Wavelet-Based Multifractal Analysis on Climatic Regime Shifts

Fumio MARUYAMA, Kenji KAI, and Hiroshi MORIMOTO

Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

(Manuscript received 10 June 2013, in final form 27 January 2015)

Abstract

A climatic regime shift is characterized by an abrupt transition from one quasi-steady climatic state to another. We attempted to explain the change of multifractal behavior of climate indices when a regime shift occurred. We used the wavelet transform method to analyze the multifractal behaviors of the El Niño/Southern Oscillation (ENSO) index (Niño3.4 index), Pacific Decadal Oscillation (PDO) index, North Pacific Index (NPI), Pacific/North American pattern (PNA) index, and West Pacific pattern (WP) index. We showed the change of multifractality of these climate indices. When the wavelet coherences between the Niño3.4 index and NPI, NPI and PDO index, and Niño3.4 and PDO indices became strong, changes from multifractal to monofractal behavior were observed at climatic regime shifts. It may be possible to explain the background of the change of fractality by regarding climate change as the consequence of mutual interactions of various climatic elements. A fluctuation increase is observed in a coupled chaotic system just before chaos synchronization, which is when fractality and states change. We expect that a similar mechanism possibly exists for a climatic regime shift. When fluctuations became large and multifractality became strong, a climatic regime shift occurred and a change from multifractal to monofractal behavior was observed. The strong interaction of climatic phenomena, such as the ENSO, PDO, and Aleutian Low, caused a climatic regime shift. The fractality change of the PDO index almost corresponded to the regime shifts. In terms of multifractal analysis, we conclude that a climatic regime shift corresponds to a change from multifractality to monofractality of the PDO index.

Keywords ENSO; climatic regime shift; atmosphere–ocean interaction; wavelet; multifractal

1. Introduction

Various objects in nature exhibit so-called self-similarity or fractal properties. Monofractal behavior shows an approximately similar pattern on different scales and is characterized by a fractal dimension. Multifractal behavior is non-uniform and more complex and is decomposed into many sub-sets characterized by different fractal dimensions. Fractal properties can also be observed in time series as representative of the dynamics of complex systems. A change of fractality accompanies a phase transition and changes of state. The multifractal properties of daily rainfall have been investigated for two contrasting climates: an East Asian monsoon climate with extreme rainfall variability and a temperate climate with moderate rainfall variability (Svensson et al. 1996). In both climates, frontal rainfall exhibited monofractality and convective rainfall exhibited multifractality. Hence, climate change can be interpreted from the perspective of fractals.

A change of fractality may be observed when climate changes. Here, we attempt to explain changes in climate, referred to as regime shifts, by analyzing their fractality. We use the wavelet transform method to analyze the multifractal behavior of the climate index. Wavelet transform methods are useful for analyzing complex nonstationary time series because they allow reliable multifractal analysis (Muzy et al.
A regime shift is characterized by an abrupt transition from one quasi-steady climatic state to another, where the transition period is much shorter than the length of the individual epochs of each climatic state (Minobe 1997). The regime shift in the 1970s was marked by significant changes in the physical environment that resulted in dramatic changes in marine and terrestrial variables in the North Pacific and western North America. Yasunaka and Hanawa (2002) showed the differences in the means of sea surface temperature (SST) and sea level pressure (SLP) between the 1971–1976 and the 1977–1988 regimes (i.e., the latter minus the former), that is, changes occurred in the 1976/77 regime shift as shown in Fig. 1. In the SST field, negative changes can be seen in the central North Pacific surrounded by positive changes and the SST in the equatorial Pacific increases. Furthermore, a significant lowering of SLP in the North Pacific can be discerned.

To identify the occurrence of the regime shifts in the SST field, the time series of the original gridded SST data and those of the EOF modes were inspected. Six regime shifts were detected during the study period from the 1910s to the 1990s: the 1925/26, 1945/46, 1957/58, 1970/71, 1976/77, and 1988/89 regime shifts (Yasunaka and Hanawa 2002). The concurrent occurrences of regime shifts and El Niño/Southern Oscillation (ENSO) events suggest that the ENSO events triggered the regime shifts (Yasunaka and Hanawa 2005). The duration between each regime shift is approximately 10 years, which is identical to the Pacific Decadal Oscillation (PDO). In addition, the PDO includes changes in the activity of the Aleutian Low (AL) activity, which plays an important role in the PDO because of tropical forcing via the atmospheric bridge (Gu and Philander 1997). These findings imply the existence of a relation between regime shifts and the PDO (Yasunaka and Hanawa 2002).

In our previous paper (Maruyama et al. 2011) a change from multifractal to monofractal behavior was observed at the 1976/77 regime shift for the ENSO index (Niño3.4), and at the 1988/89 regime shift for the North Atlantic Oscillation (NAO) index. In this study, to detect changes of multifractality at regime shifts, we examined the multifractal behaviors of the ENSO index (Niño3.4), PDO index, North Pacific Index (NPI), Pacific/North American pattern (PNA) index, and West Pacific pattern (WP) index using the wavelet transform method and compared them with the regime shifts. The NPI and PNA index are good indicators of the variation of AL intensity. Furthermore, they are demonstrably good indicators of the longitudinal shift of the AL, whereas the WP index is a good indicator of its latitudinal shift (Sugimoto and Hanawa 2009). In this paper, we clarify the following points as below:

- We examine the possibility of using multifractal analysis to identify a regime shift and reveal the change of multifractality of the climate indices.
- Relations between the ENSO, AL, and PDO indices are investigated on the basis of changes of wavelet coherence and phase of the climate indices.
- We show the physical meanings of our results and discuss the relationship between our results and the regime shifts.

2. Data and method of analysis

We used the time series of the monthly Niño3.4 index, PDO index, and NPI from January 1920 through December 2008 and those of the monthly PNA and WP indices from January 1960 through December 2008, provided by NOAA’s Climate
Prediction Center, USA (CPC), as detailed below. The monthly Niño3.4 index, which is a measure of the amplitude of an ENSO event, is defined as the monthly sea surface temperature (SST) averaged over the tropical Pacific areas, (5°N–5°S, 120°–170°W). The PDO index is the leading principal component of the monthly SST anomalies in the Northern Pacific Ocean (Mantua et al. 1997). The NPI is defined as the SLP averaged within the area of 30–65°N, 160°E–140°W (Trenberth and Hurrel 1994). The PNA and WP indices are indicators of the AL and they are computed using a rotated principal component analysis of the monthly mean 500-hPa heights in the Northern Hemisphere (Barnston and Livezey 1987), for which high-frequency noise with a period shorter than one year was filtered out. The AL Pressure Index (ALPI) is defined as the area of the AL pressure system with a pressure of less than 1005 hPa, which was provided by Fisheries and Oceans Canada.

We used the Daubechies wavelet as the analyzing wavelet because it is widely used in solving a broad range of problems, e.g., self-similarity properties of a signal or fractal problems and signal discontinuities. The data used were a discrete signal that fitted the Daubechies Mother wavelet with the capability to handle a signal or fractal problems and signal discontinuities. The data used were a discrete signal that fitted the Daubechies Mother wavelet with the capability to handle small changes in the data. For a precise calculation, the summation was considered for the entire set. Muzy et al. (1991) defined Zq(a) as the sum of the q-th powers of the local maxima of the modulus to avoid division by zero. We obtained the partition function Zq(a):

\[ Z_q(a) = \sum |W_\phi[f](a,b)|^q, \]  

where \( W_\phi[f](a,b) \) is the wavelet coefficient of the function \( f \), \( a \) is a scale parameter and \( b \) is a spatial parameter. The time window was set to six years for the following outlined reasons. We calculated the wavelets using a time window of various periods, 10, 6 and 4 years. For a time window of 10 years, a slow change of fractality was observed. Thus, this case was inappropriate to find a rapid change of regime shift because when we integrated the wavelet coefficient over a wide range, small changes were canceled. For four years, a fast change of fractality was observed. The overlap of the first and subsequent data was 3 years, which is shorter than the 9 years in the case of the 10-year calculation and thus the change of fractality was large. For six years, a moderate change of fractality was observed and hence the time window was set to this period. For small scales, we expect

\[ Z_q(a) \sim a^{\tau(q)}. \]  

First, we investigated the changes of \( Z_q(a) \) in a time series at a different scales of \( a \) 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 plotted \( \tau(q) \) vs \( q \). The time window was then shifted forward one year and the process was repeated.

In this paper, 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 classified as multifractal (Frisch and Parisi 1985). We also define that the value of \( R^2 \), which is the coefficient of determination, for the fitting of a straight line. If \( R^2 \geq 0.98 \), the time series is monofractal; and if \( 0.97 \geq R^2 \), it is multifractal; and if \( 0.98 > R^2 > 0.97 \), it is intermediate between monofractal and multifractal.

We calculated the multifractal spectrum \( \tau(q) \) of different moments \( q \) for individual records between 1920 and 2004 for the Niño3.4 index. In Fig. 2 (left), the multifractal spectrum \( \tau(q) \) between 1980 and 1994 is shown. The data were analyzed in six-year sets, e.g., the multifractal spectrum \( \tau(q) \) of n80 was calculated for the 1980–1985 period, and that of n81 was calculated for the 1981–1986 period. 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 (right). A monofractal signal would correspond to a straight line for \( \tau(q) \), while \( \tau(q) \) would be nonlinear for a multifractal signal. Most of the multifractality observed is due to the negative value of \( q \), i.e., small fluctuations are more inhomogeneous than large fluctuations. In Fig. 2 (left), the data sets were monofractal in the cases of n80–n82, n85–n87, and n89 and were multifractal in the cases of n83, n84, and n88. In Fig. 2 (right), the data sets were monofractal in the case of n98, multifractal in the cases of n91–n96 and n97, and intermediate in the case of n90. For the Niño3.4 index, PDO index, and NPI, the multifractal spectrum \( \tau(q) \) was calculated for individual records between 1920 and 2004.
We plotted the value of $\tau(q = -6)$ for each index. The large negative values of $\tau(q = -6)$ show large multifractality. For $\tau(q = -6)$, $q = -6$ is the appropriate number to show the change of $\tau$. The value of $\tau(q = -6)$ does not always correspond to the fractality obtained from the value of $R^2$.

3. Relationship between the AL and regime shifts

We investigated the intensity and the position of the AL at the time of regime shift. The time series of the cumulative sum of the monthly ALPI and NPI for 1900–2008 are shown in Fig. 3. For both the ALPI and NPI, four inflection points correspond to the 1925/26, 1945/46, 1976/77, and 1988/89 regime shifts, indicating that the regime shift is strongly related to the AL. Most regime shifts, including the 1925/26, 1945/46, 1957/58, 1970/71, and 1976/77 regime shifts, involved tropical variations, however, the 1988/89 regime shift occurred independent of these (Yasunaka and Hanawa 2003). The 1976/77 regime shift is the most well-known and following which the tropical Pacific warmed, central North Pacific cooled, and AL strengthened. These conditions lasted until the late 1980s.

The time series of the cumulative sum of the PNA and WP indices are shown in Fig. 4. The variances of the time series of the monthly PNA and WP indices for 1960–1985 and 1960–1980 are considerably larger than those for 1985–2000 and 1980–2010, respectively. The PNA index is a good indicator of the variation of AL intensity and its longitudinal shift. The WP index is a good indicator of latitudinal shift of the AL (Sugimoto and Hanawa 2009). For the 1976/77 regime shift, the WP index increased and the PNA index decreased.
index changed from a decrease to an increase. Therefore, the AL shifted to the north and shifted from the west to the east. For the 1988/89 regime shift, both the PNA and the WP indices increased and therefore, the AL shifted to the northeast. Thus, for two of the regime shifts, the AL shifted to the northeast.

4. Relationship between the AL and ENSO

We investigated the relationship between the AL and ENSO using wavelet coherence, phase and fractality. Using the Morlet wavelet, we show the wavelet coherence and phase between the Niño3.4 index and NPI in Fig. 5 (middle and bottom, respectively). The coherence between the Niño3.4 index and NPI on the 4–8-year scale is very strong except for 1960–1980 as can be seen in Fig. 5 (middle), when the AL is weak for the time series of ALPI, and the phase of the NPI mostly lags. The leads of the Niño3.4 index can be observed. The time series of $\tau(q = -6)$ of the Niño3.4 index and NPI are also shown in Fig. 5 (top), where the red squares show monofractality, and green circles show multifractality, and orange triangles show an intermediate state between monofractality and multifractality for the six years centered on the year plotted. For example, the green circle for 1953 in the Niño3.4 index shows multifractality between 1950 and 1955. The data were excluded from Fig. 5 (top) for cases where we could not distinguish between monofractality and multifractality.

The fractalities of the Niño3.4 index and NPI are similar except for the 1950s, which coincides with a weak period for the AL from the time series of ALPI. Changes from multifractal to monofractal behavior can be observed around the regime shifts of 1925/26, 1945/46, 1957/58, 1970/71, and 1976/77 in the Niño3.4 index and around the regime shifts of 1925/26, 1957/58, and 1976/77 in the NPI. The coherence between the Niño3.4 index and NPI around the 1925/26 and 1945/46 regime shifts is strong. The fractality of the Niño3.4 index leads at both the 1945/46 and 1976/77 regime shifts. From the time series of the ALPI, the AL can be seen as weak during the 1960–1977 period, which is when the influence of ENSO on the AL is weak, and the coherence between the Niño3.4 index and NPI is also weak. For the Niño3.4 index, the change from multifractal to monofractal behavior is observed in the 2000s.

Kodera (1998) pointed out the importance of ENSO events for generating both the PNA and WP teleconnection patterns. Many researchers have emphasized that the variation of AL intensity is also related to ENSO events (Hanawa et al. 1989; Zhang et al. 1996). As shown in Fig. 5, before the 1976/77 regime shift, the coherence between the Niño3.4 index and NPI strengthens and the change from multifractal to monofractal behavior occurs in both. The fractality of the Niño3.4 index and NPI is similar except for 1950–1962, which is a period of weak AL intensity.

We examined the relationship between the Niño3.4 and PNA indices. The wavelet coherence and phase
between the Niño3.4 and PNA indices and the time series of $\tau(q = -6)$ for the Niño3.4 and PNA indices are shown in Fig. 6. The coherence between the Niño3.4 and PNA indices is strong and the phase of the PNA index mostly lags. Nitta and Yamada (1989) showed that since the late 1970s, tropical SST has increased and the PNA pattern with significant lowering of the geopotential height at 500-hPa in the North Pacific has become dominant. These large atmospheric anomalies might be associated with tropical heat sources enhanced by the warming of the tropical SST (Nitta and Yamada 1989). Atmosphere – ocean coupling outside the tropical Pacific slightly modifies the atmospheric circulation anomalies in the PNA region (Alexander et al. 2002) via the atmospheric bridge. These results are the basis for the phase delay of the PNA index. Before and after the 1976/77 regime shift, the coherence between the Niño3.4 and PNA indices strengthens and the change from multifractal to monofractal behavior occurs around the 1976/77 regime shift. The fractality of the Niño3.4 and PNA indices is similar for the 1980s.
Comparing the time series of fractality of the Niño3.4 index with that of the PNA index, the lead of the Niño3.4 index can be observed. The positive phase of the PNA index tends to be associated with El Niño, and the negative phase with La Niña (Sugimoto and Hanawa 2009).

5. Relationship between the AL and PDO

We investigated the relationship between the AL and PDO using wavelet coherence, phase, and fractality. The wavelet coherence and phase between the PDO index and NPI and the time series of $\tau(q = -6)$ for the NPI and PDO index are shown in Fig. 7. The coherence between the PDO index and NPI is strong. Changes from multifractal to monofractal behavior are observed around the regime shifts of 1925/26, 1945/46, 1957/58, 1970/71, 1976/77, and 1988/89 in the PDO index. The fractalities of the PDO index and NPI are similar.

We examined the relationship between the PNA and PDO indices. For 1960–1985, the wavelet coherence between the PNA and PDO indices is especially strong and the fractalities of the indices are similar (Fig. 8). The phase lag of the PDO index can be observed. Wallace et al. (1992) showed that the SST in the North Pacific is associated with both the strength of the AL at the surface and the PNA pattern in the troposphere. A coupling between the inter-annual variability of the North Pacific and North Atlantic SSTs by their mutual relation to one of the atmosphere’s most prominent planetary wave patterns is indicated by direct singular value decomposition and canonical correlation analysis solutions (Wallace et al. 1992). Schneider and Cornuelle (2005) showed that the PDO pattern is qualitatively consistent with the atmospheric forcing associated with fluctuations in the position and strength of the AL and that to a considerable extent, the PDO is a reflection of the NPI. The relative importance of these forcing processes for the PDO is frequency depen-
dent: at periods shorter than one year, intrinsic North Pacific variability dominates; at inter-annual frequencies, changes of the AL and of ENSO are essential (Schneider and Cornuelle 2005). These results agree with the phase lag of the PDO index.

We examined the relationship between the WP and PDO indices. For 1990–2010, the wavelet coherence between the WP and PDO indices is strong and the fractalities of the WP and PDO indices for 1980–2000 are similar (not shown).

The periods of strong coherence between the PNA and PDO indices and between the WP and PDO indices correspond to large variations of the PNA and WP indices, respectively. The intensity of the PNA index is strong between 1960 and 1990 and that of the WP index is strong since the latter half of the 1980s (Sugimoto and Hanawa 2009). Hence, assuming the enhancement from the atmosphere to the ocean, the coherence between the PNA and PDO indices is strong for 1960–1985 and the coherence between the WP and PDO indices is strong for 1990–2010.

6. Relationship between the ENSO and PDO

We investigated the relationship between the ENSO and PDO using wavelet coherence, phase and fractality. The coherence between the Niño3.4 and PDO indices is very strong for 1940–1965, when the AL is strong, and the phase difference is small (not shown). Newman et al. (2003) showed that the PDO is dependent on the ENSO at all time scales and that the ENSO leads the PDO by a few months throughout the year. The ENSO affects the PDO via the atmospheric circulation and ultimately air-sea interactions in the North Pacific. Alexander et al. (2002) showed that anomalous tropical convection induced by the ENSO influences global atmospheric circulation and hence alters surface fluxes over the North Pacific. This atmospheric bridge occurs via changes in the Hadley and Walker cells and Rossby waves, and surface heat fluxes are the key component. These results show that the ENSO influences the PDO, although the phase difference between the Niño3.4 and PDO indices is small. The coherences between the climate indices around the regime shifts of 1925/26, 1945/46, and 1976/77 is strong. The fractalities of the Niño3.4 and PDO indices are similar. The fractality of the PDO index leads at the 1945/46 regime shift. For the PDO index, the change from multifractal to monofractal behavior can be observed in the 2000s, which is due to the change of sign of the PDO index. When the AL is strong or becomes strong, the coherences between the Niño3.4 index and NPI, NPI and PDO index, and Niño3.4 and PDO indices are strong.

7. Discussion

Periods of strong wavelet coherence between the Niño3.4 index and NPI (Fig. 5), NPI and PDO index (Fig. 7), and Niño3.4 and PDO indices (not shown) from 1900 through 2000 were investigated and are shown in Fig. 9. In the figure of coherence of Figs. 5 and 7, the thick and thin black contours enclose regions of confidence greater than 95 % and 90 %, respectively. We also examined the relationship between the intensity of coherence and change of fractality, and the results are shown in Table 1. Here, an arrow means that coherence is strong and the index in parentheses means that the change of fractality is not observed in the index. Actually, the change of fractality is observed when coherence becomes strong. It may be possible to explain the background of the change of fractality by regarding the climate change as a consequence of mutual interactions of various climatic elements.

In a coupled chaos model, where a coupled chaos is a system composed of chaos which interact with each other, an anomalous enhancement of the magnitude of a fluctuation is observed at the phase synchronization point (Fujisaka et al. 2005). In other words, an increase of a fluctuation is observed in a coupled chaos system just before chaos synchronization, which is when fractality and state change. Coupled chaotic systems have attracted the attention of many researchers as a good model which can realize the complicated phenomena of the natural world, and further its dynamics can yield a wide variety of complex and strange phenomena (Wada et al. 2005).

For a regime shift, a mechanism similar to the coupled chaos system might exist, i.e., coherence becomes strong and fluctuations increase, and the multifractal behavior becomes strong and a change from multifractal to monofractal behavior is observed. This implies that strong interactions of climatic phenomena cause regime shifts.

We selected those years when fractality changed but regime shift did not occur, as follows. For the PDO, the only change of fractality around 1995 relates to the change of the sign of the PDO index from plus to minus, which suggests the possibility of a regime shift. Therefore, the fractality changes of the PDO index almost correspond to regime shifts. For the Niño3.4 index, the fractality changes at 1964, 1982, and 2000 do not relate to regime shifts. Not all the ENSO events are associated with regime shifts (Yasunaka and Hanawa 2005). For the NPI, the frac-
Fractality changes around 1965 and 1991 do not relate to regime shifts. The NPI is a reflection of changes within the atmosphere, and thus, it is difficult to detect regime shift in such an index.

We examined the possible reasons for the fractality change of the Niño3.4 index other than regime shift. Multifractal consists of several monofractals. At 1964, 1982, and 2000, when the fractality changes because of reasons other than regime shift, several monofractals degrade and become noise and one of monofractals remains. The change of monofractals to noise is a well-known phenomenon and for the Niño3.4 and NPI, it seems that a fractality change occurs because several monofractals become noise.

The changes of fractality of the PDO index almost correspond to regime shifts. Hence, in terms of the multifractal analysis, we conclude that a climatic regime shift corresponds to the change from multifractality to monofractality of the PDO index.

The influences of the ENSO on the PNA and those of the PNA on the PDO are strong, according to the changes of wavelet coherence and phase, shown in Sections 4 and 5. This agrees with the results that the PNA is associated with tropical heat sources enhanced by the warming of the tropical SST, and that the PDO is associated with the strength of the PNA pattern in the troposphere. An ENSO event acts as a trigger of the regime shift (Yasunaka and Hanawa 2005), so that tropical SST excite the PNA, and teleconnections cause changes in the SST of the Northern Pacific Ocean except for the 1988/89 regime shift.

8. Conclusions

We examined the possibility of using multifractal analysis to identify climatic regime shift, and attempted to explain the changes of the multifractal behavior of climate indices when regime shift occurs. A change of fractality accompanies phase transition and changes of state. We used the wavelet transform method to analyze the multifractal behavior of the Niño3.4 index, PDO index, NPI, PNA index, and the WP index. We used the Daubechies wavelet as the analyzing wavelet and calculated the multifractal spectrum \( \tau(q) \) of different moments \( q \) for individual records of the climate indices. We showed the change of multifractality by plotting \( \tau(q = -6) \), and the relations between the ENSO, AL and PDO were investigated on the basis of the changes of the wavelet coherence and phase of those indices.

The results of this study are summarized as follows:

1. When the wavelet coherence between the Niño3.4 index and NPI, NPI and PDO index, and Niño3.4 and PDO indices from 1900 through 2000. In the figure of coherence, when the thick and thin black contours enclose regions of confidence greater than 95% and 90%, respectively, a red circle is plotted.

Fig. 9. Period of the strong wavelet coherence between the Niño3.4 index and NPI, NPI and PDO index, and Niño3.4 and PDO indices from 1900 through 2000.
and PDO indices became strong, changes from multifractal to monofractal behavior were observed at climatic regime shifts. It may be possible to explain the background of the change of fractality by regarding the climate change as the consequence of mutual interactions of various climatic elements.

(2) An increase of a fluctuation is observed in a coupled chaotic system just before chaos synchronization, which is when fractality and state change. We expect that a similar mechanism might exist for a climatic regime shift.

(3) When fluctuations became large and multifractality became strong, a climatic regime shift occurred and a change from multifractal to monofractal behavior was observed. The strong interactions of climatic phenomena such as the ENSO, PDO, and AL caused climatic regime shift.

(4) The fractality changes of the PDO index almost corresponded to regime shifts. In terms of multifractal analysis, we conclude that a climatic regime shift corresponds to a change from multifractality to monofractality of the PDO index. According to the changes of wavelet coherence and phase, the influences of the ENSO on the PNA, and those of the PNA on the PDO are strong.

References


Newman, M., G. P. Compo, and M. A. Alexander, 2003: ENSO-forced variability of the Pacific Decadal Oscil-


