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**Key Points:**
- We present a monthly resolved 106 year coral oxygen isotope record from the ECS
- Lead-lag correlation of summer coral record with winter PDO was found
- The East Asian summer monsoon is a possible driver of the PDO

**Supporting Information:**
- Readme
- Table S1
- Text S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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# A 106 year monthly coral record reveals that the East Asian summer monsoon modulates winter PDO variability

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**Abstract** The Pacific Decadal Oscillation (PDO) is a dominant climate mode in the Pacific Ocean and thought to be related to seasonal to decadal changes in sea surface conditions. Colonies of long-living *Porites* coral, widely used to reconstruct monthly to century-scale tropical sea surface temperature and sea surface salinity records, were discovered near Koshiki Island, Japan (31°N, 129°E). A monthly resolved, 106 year $\delta^{18}$O record revealed that distinct decadal-scale variability was significantly correlated with the PDO index. Our comparison showed 1 to 3 years lead-lag correlation of summer coral $\delta^{18}$O with the winter PDO index, suggesting that the East Asian summer monsoon (EASM) may act as the driving force of winter PDO variability over the last 100 years. Cross-spectral analysis between the winter PDO index and summer coral $\delta^{18}$O suggested that recent and future global warming may lead to a more frequent and/or stronger teleconnection between EASM and PDO.

## 1. Introduction

The marginal location of the East China Sea (ECS) between the Eurasian continent and the Pacific Ocean leads to complex oceanographic characteristics that are caused by regional- and global-scale climatic systems, such as the Changjiang discharge, transport by the Kuroshio Current, and monsoon rainfall [*Andres et al.*, 2009; *Lei*, 2013; *Mao et al.*, 2011; *Siswanto et al.*, 2008; *Steinman et al.*, 2012]. Previous studies have suggested that the PDO is connected to and affects the adjacent climate mode and oceanographic conditions, such as the El Niño Southern Oscillation (ENSO) [*Steinman et al.*, 2012], the Asian monsoon [*Lei*, 2013; *Mao et al.*, 2011], typhoon occurrences [*Izumiya and Koseki*, 2010], and the Kuroshio Current [*Andres et al.*, 2009]. Because long-term temperature observations from the North Pacific are limited, an extended PDO record has been reconstructed using proxy-based archives; however, these data are primarily based on terrestrial proxies, such as tree rings [*D'Arrigo and Wilson*, 2006], documentary records [*Shen et al.*, 2006], and lake sediments [*Steinman et al.*, 2012], or are based on low-resolution marine archives of ocean sediments [*Barron and Anderson*, 2011].

Coral proxy data may provide a high-resolution (monthly to seasonal) history of marine environmental changes for century-long intervals [*Cobb et al.*, 2001; *Watanabe et al.*, 2011]. In the tropical and subtropical ocean, coral records have been widely used for reconstructing century-scale sea surface temperature (SST) and sea surface salinity (SSS) histories because the coral oxygen isotope ($\delta^{18}$O) reflects both ambient temperature and water balance, which are mainly related to SSS. PDO signals have been found in coral records from tropical and subtropical areas [*Asami et al.*, 2005; *Crueger et al.*, 2009; *Deng et al.*, 2013; *Felis et al.*, 2010]; however, these signals have not been observed in the ECS. Although it is rare to encounter long-living coral colonies at midlatitude locations, we recently found a 100 year old colony of *Porites* coral, a species widely used in paleoclimate research, from Koshiki Island in southwestern Japan, which is near the latitudinal limit of the species. In this study, we present a monthly resolved, 106 year coral $\delta^{18}$O record to evaluate PDO variability in the ECS.

## 2. Materials and Methods

### 2.1. Coral Drilling

On 24 September 2008, a coral core with a length of 170 cm and a diameter of 5 cm was drilled from the maximum growth axis of a healthy and well-developed massive coral colony of *Porites heronensis* at a water

  

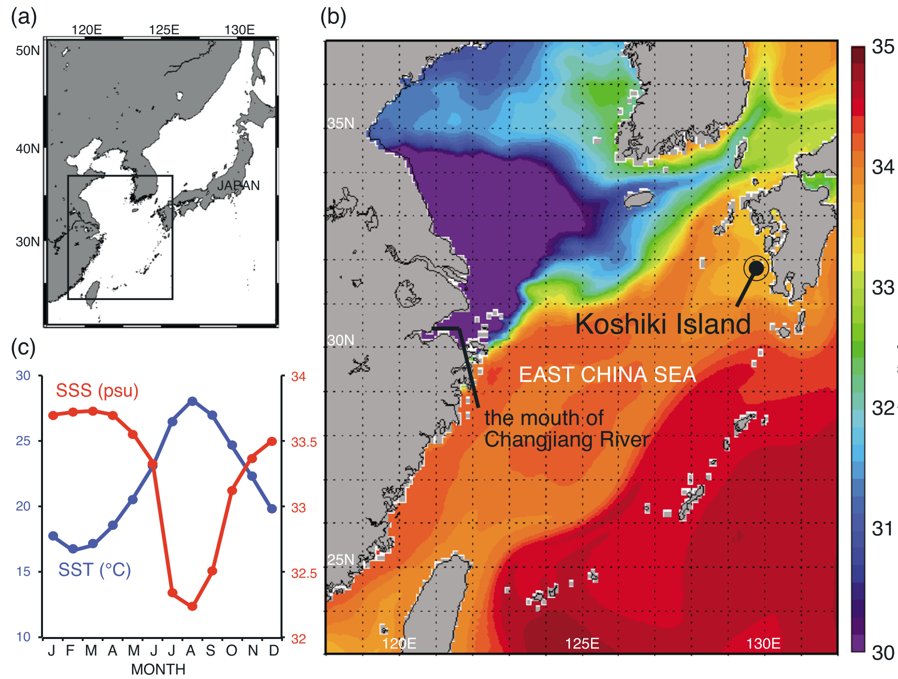


**Figure 1.** (a) Map of the Koshiki coral and observation sites in the northwestern Pacific Ocean. (b) Summer sea surface salinity (SSS) distribution in the eastern China Sea. (c) Monthly mean sea surface temperature (SST) and SSS at the Koshiki Island coral site during 1999 and 2008 and during 1986 and 2001, respectively.

depth of 5 m near Shimo-Koshiki Island, which is located 38 km from the southern part of the Kyushu Islands, Japan (Figure 1). Moreover, 5 mm thick slabs were cut and X-rayed from the core (Figure S1). To obtain carbonate powders for geochemical analysis, 1.0 mm thick ledges were prepared along the maximum growth lines on each slab, which corresponded approximately with a single corallite in this coral specimen.

### 2.2. Oxygen Isotope Analysis

The $\delta^{18}$O was obtained by weighing a total of 1086 samples into 80 mg (±15 mg) aliquots of powder that were analyzed with a Finnigan MAT 253 stable isotope ratio mass spectrometer system after the reaction with 100% $H_3PO_4$ at 70°C in an automated carbonate device (Kiel IV). The internal precision was 0.02‰ for $\delta^{18}$O using replicate measurements of the NBS-19 standard (1$\sigma$, $n = 10$). The coral records were interpolated to a monthly resolution with 12 samples per year using Analyseries software [*Paillard et al.*, 1996].

### 2.3. SST and SSS Data

Near the coral site, daily ferry-based sea surface temperature (SST) measurements are available from 1999 (Kagoshima Prefectural Fisheries Technology Development Center); monthly ferry-based sea surface salinity (SSS) measurements are available from 1986 to 2001 (Japan Oceanographic Data Center, http://www.jodc.go.jp) [*Miyazawa et al.*, 2009] (Figure 1).

### 2.4. Data Analysis

Spectral analysis in Figures 3b and 3c was performed by the multitaper method in kSpectra 3.4.1 (www.spectraworks.com) [*Ghil et al.*, 2002]. The wavelet coherence analysis [*Grinsted et al.*, 2004] in Figure 3d was performed using the Matlab package available on the website of the National Oceanography Centre, UK (http://noc.ac.uk/using-science/crosswavelet-wavelet-coherence).

## 3. Results and Discussion

In this study, $\delta^{18}$O in coral skeletons ($\delta^{18}O_{coral}$) averaged −4.37‰ and ranged from −5.81 to −2.05‰ (Figure 2). A total of 106 distinct cyclic variations were observed in the coral $\delta^{18}$O profile, which corresponded

  

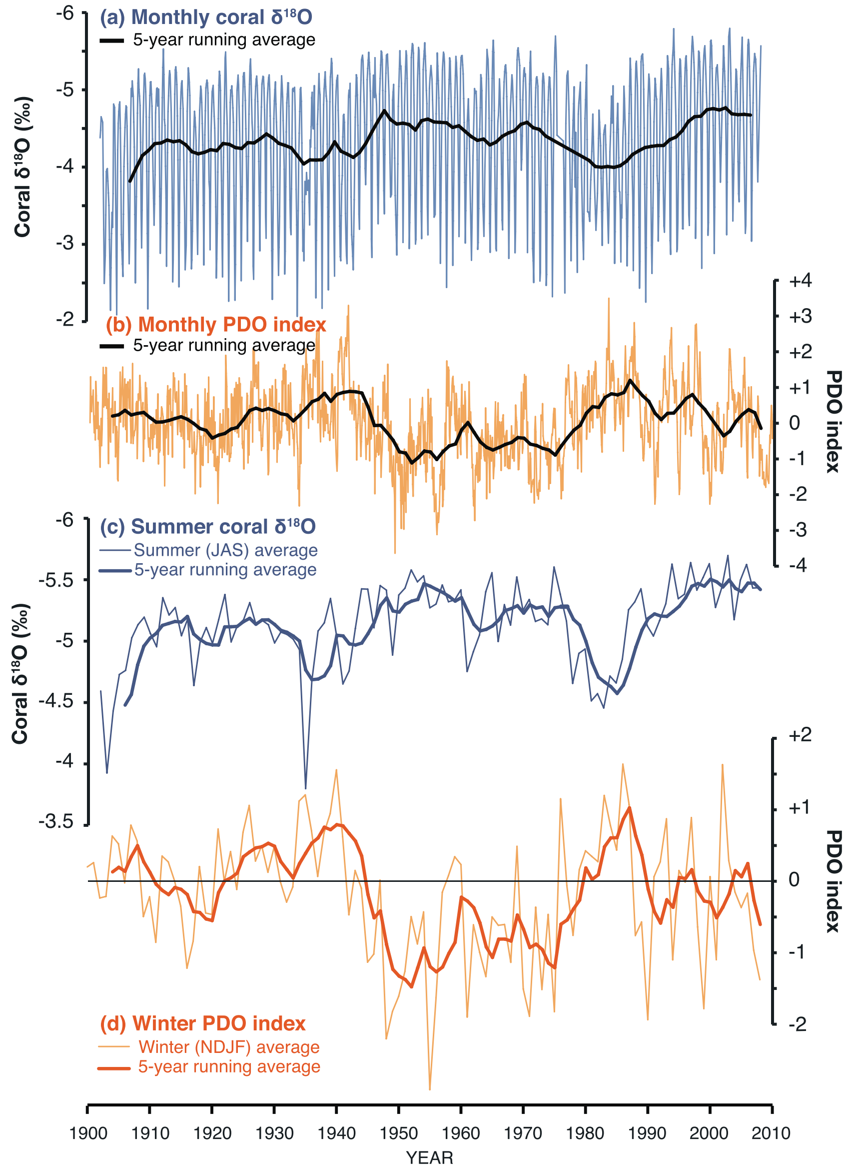


**Figure 2.** (a) Monthly Koshiki coral oxygen isotope record (thin line) and 5-year running average annual mean time series (solid line). (b) Monthly Pacific Decadal Oscillation (PDO) index (thin line) and 5 year running average annual mean time series (solid line) [*Paillard et al.*, 1996]. (c) Summer (July to September) Koshiki coral mean oxygen isotope record. (d) Winter mean (November to February) PDO index [*Mantua et al.*, 1997; http://jisao.washington.edu/pdo/].

to the couplets of annual bands observed in the corresponding X-ray image. This finding suggested that the coral $\delta^{18}$O variations captured the seasonal variability in this region. Moreover, $\delta^{18}$O in biogenic carbonates in general reflects change in both SST and $\delta^{18}$O in seawater. In this region, the seasonal SST difference is 11.6°C, ranging from 28.3°C in August to 16.7°C in February; the seasonal SSS difference is 1.5 practical salinity unit (psu), ranging from 33.2 psu in August to 34.7 psu in March (Figures 1b and 1c: monthly average from 1999 to 2008). Using the relationship between SSS and $\delta^{18}$O in seawater ($\delta^{18}O_{sw}$) in the ECS [*Oba*, 1988; $\delta^{18}O_{sw} = 0.203 * SSS - 6.76$], the average seasonal SSS difference of 1.5 psu theoretically contributed to 0.3‰ of the $\delta^{18}O_{coral}$ from 1999 to 2008, implying that 2.3‰ of the mean seasonal $\delta^{18}O_{coral}$ difference during this period can be explained by both SSS (13%) and SST (87%) variations. The −0.2 ‰ per 1°C temperature dependency in the seasonality of Koshiki $\delta^{18}O_{coral}$ agrees with observations of corals in other tropical and subtropical regions, and abiotic aragonite (Figures S2 and S3 in the supporting information: see more discussion in the supporting information). On Koshiki Island, the highest (lowest) SST and lowest (highest) SSS typically occurred at the same time, i.e., the highest SST and lowest SSS occurred in August, and the lowest SST and highest SSS occurred in February, (Figure 1c). This result indicated that both temperature and salinity similarly affected the seasonality of the coral $\delta^{18}$O record and enhanced the ability of the coral record to capture PDO variability. Our monthly coral $\delta^{18}$O record spans twice the temporal length of the regional surface water condition record; the coral record also provides a data set that is capable of reconstructing the PDO variability in the ECS and is comparable with instrumental SST and SSS data.

The 5 year moving average profile of Koshiki $\delta^{18}O_{coral}$ was significantly correlated with the PDO index (Figures 2 and 3a), demonstrating that the PDO was teleconnected in the ECS during the last 100 years. Such synchronized variability between $\delta^{18}O_{coral}$ and the PDO has been reported in coral $\delta^{18}$O records from tropical and subtropical regions, including the western subtropical Pacific (the Ogasawara Island [*Felis et al.*, 2010] and Guam [*Asami et al.*, 2005]), the western Indian Ocean (Madagascar [*Crueger et al.*, 2009; *Grove et al.*, 2013]), and the South China Sea (Hainan Island [*Deng et al.*, 2013]). During the positive phase of the PDO (cooler period in the central North Pacific region) in the Koshiki coral record (Figure 2), the combined effect of higher SST and lower SSS (lower $\delta^{18}O_w$) increased $\delta^{18}$O.

A comparison of coral $\delta^{18}$O with the PDO index revealed that the highest correlation occurred between the Koshiki summer coral record (July to September) and the winter PDO index (November to February) (Figure 3a). Moreover, spectral analysis using the multitaper method (MTM) confirmed that a 53.5 year cycle is significant both in the Koshiki coral summer $\delta^{18}$O record and winter PDO index (Figures 3b and 3c). Although the interannual variability in coral summer $\delta^{18}$O was also found on 6.2, 3.0, and 2.5 year cycle, the cross-wavelet analysis for summer coral $\delta^{18}$O and the winter PDO index showed the strongest relationship on decadal time scale ($>$30 years; Figure 3d).

The higher summer coral $\delta^{18}$O phase during the periods 1905–1910, 1935–1945, and 1980–1990 corresponded with positive events in the winter PDO index; the lower summer coral phase during the periods 1910–1915 and 1945–1980 corresponded with negative events in the winter PDO index (Figure 2). Although long-term SSS observations are lacking in the ECS, the instrumental SST record is relatively sufficient over the last 100 years (Japan Meteorological Agency). The historical SST record in the northern ECS region revealed that the summer (July to September) SST varied by 1.3°C during last 100 years (2$\sigma$), corresponding to a 30% variability in Koshiki summer $\delta^{18}$O and suggesting that PDO variability in coral $\delta^{18}$O is primarily affected by SSS fluctuations (70%). *Siswanto et al.* [2008] demonstrated the relationship between summer SSS in the ECS and the Changjiang River discharge. The freshwater discharge from the Changjiang River has significantly influenced the spatial and temporal distribution of SSS in the ECS (Figure 1). The maximum flux of the Changjiang River, which occurs in July [*Siswanto et al.*, 2008], causes the lowest summer SSS to occur in August in areas around Koshiki Island. This low SSS (low $\delta^{18}O_{seawater}$) coincided with the summer minima in coral $\delta^{18}$O and maximum SST in August. The East Asian summer monsoon (EASM) causes the high amount of precipitation in summer over eastern Asia [*Mao et al.*, 2011], leading summer discharge of the Changjiang River. Therefore, our data imply that the variability in sea surface condition of ECS was primarily influenced by the Changjiang River summer discharge through EASM. *Chan and Zhou* [2005] revealed that the interdecadal variations in the early (May–June) summer monsoon rainfall over South China could be related to El Niño–Southern Oscillation (ENSO) and PDO. Our comparison of spectral analysis did not show any strong relationship between the Koshiki summer coral record and ENSO index (Niño 3–4 SST, Figure S4).

The highest correlation between the summer coral record and the winter PDO index occurred when summer coral record led by a 2 year time lag (Figure 3a), suggesting that the EASM may be a possible driving force of winter PDO variability in this region. Although complex mechanisms with seasonal to interannual time scale and a combination of regional- and global-scale continental and oceanic climatic forcings affect PDO variability in the ECS, such as the Kuroshio Current [*Andres et al.*, 2009] and monsoon [*Lei*, 2013; *Mao et al.*, 2011] and typhoon rainfall [*Izumiya and Koseki*, 2010], the summer monsoonal rainfall in East Asia is strongly affected by the Siberia Low, the subtropical ridge over the western Pacific, and the North Pacific High [*Zhao and Zhou*, 2009].

The instrumental SST record indicates that a 1.21°C warming occurred in the northern ECS over the last 100 years (*Japan Meteorology Agency*; http://www.data.kishou.go.jp/kaiyou/shindan/a_1/japan_warm/japan_warm.html). Cross-wavelet analysis for summer coral $\delta^{18}$O and the winter PDO index (Figure 3d) demonstrated that a low-frequency period (circa 5 and 8–10 years) appeared around the beginning 1990s,

  

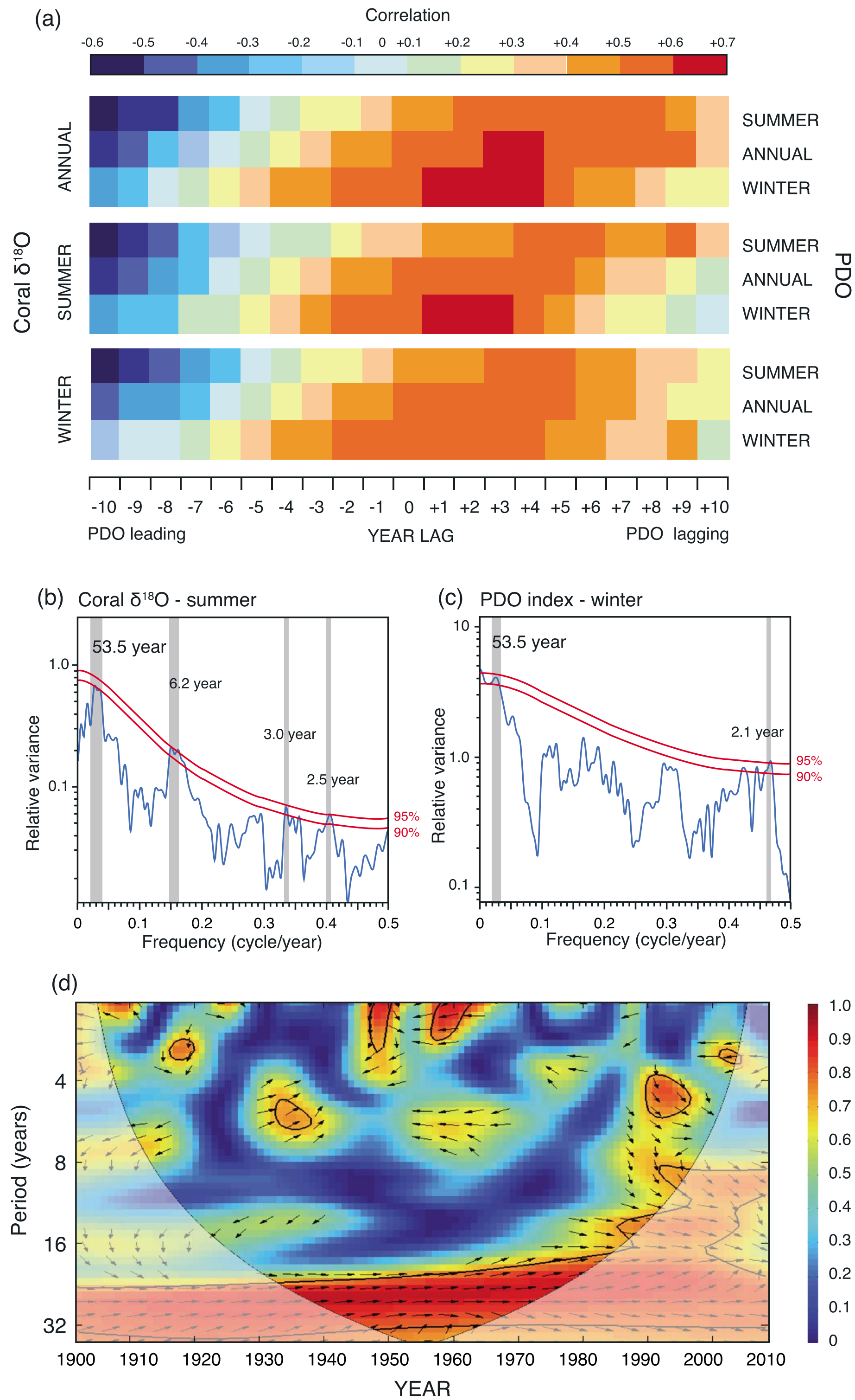


**Figure 3.** (a) Lagged cross correlations between Koshiki coral $\delta^{18}O$ and PDO variability. Note that the highest correlation occurred between summer Koshiki coral $\delta^{18}O$ and the winter PDO viability with an approximately 2 year time lag. Spectral analysis results using the multitaper method (MTM) with a red noise null hypothesis [*Ghil et al.*, 2000] for (b) the Koshiki summer coral record and (c) the winter PDO index (number of tapers, 3; bandwidth parameter, 2; 90% significance levels are indicated). (d) Wavelet coherency between the Koshiki summer coral record and the winter PDO index.

suggesting that the EASM effects on the winter PDO became more frequent with the recent warming sea surface conditions. Future global warming may produce more frequent and/or stronger teleconnections between the EASM and the PDO. The mechanisms behind the observed variations in the Koshiki coral record remain complex, and additional research is necessary.

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