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Coherency of multi-scale abrupt changes between the NAO, NPI, and PDO

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[1] A scanning *t*-test and coherency detection algorithm is used to analyze and detect multi-scale abrupt changes in three climate indices; the NAO (North Atlantic Oscillation), PDO (Pacific Decadal Oscillation), and NPI (North Pacific Index). The analysis suggests that decadal fluctuations in atmospheric and ocean circulation are linked between the Atlantic and Pacific Ocean regions. The NPI and PDO are negatively correlated on decadal scales, with change points in about 1915, 1924, 1942, 1961, 1976, and 1988. The longer NAO also displays significant change points around these dates, as well as in 1832, 1865, 1870, and 1881. Decadal changes in the NAO and NPI (PDO) were positively (negatively) correlated prior to the late 1950s, but negatively (positively) correlated during 1962–1988. Although the north Atlantic and north Pacific atmosphere is teleconnected on decadal scales, the change after 1961 suggests it has multiple spatial modes. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4215 Oceanography: General: Climate and interannual variability (3309); 9325 Information Related to Geographic Region: Atlantic Ocean; 9355 Information Related to Geographic Region: Pacific Ocean. **Citation:** Schwing, F. B., J. Jiang, and R. Mendelssohn, Coherency of multi-scale abrupt changes between the NAO, NPI, and PDO, *Geophys. Res. Lett.*, *30*(7), 1406, doi:10.1029/2002GL016535, 2003.

1. Introduction

[2] It has long been recognized that the global atmospheric system is linked on climate time scales [cf. *Walker*, 1924]. Atmospheric teleconnections link widely separated pressure centers [cf. *Namias*, 1969; *Horel and Wallace*, 1981; *Barnston and Livezey*, 1987], allowing redistributions in atmospheric mass associated with El Niño/La Niña, decadal, and other climate scales to create well-defined anomaly patterns. A number of pressure-based indices characterize and quantify climate variability; for example the Southern Oscillation (SO) [*Walker*, 1924], the North Atlantic Oscillation (NAO) [*Barnston and Livezey*, 1987], and the North Pacific Index (NPI) [*Trenberth and Hurrell*, 1994].

[3] The impacts of interannual and decadal variability in atmospheric circulation on upper ocean conditions have been the subject of several studies [cf. *Namias*, 1969; *Trenberth and Hurrell*, 1994; *Tomita et al.*, 2001, 2002; *Schwing et al.*, 2002]. Ocean anomalies are communicated to other basins via atmospheric teleconnections, also referred to as the 'atmospheric bridge' [*Lau*, 1997; *Alexander et al.*, 2002]. Through this bridge, sea surface temperature (SST) anomalies in the Pacific contribute to variations in SST in the Atlantic and Indian Oceans [*Klein et al.*, 1999; *Mo and Hakkinen*, 2001; *White and Allan*, 2001].

[4] On the other hand, a number of studies suggest that climate variations in the Atlantic and Pacific are not coupled [cf. *Trenberth and Hurrell*, 1994; *Hurrell*, 1996; *Thompson and Wallace*, 1998]. *Tomita et al.* [2001] characterize decadal-scale variability in global atmospheric circulation and SST as having separate and independent patterns associated with the SO, NAO, and NPI.

[5] The goal of this study is to investigate the temporal relationships of atmospheric forcing over the north Pacific and Atlantic, and to understand better the atmospheric teleconnection between these regions on decadal time scales. We employ a scanning *t*-test and coherency detection algorithm to carry out a coherency analysis of multi-scale abrupt changes in monthly time series of the NAO, NPI and PDO.

2. Methods and Data

2.1. Scanning t-test

[6] Similar to the wavelet transform, the scanning *t*-test objectively identifies statistically significant changes in the magnitude of time series by calculating contrasts between subsets of the data [*Jiang et al.*, 2002]. The method tests for abrupt changes in the level of a time series from one period to another at all points in a series for all time scales, and determines their statistical significance. It assumes that climate regimes - long periods when indices are relatively level, separated by relatively rapid and sharp transitions - are important signals in long time series. It also assumes that the dominant spatial patterns are stationary on decadal time scales, and vary as standing atmospheric waves.

[7] The *t*-statistic is defined as:

$$t(n,j) = \left(\bar{x}_{j2} - \bar{x}_{j1}\right) \cdot n^{1/2} \cdot \left(s_{j2}^2 + s_{j1}^2\right)^{-1/2}, \tag{1}$$

where

$$\bar{x}_{j1}\frac{1}{n}\sum_{i=j-n}^{j-1} x(i),\ \bar{x}_{j2} = \frac{1}{n}\sum_{i=j}^{j+n-1} x(i); \quad s_{j1}^2 = \frac{1}{n-1}\sum_{i=j-n}^{j-1}\left(x(i) - \bar{x}_{j1}\right)^2;$$

$$s_{j2}^2 = \frac{1}{n-1}\sum_{i=j}^{j+n-1}\left(x(i) - \bar{x}_{j2}\right)^2.$$

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The subsample size $n = 2, 3, \ldots < N/2$ is the length of the period being compared, and $j = n + 1, n + 2, \ldots, N-n$ is the reference point being tested.

[8] The "Table-Look-Up Test" [*Storch and Zwiers*, 1999] was applied to counteract autocorrelation in the series. To make the tests comparable for all subsample sizes, the t-value was normalized by the 0.05 test value. The resulting t-statistic is significant at the 95% confidence level if its absolute value is greater than one. An index of coherency detection of abrupt changes between two series u and v is:

$$t_{rc}(n,j) = sign[t_{ru}(n,j) \cdot t_{rv}(n,j)] \cdot \{|t_{ru}(n,j) \cdot t_{rv}(n,j)|\}^{1/2} \quad (2)$$

A contour center of $t_{rc}(n,j) > 1.0$ represents a statistically significant synchronous (same signed) abrupt change in both series, while a contour center of $t_{rc}(n,j) < -1.0$ denotes an asynchronous (opposite-signed) abrupt change.

2.2. Climate Time Series

[9] Three long climate index time series are analyzed. The monthly NAO series (1821–2000) represents the large-scale see-saw in atmospheric mass over the Atlantic Ocean between the subtropical Azores High and the subpolar Iceland Low, which exert a strong influence on winter climate in Europe, North America, and Northern Asia [e.g., *Hurrell*, 1995, 1996; *Hurrell and Van Loon*, 1997]. It is defined as the normalized pressure difference between the High and the Low [*Jones et al.*, 1997]. The NAO index has long been recognized as one of the three large-scale oscillations in the global atmospheric pressure system [*Walker*, 1924].

[10] The NPI (1899–2000) is calculated as the area-weighted mean sea level pressure (SLP) over the region 30°N–65°N, 160°E–140°W [*Trenberth and Hurrell*, 1994]. It depicts changes in the intensity of the Aleutian Low in winter, and characterizes decadal variations in atmospheric circulation. The NPI is related negatively to the North Pacific Oscillation, which was defined by *Walker* [1924] as another of the three large-scale atmospheric oscillations, and is negatively correlated with the Pacific-North America (PNA) pattern index [*Trenberth and Hurrell*, 1994]. The NPI also correlates negatively to the leading North Pacific SLP component, called the NPPI [*Mantua et al.*, 1997].

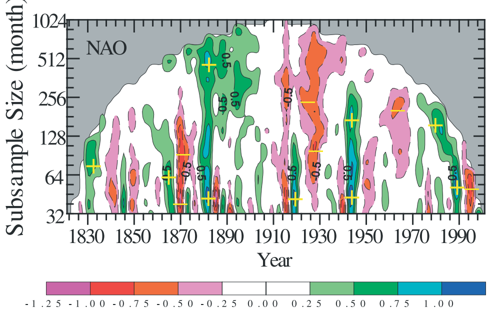

Figure 1. Contours of the scanning t-test value, standardized by the "Table-Look-up" critical value $t_{0.05}$, for the NAO (1821–2000). Y-axis is length (in months) of subsample periods. Green (Red) shading denotes abrupt change toward higher (lower) values. Plus (Minus) signs denote date and subsample length at which statistically significant abrupt increase (decrease) occurs.

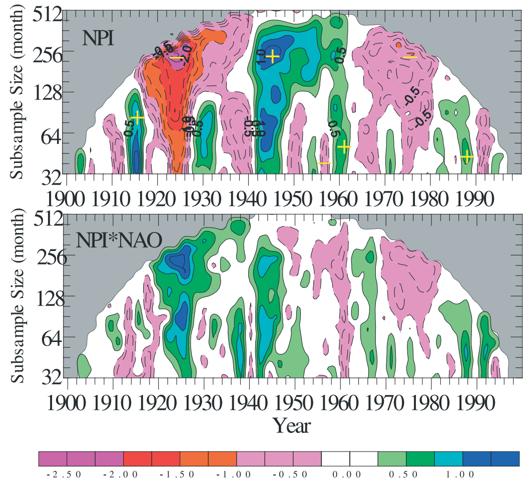

Figure 2. Same as Figure 1 but for (a) the NPI (1900–2000), and (b) coherency between the NAO and NPI. Green (Red) shading denotes positive (negative) correlation between the series.

[11] The Pacific Decadal Oscillation (PDO) (1900–2000) is the time series of the leading eigenvector of North Pacific SST anomalies north of 20°N [*Mantua et al.*, 1997]. It has closely paralleled interdecadal fluctuations in the dominant pattern of North Pacific SLP.

3. Results

3.1. Abrupt Changes in the NAO

[12] We present the scanning t-test analysis for the longer NAO to define when change points occurred over the north Atlantic (Figure 1), for comparison to the other series to follow. The NAO series displays significant increases in 1832 (on a 76-month, or 6-year subsample scale), 1865 (5-year scale), 1881 (4.4 and 43-year scales), 1918 (4-year scale), 1942 (5 and 20-year scales), 1977 (20-year scale), and 1988 (4-year scale). Significant declines in the index occurred in 1870 (3 and 9-year scales), 1925 (20-year scale), 1962 (21-year scale), and 1994 (4-year scale). Increasing change points in the NAO do not always follow a period of unusually low values (i.e., 1865, 1918, 1988).

3.2. Coherency Between the NAO and NPI

[13] Previous studies of the remote impacts of atmospheric and ocean circulation between the Atlantic and Pacific Ocean have focused on ENSO and quasi-biennial scales [*Klein et al.*, 1999; *White and Allan*, 2001]. This analysis demonstrates that atmospheric pressure over these regions also varies coincidently on decadal time scales (Figure 2a). The NPI increased abruptly in 1915 (on a 76-month, or 6-year scale), 1942 (21-year scale), 1961 (5-year scale), and 1987 (4-year scale). Significant changes toward lower values of the index occurred in 1924 (21-year scale), 1957 (3-year scale), and 1976 (21-year scale). These are consistent with sharp transitions in the NPI noted by *Trenberth and Hurrell* [1994].

[14] These change points are very similar to the NAO; the important exception is the additional change point in 1957. More importantly, changes in the NPI are positively correlated with the NAO before about 1957, but negatively correlated during 1962–1988 (Figure 2b). Since 1988, the

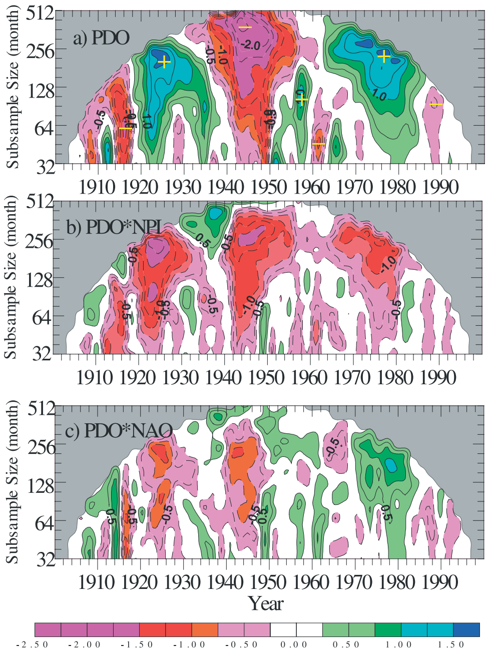

Figure 3. Same as Figure 1 but for (a) the PDO (1900–2000), and coherency between (b) the PDO and NPI, and (c) the PDO and NAO.

NAO and NPI may be positively correlated again, but the record length makes this difficult to determine definitively.

3.3. Coherency Between the NPI and PDO

[15] The coherency of abrupt changes between the NPI and PDO may be viewed as an indication of the interaction between atmospheric circulation and upper ocean processes in the Pacific Ocean on decadal and basin scales. Figure 3a shows that the PDO declined significantly in 1916 (on a 64-month, or 5-year scale), 1943 (36-year scale), 1961 (5-year scale), and 1988 (9-year scale). The PDO increased in 1924 (18-year scale), 1957 (9-year scale), and 1976 (18-year scale). *Mantua et al.* [1997] noted important transitions between climate regimes in 1942, 1977, and 1988, similar to all three indices, as well as those seen in 1918 and 1925 in the NAO.

[16] A number of negative coherency centers, denoting simultaneous but opposite-signed abrupt changes between the NPI and PDO, are shown in Figure 3b. Three negative coherency centers- 1924, 1944 and 1974- occur on a ca. 20-year scale. Two other negative centers are in 1915 and 1988 on scales of 5–10 years. The coherency of changes in 1957 between the NPI and PDO is weakly negative because the time scale is much shorter for the NPI, i.e., the atmosphere's change is much shorter-lived than the ocean's. Overall, the significant change points in the NPI and PDO are opposite-signed throughout the series and at all scales.

3.4. Coherency Between the NAO and PDO

[17] While the coherency between the NPI and PDO is negative throughout their records (Figure 3b), the coherency of abrupt changes between the NAO and PDO (Figure 3c) is similar in character to that between the NAO and NPI (Figure 2b). Prior to the 1950s, significant changes in the PDO and NAO (ca. 1918, 1925, 1942) were negatively coherent (Figure 3c). However, change points in these series after about 1960 (i.e., 1962, 1976, 1988) were of the same sign.

4. Discussion

[18] Figure 4 summarizes the significant change points and intervening climate regimes for the NAO, NPI, and PDO. The NAO was very high during 1865–1870, 1918–1925, and 1988–1994, moderately high in 1942–1962, and near neutral in 1832–1865, 1881–1918, and 1977–1988. The index was below its long-term mean prior to 1830, 1925–1942, and 1962–1977, and very low during 1870–1881 and 1994–2000. Strong abrupt decreases occurred in 1870 and 1994. The regime duration for the NAO varies from 5–37 years and is 16 ± 11 years on average.

[19] The NPI was unusually high in 1915–1924, low during 1924–1942, and near neutral during 1942–1957, matching the NAO pattern quite closely. However the NPI was briefly negative during the period associated with a very strong El Niño (1957–1961). After this event, the NPI displayed abrupt changes corresponding with those of the NAO, but in the opposite direction. Changes in the PDO were consistent with those of the NPI throughout the record, but directed oppositely. While the abrupt decadal changes are global in scale, they do not occur in phase. The NPI changes lead the PDO by an average of six months (compared to 1–2 months in *Trenberth and Hurrell* [1994]), and lead the NAO by 16 months on average.

[20] These results suggest that changes in the NPI and PDO are negatively correlated persistently. For example, a sudden shift toward negative NPI values (unusually low pressure over the north Pacific) is associated with a simultaneous and equally abrupt shift to a positive PDO pattern (warm SST anomalies in the tropical and northeast Pacific). However the relationship between the NAO, and the NPI and PDO changed after 1961, possibly in association with the 1957–1958 El Niño event. Decadal changes in the NAO and NPI

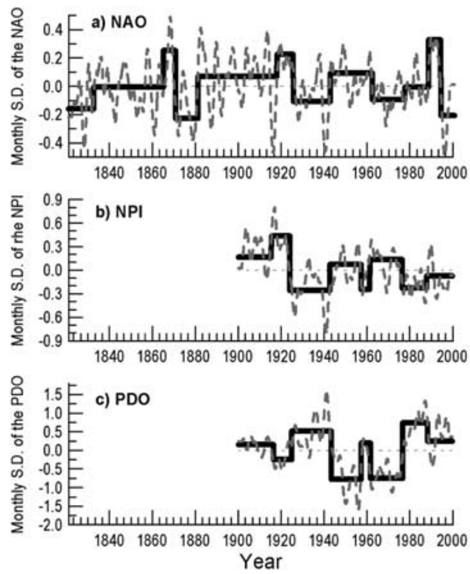

Figure 4. Episode-average (thick solid line), value smoothed with a 39-year Gaussian filter (thick dashed curve), and series mean (thin dotted line) for the NAO (a), NPI (b), and PDO (c).

(PDO) were positively (negatively) correlated prior to about 1957 (i.e. abrupt changes in the indices were in the same (opposite) direction), but these relationships were roughly reversed during 1962–1988. Since 1988, the NAO and NPI again appear to be positively correlated, although the analysis is inconclusive for this short time period.

[21] Thus while there is a remarkable correspondence between these three climate series with respect to the timing of the regime shifts they represent, the reversal in the directional relationship of abrupt changes in conjunction with the 1957–1958 El Niño results in the entire series being poorly correlated, as was found by *Hurrell* [1996], *Thompson and Wallace* [1998], and *Tomita et al.* [2001] for the NAO and NPI.

[22] Multidecadal climate variability in the north Pacific atmosphere and ocean is strongly coupled. However the atmospheric teleconnection between the north Atlantic and north Pacific, while connected, appears to have multiple modes. While atmospheric variations often occur in characteristic standing wave patterns [*Wallace and Gutzler*, 1981], they can change in orientation and give the appearance of propagation [*Schwing et al.*, 2002], and change in wavelength and frequency. An oscillation in the standing wave patterns would lead to the abrupt changes in the indices described here. We suggest that the fundamental atmospheric wave number varies on decadal scales, and switched from a pattern where the Atlantic and Pacific were in phase prior to 1957, but out of phase during 1962–1988.

[23] Perhaps the 1957–1958 El Niño was part of this shift, or even contributed to it. El Niño signals in the tropical Pacific are coupled to global atmospheric variations [*Pan and Oort*, 1983] and are reflected differently in the extratropical ocean in the northeast Pacific [*Mendelssohn et al.*, 2003]. The 1957–1958 event may have impacted the extratropics in a unique way, compared to other El Niño events, that led to a new relationship in atmospheric interactions over the north Atlantic and Pacific. In a future paper, we will examine the temporal and spatial evolution of the atmospheric planetary wave in the Northern Hemisphere, in the context of the changing relationship between the Atlantic and Pacific climate signals.

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