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Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: Role in climatic regime shifts

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Abstract. The roles of interdecadal oscillations in climatic regime shifts, which are observed as rapid strength changes in the Aleutian low in winter and spring seasons, have been analyzed. A regime shift results from simultaneous phase reversals between pentadecadal and bidecadal variations, which synchronize with one another at a relative period of three. The pentadecadal variation, which is observed in both winter and spring seasons, provides the basic timescale of regime shifts, while the bidecadal variation, which is observed only in winter, characterizes the rapidity of the shifts. A Monte-Carlo simulation has shown that the simultaneous phase reversals or resonance between the pentadecadal and bidecadal variations reflect a physical linkage between them and do not coincide accidentally. The role of this synchronization feature for assessing and predicting regime shifts is discussed.

Introduction

Recent studies have revealed that the climate variability over the North Pacific possesses substantial interdecadal variations. In particular, a number of studies have been devoted to the discussion of decade-timescale strengthening of the Aleutian low and related climate changes in the late 1970s [e.g., *Nitta and Yamada*, 1989; *Trenberth*, 1990; *Tanimoto et al.*, 1993; *Graham*, 1994; *Trenberth and Hurrel*, 1994; *Nakamura et al.*, 1997]. The climate change in the 1970s is often called a climatic regime shift, reflecting the fact that a transition from one climatic state to another has occurred within a period substantially shorter than the lengths of the individual epochs of each climatic state. 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 [see the summary reviews in *Trenberth and Hurrel*, 1994, and *Mantua et al.*, 1997]. The regime shift in the 1970s is not a unique phenomenon. Pan-Pacific regime shifts have been observed also in the 1920s and the 1940s in the averaged winter-spring (Dec.–May) strength of the Aleutian low (Fig. 1) and in a number of other physical variables [*Kondo*, 1988; *Parker et al.*, 1994; *Dettinger and Cayan*, 1995; *Hare and Francis*, 1995; *Zhang et al.*, 1997; *Minobe*, 1997; *Mantua et al.*, 1997]. The periodicity of a climate oscillation associated with these regime shifts is estimated to be about 50–70 years (hereafter referred to as pentadecadal variability) based on instrumental records for the North Pacific Ocean and North America, and also on tree-ring records for western North America [*Minobe*, 1997].

Although the regime shifts in the present century are characterized by a pentadecadal timescale, rapid transitions from one regime to another cannot be attributed to a single sinusoidal-wavelike variability. The rapid-transition nature of 20th century regime shifts suggests that the pentadecadal variability is characterized by a non-sinusoidal variation such as a rectangular wave or that it is synchronized or phase-locked with another climate variation on a shorter timescale. In the present paper, therefore, we examine time-frequency structures of interdecadal climate variability in the North Pacific to obtain a better understanding of these regime shifts. In order to address whether an entire time-frequency structure associated with the regime shift originates as a single phenomenon, we specifically analyze the seasonal dependence of these variations.

Data and Method

We examine an univariate time series representing the strength of the Aleutian low known as the North Pacific Index (NPI) [*Trenberth and Hurrel*, 1994]. The NPI is defined as the area-averaged Sea Level Pressure (SLP) anomaly in the region 160°E–140°W, 30–65°N. The NPI is calculated from 1899 to 1997 based on an updated version of the SLP data set of *Trenberth and Paolino* [1980].

We have analyzed the NPI, employing a Morlet wavelet transform. The mother wavelet for the Morlet wavelet is the same as used by *Torrence and Compo* [1998]. In order to avoid “end effects” before making the wavelet transform, we extend the time series by 30% at the beginning and end, using an auto-regressive model based on a Maximum Entropy Method of order 25.

Results

In order to identify seasonally dependent time-frequency structures associated with regime shifts, we have performed separate wavelet transforms of the data from the winter (Dec.–Feb.) and spring (Mar.–May) NPI. These results are shown in Fig. 2. In addition to significant pentadecadal signals both for winter and spring seasons, a signature on about a 20-year timescale (hereafter referred to as bidecadal variability) is evident in the winter season. The pentadecadal (bidecadal) signal is captured as a cluster of large wavelet amplitudes in periodic intervals from 30 to 80 (10 to 30) years. The amplitude of the bidecadal variability increased from 1930 to 1950, and at the same time the period lengthened from about 15 to about 20 years. The latter feature of the phase modulation is consistent with the air-temperature variability over Alaska (not shown, see *Royer* [1989]). The Aleutian low has been identified as one center of action in the global distribution of strong bidecadal time scale variability [e.g., *Mann and Park*, 1994; 1996; *Polovina et al.*, 1995; *White et al.*, 1997; *White and Cayan*, 1998]. The bidecadal and pentadecadal variations exhibit different seasonal dependencies, suggesting that these two interdecadal signals are not in a subharmonic relation, which is expected to hold for a rectangular wave-like pentadecadal signal. The different seasonality with a distinct separation on the time-frequency domain further suggests that these two interdecadal variations are unlikely two aspects of a single phenomenon, but probably arise from two physical mechanisms.

The winter-spring NPI, filtered within a periodic band from 10 to 80 years, exhibit prominent phase reversals in the 1920s, 1940s and 1970s (Fig. 3a), which correspond approximately to the three climatic regime shifts identified by *Minobe* [1997] and *Mantua et al.* [1997]. Here, we use a band-pass wavelet-filter defined by a superposition of wavelet transform coefficients (see Eq. 11 of *Torrence and Compo* [1998]). Interestingly, between the two phase reversals or zero-crossings from the 1920s–1940s (1940s–1970s) there are two troughs (peaks) of shorter-periodic variation on the bidecadal timescale. We further isolate the pentadecadal and bidecadal signals by using two band-pass wavelet-filters with a 10–30-year period band (bidecadal filter) and a 30–80-year band (pentadecadal filter). The three phase reversals in the 10–80-year filtered NPI data are closely related with the phase reversals in the pentadecadal variability. A remarkable feature is that, around each of the three pentadecadal phase reversals, a bidecadal phase reversal also occurred with the same relative polarity. Between the bidecadal phase reversals accompanying the two successive pentadecadal phase reversals, there are another two bidecadal phase reversals. These results suggest that the pentadecadal variation is synchronized or phase-locked to the bidecadal variation with a relative period of three. A regime, which is approximately a half period of the pentadecadal oscillation, corresponds to one and half periods of the bidecadal oscillation.

These two climate oscillations play important roles in regime shifts. The pentadecadal variability provides the basic regime timescale as shown by *Minobe* [1997]. Phase reversals of the bidecadal variability combined with quasi-simultaneous phase-reversals of the pentadecadal variability characterize the rapidity of the transition between two successive regimes. Therefore, we conclude that the pentadecadal and bidecadal variations, which apparently synchronize or phase-lock with one another, provide climatic regimes lasting 20–30 years with their associated rapid transitions.

Because the pentadecadal and bidecadal variations are involved in regime shifts with different seasonal dependencies, it is useful to examine the interplay of the pentadecadal and bidecadal variations separately in the winter and spring seasons. For the winter NPI data, the relation of the bidecadal and pentadecadal variations is essentially the same as that of all the winter-spring data (Fig. 3b). However, the contrast between before and after the shift in the 1920s is less pronounced than those for the shifts in the 1940s and 1970s, due to the aforementioned smaller bidecadal amplitude in the first few decades. Moreover, the 10–80-year band-pass filtered wintertime NPI exhibits short periods with polarities opposite in sign to the regime-averaged polarity during 1960–65 and 1989–1992, whereas the filtered winter-spring NPI yields the same polarity in every case. Hence, the winter-spring NPI is the more useful tool for the assessment of regime shifts. These short periods result from the fact that bidecadal amplitude compared with the pentadecadal amplitude is stronger in the winter NPI data than for the combined winter-spring data, associated with the stronger bidecadal amplitude in the winter season than in the spring season shown in Fig. 2.

In the spring season, a synchronous relationship between the bidecadal and pentadecadal changes is not observed (Fig. 3c). Consequently, pentadecadal phase reversals do not generally result in rapid transitions in the 10–80-year band-pass filtered springtime NPI data, but they only produce gradual changes in the index with some interdecadal fluctuations. The pentadecadal amplitude in the spring NPI data is as strong as in the winter-spring averaged NPI data. The lack of distinctive regime-shift features in the spring data confirms that the synchronization between the pentadecadal and bidecadal variations is essential for a sharp regime shift.

As a representative time series for the pentadecadal and bidecadal signals, we employ the pentadecadal-filtered winter-spring NPI and the bidecadal-filtered winter NPI, respectively, in order to take into account the seasonality of these two variations. The years of the phase-reversals are identified in 1922/23, 1948/49 and 1975/76 for the pentadecadal variation, and in 1923/24, 1946/47 and 1976/77 for the bidecadal variation. An averaged oscillation period is 53 (17) years for the pentadecadal (bidecadal) variability. The 17-year periodicity is consistent with a period estimated for the bidecadal variability over the northern hemisphere [*Mann and Park*, 1996].

An important question has been whether the simultaneous transition of the bidecadal and pentadecadal variations occurs accidentally or reflects a physical linkage between the two long-term climate variations. In order to address this question, we have employed a Monte Carlo simulation to test for the possibility that the independent bidecadal and pentadecadal variations do indeed reverse their phases simultaneously as observed in the NPI data. Assuming that the periods between the two successive bidecadal phase-reversals have a Gaussian mother distribution with an observed mean and standard deviation, we randomly generate 10,000 surrogate sequences of the years of bidecadal phase reversals with alternating polarities. Then, for each of the surrogate sequences of the bidecadal phase-reversal years, we judge whether the observed pentadecadal phase reversals are accompanied by surrogate bidecadal phase reversals occurring simultaneously. A surrogate sequence is judged to be synchronized with the observed pentadecadal phase reversals, when the following four conditions are satisfied. (1) Each of the three pentadecadal phase reversals is accompanied by a surrogate bidecadal phase reversal within the observed maximal year between the pentadecadal phase reversal and the corresponding bidecadal phase reversal. (2) The sum of the absolute values of difference years between the pentadecadal and bidecadal phase reversals is less than or equal to that observed. (3) The sign or polarity of the changes for the pentadecadal phase reversal is the same as that for the corresponding bidecadal phase reversal. (4) Between the bidecadal phase-reversals accompanying the two successive pentadecadal phase reversals, there are another two bidecadal phase reversals (the relative period being three). The population ratio for the number of sequences satisfying these conditions yields a p-value for the possibility that the quasi-simultaneous observation of three phase reversals between the pentadecadal and bidecadal variations may have occurred by chance.

Based on aforementioned pentadecadal (bidecadal) phase-reversal years for the winter-spring (winter) NPI time series, the differences in years between the pentadecadal and bidecadal phase reversals are equal to or less than two years, and the sum of the three absolute values of the differences is four years. The resultant p-value obtained via the Monte-Carlo simulation is very small at 2.2 %. Therefore, we interpret the observed simultaneous phase reversals of the bidecadal and pentadecadal signals with a relative period of three as evidence of a physical linkage between these two interdecadal climate oscillations. If one takes account of the possibility that all of the observed bidecadal phase-reversal years for the shifts are biased closer to the corresponding pentadecadal phase-reversal years (biased to yield a smaller p-value), one may employ three years for the maximal difference years and seven years for the sum of absolute difference years instead of the respective observed values. In this case, the p-value is 8.1 %, and hence the above interpretation still holds at the 90 % confidence limit.

Summary and Discussion

We have shown that the pentadecadal and bidecadal variations are synchronized with a relative period of three. The pentadecadal variation provides the basic timescale for regimes, whereas the bidecadal variation characterizes the rapid transition between regimes. The different seasonal dependence and the prominent time-frequency separation between the pentadecadal and bidecadal variations suggest that the two interdecadal climate variations arise from different mechanisms. The quasi-simultaneous phase reversals of these two signals, which appear unlikely to occur by chance, suggest that pentadecadal and bidecadal variations interact and this interaction between variations on different timescales implies that the nonlinearity in the pentadecadal and bidecadal variations plays an important role in the climate phenomenon over the North Pacific.

Several modeling papers attributed the interdecadal variations over the North Pacific to delay negative-feedback processes in the atmosphere and ocean, with the ocean playing an essential role in providing a memory or timescale for the variations [e.g., *Latif and Barnett,* 1994; *Gu and Philander,* 1997; *Yukimoto et al., submitted to J. Geophys. Res.,* 1998]. In these models, the midlatitude atmospheric circulation plays important roles to drive *delayed oscillators,* though specific processes responsible for the delays are different among papers. The author speculates that different oscillation mechanisms for the pentadecadal and bidecadal variations co-exist in the North Pacific sector, and the Aleutian low is the keystone to connect them. The author would like to further suggest a possibility that the bidecadal Aleutian-low variability drives a delayed oscillator for the pentadecadal variation, resulting in the synchronization between these two variations. *Wu et al.* [1993] showed that a forced delayed-oscillator can be phase-locked to the forcing with a relative period of three. Although they studied the phase-locking of the El Niños to the annual cycle reported by *Rasmusson and Carpenter* [1982], the phase-locking with the relative period of three has been found on the interdecadal timescale in the present study.

If we assume that the synchronization between the bidecadal and pentadecadal variations with a relative period of three observed in this century will continue, we can predict the next shift by predicting the third bidecadal phase reversal after the reversal that is a part of the climatic regime shift in the late 1970s. Making this assumption, we briefly examine a prediction regarding the next regime shift. After the phase reversal in the 1970s, two more phase-reversals occur in the bidecadal-filtered winter NPI data shown in Fig. 3b. Thus, the next bidecadal phase reversal may be accompanied by a pentadecadal phase reversal and mark the next regime shift. By assuming a Gaussian distribution for periods between successive bidecadal phase reversals, future bidecadal oscillation periods should be in the range from five to twelve years at the 95% confidence level. The last bidecadal phase reversal has been observed in 1994/1995. Therefore, the next bidecadal phase reversal will likely occur between 1999/2000 and 2006/2007. The year for a regime shift determined via an unfiltered time series differed by a few years from that obtained for the bidecadal phase reversal due to the effects of a superposed interannual variation. Therefore, the next climatic regime shift is most likely to occur in the coming decade, with the assumption that the synchronization will continue until the next shift.

An important problem for predicting the next regime shift is, therefore, whether the pentadecadal variation changes its phase quasi-simultaneously with the next bidecadal phase reversal. Although a synchronizing feature between the pentadecadal and bidecadal variations is observed for all three climatic regime shifts in the present century, it does not mean that the synchronization will continue into the future. Actually, near the beginning of this century, the synchronizing relationship does not seem to hold (see Fig. 3a).

If the pentadecadal variability changes its phase independently of the next bidecadal phase reversal, the strength of the Aleutian low will not exhibit a regime shift or a rapid transition from the present climate to another one. In this case, the Aleutian low strength will only change gradually with some interdecadal fluctuations. Consequently, interactions between the pentadecadal and bidecadal oscillations are likely to effect future climatic regime shifts like those which contributed so strongly to the 20th century climate history over the North Pacific.

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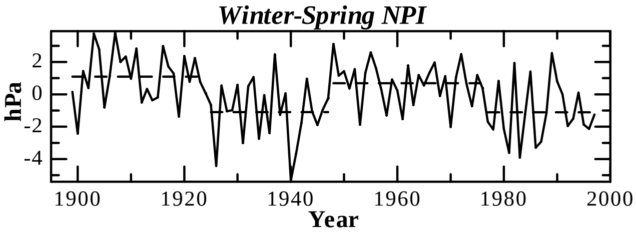

Figure 1. The North Pacific Index (NPI) averaged over winter-spring (Dec.–May) seasons (solid curve), and the respective averages for 1899–1924, 1925–1947, 1948–1976 and 1977–1997 (dashed lines). This graph is an updated version of Fig. 1c in *Minobe* [1997].

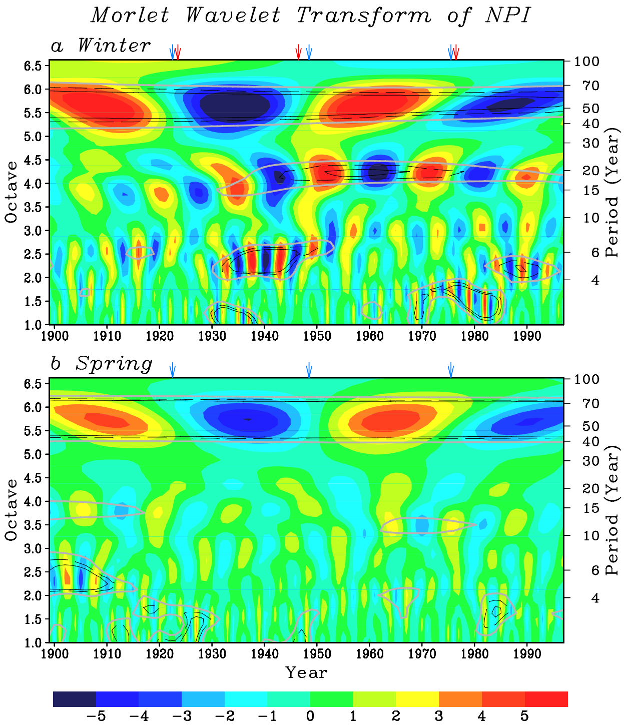

Figure 2. The NPI wavelet transform coefficient is plotted for (a) the winter season (Dec.–Feb.) and (b) the spring season (Mar.–May). The colors indicate the amplitude of the real part of the wavelet coefficient. The black-solid, black-dashed and gray contours indicate that the local wavelet spectrum (which is defined as the square of the absolute wavelet transform coefficient) is significant at the 95, 90 and 80 % confidence levels, respectively. The significance of the wavelet amplitude is evaluated by a Monte Carlo simulation based on a red-noise (AR-1) model for the observed lag-1 correlation coefficient using 10,000 surrogate time series. The blue arrows at the top of each panel indicate the phase-reversal years for the pentadecadal-filtered winter–spring NPI shown in Fig. 3a, and red arrows indicate the corresponding phase-reversal years for the bidecadal-filtered winter NPI in Fig. 3b. A octave for the left axes is given by log $_2(a)$, where a is a scale dilation parameter in units of years.

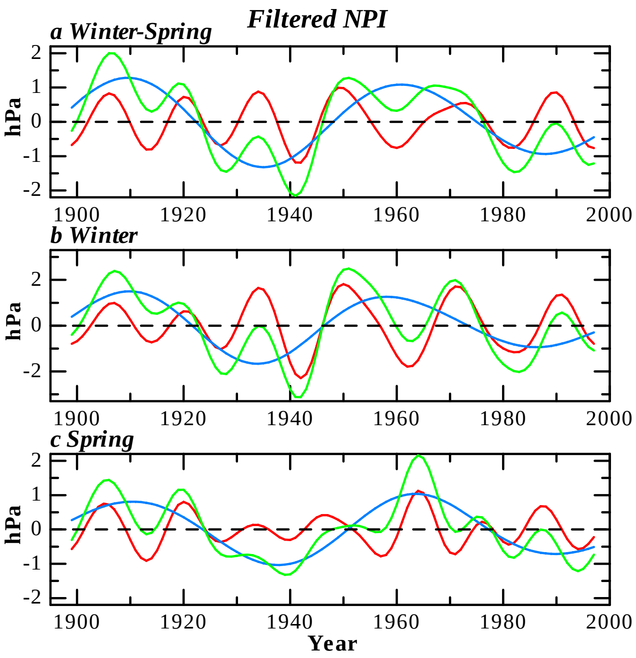

Figure 3. Filtered NPI (a) in the winter–spring, (b) in the winter and (c) in the spring season. The green curves indicate the 10–80-year band-pass filtered NPI data, the red curves indicate the 10–30-year band-pass filtered (bidecadal filtered) NPI data, and the blue curves indicate the 30–80-year band-pass filtered (pentadecadal filtered) NPI data.