

## Sardine biomass is poorly correlated with the Pacific Decadal Oscillation off California

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[1] Pacific sardines (*Sardinops sagax*) fluctuate widely in abundance over interannual to multidecadal time scales. For Pacific sardines, there have been repeated attempts to link fluctuations in biomass to indices of climatic variability, such as the Pacific Decadal Oscillation (PDO). Correlations between the PDO with periods of 40–76 years, and sardine biomass with periods of 40–70 years, have been inferred using 90-year time series (e.g. 1920–2010). The inferred correlations cannot be tested because the long-period fluctuations are outside the observation window that can be analysed statistically, i.e. the period (40–76 years) is greater than half the length of the series (45 years). To date, there has been no attempt to test the relationship between low-frequency fluctuations of sardine biomass and the PDO using longer paleoclimatic time series proxies for sardine biomass and the PDO. Here we use a 370-year record of paleoclimatic proxies to show that fluctuations in sardine biomass off California are not related to the PDO, despite the appearance of correlation in the 90-year record from 1920 to the present day. **Citation:** McClatchie, S. (2012), Sardine biomass is poorly correlated with the Pacific Decadal Oscillation off California, *Geophys. Res. Lett.*, 39, L13703, doi:10.1029/2012GL052140.

### 1. Introduction

[2] Low-frequency fluctuations of small pelagic fish populations in relation to climate variability are important for planning commercial fishing investment [*Klyashtorin and Lyubushin*, 2007], for developing environmental indices for stock assessment [*Jacobson and MacCall*, 1995; *McClatchie et al.*, 2010], and for integrated ecosystem assessments [*Link*, 2002]. Several studies concluded that there are environmentally driven fluctuations in small pelagic fish populations with periods of 40–70 years [*Baumgartner et al.*, 1992], 50–75 years [*Ware*, 1995], 65 years [*Klyashtorin and Lyubushin*, 2007] and 100–120 years [*Ito*, 1961]. Pacific sardines (*Sardinops sagax*) fluctuate widely in abundance over interannual to multidecadal time scales [*Baumgartner et al.*, 1992; *Schwartzlose et al.*, 1999; *MacCall*, 2011]. For sardines, there have been repeated attempts to link biomass fluctuations to indices of climatic variability, like the Pacific Decadal Oscillation

(PDO) [*Schwartzlose et al.*, 1999; *Chavez et al.*, 2003; *Alheit et al.*, 2009; *Zwolinski and Demer*, 2012]. Correlations between the PDO with periods of 40–76 years [*Overland et al.*, 2008], and sardine biomass with periods of 40–70 years [*Baumgartner et al.*, 1992], have been inferred using 90-year time series (e.g. 1920–2010) [*MacCall*, 1996; *McFarlane et al.*, 2002; *Chavez et al.*, 2003; *MacCall*, 2009; *Zwolinski and Demer*, 2012]. These correlations cannot be tested because the long-period fluctuations are outside the observation window that can be analyzed statistically, i.e. the period (40–76 years) is greater than half the length of the series (45 years) [*Legendre and Legendre*, 1994]. Using 370 years of paleoclimatic data, I show there is no significant correlation between the PDO and sardine biomass.

[3] On longer time scales the paleoclimatic record from fish scales in sediment cores shows that large fluctuations in Pacific sardine and northern anchovy off California, including extreme events (outbreaks and crashes) of the order of 3 standard deviations from the mean, occur in the absence of fishing [*Soutar and Isaacs*, 1974; *Baumgartner et al.*, 1992]. The mechanisms driving these fluctuations are poorly understood. Abundance of modern sardine is affected by environment, biological interactions, and by commercial fishing. Modern data show that forces driving abundance fluctuations are primarily environmental and strongly influenced by ENSO (El Niño-Southern Oscillation) events [*MacCall*, 1996; *Norton and Mason*, 2005; *Song et al.*, 2012]. Key factors include temperature, level of production, large scale advective flow, mesoscale variability and predation pressure. Although alternation of species, or species groups (e.g. sardine, anchovy and mackerels) may also play a role in determining abundance [*MacCall*, 1996], there appears to be little evidence for alternation of species in the paleoclimatic record [*Field et al.*, 2011]. In addition to environmental influences, fishing pressure also has an influence on population abundance, but simulation showed that fishing intensity affects the magnitude, but not the period, of fluctuations [*MacCall*, 1979].

[4] Long time series are needed to statistically test for correlation between the PDO and sardine abundance. To date, there has been no attempt to test the relationship between low-frequency fluctuations of sardine biomass and the PDO using longer time series proxies for sardine biomass and the PDO. Here I use a 370-year record of paleoclimatic proxies [*Baumgartner et al.*, 1992; *Gedalof and Smith*, 2001] to show that fluctuations in sardine biomass off California are not related to the PDO, despite the appearance of correlation in the 90-year record from 1920 to the present day [*MacCall*, 1996; *McFarlane et al.*, 2002; *Chavez et al.*, 2003; *MacCall*, 2009; *Zwolinski and Demer*, 2012]. The proxy for the PDO (henceforth referred to as

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‘paleo-PDO proxy’) is derived from tree ring data along the west coast of North America [Gedalof and Smith, 2001]. The proxy for sardine biomass (henceforth referred to as ‘paleo-sardine proxy’) is derived from fish scales in sediment cores from the Santa Barbara Basin (SBB), Southern California [Baumgartner et al., 1992] (see section 2 for details). By using paleoclimatic series [Baumgartner et al., 1992; Gedalof and Smith, 2001] I overcome the statistical limitations of short time series that prevent quantification of any relationship between the PDO and low-frequency variability of sardine biomass.

[5] One potential problem with interpreting the paleo-sardine proxy as biomass is that the fluctuations in the series may reflect a shift north or south along the west coast of the center of the fish population, rather than a change in biomass. Ideally I would compare time series from two or more spatially separated sites and test for coherence between the series to address this issue. Unfortunately, there are few locations with anoxic sediments that produce varved layers, and the SBB core data are the only series available on the Pacific west coast.

[6] Another problem is that the Santa Barbara Basin may not be representative of the broader region. However, Field et al. [2006] noted: “Although the Santa Barbara Basin lies within an upwelling environment, regional- and basin-scale processes are considered more influential than high-frequency, local processes. The major interannual, decadal, and secular variations observed in sea surface temperature (SST) and zooplankton abundance at or near the SBB clearly follow the same patterns of variability observed coherently throughout the California Current.” [Field et al., 2006].

[7] The PDO is derived from the spatial field of sea surface temperatures using a common method of reducing the dimensionality of spatio-temporal climate data, and is the first principal component of sea surface temperature in the North Pacific, north of 20°N [Mantua et al., 1997]. Low-frequency oscillations in northeast Pacific sea surface temperatures and alongshore winter wind stress have dominant periodicities of about 25 and 50 years [Ware, 1995]. Variability occurs at all scales in these environmental time series, but Ware [1995] determined that there were dominant periodicities at 2–3, 5–7, 21–25 and 50 years. The ENSO-scale periodicities (5–7 years) were particularly prominent in the time series of winter wind stress. In contrast the very-low-frequency component (50 years) dominated the variability in sea surface temperatures. Ware’s work [Ware, 1995] indicates that the dominant periodicities for variation in sea surface temperatures (50–75 years) are the same order as the low-frequency fluctuations in sardine abundance (40–70 years [Baumgartner et al., 1992]). However, the low-frequency component of the temperature series was difficult to resolve [Ware, 1995] because of the relative lengths of the period and the time series, as mentioned above.

[8] One might argue that correlating the paleo-PDO proxy with the paleo-sardine proxy from the SBB in Southern California may not be informative. However, sardine seasonally migrate along the coast from a spawning ground off Southern and Central California to the Pacific Northwest, as far north as northern Vancouver Island. As such, the mature fish that migrate effectively integrate the environmental conditions along the Pacific west coast, rather than just in the

Southern California area, so relating their biomass to the PDO is reasonable.

## 2. Methods

### 2.1. Paleoclimatic Proxy Series

[9] The paleo-sardine proxy data were digitized from Baumgartner et al. [1992]. In that study a paleo-sardine proxy was constructed from sardine scale deposition rates, and a linear regression relating the biomass of two-year and older sardine to scale deposition rates. Scale deposition rates were determined from four box cores covering A.D. 1810–1970 [Soutar and Isaacs, 1974], combined with two piston cores covering the period A.D. 270–1810, all collected from the Santa Barbara Basin. The sample resolution of the combined chronologies is 10 years [Baumgartner et al., 1992], producing a decadal series. In this study I restricted my analysis to 1600–1970 to permit comparison with the paleo-PDO proxy.

[10] A paleo-PDO proxy for the March–May season from 1600–2000, constructed from 6 tree ring chronologies of mountain hemlock (*Tsuga mertensiana*) from southern Oregon to the Kenai Peninsula, Alaska, was digitized from Gedalof and Smith [2001], producing an annual series. The paleo-PDO proxy is the first principal component of a robust mean from six tree ring time series, and is totally independent of the modern PDO. Summer temperature is the dominant factor affecting the tree rings of mountain hemlock at higher altitude and winter precipitation is the dominant influence at lower altitudes [Gedalof and Smith, 2001]. Sample replication was acknowledged to be poor prior to 1650 [Gedalof and Smith, 2001]. The paleo-PDO proxy was averaged over 10-year periods for cross-correlation with the paleo-sardine proxy.

### 2.2. Modern Series

[11] The modern PDO index from 1900–2012 was downloaded from a University of Washington Joint Institute for the Study of the Atmosphere and Ocean web page ([http://jisao.washington.edu/data/#time\\_series](http://jisao.washington.edu/data/#time_series)). A time series of sardine fishery landings was digitized from Schwartzlose et al. [1999], and sardine spawning stock biomass was obtained from the most recently published Pacific sardine stock assessment [Hill et al., 2011].

### 2.3. Analyses

[12] All analyses in this paper are based on previously published data [Baumgartner et al., 1992; Schwartzlose et al., 1999; Gedalof and Smith, 2001; Hill et al., 2011]. The length of the series and the spacing of data in the series limits the periods that can be resolved. To resolve an oscillation like the PDO with a period of 40–76 years requires a series twice as long as the maximum period (150 years, and preferably 300 years) [Legendre and Legendre, 1994]. The 370-year long paleoclimatic time series used in this study is long enough to resolve the PDO, but the 90-year long modern series for which matching fishery landings data exist is not long enough.

[13] The smallest period that can be resolved in a series depends on the sample intervals. Nyquist theory demands that at least two points must be available within each period to be able to resolve the period [Legendre and Legendre, 1994]. The resolution of the paleo-sardine proxy from

sediment cores is only 10 years, in contrast to the PDO proxy from tree rings which is annual. This means that the resolution of the sardine proxy would be inadequate to resolve ENSO periodicity which is 4–7 years.

[14] The resolution of the paleo-sardine proxy also limits the cross-correlation analysis to decadal intervals, so prior to this analysis, the paleo-PDO series was averaged into 10-year intervals. For the purpose of comparing time series, the regularized series were standardized by  $(x - \bar{x})/SD$  to produce series with comparable standard deviation units. Before autocorrelation or cross-correlation analysis, the regularized series were detrended using first differencing. Autocorrelations and cross-correlations were tested at lags of up to one-third the length of each series. All analyses were done with the R statistical language [Ihaka and Gentleman, 1996].

### 3. Results and Discussion

[15] The historical trend of the Pacific sardine fishery and sardine biomass off California shows similarity to the fluctuations in the PDO (Figure 1a). The PDO has been used to model variability in climate patterns in the North Pacific [Mantua et al., 1997; Bond et al., 2003; Overland et al., 2006, 2010]. While the monthly values of PDO anomalies vary considerably, the shift from predominantly negative to positive anomalies in the California Current system, referred to as a shift from the cool phase (PDO<sup>-</sup>) to the warm phase (PDO<sup>+</sup>), occurred in phase with the collapse of the sardine fishery in the 1930s, and subsequent recovery in the late 1980s (Figure 1a). A key feature of the PDO time series is the shift from PDO<sup>-</sup> to PDO<sup>+</sup> in 1976/77, interpreted as a “regime shift” in oceanographic and atmospheric conditions. About 10 years after the 1976/77 “regime shift” from cool to warm conditions in the California Current system, the sardine population off California began to increase rapidly, as a recovery from its collapsed state began (Figure 1a). The population continued to increase, although with considerable variability in rate of growth, for the next ≈15 years, but began a declining trend after 2000 (Figure 1a). There was controversy [Greene, 2002; Chavez et al., 2003; Peterson and Schwing, 2003] as to whether a second phase shift of the PDO occurred when PDO<sup>+</sup> reverted to PDO<sup>-</sup> in 1999–2002, coincident with the shift to a downward trend in the sardine abundance (Figure 1a).

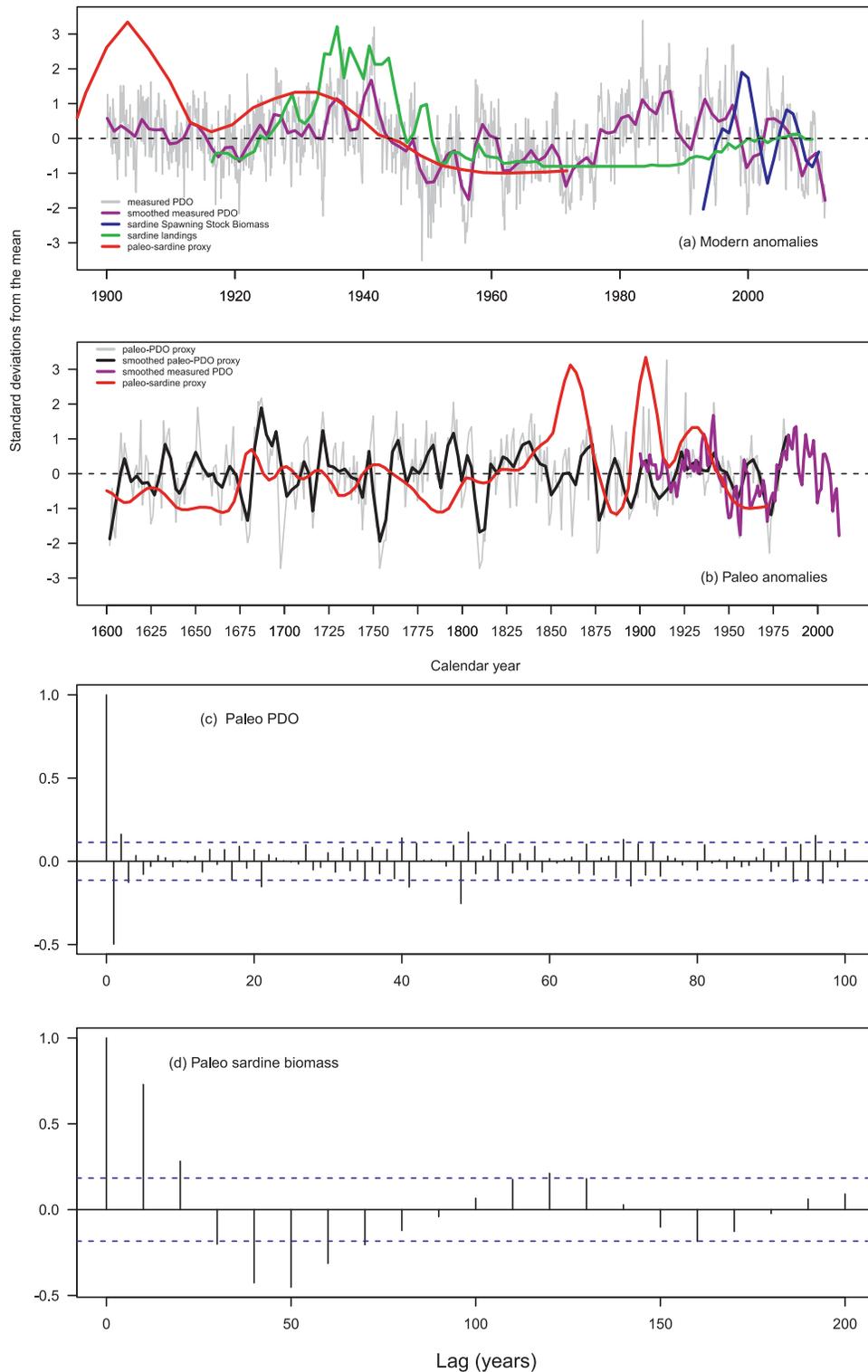
[16] Subsequent data showed that the PDO during 2000–2010 included fluctuations between positive and negative phases, fueling doubts about the regime shift concept, and methods for detecting regime shifts [Rudnick and Davis, 2003; Overland et al., 2006, 2008]. It is now known that the PDO, which is the leading pattern of climate variability in the North Pacific, incompletely characterizes North Pacific climate [Bond et al., 2003]. Overland et al. pointed out that: “If the underlying [climate] process [of the PDO] were more cyclic and deterministic, then there would be more possibility to say when a future shift might occur. But with red noise, the large shifts occur when the different contributions add together in a random manner, with little potential predictability. Thus if the true underlying climate process was close to red noise, predictions from extrapolation by curve fitting of 20th century data would be a misleading and dangerous exercise” [Overland et al., 2010].

[17] Recently, Zwolinski and Demer [2012] inferred, from earlier studies and recent surveys, that Pacific sardine are currently showing trends similar to the fishery collapse of the 1940s. They suggested that a cold regime, described as a predictable phase of a cyclic PDO, combined with fishing pressure on the larger, more fecund fish, and increasing abundance of mackerels (a likely competitor and predator) was driving another collapse of the sardine fishery [Zwolinski and Demer, 2012]. The implication drawn from their review of the literature, is that the “cold regime” of the PDO is unfavorable to sardine. Here I question whether the PDO is the correct index of environmental variability to relate to sardine variability.

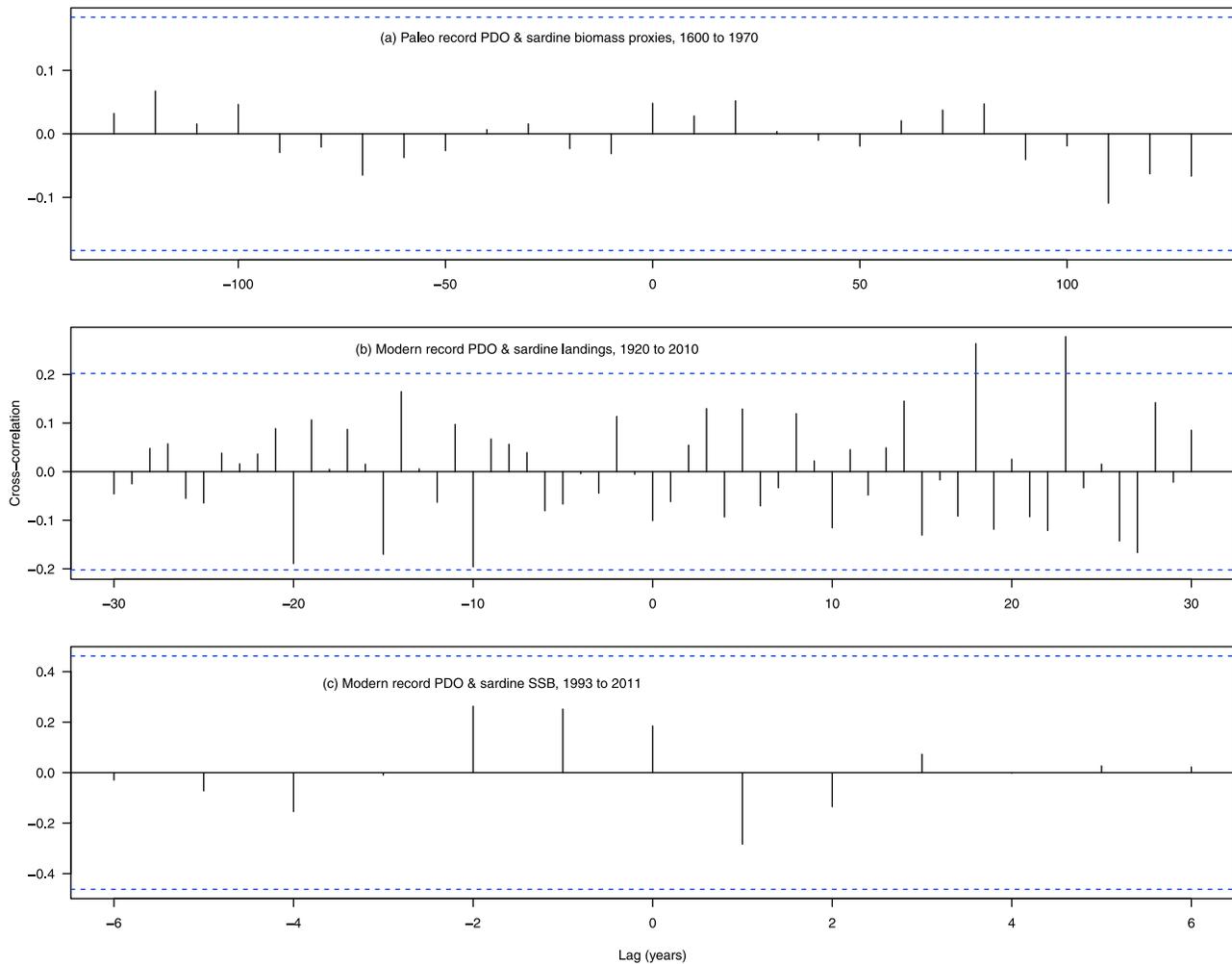
[18] For the period of overlap between 1900 and 1970, the paleo-PDO proxy shows anomalies of approximately the same magnitude (approx. 2 standard deviations from the mean) as the modern PDO derived from SST (Figure 1b). The phase of the two series is also coherent during the 70 years when they overlap (Figure 1b). The coherence between the modern PDO and the paleo-PDO suggests that the paleo-PDO is a reasonable approximation to the actual PDO series. A full validation of the chronology for this paleo-PDO proxy was published by Gedalof and Smith [2001].

[19] Comparing the paleo-sardine proxy with the paleo-PDO proxy, there was no extreme fluctuation in the paleo-PDO series at the time when the extreme events occurred in the paleo-sardine record, nor at reasonable lags given a maximum lifespan of about 8 years for sardine (Figure 1b). Unfortunately there is no overlap between the paleo-sardine proxy, which ends in 1973, and modern estimates of sardine spawning stock biomass that begin in 1993 (Figure 1a). Fishery landing data do overlap with the paleo-sardine proxy, but the relationship between fishery landings data and sardine biomass is complicated by the development phase of the sardine fishery, as well as by subsequent changes in effort. The rising arm of the sardine landings curve reflects increasing exploitation of the resource as the fishery developed in the 1920s, rather than increasing biomass of sardine (Figure 1a). In fact, contrary to appearance given by the fishery landings data, the paleo-sardine proxy indicates that sardine biomass was greater than the mean in the years (1920–1930) immediately prior to the development of the fishery in California. These data show that that the lead up to the peak in fishery landings does not reflect an increase from low sardine biomass (Figure 1a).

[20] Autocorrelation of the detrended (first-differenced) paleo-PDO proxy shows no significant periodicity over lags up to one-third the length of the time series (Figure 1c). We note that Gedalof and Smith [2001] reported intervals when there is no evidence of regime shifts, e.g. 1840–1923, and there are other periods where most of the inter-decadal activity (periods 30–70 years) is concentrated, e.g. prior to 1840. Given these qualifications, it is reasonable to say there is no consistent periodicity in the series. The results presented here show that the paleo-PDO proxy has no dominant periodicity, which is a conclusion consistent with analyses of the modern PDO summarized by Overland et al. [2006, 2008, 2010]. In contrast to the paleo-PDO proxy, the paleo-sardine record shows significant negative autocorrelation at lags of 40–60 years (Figure 1d), indicating a period of 80–120 years, partially supported by the positive autocorrelation at 100–120 years. This periodicity is somewhat longer than



**Figure 1.** Time series of climate indices and sardine biomass. (a) Time series of the PDO based on sea surface temperatures for the last 111 years overlaid on three independent time series indices of sardine biomass. (b) Time series of the paleo-PDO proxy and paleo-sardine proxy over 370 years. The PDO based on sea surface temperatures is overlaid on the paleo-PDO proxy in the last 111 years to show the coherence between the modern and paleoclimatic indices. Smoothed curves are fitted by locally weighted robust regression (LOWESS). (c) Autocorrelation of the detrended (first-differenced) annual paleo-PDO proxy derived from tree rings. (d) Autocorrelation of the detrended decadal (10-year resolution) paleo-sardine proxy. Dotted lines indicate significance level ( $p = 0.05$ ).



**Figure 2.** Cross-correlation between detrended (first-differenced) paleo-PDO proxy and paleo-sardine proxy at three different time scales. (a) At a  $\approx 370$ -year time scale, paleo-PDO proxy is derived from tree rings and the paleo-sardine proxy is derived from fish scales in sediment cores. The paleo-PDO proxy was averaged over 10-year periods to match the resolution of the paleo-sardine proxy (see Figure 1). (b) At a  $\approx 90$ -year time scale, the PDO is derived from Sea Surface Temperatures (SST) and sardine abundance is represented by commercial landings. (c) At  $\approx 20$ -year time scale, the PDO is derived from SST and sardine biomass is presented as Spawning Stock Biomass (SSB). Dotted lines indicate significance level ( $p = 0.05$ ).

that found by *Baumgartner et al.* [1992], who reported peaks in the power spectra of the paleo-sardine proxy at 40, 60 and 70 years.

[21] The detrended PDO and indices of sardine biomass were not correlated at any of the three scales I tested. These three scales were 370 years from 1600–1970 (Figure 2a), 92 years from 1920–2012 (Figure 2b), and 18 years from 1993–2011 (Figure 2c). There is no significant correlation between the PDO and indices of sardine biomass on either longer or shorter time scales, based on either paleoclimatic proxies or modern data. Although we know that climate variability affects fisheries, inferring causality from apparent coincidence of change is not proper science. ENSO affects the PDO on all scales [*Newman et al.*, 2003] so the lack of significant correlation between the paleo-PDO and paleo-sardine biomass probably reflects the greater importance of mechanisms operating on time scales of a few years (ENSO) rather than mechanisms operating on the slow multi-decadal time scales of the PDO. The ENSO-related mechanisms forcing sardine biomass are the topic of further research.

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