with Pacific decadal SST variability (Figures 3a and 3b) are likely externally related.

Streamflow Linkages

The streamflow linkages were computed for 1047 stations from the U.S. Geological Survey's Hydro-Climatic Data Network data set [*Slack and Landwehr*, 1992]. All computations are based on the natural logarithm of the data, producing a more normal distribution in time for streamflow and facilitating comparison among the U.S. stations, which have vastly different flow volumes.

The general agreement with the drought relationships was good for both modes, and the statistical field significances are 96% and 99%. The largest differences were in the southwest, where there was substantial signal in the drought relationship but not in streamflow, which had very small values during summer in this arid region. As with the drought index, rotated principal component analysis of streamflow alone [*Lins*, 1997] yielded strongly regionalized patterns. While our hydrologic analysis was based on the Pacific decadal SST modes, Cayan et al.[1998] conducted principal component analysis of the decadal precipitation variability over western North America and showed linkages to Pacific SST.

Drought Reconstruction

The SST-drought relationships were used to compute the (linear) SST-related drought signal during the major drought periods in the analyzed record. For the droughts in both the 1950s and 1960s, the computed signals were quite consistent with the observed drought patterns, although the computed amplitudes were considerably smaller.

The severe 1962-1966 drought in the northeast United States [*Namias*, 1966] had averaged Palmer Index values as high as -3.0. The Pacific SST anomalies, identified by Namias as possibly important to the drought, were quite similar to the North Pacific mode (Figure 2c). The presence of the North

Pacific mode in a 5-year average of SST anomalies both validates the modal analysis and highlights the longer timescales of the mode.

The drought signal computed using the two decadal Pacific SST modes and their drought linkages (see Figures 2, 3a, and 3b) is shown in Figure 1c; the observed and computed drought structures are in remarkable agreement, but the computed amplitudes are considerably smaller, by a factor of 3 to 4. The amplitude discrepancy was not unexpected given the role of local hydrologic feedback and possible regional interactions in amplifying the signal from the “incipient drought” to the “severe drought” category.

The North Pacific mode contributed the most to the computed drought, as expected from the close similarity between the observed 1962-1966 Pacific SST anomalies (Figure 1b) and the North Pacific SST modal structure (Figure 2c). The computed streamflow pattern during the 1962-1966 drought period (not shown) was also in close agreement with the observed anomalies and with the North Pacific SST mode-related streamflow signal.

Analysis of the horizontal propagation of stationary wave activity in the upper troposphere [e.g., *Karoly et al*., 1989] (Figure 4), averaged for the 1962-1966 summers, revealed a current of wave activity emanating from the North Pacific and extending to the east coast of the United States. The associated height anomalies exhibited vertical coherence, consistent with remote forcing.

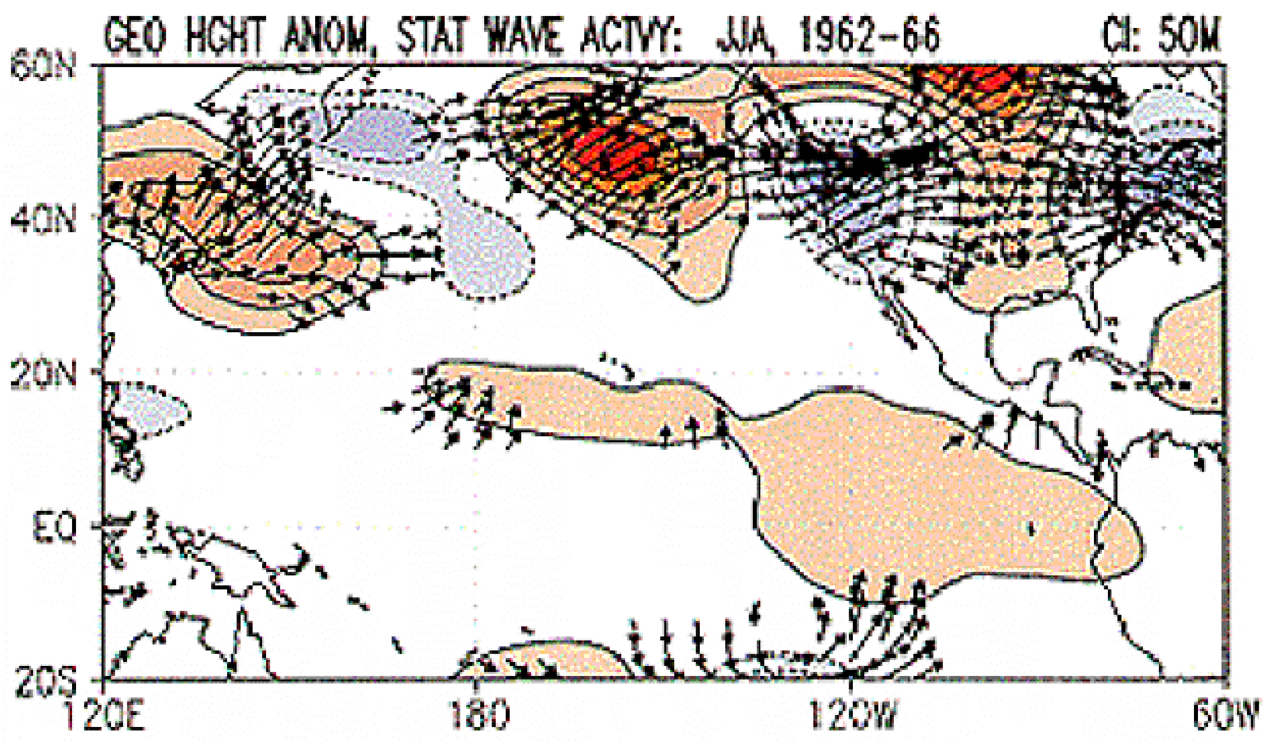

Fig. 4. Horizontal stationary wave activity flux vectors and geopotential height anomalies (zonal mean removed) for June, July, and August, averaged 1962-1966, at 300 hPa. The flux vectors were calculated as by Karoly et al. [1989]. As the calculation was based on geostrophic winds, flux vectors are not shown within 10° of the equator.

Notable SST anomalies were also present in the Atlantic Ocean adjacent to the “Northeastern” drought area, as noted by Namias, who suggested that positive feedback between the local Atlantic SST and circulation anomalies contributed to the persistence of this drought. These negative anomalies were accompanied by positive anomalies off the southern coast of Greenland throughout the drought episode, forming a dipole structure.

The dynamics of the dipole, particularly its relationship with North Atlantic Oscillation variability during boreal summer, needs to be investigated. An index of the Atlantic dipole shows considerable correlation to drought in the northeast, suggesting a more local, reinforcing role for the Atlantic, in comparison with the large-scale structure of the Pacific related variability.

Although suggestive, this diagnostic analysis of the northeast drought should be followed by a modeling analysis so that the roles of Pacific and Atlantic SST anomalies in generating the incipient drought signal can be established in a more interactive environment.

Acknowledgments

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