Wavelet-based multifractal analysis of the El Nino/Southern Oscillation, the Aleutian Low and the Pacific Decadal Oscilation

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Abstract

Climate change can be interpreted from the perspective of fractals. This study uses the wavelet transform to analyze the multifractal behavior of the El Nino/Southern Oscillation index (Nino3.4), the Pacific Decadal Oscilation (PDO), the Indian Ocean Dipole Mode Index (DMI), the North Pacific Index (NPI), the Pacific/North American pattern (PNA) index and the West Pacific pattern (WP) index. Changes from multifractal to monofractal behavior were observed at the regime shift in the 1920s for Nino3.4, DMI and NPI, at the regime shift in the 1940s for Nino3.4, PDO and NPI, at the 1976/77 regime shift for Nino3.4, PDO, DMI, NPI and PNA, and at the 1988/89 regime shift for PDO, DMI and WP. We found that a regime shift occurs when the fluctuation is large and multifractality is strong. Multifractal analysis is applicable to the identification of regime shifts. For the 1976/77 and 1988/89 regime shifts, the PNA and WP indices increase, which shows that the Aleutian Low (AL) leans to the east and north and strengthens. The occurrence of regime shift for 1976/77 and 1988/89 is related to the strengthening of the AL strongly. The influences of ENSO on PNA and NPI, and PNA and NPI on PDO are strong from the change of fractality and wavelet coherence and phase. Nino3, Nino3.4 and Nino4 are triggers of PNA and WP, and Nino3 is the largest trigger. ENSO event acts as a trigger of the regime shift, so tropical SST became a trigger of PNA and WP, and the teleconnection causes the change of SST. The strong coherency causes a regime shift.

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1. Introduction

Wavelet methods are attractive for the analysis of complex non-stationary time series. The wavelet transform allows reliable multifractal analysis to be performed (Muzy et al. 1991). A few studies have previously employed fractal analysis in climate field, for example, Huang and Morimoto (2008) analyzed the fractal dimension H in order to measure the noise characteristics of the monthly El Nino/Southern Oscillation index (Nino3.4) and showed that the oscillation pattern of H corresponds mostly to the development of El Nino. Relationships between multifractality and the behavior of the El Nino/Southern Oscillation, Indian Ocean Dipole Mode, and the North Atlantic Oscillation were documented (Maruyama et al. 2011). In addition, the multifractal properties of daily rainfall were investigated in two contrasting climates: an East Asian monsoon climate with extreme rainfall variability and a temperate climate with moderate rainfall variability (Svensson et al. 1996).

Monofractal signals are homogeneous and have the same scaling properties and linear properties. Multifractal signals, on the other hand, are intrinsically more complex and inhomogeneous, and have different scaling properties and nonlinear properties (Stanley et al. 1999). We attempt to explain changes in climate, the regime shift, by analyzing fractality, as phase transition and changes of state accompany a change of fractality. The relationship between the multifractality and the change of climate is important .

In this study, to reveal the mechanism of regime shift we examine the changes of multifractality in Nino3.4, PDO, NPI, DMI, PNA and WP indices using the wavelet transform and compare these changes with regime shift. And we compare those results with the wavelet coherence and phase of those indices. The NPI and PNA indices are good indicators of the Aleutian Low, AL, intensity variation and are demonstrably the best indicator of longitudinal shift. The WP index is demonstrably the best indicator of latitudinal shift of AL (Sugimoto et al. 2009). We investigate the relationship between

ENSO and AL, and triggers of PNA and WP. Furthermore, we investigate the relationship between the AL and PDO.

2. Data and method of analysis

We use the time series of the monthly Nino3.4, PDO, DMI, NPI and NAO from January 1920 through December 2008 and those of the monthly PNA, WP, Nino3 and Nino4 from January 1960 through December 2008, provided by NOAA's Climate Prediction Center, USA (CPC), as detailed below. The El Nino/Southern Oscillation index, which is a measure of the amplitude of an ENSO event, Nino3, Nino3.4 and Nino4 are defined as the monthly sea surface temperature averaged over the tropical Pacific 5°N-5°S, 90°W-150°W, 5°N-5°S, 120°W-170°W, and 5°N-5°S, 150°W-160°E, respectively. Pacific Decadal Oscillation (PDO) index is the leading PC of monthly SST anomalies in the North Pacific Ocean. The Indian Ocean Dipole Mode Index (DMI), which is the intensity of the IOD, is defined as the sea surface temperature anomaly difference between the tropical western Indian Ocean (50°E-70°E, 10°S-10°N) and the tropical southeastern Indian Ocean (90°E-110°E, 10°S-equator). DMI is derived from the Hadley Centre Sea Ice and SST Data Set (HadISST) provided by the Hadley Centre, Met Office, UK. The North Pacific Index (NPI) is defined as the sea level pressure averaged within the area of (30°N-65°N, 160°E-140°W). The Pacific/North American pattern (PNA) and the West Pacific pattern (WP) are provided by CPC and high-frequency noise with a period shorter than one year was cut. The Aleutian Low Pressure Index (ALPI) is defined as the area of the AL pressure system with pressure of less than 1005 hPa and is provided by Fisheries and Oceans Canada.

We used derivatives of the Daubechies function as the analyzing wavelet. We then estimated the scaling of the partition function $Z_q(a)$, which is defined as the sum of the qth powers of the modulus of the wavelet transform coefficients at scale a. In our study, the wavelet transform coefficients do not become zero, so the summation is taken over the whole set for precise calculation. Muzy et al. (1991) defined $Z_q(a)$ as the sum of the qth powers of the local maxima of the modulus to avoid division by zero. A time window of the SST time series was selected with a period of 72 months so as to involve ENSO cycles of 2 to 6 years, starting from January. For small scales, we expect

$$Z_q(a) \sim a^{\tau(q)}. \qquad (1)$$

First, we investigate the changes of $Z_q(a)$ in the Nino3.4 SST time series at a different scale a for each q. A plot of the logarithm of $Z_q(a)$ against the logarithm of time scale a was created. Here $\tau(q)$ is the slope of the linear fitted line on the log-log plot for each q. Next, we plot $\tau(q)$ vs q. The time window was then shifted forward one year and the process repeated. We define monofractal and multifractal as follows: If $\tau(q)$ is linear with respect to q, then the time series is said to be monofractal, if $\tau(q)$ is convex upwards with respect to q, then the time series is called multifractal.

3. Results and Discussion

3.1 Regime shifts observed in Nino3.4, NPI, PDO and DMI

The time series of cumulative sum of monthly ALPI and NPI for 1900-2008 are shown in Fig. 1. In both, the time series of cumulative sum has four inflection points and those correspond to the 1925/26, 1945/46, 1976/77 and 1988/89 regime shifts. So the regime shift is related to the AL strongly. A regime shift is characterized by an abrupt transition from one quasi-steady climatic state to another, and its transition period is much shorter than the length of the individual epochs of each climatic state (Minobe 1997). Most regime shifts, the 1925/26, 1945/46, 1957/58, 1970/71, and 1976/77 regime shifts, included tropical variations, but the 1988/89 regime shift occurred independently of those (Yasunaka and Hanawa 2003). The 1976/77 regime shift is the most well-known and after this event, the tropical Pacific experienced warming, the central North Pacific cooling, and the AL strengthened. These conditions lasted until the late 1980s.

We calculated the multifractal spectrum $\tau(q)$ of different moments q for individual records between 1950 and 2004 for Nino3.4. In Fig. 2(a), the multifractal spectrum $\tau(q)$ between 1980 and 1994 is shown. The data was analyzed in 6 year sets, for example, the multifractal spectrum $\tau(q)$ of n80 was calculated between 1980 and 1985, and that of n81 was calculated between 1981 and 1986. To examine the change of fractality, the time window was then shifted forward one year and the multifractal spectrum $\tau(q)$ was calculated from n80 up to n89. The multifractal spectrum $\tau(q)$ between 1990 and 2004 is shown in Fig. 2(b). A monofractal signal would correspond to a straight line for $\tau(q)$ and for a multifractal signal, $\tau(q)$ is nonlinear. Most of the multifractality observed are due to negative moments, i.e., small fluctuations are more inhomogeneous than large fluctuations. In Fig. 2(a), the data sets were monofractal in the case of n80-82, n85-n87 and n89 and were multifractal in the case of n83, n84, and n88. In Fig. 2(b), the data sets were monofractal in the case of n90 and n98 and were multifractal in the case of n91-96 and n97. For Nino3.4, PDO and NPI, the multifractal spectrum $\tau(q)$ was calculated for individual records between 1920 and 2004.

We show the wavelet coherence and phase using the Morlet wavelet between Nino3.4 and NPI in Fig. 3 (middle) and (bottom), respectively. The coherence of Nino3.4 and NPI is very strong except for 1960 – 80, when AL is weak, and the phase of NPI lags mostly. The leads of Nino3.4 are observed. Time series of $\tau(q=-6)$ of Nino3.4 and NPI are also shown in Fig. 3 (top). The value of $\tau(q=-6)$ is the index of the fractality and negative large values show large multifractality. The red square shows monofractality and the green circle shows multifractality for the 6 years centered on the year plotted. For example, the green circle for 1953 in Nino3.4 shows multifractality between 1950 and 1955. The data was excluded from Fig. 3 (top) for cases where we could not distinguish between monofractality and multifractality. The fractality of

Nino3.4 and NPI is very similar except for the 1950s which is the weak period of AL. The changes from multifractal to monofractal behavior were observed at the 1925/26, 1945/46 and 1976/77 regime shifts in Nino3.4 and at the 1925/26, 1945/46 and 1976/77 regime shifts in NPI. The coherences at the 1925/26 and 1945/46 regime shifts are strong. The fractality of Nino3.4 leads at the 1945/46 and 1976/77 regime shifts. When AL is weak for 1960-1980, the influence of ENSO on AL is weak and the coherence of Nino3.4 and NPI is weak.

We show the wavelet coherence and phase using the Morlet wavelet between PDO and NPI in Fig. 4 (middle) and (bottom), respectively. The coherence of PDO and NPI is very strong for 1920-40 and 1975-2000, when AL becomes strong, and the phase of PDO lags mostly. The leads of NPI are observed. Time series of $\tau(q=-6)$ of PDO and NPI are also shown in Fig. 4 (top). The changes from multifractal to monofractal behavior were observed at the 1945/46, 1976/77 and 1988/89 regime shifts in PDO. The fractality of PDO and NPI is very similar. The coherences at the 1925/26, 1945/46 and 1976/77 regime shifts are strong. The fractality of NPI leads at the 1925/26 regime shift. The influence of PDO on NPI is larger than that of Nino3.4 on NPI from the wavelet coherence.

We show the wavelet coherence and phase using the Morlet wavelet between Nino3.4 and PDO in Fig. 5 (middle) and (bottom), respectively. The coherence of Nino3.4 and PDO is very strong for 1940-65, when AL is strong, and the phase difference is small. For 1940-65 AL is strong. The coherence of Nino3.4 and NPI is strong and the phase of NPI lags, so Nino3.4 influence to NPI. And the coherence of NPI and PDO is strong and the phase of PDO lags, so NPI influence to PDO. So the coherence of Nino3.4 and PDO became strong. Time series of $\tau(q=-6)$ of Nino3.4 and PDO are also shown in Fig. 5 (top). The fractality of Nino3.4 and PDO is very similar. The coherences at the 1925/26, 1945/46 and 1976/77 regime shifts are strong. The fractality of PDO leads at the 1945/46 regime shift.

We show the wavelet coherence and phase using the Morlet wavelet between Nino3.4 and DMI in Fig. 6 (middle) and (bottom), respectively. The coherence of Nino3.4 and DMI is very strong for 1920-40 and 1975-2000, when AL becomes strong, and the phase of Nino3.4 lags. Time series of $\tau(q=-6)$ of Nino3.4 and DMI are also shown in Fig. 6 (top). The fractality of Nino3.4 and DMI is very similar. The coherences at the 1925/26, 1945/46 and 1976/77 regime shifts are strong and the fractality of DMI leads.

When AL is strong or AL becomes strong, the coherences between Nino3.4 and NPI, NPI and PDO, Nino3.4 and PDO, and Nino3.4 and DMI are strong. The influence of DMI on Nino3.4, Nino3.4 on NPI, NPI on PDO and Nino3.4 on PDO are considered. For example, before the 1976/77 regime shift, the Nino3.4, NPI and PDO had high coherence and strong multifractality was observed. Hence, we infer that a regime shift occured when coherence was strong and fluctuations were large and multifractality was strong. And the change of multifractal to monofractal bahaviour was observed.

3.2 The relationship between the AL and regime shifts

The fractality of NPI and Nino3.4 is similar as shown in 3.1. To investigate the relationship between the AL and ENSO in detail, we examine the fractality of the NPI, PNA and WP indices. The time series of monthly PNA and WP indices for 1960-2008 are shown in Fig. 7. Especially the change of WP is large for 1960-80 and is small for 1980-2010. From the wavelet power spectra, the period of PNA and WP are about twenty and ten years, respectively. Time series of cumulative sum for PNA and WP indices are shown in Fig. 8. The PNA index is good indicator of the AL intensity variation and longitudinal shift. The WP index is good indicator of latitudinal shift of the AL. The period of WP is observed to be about ten years. For the 1976/77 regime shift, the AL leans to the north and leans from the west to the east. For the 1988/89 regime shift, the PNA and WP indices increase, so the AL leans to the east and north.

For three regime shifts, the AL leans to the east and north.

The time series of $\tau(q=-6)$ for PNA and WP indices are presented in Figs. 9 and 10, respectively. For the PNA index, the change from multifractal to monofractal behavior was observed at the 1976/77 regime shift. For the WP index, the change from multifractal to monofractal behavior was observed at the 1988/89 regime shift. That was not observed at the 1976/77 regime shift, the reason is that the periodity of the time series of the WP index in the 1970s is strong as shown in Fig. 7 and the monofractal behavior was observed in the 1970s. In the latter half of the 1990s when the 1997/98 ENSO occurs, multifractal is strong. The fractality of the PNA and WP indices was inverse except for before and after 1990. The fractality of NPI and WP indices is similar from the second half of the 1980s. The coherence of the NPI and PNA indices, which are demonstrably the best indicators of longitudinal shift, is very strong and the time series of $\tau(q=-6)$ for NPI and PNA indices are similar.

3.3 The relationship between the AL and ENSO

As shown in Fig. 3, before the 1976/77 regime shift, the coherence of Nino3.4 and NPI strengthens and the change from multifractal to monofractal behavior occurs in both. The coherence of Nino3.4 and NPI is very strong and the phase of NPI lags mostly. The fractality of Nino3.4 and NPI is very similar except for 1950-62 which is the weak period of AL. The lag and lead of the phase of Nino3.4 exist. Hence, the influence of ENSO on NPI is strong and that of NPI on ENSO is small.

We show the wavelet coherence and phase using the Morlet wavelet between Nino3.4 and PNA in Fig. 9 (middle) and (bottom), respectively. The coherence of Nino3.4 and PNA is very strong and the phase of PNA lags mostly and leads before and after 1970. The time series of $\tau(q=-6)$ for Nino3.4 and PNA indices are presented in Fig. 9 (top). Before and after the 1976/77 regime shift, the coherence of Nino3.4 and PNA strengthens and the change from multifractal to monofractal behavior occurs in both.

The fractality of Nino3.4 and PNA is similar for the 1980s. The lag and lead of the phase of Nino3.4 exist. Comparing the time series of Nino3.4 with that of PNA, the leads of the Nino3.4 are observed. Hence the influence of ENSO on PNA is large and that of PNA on ENSO is small. The positive phase of the PNA tends to be associated with El Nino, and the negative phase tends to be associated with La Nina.

We show the wavelet coherence and phase using the Morlet wavelet between Nino3.4 and WP in Fig. 10 (middle) and (bottom), respectively. The coherence of Nino3.4 and WP is very strong and the phase of WP leads before and after 1980 and 2000-10 and lags for the others. The time series of $\tau(q=-6)$ for Nino3.4 and WP indices are presented in Fig. 10 (top). Before the 1988/89 regime shift, the coherence of the Nino3.4 and WP indices strengthens and the change from multifractal to monofractal behavior occurs in the WP index. The fractality of Nino3.4 and WP is not similar for the 1980s. The lag and lead of the phase of Nino3.4 exist. Comparing the time series of Nino3.4 with that of WP, the most leads of the Nino3.4 are observed. Hence the influence of ENSO on WP and that of WP on ENSO exist. The positive phase of the WP tends to be associated with El Nino, and the negative phase tends to be associated with La Nina.

We show the wavelet coherence and phase using the Morlet wavelet between Nino3.4 and PNAWP in Fig. 11 (middle) and (bottom), respectively. We define that PNAWP is 0.5*PNA + 0.5*WP. The simple average of the two indices, 0.5*PNA + 0.5*WP, produces excellent correlation (0.739) with the SST index (Kodera 1998). The coherence of Nino3.4 and PNAWP is very strong and the phase of PNAWP leads and lags. The time series of $\tau(q=-6)$ for Nino3.4 and PNAWP indices are presented in Fig. 11 (top). The fractality of Nino3.4 and PNAWP is not similar for the 1970s. For the 1980s, the coherence of the Nino3.4 and PNAWP indices strengthens and after that the fractality of Nino3.4 and PNAWP becomes similar. The change from multifractal to monofractal behavior occurs for the 1976/77 regime shift in the both indices. The fractality of Nino3.4 and AL is most similar for PNAWP. The lag and lead of the wavelet phase of Nino3.4 exist. Hence the influence of ENSO on PNAWP and that of PNAWP on ENSO exist.

The influence of AL on ENSO is considered as below. The influence of AL on ENSO at winter in 1996/97 is explained as below. The AL is strong and a typical winter pressure pattern appears in high frequency of occurrence. Midlatitude atmospheric transient forcing (cold surge) appears (Yu et al. 2003). Two tropical cyclones on either side of the equator appear. Westerly wind bursts (WWB) blow. This influence seawater and is the cause of occurrence of large-scale ENSO in 1997/98. An influence of midlatitude atmospheric variability on interannual ENSO and decadal ENSO-like variability is established and investigated in the Commonwealth Scientific and Industrial Research Organisation coupled general circulation models. The effect of midlatitude atmospheric variability is felt in the Tropics via the previously hypothesized seasonal footprinting mechanism, in which a tropical circulation is forced during spring and summer by tropical SST anomalies that are generated by midlatitude atmospheric variability during the previous winter (Daniel et al. 2003). The influence of the Northern Hemisphere annular mode (NAM) on ENSO by modulating westerly wind bursts was examined using 41-year reanalysis data and an atmospheric general circulation model (AGCM). Significant lag correlations between the NAM index for spring and the Nino3 index for the following winter were revealed (Nakamura et al. 2006).

3.4 Trigger of PNA and WP

Kodera (1998) pointed out the importance of El Nino/Southern Oscillation (ENSO) events for the generation of both PNA and WP teleconnection patterns. Many authors have emphasized that the intensity variation of AL is also related to the ENSO events (Hanawa et al. 1989; Zhang et al. 1996).

To investigate a trigger of PNA, we examined the relationship between PNA and Nino3, and PNA and Nino4 by wavelet coherence and phase and fractality. Nino3 is the average sea surface temperature anomaly in the region bounded by 5°N to 5°S, from 150°W to 90°W. Nino3.4 is that in the region bounded by 5°N to 5°S, from 170°W to 120°W. Nino4 is that in the region bounded by 5°N to 5°S, from 160°E to 150°W. The PNA pattern is comprised of four centers; one is located near Hawaii (20°N, 160°W), a second over the North Pacific Ocean (45°N, 165°W), a third over Alberta (55°N, 115°W), and a fourth over the Gulf Coast region of the United States (30°N, 85°W) (Wallace et al. 1981). The difference of wavelet coherence, phase and the time series of tau(q=-6) is small between Nino3 and PNA, Nino3.4 and PNA, and Nino4 and PNA. The lags of the wavelet phase of PNA are observed for all. Between Nino3.4 and PNA, the tendency is most similar, so Nino3 is the largest trigger of PNA.

To investigate a trigger of WP, we examine the relationship between WP and Nino3, and WP and Nino4. The WP pattern is comprised of two centers; one is located to be near 60°N, 155°E and a second to be near 30°N, 155°E (Wallace et al. 1981). The time series of $\tau(q=-6)$ for Nino3 and WP indices, and Nino4 and WP indices are presented in Fig. 12. The difference of wavelet coherence, phase and the time series of $\tau(q=-6)$ is small between WP and Nino3, WP and Nino3.4, and WP and Nino4. Between Nino3 and WP the tendency is most similar, so Nino3 is the largest trigger of WP.

3.5 The relationship between the AL and PDO

We examined the relationship between PNA and PDO. We show the wavelet coherence and phase using the Morlet wavelet between PNA and PDO in Fig. 13 (middle) and (bottom), respectively. The time series of $\tau(q=-6)$ for PNA and PDO indices are presented in Fig. 13 (top). For 1960-85, the wavelet coherence between PNA and PDO is especially strong and the fractality of PNA and PDO is similar. The lag of the phase of PDO is observed. For 1960-85, the wavelet coherence between DMI and PNA, and DMI and PDO are strong and the lead of the phase of DMI is observed. For 1960-85, the wavelet coherence between Nino3.4 and PNA, and Nino3.4 and PDO are strong and the lag of the phase of PNA is observed. The fractality of DMI, PNA, PDO and Nino3.4 for the 1970s is similar. Hence DMI and Nino3.4 influence to PNA and PDO and the coherence of PNA and PDO became strong. For 1960-85, the wavelet coherence between DMI and Nino3.4 is strong and the phase difference is small. The Indian Ocean Dipole (IOD) index shows a significant correlation with the sea anomaly at Darwin and the lead role of the IOD is shown (Yamagata et al., 2003). When PNA and PDO, and PNA and Nino3 had high coherence, with increasing fluctuations by interaction, strong multifractality was observed in both PNA and PDO, and PNA and Nino3. Then the change of multifractal to monofractal behavior was observed for PNA in the 1970s.

We examined the relationship between WP and PDO. We show the wavelet coherence and phase using the Morlet wavelet between WP and PDO in Fig. 14 (middle) and (bottom), respectively. The time series of $\tau(q=-6)$ for WP and PDO indices are presented in Fig. 14 (top). For 1990-2010, the wavelet coherence between WP and PDO is strong and the fractality of WP and PDO is similar for 1980-2000. The lag and lead of the phase of PDO were observed for 1970-90 and 1990-2000, respectively. When WP and PDO, and WP and Nino4 had high coherence, with increasing fluctuations by interaction, strong multifractality was observed in both WP and PDO, and WP and Nino4. Then the change of multifractal to monofractal behavior was observed for WP in the 1980s and about 2000.

We examined the relationship between PNAWP and PDO. For 1960-85, the wavelet coherence between PNAWP and PDO is strong and the fractality of PNAWP and PDO is similar. The lag and lead of the phase of PDO were observed in 1965-90 and 1990-2000, respectively.

As shown in 3. 1, 3. 3 and 3. 5, the influences of ENSO on PNA and NPI, and PNA and NPI on PDO, and DMI on Nino3.4, PNA and PDO are considered from the change of fractality and the wavelet coherence and phase.

For the 1976/77 regime shift, the wavelet coherence between Nino3.4 and PNA, PNA and PDO, DMI and PDO, DMI and Nino3.4, and Nino3.4 and PDO are strong and the change from multifractal to monofractal behavior was observed. ENSO event acts as a trigger of the regime shift (Yasunaka and Hanawa, 2005). So the tropical SST became a trigger of PNA and WP and the teleconnection cause the change of SST(PDO), which is a regime shift. The strong coherence causes a regime shift.

4. Conclusion

In this study, we have analyzed the multifractal behavior of Nino3.4, PDO, NPI, PNA and WP using the wavelet transform. Changes from multifractal to monofractal behavior were observed at the 1976/77 regime shift for Nino3.4, PDO, DMI, NPI and PNA indices, and at the 1988/89 regime shift for PDO, DMI, WP and NAO indices. We found that a regime shift occurs when the fluctuation is large and multifractality is strong. Multifractal analysis is applicable to the identification of regime shifts. For the 1976/77 and 1988/89 regime shifts, the PNA and WP indices increase. That is, the AL leans to the east and north and the AL strengthens. The occurrence of regime shift is related to the strengthening of the AL strongly. The influences of ENSO on PNA and NPI, and PNA and NPI on PDO are strong from the change of fractality and the phase of wavelet. Nino3, Nino3.4 and Nino4 are triggers of PNA and WP and Nino3 is the largest trigger. ENSO event acts as a trigger of the regime shift, so tropical SST became a trigger of PNA and WP and the teleconnection causes the change of SST. The strong coherence causes a regime shift.

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Figure Captions

Fig. 1: Time series of cumulative sum for ALPI and NPI.

Fig. 2: Multifractal spectrum $\tau(q)$ for individual Nino3.4 records (a) between 1980 and 1994 and (b) between 1990 and 2004.

Fig.3: (Top) Time series of $\tau(q=-6)$ of Nino3.4 and NPI. The red squares show monofractality and the green circles show multifractality for 6 years centered on the year. Wavelet coherence (middle) and phase (bottom) between Nino3.4 and NPI. The thick black contour encloses regions of greater than 95% confidence. The cone of influence, which indicates the region affected by edge effects, is shown with a black line.

Fig. 4: As for Fig. 3 but for PDO and NPI.

Fig. 5: As for Fig. 3 but for Nino3.4 and PDO indices.

Fig. 6: As for Fig. 3 but for Nino3.4 and DMI indices.

Fig. 7: Time series of PNA and WP indices.

Fig. 8: Time series of cumulative sum for PNA and WP indices.

Fig. 9: As for Fig. 3 but for Nino3.4 and PNA indices.

Fig. 10: As for Fig. 3 but for Nino3.4 and WP indices.

Fig. 11: As for Fig. 3 but for Nino3.4 and PNAWP indices.

Fig. 12: Time series of $\tau(q=-6)$ of Nino3 and WP, and Nino4 and WP indices.

Fig. 13: As for Fig. 3 but for PDO and PNA indices.

Fig. 14: As for Fig. 3 but for PDO and WP indices.