**A 500 year climate catch:
Pelagic fish scales and paleoproductivity in the Santa Barbara Basin from the
Medieval Climate Anomaly to the Little Ice Age (AD 1000 – 1500)**

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Abstract

Based upon observations from the 20th century, populations of lower trophic level, short-lived fish species are thought to be controlled by large scale ocean-atmosphere circulation shifts. Here, we provide a new 500 year reconstruction of northern anchovy and Pacific sardine fish scale deposition rates (SDRs) and relative abundance from Santa Barbara Basin (SBB), through the transition from the Medieval Climate Anomaly into the Little Ice Age (AD 1000 to 1500). Three intervals of high anchovy biomass (high SDRs) were coincident with increased upwelling diatom abundance in SBB and cool/negative Pacific Decadal Oscillation (PDO) events at 1130-1160, 1280-1310 and 1410-1450. Intervals of absent or low SDR of both sardine and anchovy in SBB sediments occurred in association with increased wave activity (benthic diatoms), California Current diatoms, and the relative dominance of sardine over anchovy. Thus although ocean-atmosphere circulation shifts such as the PDO appear to play a role in shifting the dominance of anchovy over sardine, the biomass of sardines as indicated by SDRs has a more complicated response to environmental change.

1. Introduction

Complex marine food webs have been observed to shift significantly in response to small changes in the surrounding physical environment. Over the last two millennia, sardine and anchovy populations worldwide have been observed to fluctuate with a periodicity of ~50 years in upwelling regions (Baumgartner et al., 1992; Kawasaki, 1983). Globally, sardine and anchovy populations are associated with productive upwelling

environments along eastern ocean boundaries off the coasts of California, Peru, the Canary Islands and South Africa (Schwartzlose et al., 1999; Struck et al., 2002). These fish populations can also be observed along western ocean boundaries in more productive regions, such as the coastal regions of Japan and Argentina (Soutar, 1967). Variations in sardine and anchovy landings recorded by the fishery industry appear to fluctuate nearly synchronously in widely separated regions (Schwartzlose et al., 1999), and are similar in phase and duration to regional multidecadal climate regime shifts, such as the Pacific Decadal Oscillation (PDO).

During the 1976-77 regime shift of the northeast Pacific climate system, significant changes in environmental conditions experienced by pelagic fish populations can be identified through a wide range of physical and biological ocean timeseries (Miller et al., 1994). Before the regime shift, under relaxation of the Aleutian Low (AL) atmospheric pressure system, a stronger California Current System (CCS) shifted away from the coast and was associated with a shallow nearshore thermocline, enhancing coastal upwelling, and subsequently primary productivity from California to British Columbia (Chavez et al., 2003; Roemmich and McGowan, 1995). These conditions were coincident with sizeable anchovy landings off Peru (Chavez et al., 2003). After 1976-77, intensification of the AL was associated with warmer sea surface temperatures (SST) and weaker CCS flow that moved shoreward as the North Pacific gyre relaxed, deepening the coastal thermocline from California to British Columbia (Miller et al., 1994). Sardine landings increased off Peru, while salmon, zooplankton and seabirds declined off the west coast of North America (Benson and Trites, 2002; Hare and Mantua, 2000; Veit et al., 1996). Based on these observations, Chavez et al. (2003) posited that a multidecadal sardine regime was associated with intensification of the AL, and a positive, warm PDO, while an anchovy regime represents a weak AL during a negative, cool PDO. However, differences in species specific life-history traits (Lindegren et al., 2013), regionally-specific influences on upwelling (Rykaczewski and Checkley Jr, 2008), sensitivity of fish-stock recruitment to the stress of overfishing in addition to environmental factors such as temperature (Jacobson and MacCall, 1995) complicate the relationship between climatic environmental forcing and fish biomass. Indeed, a recent re-examination of the paleoproductivity record for sardines (Baumgartner et al., 1992) alongside a paleo-PDO

proxy (Gedalof and Smith, 2001) extended over the most recent 370 years suggests that sardine biomass is poorly correlated to indices of climate variability (McClatchie, 2012).

The assertion that sardine and anchovy populations track large-scale ocean-atmosphere climate shifts in the North Pacific subtropical gyre has been used to manage the sardine fishery. Harvest guidelines are based on the positive relationship between sea surface temperature (SST) and sardine productivity (Hill et al., 2010). The current (2008-2013) shift toward a cool, negative PDO, combined with high rates of exploitation has been predicted to collapse the CCS sardine stock (Zwolinski and Demer, 2012). Recruitment from 2010-13 was among the weakest in recent history (Pacific Fishery Management Council, 2014) and the 2015-16 Pacific sardine fishery was closed because the biomass forecast was significantly below the 150,000 t threshold for a directed fishery (Pacific Fishery Management Council, 2015). Fishery exploitation of the California sardine population is estimated to range between 10-20% and such conservative management potentially improves the tolerance of the fishery to declining recruitment (MacCall et al., 2012). However, if sardine and anchovy populations are indeed controlled by large-scale ocean-atmosphere interactions, population collapses witnessed in the 20th century may not be easily rectified by lowering fishing pressure.

Well-preserved, continuous fish scale records of pelagic fish populations have been identified in Santa Barbara Basin (SBB; Soutar, 1967). The sediments of SBB provide an excellent opportunity for studying fish populations because unusually high sedimentation rates and low bottom water oxygen concentrations preserve the organic-rich sediments. The pH of these sediments (~8.0) allows for the preservation of scale and bone constituents such as inorganic carbonates and apatites (Field et al., 2009; Soutar and Isaacs, 1969). Additionally SBB receives waters from the CCS, and so is positioned to record biogenic responses to changes in North Pacific gyral circulation (Soutar and Isaacs, 1969). Paleo-environmental reconstructions of recent sediments in SBB demonstrate that regional- and basin-scale ocean-atmospheric circulation process have more influence on SSTs and zooplankton abundance than local high-frequency processes (Field et al., 2006).

The SBB, off the coast of California, is ideally situated near the spawning and feeding grounds of the Pacific sardine, *Sardinops caerulea* and northern anchovy, *Engraulis mordax*, (Baumgartner et al., 1992; Soutar and Isaacs, 1974). Sardine spawn

offshore multiple times a year, increasing spawning rates with age, while anchovy spawn near the coast, generally in winter (Schwartzlose et al., 1999). The two planktivores do not generally compete for food resources as juvenile sardine have specialized gill rakers to retain small planktonic prey ($>10\ \mu\text{m}$) while anchovy use coarse gill rakers to capture larger prey (Rykaczewski and Checkley Jr, 2008). Rykaczewski and Checkley Jr (2008) suggest anchovy feed in coastal upwelling settings, while sardine more efficiently utilize small plankton in slower offshore wind-stress curl upwelling systems. Pacific sardine and northern anchovy scales dominate scale deposition in SBB sediments alongside those of the predatory Pacific hake, *Merluccius productus* (Soutar and Isaacs, 1974; Fig. 2). Using sediment from several cores in SBB, Soutar and Isaacs (1969) and Baumgartner et al. (1992) have suggested that the Scale Deposition Rate (SDR) and relative abundance of fish scales in the annually varved SBB sediment are strongly correlated with decadal to millennial fluctuations in population biomass and environmental conditions, as well as changes in ecosystem structure unrelated to fishing (Baumgartner et al., 1992). The ratio of sardine to anchovy scales observed by Soutar and Isaacs (1974) reveals a cyclical distribution, since the 1700s, which is consistent with the assertion that the species vary inversely and show in-phase periodic variability (Soutar and Crill, 1977; Soutar and Isaacs, 1969).

In previous paleoproductivity studies in SBB such as those of Baumgartner et al. (1992) and others, chronologies were developed using X-radiography to count varves - annual sediment laminae consisting of a spring-summer biogenic component and a winter siliciclastic component. Uncertainties in age estimations (Baumgartner et al., 1992) generated by this method were recently shown to be underestimated, increasing dramatically with depth by up to 30% per 100 years due to undercounting of varves (Hendy et al., 2013). Errors in the varve chronology may come from: discontinuous sedimentation during drought years, bioturbation, and/or erosion of varves by intermittent turbidite or flood deposits (Hendy et al., 2013; Schimmelmann et al., 2013). The SBB varve chronology (Schimmelmann et al., 2006) is younger than a ^{14}C chronology generated by terrestrial organic matter such as seeds, leaves, wood and charcoal, by ~200 years at 1300, the Medieval Climate Anomaly (MCA) - Little Ice Age (LIA) transition (Hendy et al., 2013). The SBB marine planktonic foraminiferal ^{14}C chronology (Kennett

et al., 2006) is also associated with significant age uncertainty as the reservoir age required to calibrate marine ^{14}C ages varied by 480 to 750 years over the last two millennia (Hendy et al., 2013).

Using the new chronology proposed by Hendy et al. (2013), this study presents a high-resolution record of Pacific sardine, northern anchovy, and Pacific hake scale deposition from a new kasten core collected from SBB in 2009 (Fig. 1). With a continuous ~5 year sampling resolution of multiple marine and terrestrial proxies, this new fish scale census study resolves multidecadal to centennial scale changes in coastal productivity and climate from AD 1000 to 1500. This study quantifies changes in the relative abundance of sardine and anchovy populations, coupled with marine paleoproductivity proxies in the SBB. These observations, compared with co-occurring changes in paleo-PDO and SST proxies, highlight the complexity of the MCA-LIA transition.

2. Methods

Kasten core SPR0901-02KC, was collected from a water depth of 588m, at $34^{\circ}16.845'\text{N}$, $120^{\circ}02.332'\text{W}$ close to Ocean Drilling Program Site 893 (Fig. 1). This 17 cm square core (with an area of 289 cm^2) was continuously sampled every 0.5 cm, however, this study only examined samples between 125.5cm to 75.5cm below core top (cmbct), corresponding to the time interval between ~1000 and 1500. Samples were wet sieved with D.I. water over a $125\mu\text{m}$ screen with the fine fraction ($<125\mu\text{m}$) retained for pollen and diatom analyses and the coarse fraction ($>125\mu\text{m}$) collected for fish scale analysis. Fish scales were picked under a binocular dissecting microscope and mounted on cardboard assemblage slides. Identification of northern anchovy, Pacific sardine, Pacific hake, and surfperch scales (Family Embiotocidae) were made by comparison with a reference scales assembled from the fish collection at the University of Michigan Exhibit Museum (Gerald Smith, pers. com.). Fish scales, otoliths, and bones were separated from sediment by sieving primarily in the $>250\mu\text{m}$ size fraction. Scale length and width dimensions are on the order of several millimeters (Fig. 2). Bone and scale samples were mounted on slides and moistened with deionized water to transport them via a small brush, to remove tar and to prevent curling or fracturing.

Pacific sardine, northern anchovy, Pacific hake and surfperch scales were identified based on scale shape, the appearance of circuli, and the presence of lateral field lines. Circuli are the pattern of fractures resembling radii, and describe elevated lines following the scale outline (Patterson et al., 2002). Radii are defined as grooves that radiate outwards from the focus, or central site of scale growth. Lateral field lines occupy the outer regions of the scale, and can feature angulations of circuli (Patterson et al., 2002). Scale size varied greatly throughout the core. Distinguishing characteristics of Pacific sardine scales include linear, lateral radii that remain parallel to one another (Patterson et al., 2002). They are relatively large compared to other scales present, and the shape is variable with size where smaller scales are ovate, and larger scales are distinctly rectangular. The circuli of Pacific sardine scales are straight to curved along the edges, and compacted tightly. There are no radii, however, fractures resembling radii run parallel to circuli along the edges of the scale (Patterson et al., 2002). Northern anchovy scales are more ovoid than Pacific sardine scales, and they are tri-lobed in the anterior field (bounded by lines connecting the dorsal and ventral corners of the scale; (Patterson et al., 2002). The posterior field (bounded by lines connecting the dorsal and ventral corners with the focus) is highly variable in shape, and susceptible to fracturing. The position of the focus is identified as the area with the first concentric circuli, and is not uniformly positioned across samples (observed). Circuli are not continuous between lobes in outer regions of the scale, but are continuous within lobes. While there are also no radii for Northern anchovy scales, predictable fracturing and grooving occurs transverse to the circuli, especially in the center of the scale.

Hake scales, present throughout the core, are relatively small in size and oval in shape, with continuous circuli surrounding a focus located at approximately the center of the scale (Patterson et al., 2002). Surfperch species cannot be easily identified by scale, however, Embiotocidae are moderately sized, square-shaped scales with a rounded posterior field. Circuli are generally continuous, following the shape of the scale and surrounding a focus proximal to the posterior edge (Patterson et al., 2002). The outer edge of the anterior field is scalloped, easily distinguishing them from the other species. Fragments were only included in the total counts when they showed distinct radii and distinguishing characteristics as described in Patterson et al. (2002). Scales were not

observed to degrade with depth; however, comparing bone and otolith counts to those of scales could provide insight into the effect of degradation. While otoliths and bones were collected from SPR0901-02KC, they were not easily identifiable to the species level and were excluded from this study.

Various age models for reconstructing fish populations in SBB have previously utilized the well-preserved laminae couplets as varves. However, the chronology employed in this study is based on high-resolution ^{14}C dating of terrestrial organic material and marine carbonate from a companion kasten core - SPR0901-06KC (34°16.914'N, 120°2.419'W; Hendy et al., 2013). Radiocarbon ages from terrestrial organic carbon samples were calibrated using Intcal09 and planktonic foraminifera carbonate samples were corrected for variable radiocarbon reservoir ages (ΔR) and calibrated using Marine09 (Hendy et al., 2013; Reimer et al., 2009). All ages in this publication refer to years AD.

As SBB sediments are interrupted by instantaneous homogenous sedimentary events including turbidites and flood deposits on the scale of one to several centimeters, SPR0901-02KC samples associated with the 1108 turbidite (120.5-115.5 cmbct) and 1269 (100.5 -98.5 cmbct) and 1380 (88-87.5 cmbct) flood layers were excluded. However, these basin-wide sedimentary events were employed as stratigraphic markers between companion Sproul cores (Supplementary Fig. 1; Hendy et al., 2013) creating linear sedimentation rates (Supplementary Table 1). Sedimentation rates vary down-core in the following intervals: 88.8 cm ky^{-1} from 1380-1500, 96.5 cm ky^{-1} from 1270-1380, 93.8 cm ky^{-1} from 1110-1270, and 45.4 cm ky^{-1} from 1000-1110. Scale deposition rates were calculated using the following equation:

$$\text{Scale Deposition Rate (scales*1000 cm}^{-2} \text{ y}^{-1}) = \text{Linear Sedimentation Rate (cm y}^{-1}) \times \text{fish scale count (scales cm}^{-3}) \times 1000$$

Diatom methods are detailed in Barron et al. (2010, 2014). Counts of at least 300 individuals were made while traversing slides at 790x under the light microscope. Pollen methods are presented in (Heusser et al., 2014) with at least 300 pollen grains identified under a light microscope at 400x. Principal component analysis (PCA) was used to put the pollen constituents into a set of values of linearly uncorrelated variables (Heusser et al., 2014). Only the first principal component (PC1), which explains 21% of the variance,

is shown here. PC1 positively loads mesic arboreal pollen (*Pinus*, *Cupressaceae*, *Alnus*, and *Quercus*), while negatively loading the xeric shrubs, herbs and grasses comprising chaparral and coastal scrub (Heusser et al., 2014). The extent of linear relationships between variables was determined using a Pearson product moment correlation coefficient. All data sets used in the Pearson correlation were resampled at 10 y intervals between 1000 and 1500, with the diatom data trimmed to 1000-1380 for the correlations. As the only variable showing a linear trend between 1000 and 1500, the PDO estimate based on tree rings (MacDonald and Case, 2005) was detrended before correlations were calculated.

3. Results

3.1 Scale Deposition Rates

Scale deposition rates (SDRs) for both whole scale and combined whole and fragmented (total) scales of fish species counted in SPR0901-02KC are displayed in Fig. 3. Sardine and anchovy scale deposition rates (SDRs) and fish bone debris generally decrease from 1000 to 1500 (Fig. 3). Northern anchovy are the most abundant scales in SBB sediments. Peak total SDRs of >10 scales $\times 1000 \text{ cm}^{-2} \text{ y}^{-1}$ are centered on 1030, 1120, 1160, 1240, 1275, 1310, 1340, 1430, and 1470 (Fig. 3A). The interval from 1110 to 1170 contains the highest SDRs of anchovy scales. A second notable peak of ~ 30 scales $\times 1000 \text{ cm}^{-2} \text{ y}^{-1}$ occurs between 1410-1440. [ENREF 4](#) Intervals of high anchovy SDR are frequent but rarely longer than 10-20 years in duration with the exception of the 1110-1170 event (Fig. 3A). [ENREF 4](#) The drop in anchovy SDR at 1170 was followed by the longest (60-80 year) intervals of low biomass.

Pacific sardine scales are less abundant than anchovy in SBB sediments but display a similar temporal pattern in peak abundance. Peaks in sardine SDR of >5 scales $\times 1000 \text{ cm}^{-2} \text{ y}^{-1}$ occur at 1030, 1120, 1160, 1240, and 1430 (Fig. 3B). Sardine SDRs are prominent during the interval between 1110 and 1170 in agreement with the anchovy SDRs, but sardine SDRs drop dramatically between 1135 and 1150. [ENREF 52](#) High sardine SDR intervals are ~ 10 years in duration and ~ 60 years apart. Again the decreases in sardine biomass at 1170 and 1360 are followed by long intervals of low SDR. The open ocean dwelling predatory Pacific hake SDRs contain intervals of more consistent

deposition than the smaller, lower-trophic level species from 1010-1050, 1100-1170, 1190-1260, 1280-1340 and 1380-1480, with a trend toward higher SDRs during later depositional intervals (Fig. 3C). Nearshore dwelling surfperch and other fish species have a low deposition throughout the record, with only two samples where the SDR is >5 scales $\times 1000 \text{ cm}^{-2} \text{ y}^{-1}$ at 1115 and 1175 (Fig 3C).

There are several intervals during which there is no scale deposition for any species (Fig. 3). Three of these centimeter-scale intervals are associated with turbidite and flood deposition. The upper portion of the 1108 events spans the 118.5-116.0 cm depth interval, and represents an oxygenated turbidite event associated with inorganic sediment deposition. The intervals from 1260 to 1275, and 1380 are associated with flood events, and increased riverine sediment input. Three intervals of low SDR not associated with inorganic sediment deposition are observed at 1060-1100, 1180-1200, and 1360-1400.

3.2 Relative Scale Abundance

As processes not related to fish population dynamics, such as preservation, may affect scale deposition we also present the scale counts in relative abundance (%; Fig. 4). The relative abundance of sardine to anchovy scales as ratios are presented in Fig. 4A and B. Relative anchovy abundance dominates for much of the record, however the ratio of sardine to anchovy is >0.75 at 1070, 1210, 1360 and 1480 (Fig. 4A and B). The relative abundance of sardine and anchovy to other fish generally decreases through the record. Intervals where the planktivores are $>50\%$ relative to other fish include 1000-1060, 1110-1170, 1270-1290, 1330-1370, 1410-1430 and 1460 to the end of the record (Fig. 4C).

3.3 Correlations

Pearson correlation coefficients (Table 1) provide a measure of the linear correlation between two variables, from a total positive correlation (1) to a total negative correlation (-1), where 0 is no correlation. The SDRs of both fish are very strongly positively correlated to each other and moderately to strongly negative correlated to CCS and benthic diatoms. The anchovy SDR is weakly negatively correlated to the PDO (correlating with negative/cool PDO events), moderately positive correlated to upwelling

diatoms and moderately to strongly correlated to the ratio of anchovy to sardine. The relative abundance of sardine is weakly positively correlated with the PDO, North Pacific SSTs, and CCS and benthic diatoms, while moderately negatively correlated with upwelling diatoms. The relative abundance of anchovy is also weakly positively correlated with the PDO and North Pacific SSTs, but weakly to moderately negatively correlated to CCS and benthic diatoms. The ratio of anchovy to sardine is moderately to strongly negatively correlated to the PDO (positive/warm phase) and benthic diatoms, while being strongly correlated to upwelling diatoms. Upwelling diatoms are strongly negatively, and benthic diatoms are moderately positively correlated to the PDO (positive/warm phase). There are no correlations between North Pacific SSTs and diatoms although North Pacific SSTs are weakly positively correlated to the PDO (positive/warm phase). Finally upwelling diatoms are also moderately negatively correlated to CCS diatoms and strongly negatively correlated to benthic diatoms.

4. Discussion

Northern anchovy and Pacific sardine have been the focus of fish paleoproductivity studies because their distinctive scales enable easy assessment of biomass through time, and because these short-lived, low-trophic level fish play an important role in coastal upwelling ecosystems. Sardines and anchovies are recognized globally for their dramatic collapses/recoveries during the 20th century with significant consequences for local fisheries (Radovich, 1982). The Pacific sardine collapse in California in 1951-52 highlighted the fragility of an over-exploited and poorly understood fishery, and led to a fishery moratorium in 1967 (Radovich, 1982). During the period of low sardine biomass that followed, anchovy biomass increased. It was this trend that led to the formulation of the hypothesis suggesting warm coastal SST regimes associated with positive PDO favored sardines, while cool SST intervals associated with negative PDO favored anchovies (Chavez et al., 2003; Jacobson and MacCall, 1995; Schwartzlose et al., 1999). Yet the sardine and anchovy biomass records in the CCS only span 60 years and are significantly affected by anthropogenic environmental change. The high resolution SBB record can extend sardine and anchovy biomass reconstructions through the transition from the MCA into the LIA using scales found in sediments,

improving understanding of the relationship between sardine and anchovy biomass and large-scale ocean-atmosphere dynamics in the CCS.

Sardine and anchovy, alongside other fish, naturally shed scales during schooling, pursuit, and predation, with the rain of scales varying with fish density (Baumgartner et al., 1992; Field et al., 2009). New scales grow where previous scales are lost. A relationship between sardine SDR and biomass has been developed with the observation that >90% of sardine scales in SBB sediments are from fish younger than 2 years (Baumgartner et al., 1992; Soutar and Isaacs, 1974). A weakness of this approach however, is that the number of scales deposited within the area of a core is low, therefore SDRs from sediment cores likely have large and poorly quantified errors. Here we present results from only one core with a sampling area of 289 cm². Previously Baumgartner et al. (1992) found only 30% of the variance of absolute fish scale counts was shared between cores where the samples represented an area of 45 cm², yet shared signals were clearly observed in correlations between cores. In this contribution, strong correlations between sardine and anchovy SDR and relative abundance conform to our understanding of regional marine ecosystems and agree with the conclusions of Baumgartner et al. (1992).

[ENREF 34.1](#) *Sardine and Anchovy Scale Deposition from AD 1000 to 1500*

The decrease in sardine and anchovy SDR through the 500 year record indicates lower trophic level fish biomass diminished from the MCA into the LIA. This is more apparent when relative fish scale counts are compared (Fig. 4C), as the higher trophic level hake do not display a similar trend. A similar pattern was found by both Baumgartner et al. (1992) in SBB and Finney et al. (2002) in the Gulf of Alaska, with both sardine and anchovy SDRs generally decreasing from ~ 900 to 1600. Several possibilities exist to explain this observation. Scale deposition may be biased by preservation as dissolution can occur in the water column and at the sediment-water interface (Salvatteci et al., 2012). Thus higher anchovy scale counts relative to sardine, hake and surfperch counts may be a result of the greater resistance of anchovy scales to dissolution due to a predisposition towards mineralization in sediments (Wright et al., 2005). Dissolution rates are slower in an oxygen-depleted environment like the sediment-

water interface of SBB (Devries and Percy, 1982). There is no evidence of shifting porewater oxygen concentrations between 1000 and 1500 similar to the SBB *Macoma* event of ~1840 (Schimmelmann et al., 1992). Increased preservation of organic matter has been ascribed to the sudden burial of laminations directly beneath the massive grey layers in SBB (Schimmelmann and Kastner, 1993), however, lower SDRs beneath the ~1270 and 1380 flood events are opposite to predictions of a preservational response. Finally, hake SDRs do not exhibit a similar decreasing trend and continue to cycle through the record indicating preservation may not be driving this long-term trend.

Superimposed on the long term trend of decreasing SDRs, both sardine and anchovy SDRs fluctuate throughout the 500 year record indicating decadal changes in the marine environment occurred. However, high SDRs do not simply translate to switching between sardine- or anchovy-dominated regimes. Both anchovy and sardine SDRs are highly correlated and SDR of each species is correlated to their relative abundance, yet, sardine SDRs are also positively correlated to anchovy relative abundance (Table 1) and have no coherence with PDO, SSTs or upwelling diatoms. Thus sardine biomass appears to be independent of the sardine-dominated regime. Modern observations of anchovy population growth during intervals of high nutrient supply associated with increased coastal upwelling are expected. In contrast paradoxical significant sardine biomass during warm CCS conditions have been associated with the more expansive wind-stress curl upwelling offshore (Rykaczewski and Checkley Jr, 2008). The relationship of sardine biomass with wind-stress curl upwelling may provide an explanation for the lack of coherence between sardine SDRs (Baumgartner et al., 1992) and environmental conditions that have been associated with the sardine regime (Chavez et al., 2003).

[ENREF 4 ENREF 4 ENREF 4 ENREF 4](#)4.2 *Fish scales relationship with environmental change in Santa Barbara Basin*

[ENREF 8](#)Multiple proxies for paleoproductivity and rainfall have been produced for SPR0901-02KC such that SDRs and the ratio of sardines to anchovy can be directly compared with diatom, silica flagellate (Barron et al., 2014) and pollen census data (Heusser et al., 2014) without potential age model errors (Fig. 5). The response of marine primary productivity to upwelling in SPR0901-02KC sediments can be estimated by

examining the relative abundance of an upwelling diatom - *Rhizosolenia* spp., and a silicoflagellate - *Distephanus speculum* (Barron et al., 2014). Upwelling conditions were recorded by *D. speculum* at 1120-1135, 1310-1315 and 1450, while *Rhizosolenia* abundance was high between 1140-1145, 1290-1300 and 1450 (Barron et al., 2014). Upwelling diatoms correlate with high anchovy SDRs and especially the anchovy to sardine ratio (Table 1), indicating that anchovy biomass increased due to coastal upwelling during an anchovy dominated regime.

Benthic diatom species were found in higher abundance between 1040-1100 and 1170-1210, indicating transport of sediment from the nearshore, photic environment into the center of the basin (Barron et al., 2014). Such sediment transport may occur when significant wave events carry sediment across the shelf and downslope (Warrick and Mertes, 2009). The wave conditions for SBB are dominated by mid-latitude winter storms that produce swell approaching from the northwest during strengthened Aleutian Low intervals and during La Niña years (Adams et al., 2008). The position of the Channel Islands shelters SBB from the less frequent south to southwest swell from the Southern Hemisphere or tropical storms (Adams et al., 2008). Thus benthic diatoms may indicate increased storm activity associated with a strong Aleutian Low. Both intervals of increased storm activity are associated with low SDRs, but high relative sardine abundance, and the absence of upwelling diatoms – conditions consistent with positive warm PDO events. Finally SDRs are generally low during intervals dominated by the cosmopolitan diatom *Thalassionema nitzschioides*, while the relative abundance of sardine is generally high. This diatom species prefers a shallow thermocline and cooler water, and is associated with the offshore portion of the CCS (Barron et al., 2014). Thus the presence of *T. nitzschioides* in SBB sediments between 1090-1120 and ~1200-1240 may indicate a relaxation of the CCS.

Strong upwelling has been associated with drought in southern California as the North Pacific high (NPH) pressure cell intensifies in a climate pattern similar to the negative or cool PDO and/or La Niña (Mantua and Hare, 2002). SPR0901-02KC spans the transition from the relatively dry MCA to the wetter LIA (~1100 – 1300). The climate of western North America during the last two millennia was exceptionally variable (Davis, 1992). Terrestrial proxies such as tree rings, lake levels, and estuarine salinity

provide local indications of drought in southern California during the interval spanning the MCA, with sporadic flood events from 1200 – 1800 (Byrne et al., 2001; Larson and Michaelsen, 1989; Schimmelmänn et al., 2006; Stine, 1994). Periods of drought in SPR0901-02KC are identified by increased chaparral and coastal scrub pollen relative to aboreal pollen (Heusser et al., 2014) prior to 1070 and between 1200-1300.

4.3 Sardine-Anchovy Regimes and Climate Change.

Through the MCA-LIA transition (1000-1500), abrupt, decadal-scale changes in sardine and anchovy populations are observed that are consistent with modern fluctuations in sardine and anchovy biomass recorded in modern CCS waters (Demer et al., 2012). The estimated high sardine biomass from 1930-1950 with the subsequent collapse in 1951-52 and recovery by the late 1990s (Norton and Mason, 2005; Radovich, 1982; Schwartzlose et al., 1999) follows the PDO. As the PDO is estimated to have a 50-70 year cyclicity (Minobe, 1997), 20th century fluctuations are insufficient to fully understand the response of fish biomass to climate change. To determine the relationship between fish biomass and large-scale atmosphere-ocean conditions, we compare SPR0901-02KC to both a PDO index reconstruction based on tree ring networks (MacDonald and Case, 2005) and a SST reconstruction based on the $\delta^{18}\text{O}$ of a Sierra Nevada speleothem (McCabe-Glynn et al., 2013) (Fig. 5).

The paleo-PDO Index takes advantage of the tree ring response to drought and inverse relationship between drought in the American Southwest relative to higher precipitation in the Pacific Northwest during cool (negative) PDO events (MacDonald and Case, 2005). The paleo-PDO index was generated using a network of tree rings in southern California and Alberta (MacDonald and Case, 2005). Although tree ring width in the American Southwest is dominantly controlled by precipitation, tree ring width at higher latitudes is strongly influenced by air temperature (D'Arrigo et al., 2008). The PDO Index reconstruction was the only variable showing a linear trend from 1000 to 1500. Cooling air temperatures could have both slowed tree growth in northern Alberta range of the network as well as reducing water stress in the southern California range of the network. The climatic cooling associated with the LIA (Wiles et al., 2014) may have produced the long term trend from strong negative PDO to positive PDO seen in the

1000-1500 interval of the record (MacDonald and Case, 2005). The Crystal Cave speleothem from the Sierra Nevada was produced by winter precipitation as a result of the Mediterranean climate of California (McCabe-Glynn et al., 2013). The $\delta^{18}\text{O}$ of the calcite precipitating in Sierra Nevada cave systems is related to the SST of water evaporating off the western North Pacific Ocean. When storm systems intersecting the Sierra Nevada transport water from the warm Kuroshio Current region, SSTs along the margin of North America are cool, while storm systems tracking from higher latitudes carry cooler water from the NW Pacific and are coincident with warm SSTs on the California Margin (McCabe-Glynn et al., 2013). Therefore warm northwest Pacific SSTs in the Crystal Cave speleothem should negatively correlate the PDO index reconstruction, but instead a weak positive correlation is observed. Weak correlations with the SST reconstruction maybe the results of age model differences between the records or seasonal biases in each record.

Between 1000 and 1500 anchovies dominated the fish scale record both in relative and absolute abundance in association with a cool/negative PDO index (MacDonald and Case, 2005) and were coincident with dry conditions in southern California supported for the most part by xeric vegetation pollen in SBB sediments (Heusser et al., 2014). Anchovies additionally appear closely linked to diatoms associated with coastal upwelling. Drought and coastal upwelling in southern California provides evidence for a strong NPH – environmental conditions that have been associated with the anchovy regime and resulting in the proposed linkage to the cool/negative PDO index. These conditions occurred from 1125-1145, 1260-1320, and from ~1410-1470. This interpretation differs from MacDonald and Case (2005) who assign longer duration cool/negative PDO conditions to the MCA rather than 20-60 year events.

Chavez et al. (2003) described the warm sardine regime from 1975 as being associated a strong AL and a weak shoreward movement of the CCS during a warm/positive PDO index. These conditions have also been linked to the 1982 El-Niño event (Valdes et al., 2008). The relative abundance of sardine to anchovy in SBB between 1000 and 1500 does strongly correlate with positive PDO (MacDonald and Case, 2005) alongside weak correlations to CCS diatoms and increased wave activity (benthic diatoms; Barron et al., 2014). A strong AL associated with more storm activity in the NW

Pacific is a likely cause of greater wave activity in SBB. These conditions appear between 1060-1100, 1160-1210 and 1350-1380. However missing or antiphase correlation between sardine biomass (SDR) and marine environmental conditions representing warm/positive PDO supports assertions that there is no consistent phase shift between sardines and anchovy (Baumgartner et al., 1992; Field et al., 2009; Lindegren et al., 2013). Recently, McClatchie (2012) suggested sardine biomass was poorly correlated with PDO because different environmental processes contributing to the oceanographic regime shifts observed in the 20th century operate on different time scales such that they augment each other in a random fashion. The results of this research agree that the red noise associated with different components of the North Pacific ocean-atmosphere climate system may be operating independently of each other

Longer duration fluctuations of sardines compared to anchovies in the SDR record have been ascribed to the slower growth, later maturation and lower natural mortality of sardines (Lindegren et al., 2013). Additionally, coastal upwelling may not be the only process supplying nutrients into the CCS as wind-stress curl-driven upwelling offshore slowly bring nutrients to the surface over a more expansive region (Rykaczewski and Checkley Jr, 2008). This results in small but abundant phytoplankton more readily utilized by sardines. Additionally a complex relationship between the seasonality of upwelling and early life stages when the marine environment has the most influence on survival of new recruits may be producing a mismatch between sardine biomass and large scale ocean-atmosphere climate regimes. Seasonality may be changing alongside decadal ocean-atmosphere circulation shifts. SST reconstructions in SBB do not agree with each other between 1000 and 1500, suggesting that significant seasonality changes occurred during this interval (Barron et al., 2010; Fisler and Hendy, 2008; Kennett et al., 2006). Finally, the sensitivity of sardines to SST appears to vary based on population, such that there is little relationship when sardine biomass is low, perhaps because sardines cannot respond to favorable environmental conditions with an insufficient spawning population (Deyle et al., 2013). Thus the two oceanographic regimes posited by Chavez et al. (2003) to describe the relationship between multidecadal climate change and sardine/anchovy fish stocks may not fully capture marine environmental changes produced by the North Pacific ocean-atmosphere climate system.

5. Conclusions

Regional records of low trophic level, short-lived fish populations complement multiple paleo-environmental proxies in the reconstruction of ecosystem shifts and may serve as a template for the response of southern California ecosystems to climate change. The record of fish scales deposited in Santa Barbara Basin sediments from a new kasten core – SPR0902-02KC – during the interval from 1000 to 1500 shed light on possible causes of fish stock variability in the 20th century. Strong positive correlations between upwelling diatom species (Barron et al., 2014) and the ratio of northern anchovy to Pacific sardine indicates that lower trophic level fish can track upwelling induced marine productivity over multidecadal timescales (Baumgartner et al., 1992; Chavez et al., 2003; Soutar and Isaacs, 1974). Thus marine productivity was high in SBB during the interval from 1120-1170, 1290-1315, and 1435-1455, with a general trend of decreasing lower trophic level fish biomass through the 500 year interval investigated in this study.

Chavez et al. (2003) and Jacobson and MacCall (1995) linked large-scale ocean-atmosphere climate shifts with fluctuating sardine and anchovy biomass in the North Pacific. A sardine regime was associated with higher precipitation, higher sea surface temperatures (SSTs) and lower nutrients in the waters off California similar to the warm/positive Pacific Decadal Oscillation (PDO), while the anchovy regime was associated with the opposite conditions similar to the cool/negative PDO. The improved chronology of SPR0901-02KC allows the SBB records to be compared with proxies for western North Pacific SSTs and the PDO index. A tree-ring based PDO reconstruction correlates well with the relative abundance of sardine and anchovy. Wetter conditions in southern California associated with higher wave activity (increased storm activity in the NW Pacific) similar to the warm/positive PDO were associated with low anchovy to sardine ratios. Cool/negative PDO climate conditions including greater coastal upwelling and dry southern California weather were associated with high anchovy relative and absolute abundance.

The high variability of sardine and anchovy abundance adds additional environmental information through the MCA-LIA transition off southern California, supporting the concept that climate regime shifts can be identified through the response of marine

organisms. However, absolute abundance (biomass) responses may differ from relative abundance (the dominance of one species over another) responses. Life-history traits (Lindegren et al., 2013), regional upwelling conditions (Rykaczewski and Checkley Jr, 2008), and recruitment sensitivity to environmental factors (Jacobson and MacCall, 1995) are complications to simplistic approaches to fish biomass. If scale deposition rates (SDRs) are used to estimate fish biomass (Baumgartner et al., 1992; Soutar and Isaacs, 1974) then sardine SDRs through the 500 year record do not support high sardine biomass during warm/positive PDO. Instead high sardine biomass maybe related to more diffuse upwelling (Rykaczewski and Checkley Jr, 2008) or population dynamics such as the size of the juvenile cohort during optimal environmental conditions (Deyle et al., 2013). This SDR response to the PDO supports assertions that despite the appearance of correlation from 1920 to 2010, sardine biomass is not related to the PDO (Baumgartner et al., 1992; McClatchie, 2012).

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Figure 1. Map of the Santa Barbara Basin (SBB) showing the location of core sites SPR0901-02KC, SPR0901-03KC, SPR0901-06KC and ODP 893. Arrows indicate surface ocean current directions. Topography and bathymetry are in 100 m increments.

Figure 2. Light microscope images of fish scales counted in SPR0901-02KC. A. Northern anchovy (*Engraulis mordax mordax*), B. Pacific sardine (*Sardinops caerulea*), C. Pacific hake (*Merluccius productus*), and D. Surfperch (Embiotocidae spp.). Scale bar = 1mm.

Figure 3. Rates of scale deposition (SDR in scales $\times 1000 \text{ cm}^2 \text{ y}^{-1}$) of A. Northern anchovy, B. Pacific sardine and C. Pacific hake (blue shaded bars) and surfperch (including unidentified scales; yellow shaded bars) for the interval 1000-1500. Fish scale fragments for anchovy and sardines are shown in dark blue shaded bars, while whole fish scales are shown in yellow.

Figure 4. Relative abundances in percentages of A. whole Pacific sardine scales to northern anchovy (red line), B. total fragments and whole sardine scales to anchovy (black line), and C. all sardine (grey bars) and anchovy (pink bars) scales relative to the scales of all other fish species (black bars). D. Scale deposition rates (SDR in scales $\times 1000 \text{ cm}^2 \text{ y}^{-1}$) for Northern anchovy (red bar), Pacific sardine (blue bar), Pacific hake (grey bar) and surfperch and other species (green bar).

Figure 5. Comparison of fish scale deposition rates with diatom and pollen census data from SPR0901-02KC for the interval 1000 to 1500. A. The first principal component of the pollen census, which has high loadings for arboreal mesic species (green line; Heusser et al., 2014), B. The Pacific Decadal Oscillation (PDO) index generated from western Canadian and southern California tree ring networks with warm/positive PDO shaded red and cool/negative PDO shaded blue (MacDonald and Case, 2005), C. Sea surface temperature anomalies for evaporated water falling as precipitation in the Sierra Nevada (McCabe-Glynn et al., 2013) with negative anomalies associated with warm California Current System sea surface temperatures (CCS SST; shaded red) and positive anomalies with cool CCS SST (shaded blue), D. relative abundance of CCS proxy diatom, *Thalassionema nitzschoides* (blue line), benthic diatoms (red line) and upwelling proxy diatom *Rhizosolenia* spp. (green line; Barron et al., 2014) compared to E. Scale deposition rates (SDR in scales $\times 1000 \text{ cm}^2 \text{ y}^{-1}$) for Northern anchovy (red bar), Pacific sardine (blue bar), Pacific hake (grey bar) and surf perch and other species (green bar). Flood events of 1270 and 1380 are shown (grey lines) alongside the massive olive layer interpreted as a turbidite at 1180 (Hendy et al., 2013).

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Figure 1

Figure 2

Figure 3

Figure 5

Table 1

Table 1: Pearson correlation coefficient for sardine and anchovy scale deposition rates (SDRs) and relative abundance to each other (5), selected diatom relative abundance (%; Barron, et al., 2014), tree ring-based Pacific Decadal Oscillation estimate (MacDonald et al, 2005) detrended for potential temperature effects and North Pacific sea surface temperatures based on Crystal Cave $\delta^{18}\text{O}$ (McCabe et al., 2012). Strong positive correlations are indicated by orange boxes, medium positive correlations by peach boxes, weak positive correlations by pale peach and no correlation by white boxes. Strong negative correlations are indicated by dark blue boxes, medium negative correlations by blue boxes, and weak negative correlations by pale blue boxes. n=53, except for the diatom data where n=38

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