**Particle-size Evidence of Barrier Estuary Regime as a New Proxy for ENSO Climate Variability**

**Short title: ENSO driven meso-scale periodicity in barrier estuary sediments.**

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**Abstract.**

We investigate a new proxy for ENSO climate variability based on particle-size data from long-term, coastal sediment records preserved in a barrier estuary setting. Corresponding ~4-8 year periodicities identified from Wavelet analysis of particle-size data from Pescadero Marsh in Central Coast California and rainfall data from San Francisco reflect established ENSO periodicity, as further evidenced in the Multivariate ENSO Index (MEI), and thus confirms an important ENSO control on both precipitation and barrier regime variability. Despite the fact that barrier estuary mean particle size is influenced by coastal erosion, precipitation and streamflow, balanced against barrier morphology and volume, it is encouraging that considerable correspondence can also be observed in the time series of MEI, regional rainfall and site-based mean particle size over the period 1871-2008. This correspondence is, however, weakened after c.1970 by temporal variation in sedimentation rate and event-based deposition. These confounding effects are more likely when (i) accommodation space may be a limiting factor, and (ii) particularly strong El Niños, e.g. 1982/83 and 1997/98, deposit discrete >cm-thick units during winter storms. The efficacy of the sediment record of climate variability appears not to be compromised by location within the back-barrier setting, but it is limited to those El Niños that lead to barrier breakdown. For wider application of this particle size index of ENSO variability, it is important to establish a well-resolved chronology and to sample the record at the appropriate interval to characterize deposition at a sub-annual scale. Further, the sample site must be selected to limit the influence of decreasing accommodation space through time (infilling) and event-based deposition. It is concluded that particle-size data from back-barrier sediment records have proven potential for preserving evidence of sub-decadal climate variability, allowing researchers to explore temporal and spatial patterns in phenomena such as ENSO.

**Key words**

ENSO, wavelet analysis, periodicity, barrier estuary, particle size analysis, Central Coast California.

**Introduction: Proxy Records of ENSO, Decadal and Multi-decadal Climate Variability.**

Here we present a new proxy for ENSO climate variability based on particle-size data from long-term, coastal sediment records preserved in a barrier estuary setting. The aim is to establish a method for providing detail on the expression of ENSO phenomena where instrumental records are unavailable.

Extending evidence of climate variability beyond the duration of instrumental data is based mainly on biological and/or sedimentary records (cf. Donders et al., 2008). These proxies refer either directly to moisture balance (e.g. tree rings, pollen), water level (e.g. lake level, river discharge) or changes in source terms (e.g. terrestrial sediment influx, ocean mixing volumes). The best established proxy, particularly for western North America is that of tree ring records (Cook et al., 2004; Knapp et al. 2004; Meko and Woodhouse, 2005). For example, an analysis of long-term coastal air temperature reconstructed from five tree ring records for the northeast Pacific by Ware and Thomson (2000) reveals that climate has oscillated at three dominant timescales over the last 400 years: 2-8 years, 20-40 years and 60–80-years. The 2-8-year ENSO timescale is the perhaps most prominent inter-annual variability in the North Paciﬁc and in high-resolution temperature and/or moisture reconstructions for the mid- to late Holocene (Michaelsen 1989; Haston and Michaelson, 1994; Cook et al. 1995; Ware and Thomson, 2000; Li et al., 2011). Other biological indicators tend to provide data on longer-term, underlying trends in this sub- to multi-decadal variability due to the temporal resolution of the sediment record. Fossil ostracode, foraminiferal and molluscan assemblage data, often coupled with stable isotope or geochemical analyses, reveal sub- and multi-decadal climate signatures (and longer-term patterns therein) in marine and coastal settings, generally linked to changes in SST, salinity and/or river inflow (Sandweiss et al., 1996; Koutavas et al., 2002; Cronin et al. 2002; Stott et al., 2004; Buzas-Stephens et al., 2014; Carré et al., 2014). In addition, corals offer both stratigraphic and morphological evidence of changing climate variability, mostly in the form of SST and water source proxies as a measure of ENSO occurrence and intensity (Gagan et al., 1998; Tudhope et al., 2001; McGregor and Gagan, 2004). Pollen data from a range of sedimentary records also have the potential to reveal decadal and centennial climate variability in terms of vegetation response to changing moisture balance and aridity, although the recent record is ‘contaminated’ by human influence on land-use and fire history (e.g. Sweetnam and Betancourt, 1990; Sirocko et al., 1996; Heusser and Sirocko, 1997).

The combination of sediment composition and particle size data also provides an effective proxy for sub- and multi-decadal climate variability in marine, coastal and lacustrine settings but the resolution of the reconstruction is often limited by low sedimentation rates or lack of continuity (Conroy et al., 2008). Several lake sediment-based studies of lake level demonstrate a clear covariance between sediment composition (including magnetic properties, inorganic and organic geochemistry, and stable isotopic data) and particle size as a function of periodic variability in either deep vs. shallow water or increasing terrigenous influx (e.g. Rodbell et al., 1999; Moy et al., 2002; Nelson et al., 2011; Bird et al., 2014). Conroy et al. (2008) identify ENSO variability in the eastern tropical Pacific from down-core patterns in clay vs. silt content and C/N ratios of lake sediments from the Galapagos, in which higher rainfall from more frequent ENSO events from the mid-Holocene transports larger particle sizes (increased silt content) into the lake basin. Similarly, Nelson et al. (2011) interpret periodicities in sediment greyscale and δ18O from Wavelet analysis of a well-dated, high-resolution core from Castor Lake, Washington in the context of changes in regional, decadal-scale variability in effective moisture associated with ENSO and the Pacific Decadal Oscillation (PDO). This aspect of variable terrigenous influx as a function of enhanced streamflow due to phenomena such as ENSO, the PDO or North Atlantic Oscillation (NAO) has also been explored in near- and offshore depositional settings. Based on Wavelet analysis, Dean et al. (2004) identify a 20-year PDO cycle in the geochemistry of sediment cores from the Guaymas and Carmen basins in the Gulf of California, whilst shorter periodicities of 4-8 and 8-16 years in detrital clastic influx may be linked to ENSO.

Wavelet analysis of variability in particle size data is the primary focus of this paper in terms of establishing an effective ENSO (and/or PDO) proxy for the western Pacific region. Developing the Wavelet transform approach established by Gu and Philander (1995), and as applied by Dean et al. (2004) to the analysis of sediment-based proxies of ENSO forcing, we examine the potential for ENSO cyclicity and specific El Niño years to be evidenced in the mean particle size of barrier estuary sediment records from Central Coast California. Many studies in the western Pacific region link increased particle size to enhanced rainfall or streamflow. For example, comparison between lake level, sediment particle size, San Jacinto River discharge, and the twentieth century PDO index (Kirby et al., 2010) indicates that sand content in a core from Lake Elsinore is a suitable, qualitative proxy for PDO-related hydrological variability at both event and multi-decadal to centennial timescales. Romans et al. (2015) record variability in coarse-grained terrigenous influx into the Santa Monica Basin, California, linked primarily to the increased magnitude and frequency of El Niño events from ca. 2 ka. In depositional settings that are essentially sinks, changes in the source (nature, amount) are readily recorded providing there is no significant moderation of the source term. Our investigation is more complex in that we aim to explore this principle for ‘transmission’ depositional settings where the efficiency of transmission undergoes temporal modulation over a range of timescales as a function of annual streamflow and its inter-annual to decadal variability.

**Recording Sub- and Multi-decadal Climate Variability in Barrier Estuary Settings.**

The sediment record is not necessarily a complete archive of environmental change; this is particularly true for coastal locations where sediment throughput (by-passing) or erosional events are an important consideration. Further, there may be many interacting drivers of coastal environmental change reflected in down-core particle size trends, e.g. relative sea level, coastal hydrodynamics, accommodation space, accumulation rate, resuspension, estuary mixing, changing sediment provenance, and the ecohydrological role of vegetation (Dyer, 1986; Boyd et al., 1992; Dalrymple et al., 1992; Christiansen et al., 2000; Dalrymple and Choi, 2007; Edwards, 2007; Fitzgerald et al., 2008; Shi, 2010). These shortcomings aside, particle-size analysis is an established tool for distinguishing depositional environments (e.g. Folk and Ward, 1957; Visher, 1969; Tanner 1991), which can be used effectively to reconstruct past environments, and environmental change, when and where observational records are unavailable (e.g. Lario et al., 2002; Clarke et al., 2014a, b; Rahman and Plater, 2014).

A key characteristic of barrier or ‘bar-built’ estuaries, i.e. those where coastal processes build a sand bar across the estuary mouth, is their intermittent connection with the sea. Essentially, a quasi-annual ‘cycle’ operates in which waves block the estuary through sediment accretion whilst high streamflow has the capacity to break through this obstruction (Behrens et al., 2013). Rainfall and runoff are major factors in barrier opening, particularly in Mediterranean climates (Elwany et al., 1998; Ranasinghe and Pattiaratchi, 1998, 1999, 2003; Smakhtin, 2004; Gale et al., 2007; Kraus et al., 2008; Behrens et al., 2013; Rich and Keller, 2013), although wave energy, storms and other low frequency high magnitude events are also important factors (Cooper, 2001; 2002; 2009). Focussing in particular on California barrier estuaries, Elwany et al. (1998) recognize that river flow – as a function of rainfall - is the major control on tidal inlet condition (i.e. open vs. closed) for the San Dieguito Lagoon, S. California over timescales longer than a few years, whilst over shorter timescales (months to several years) tidal prism and alongshore sediment transport are more important. Testing their model of barrier breaching and closure on Carmel Lagoon, Central Coastal California, Rich and Keller (2013) confirm the seasonal pattern of inlet status as reflecting seasonality in streamflow, but wave overtopping causes short-term breaching during conditions of low streamflow. In their study of documentary, photographic and instrumental records from the Russian River mouth, a bar-built estuary in N. California, Behrens et al. (2013) determine inlet condition to be a product of tide- and river-induced scour balanced against wave-induced sediment deposition. Whilst these studies indicate a degree of spatial and temporal inconsistency in barrier estuary response to seasonal streamflow across the region, it is important to consider this in the context of (a) the wider impacts of ENSO variability on the California coast and (b) contrasts in the expression of El Niño years in rainfall and streamflow between N. and S. California.

El Niño years are generally associated with enhanced beach loss due to elevated tidal levels of the order of 0.3-0.4 m, higher-energy waves, more direct storm approach, and northward sediment transport (Komar, 1998; Storlazzi and Griggs, 2000; Allan and Komar, 2006; Revell et al., 2011), although Barnard et al. (2012) suggest that the northward extent of this erosion may be tempered during El Niño events in which the maximum warm SST anomaly occurs in the central equatorial Pacific (CP-El Niños, cf. Ashok et al., 2007). The integrity of coastal barriers is degraded by such wave and storm incidence, enhancing the potential for inlet opening under the influence of high streamflow.

With respect to streamflow, both El Niño and La Niña years are associated with abnormal rainfall in the Central Coast region, but this can be both high and low in either case. In the western Central Coast region, El Niño years tend to be the wettest but drought is also possible (Schoner and Nicholson, 1989). In essence, the Central Coast lies in a transition zone between relatively distinct ‘northern’ and ‘southern’ modes of climate behaviour. Mitchell and Blier (1997) recognized that extreme wet months for the north California coast are associated with stronger, more zonal upper-level ﬂow over the eastern Paciﬁc Ocean, displacing the surface subtropical high southward and resulting in onshore ﬂow into northern California, whilst extended wet and dry periods in southern California are consistent with ENSO ﬂuctuations (e.g. Zhang et al., 1997). Whilst S. California rainfall then demonstrates a clearer connection with ENSO, that of N. and Central Coast California is more equivocal (Fu et al., 1986; Yarnal and Diaz, 1986; Schoner and Nicholson, 1989; Redmond and Koch, 1991; McCabe and Dettinger, 1999; Piechota et al., 1997; Cayan et al., 1999; Mitchell and Blier, 1997; Andrews et al., 2004). It is, therefore, unsurprising that the inter-annual cycles identified by Behrens et al. (2013) in streamflow and river mouth closure in the southern part of the N. California coast (or the northern Central Coast) cannot be linked statistically to either ENSO or the PDO, although some coincidence is evident.

**Research Approach and Case Study.**

*Underpinning Principles for a Particle Size Proxy of ENSO Variability:*

Acknowledging the spatial and temporal limitations of site-specific reconstructions of ENSO and other inter-annual and multi-decadal sources of climate variability (Jones et al., 2001), this paper seeks to establish the efficacy, fidelity and reproducibility of barrier estuary sediment records in evidencing sub-decadal climate variability. The basis for this connection between ENSO climate variability and barrier estuary particle size derives from previous work on Pescadero Marsh (Fig. 1) (as well as understanding of other bar-built estuaries - see previous section) in which the system undergoes a seasonal switch from a back-barrier lagoon to an open (or partly restricted) barrier estuary. Each year is, in principle, characterized by a depositional couplet of fine grained lagoonal muds and coarser barrier estuary sandy-silts laid down on a salt marsh and tidal channel margin, over time the changing balance between these two components is conceptualised as barrier ‘openness’ – with episodic storms being preserved as sandy layers of variable thickness and extent (Clarke et al., 2014a, b). Here we don’t attempt to distinguish the specific driver of barrier ‘openness’ due to the interaction of high rainfall and coastal erosion during El Niño years, nor can we resolve specific overwash events due to the temporal resolution of the sediment record. Whilst it seems most likely that barrier opening is driven by high rainfall, barrier breakdown due to marine erosion (e.g. Krauss et al., 2002) has also been documented. Hence, the sediment record is treated here as a ‘time series’ of barrier regime state. Extended periods of barrier closure will increase the relative proportion of the lagoonal muds, whilst longer periods of open barrier estuary conditions will limit their deposition. Even though extensive exploration of particle size distribution shape (Clarke et al., 2014a) and statistical analysis of grain size components (Clarke et al., 2014b) has been undertaken, mean particle size has proved to be a very effective, integrative proxy for variability in barrier ‘openness’, i.e. the duration and extent of annual barrier inlet opening, and identifiable regime shifts in relation to disturbance and recovery from extreme events. The mean particle-size trend can therefore be used in combination with a robust chronology (based on multiple chronological markers and radiometric dating) to evidence changes in depositional energy at sub-annual resolution – if sampled at sufficient resolution - over a period of >150 years (in the specific case of PM08, Clarke et al., 2014a, b).

Following on from this sedimentary index for barrier estuary ‘openness’, the link to ENSO cyclicity comes from variability in rainfall and, hence, streamflow. As noted previously, ENSO is an important driver of inter-annual variation in rainfall and streamflow, as well as storminess and coastal erosion in Central Coast California (Schoner and Nicholson, 1989; Storlazzi and Griggs, 2000), all of which contribute heavily to multi-annual variance in barrier openness (Elwany et al., 1998; Ranasinghe and Pattiaratchi, 1998, 1999, 2003; Kraus et al., 2008; Behrens et al., 2013; Rich and Keller, 2013). In the simplest condition, high streamflow causes the barrier to breach, thus transforming a back-barrier lagoon to an open barrier estuary. Furthermore, strong El Niño years may cause rapid barrier degradation events followed by gradual recovery (*cf*. Cooper, 2001; 2002; 2009). As such, ENSO variability provides an important meso-scale control on barrier openness and, therefore, back-barrier depositional environments.

However, as noted previously, ENSO variability is not recorded unequivocally in the instrumental record of rainfall or streamflow in the Central Coast region. Further, it is acknowledged that the susceptibility of the barrier system to breakdown or breaching during any given winter is also influenced by wave climate, coastal storms and sediment supply. Indeed, we recognize that Pescadero Marsh, as the test case, lies beyond the northern limit of a clear ENSO signature in rainfall, streamflow and high energy waves, and thus represents a critical examination of inter- or multi-annual cyclicity in barrier estuary behaviour. It is therefore essential that this research explores the correspondence between mean particle size and various metrics and data on ENSO variability (see *Study Area and ENSO Data* section). In successfully establishing synchronous behaviour across the sedimentary archive, the instrumental record of precipitation, and the Multivariate ENSO Index, for example, we also aim to provide a novel and effective proxy for either extending and enhancing instrumental data (*cf*. Cook et al., 2004 for tree-ring data) or providing evidence of rainfall and streamflow variability where instrumental records are absent.

*Study Area and ENSO data:*

Located in San Mateo County, Central Coast California, Pescadero Marsh Natural Preserve (Fig. 1) incorporates an intermittently open sandbar barrier, a back-barrier lagoon and extensive wetlands ranging from salt marsh to fresh water reedswamp. This diverse landscape results from the Pescadero and Butano creeks converging then meeting the Pacific Ocean. At present, the back-barrier area at Pescadero Marsh is characterised by a seasonal regime switching between predominantly tidal salt marsh and predominantly closed lagoon conditions. Barrier opening events generally take place during the wet winter season with closure occurring during the dry summer (Kerbavaz, 2007). The Pescadero-Butano watershed receives on average ~1,000 mm of precipitation each year; almost all of which falls between November and April, often during intense storm events (Hedlund et al., 2003).



Fig. 1: Map of Pescadero Marsh Natural Preserve illustrating the main geomorphological features; PM08 and PM09 core sampling locations are illustrated.

At Pescadero, a significant component of inter-annual variability in rainfall, streamflow and storminess can likely be explained by the ENSO phenomenon, and potentially by high rainfall during El Niño years. However, it is emphasized that many other processes and weather/climate events also exert a degree of control on barrier openness and, thus, back-barrier sedimentation (see ‘Recording Sub- and Multi-decadal Climate Variability in Barrier Estuary Settings’ section). Importantly, Pescadero lies within the Central Coast ENSO transitional zone (Schoner and Nicholson, 1989), meaning that El Niño rainfall varies from large increase to large decreases, with no observable impact also a possibility.

In order to better understand the correspondence between ENSO variability, specific El Niño years and the Pescadero sediment record, complimentary climate datasets for the study area are analysed. Given the range of environmental and geomorphic controls on sediment deposition, the expectation is not necessarily to establish that all El Niño years are preserved in the sediment record of Pescadero Marsh. However, ENSO cyclicity should certainly be detectable in the mean particle-size data, as well as a depositional ‘fingerprint’ of notably strong El Niño years. To this end, a well-established ENSO index and a local rainfall record are examined for their principal periodicities and alignment of El Niño indicators. For the duration of the study period, the rainfall data has potential to offer a very local record of ENSO evidenced via precipitation variability whilst the MEI data provide a direct metric of past global ENSO activity.

The most complete and reliable rainfall data set for the Euro-American Era in central California comes from downtown San Francisco, ~40 km north of the Pescadero-Butano watershed. Monthly rainfall totals have been recorded at this site since July 1849. These data are available from the National Oceanic and Atmospheric Administration (NOAA) website (http://w2.weather.gov/climate/xmacis.php?wfo=mtr).

Further to the rainfall data, the Extended Multivariate ENSO Index (MEI), 1871-2004, was also used. The MEI data derives from records of sea surface pressure and sea surface temperature over the tropical Pacific reconstructed by the Hadley Centre. Strong positive and negative values in this index directly represent El Niño and La Niña, respectively (Wolter and Timlin, 2011). These MEI data are also available through the NOAA website (http://www.esrl.noaa.gov/psd/enso/mei.ext/).

**Methods.**

*Selection of Core Location and Particle-size Analysis:*

At carefully selected locations, back-barrier sediments from Pescadero Marsh provide a high temporal resolution record of late Holocene system behaviour (Clarke et al., 2014a, 2014b). A time series of maps and aerial photographs was used to first identify areas of Pescadero Marsh where sedimentation had consistently been influenced by seasonal changes in barrier openness, i.e. seasonal switching between tidal salt marsh and closed lagoon, since at least 1854 (Clarke et al. 2014b). Further site selection criteria excluded areas of human influence (reclamation for farming, embanked areas) and focussed on locations where there was evidence of consistent salt marsh vegetation over the period of the photographic and cartographic record (Clarke et al., 2014b). A 185 cm sediment core, PM08, was taken from the centre of a saltmarsh lobe (Fig. 1) at a site considered to be remote from the influence of overbank deposition. A second core, PM09, was also collected to test the repeatability of the particle-size record of barrier openness and the sensitivity of the record to creek proximity. Thus, while the PM08 location was selected to reduce the fluvial influence on sedimentation to a minimum, the PM09 site was located close to the main Butano Creek channel (Fig. 1) where overbank deposition would be expected to be an important factor in the sedimentary regime. Although the depositional environment differs between the two core locations in terms of channel proximity, multi-annual controls on sedimentary regime, i.e. variations in rainfall and streamflow, are assumed to be broadly consistent across the back-barrier area.

Cores were returned to the laboratory, where they were cold-stored and then sliced into consecutive 2 mm samples. Particle-size analysis was performed on each sample using a Coulter LS200 laser granulometer. Full details of the methodology, including data analysis, are given in Clarke et al. (2014b). Here, only the mean particle-size data are examined.

*Chronology:*

A well constrained composite chronology exists for the upper 75 cm of the PM08 core; representing ~1860 – 2008 (Fig. 2). Contributions to the chronology come from a peak in atmospheric 137Cs fall-out from nuclear weapons testing, a stable lead pollution trend linked to automobile use, and other geochemical signals linked to human activity in the local area. Whilst the gamma spectrometry sought to establish unsupported 210Pb chronologies for the back-barrier sediment record, the measured 210Pb activities were too low to provide reliable unsupported 210Pb data (Clarke, 2011). This is not unexpected considering the west coast US location of Pescadero, i.e. no significant upwind source of unsupported 210Pb. Details of the ‘chronological waypoints’ used in the construction of this core chronology are given in Clarke et al. (2014b). For simplicity, a constant sedimentation rate of 5.06 mm/yr (72.1 days/mm) was applied for the PM08 time-series analysis. Although changes in sedimentation rate through time are likely, e.g. deposition of identifiable sand units during extreme events, a constant rate was applied as a further potential limiting factor on the approach. Similarly, as a chronology was not available for the PM09 core, the PM08 sedimentation rate was also applied to the PM09 mean particle-size trend. This was justified on the basis of the similarity in the elevation of the two locations and the vegetation of the depositional environment over the period of the photographic record.



Fig. 2: Mean particle-size trend for the upper 75 cm of PM08 core plotted against depth. Chronological markers (Clarke et al., 2014b) are illustrated, showing a consistent linear sedimentation rate throughout the period of record. For further detail on the core chronology, readers are directed to Clarke (2011).

*Wavelet analysis:*

Wavelet analysis, or wavelet transform, is well established for the exploration of temporal structure in ENSO data (Gu and Philander, 1995; Wang and Wang, 1996; Torrance and Campo, 1998) and sediment-based proxies of ENSO (e.g. Dean et al., 2004). This enables the analysis of localized variations of power in time series, thus revealing the dominant modes of variability and how these modes vary through time. The selection of the wavelet function (e.g. Morlet, Paul, ‘Mexican hat’) has a bearing on the analysis, and its ‘admissibility’ is dependent upon the assumption that this function is localized in both time and space and has a zero mean. Whilst there are inherent differences in the MEI, rainfall and particle-size time series – linked to (i) regional variability in the expression of ENSO in the San Francisco rainfall data and (ii) complexity in the ENSO control on barrier ‘openness’ through a combination of coastal erosion, catchment rainfall/streamflow and barrier resilience – we apply the same wavelet transform across all datasets to avoid any difference in the resultant periodicities being due to the analysis itself.

The analysis was under taken using Wavelet software freely available at: http://paos.colorado.edu/research/wavelets (Torrence and Compo, 1998). Time-series analysis was performed using a Morlet wavelet transform with a non-dimensional frequency of 6 to satisfy the admissibility condition. To determine significance above a background of random variability, a white noise spectrum was selected to establish the null hypothesis for the significance of peaks in the wavelet power spectrum. Additionally, selection of significance at the 5% level was set to ensure the identification peaks in the power spectrum at the 95% confidence level. The cone of influence (COI) (denoted by cross-hatching on the power spectrum plot) was added to account for errors that arise at the start and end of the wavelet power spectrum. The COI is therefore the region of the wavelet spectrum in which these edge effects become important and, thus, limited confidence can be placed on this part of the power spectrum. On the Wavelet Power Spectrum plot, the Period axis denotes the length - in years - of any given periodicity of given strength (white = weakest, red = strongest) whilst the Time axis illustrates the calendar years (i.e. duration) for which this periodicity applies. Colour shading indicates the power of the periodicity, with that above the 95% confidence level being indicated by a solid black line. The global wavelet spectrum provides a time-averaged measure of power, again relative to background variability. The Global Wavelet plot therefore provides a smoothed assessment of the significant periodicities evidenced in the wavelet power spectrum. For a more detailed guide to the application and principles of Wavelet analysis, the reader is guided to Torrence and Compo (1998).

Using the same settings, wavelet analysis was also performed on the mean particle-size data from the upper 75 cm of PM08 and the upper 70 cm from PM09 (each core was sampled every 2 mm), historical San Francisco rainfall data (1850-2014: monthly totals and annual mean values), and the Extended Multivariate ENSO Index (1871-2004: monthly for three month running mean and annual mean values calculated June/July/August through May/June/July). In order to explore the impact of distinct >cm-thick, coarse ‘high energy event’ layers on the determined power spectrum, wavelet analysis was also undertaken on the PM08 mean particle-size record with these layers removed from the dataset.

*Correspondence Across Climate and Particle-size Time Series:*

In addition to Wavelet analysis, the Extended MEI, San Francisco rainfall record, and PM08 mean particle size trend were plotted against time and directly cross-compared. This method was employed to demonstrate any directly observable correspondence between local rainfall and El Niño years, and to demonstrate the ability of the sediment record to evidence individual El Niños. Due to the subjective nature of this exercise, we use it to examine why known El Niños are either absent or temporally offset in the sediment record – thus establishing any limitations to the sediment-based metric.

**Results.**

The results section consists of three components, namely: i. exploration of the wavelet periodicities exhibited in the MEI and San Francisco rainfall data to establish the extent to which ENSO variability is apparent in the regional rainfall record; ii. investigation of wavelet periodicities expressed in the back-barrier sediment record from different core sites, and with and without ‘extreme event’ deposits being included in the analysis; and iii. examination of the correspondence between MEI, rainfall and particle size indicators of known El Niño years, and the extent to which the sediment record is a faithful archive of such years.

***Wavelet Analysis:***

*MEI and Regional Rainfall*

1. Multivariate ENSO Index (1871-2004)

Wavelet analysis of the MEI index dating back to the 19th century shows concentrations of power centred between 4-8 years, forming a broken band across the plot (Fig. 3b). In some instances, where this band is broken, stronger periodicities are present in the 2-4 year range. The Global Wavelet chart (Fig. 3c) also highlights a significant periodicity between 4 and 8 years, although this appears to shorten slightly through the record, initially being centred at or close to 8 years but moving closer to 4 years approaching the present. In both the Wavelet Power Spectrum and the Global Wavelet plots, there is also some suggestion of a longer duration periodicity, centred closer to 16 years, however these concentrations of power are largely within the COI and no significance is indicated by the Global Wavelet chart at this duration. (We exclude mention of the 64 year periodicity for the same reasons.)

Although we do not present wavelet analysis of monthly MEI data, this revealed that the strongest and most consistent concentrations of power also occur between 2-8 years.



Fig. 3: (a) Annual mean MEI values (1871-2004). (b) The wavelet power spectrum. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region is the cone of influence (COI), where zero padding has reduced the variance. Bold contour is the 5% significance level, using a white-noise background spectrum. The Time axis relates to calendar years. (c) The global wavelet power spectrum (black line); the dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in (b). (After Torrence and Compo, 1998.)

1. San Francisco Rainfall (1850-2014)

The most striking feature of the Wavelet plot of monthly rainfall data from San Francisco is the red band centred at 1 year on the Period axis (Fig. 4b), with a corresponding peak in variance dominating the Global Wavelet (Fig. 4c). This feature is expected as it results from seasonal variation in precipitation. Occasional discontinuities in this periodicity, primarily relating to years with relatively low rainfall (see Fig. 4 panels a and b), illustrate that the characteristic wet/dry seasonal regime has been subject to significant inter-annual variation since 1850. Attention is also drawn to concentrations of power occurring across this spectrum (Fig. 4c), centred between ~4 and 8 years. In addition, from ~1915 and extending into the COI, a periodicity centred close to but slightly shorter than 16 years is present. Peaks in variance on the Global Wavelet chart occur at ~4-6 and ~12-16 years (Fig. 4c), however these periodicities are of lower significance due to the overwhelming dominance of the annual variation in the data set. (Again, relatively coherent bands of power concentration at 16-32 and 32-64 years are dismissed due to substantial overlap with the cone of influence.)

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Fig. 4: (a) San Francisco monthly rainfall totals (mm). (b) The wavelet power spectrum (the Time axis relates to calendar years). (c) The global wavelet power spectrum (black line). See Fig. 3 caption for further details.

In comparison with the monthly rainfall data, Wavelet analysis of the San Francisco annual rainfall from 1850 to 2014 (Fig. 5b) exhibits stronger but less consistent concentrations of power centred in the range of 4-8 years. Another strong period at ~16 years persists from ~1915 to 2000. Significant peaks of variance on the Global Wavelet Power Spectrum suggest these periodicities are closer to 4-6 years and 12-16 years, respectively (Fig. 5 panel c). (Relative to the monthly rainfall plot, further coherent bands of high variance are observed at 16-32 and 32-64 years, but again they are rendered insignificant by the COI.)

The main distinction between the monthly and annual rainfall Wavelet plots is that the latter does not exhibit any seasonal periodicity in the data. This will be considered further in the Discussion with respect to the temporal sensitivity of the particle size evidence.



Fig. 5: (a) San Francisco annual rainfall totals (mm). (b) The wavelet power spectrum (the Time axis relates to calendar years). (c) The global wavelet power spectrum (black line). See Fig. 3 caption for further details.

*Back-barrier Particle Size*

1. PM08 Mean Particle Size

Excluding the section of the Wavelet plot covered by the cone of influence, an unbroken band of higher power spans across the PM08 mean particle-size Wavelet Power Spectrum chart (Fig. 6b). This concentration of power reveals a periodicity within the down-core trend in mean particle-size that evolves through time. The majority of the band is centred between 4 and 8 years on the Period axis, with the periodicity decreasing slightly, i.e. moving closer to 4 years, towards the present. Between ~1890 and 1970, the higher power band is surrounded by bold contour lines, indicating 95% confidence, with respect to the white noise spectrum, in the periodicity. Before 1890 and briefly ~1925 the periodicity is centred just below (i.e. longer than) 8 years, however a periodicity of between 4-8 years remains the characteristic feature of the core section.

The variance trend of the Global Wavelet chart (Fig. 6c) appears to offer some confirmation of this observation, by identifying a significant periodicity at 6-8 years, however a subsequent peak in variance at 8-16 years overlaps and obscures the 6-8 year peak, rendering this observation tentative. The 8-16 year peak in variance is caused by two concentrations of power between ~1890-1935 and 1955-2008. The former (a narrow green band on Fig. 6b) is centred at ~16 years, the latter, a more powerful and wider band (indicated in light green and red on Fig. 6b) is initially centred between 8 and 16 years, decreasing slightly toward the end of the record. While this 8-16 periodicity clearly registers as significant on the Global Wavelet chart (Fig. 6d), a significant proportion of the 1955-2008 band falls within the COI for recent years, and hence is of lower confidence.



Fig. 6: (a) PM08 mean particle-size (ⱷ) trend from 75-0 cm. (b) The wavelet power spectrum (the Time axis relates to calendar years calculated from the core chronology). (c) The global wavelet power spectrum (black line). See Fig. 3 caption for further details.

1. PM08 Mean Particle Size excluding ‘Event Layers’

Embedded within the Wavelet analysis of the PM08 data are several discrete coarse-grained units that evidence the occurrence of extreme events in the Pescadero barrier estuary. It is likely that some of these ‘Event Layers’ may well be related to El Niño years whereby the coast was eroded preferentially (cf. Storlazzi and Griggs, 2000). Their preservation potential has probably been enhanced by the location and depositional setting of the PM08 site, i.e. upper intertidal wetland at some distance from the main Butano Creek channel whereby subsequent reworking by tidal flushing is limited due to their elevation above normal high tides. Due to ‘instantaneous’ deposition of c. 1 cm-thick sedimentary units, these event layers have potential to disrupt the background rate of sediment accretion and distort the periodicity of the mean particle-size trend when a linear sedimentation rate is applied. Thus, an additional Wavelet analysis was undertaken on the PM08 dataset limiting the disproportionate effect of ‘event layers’ on the Wavelet periodicity by excluding all but one data point coarser than 5 ⱷ from each relevant layer.

In practice, this data ‘pruning’ does little to change the overall pattern of periodicity, the Global Wavelet chart (Fig. 7c) still clearly illustrates significant periodicity between 4-16 years with peaks in variance between 4-8 and 8-16 years. Another less prominent but also significant periodicity is present close to 16 years. The Wavelet plot (Fig. 7b) is still dominated by a power band initially centred just below 8 years, which moves closer to 4 years as time progresses. The power of this band is increased relative to the full mean particle-size wavelet analysis. As with the un-pruned particle-size data, there are again concentrations of power in the 8-16 year range from ~1955 onwards, although in the pruned data it is more difficult to distinguish these concentrations of power from those present between 4-8 years over the same time period. Indeed, the pruning of extreme events has the most visible impact on the wavelet plot after the year 1980, however the majority of this section below the 8-year periodicity line is within the COI.



Fig. 7: (a) PM08 mean particle-size (ⱷ) trend from 75-0 cm with all but one data point coarser than 5 ⱷ removed from each event layer (the Time axis relates to calendar years calculated from the core chronology). (b) The wavelet power spectrum. (c) The global wavelet power spectrum (black line). See Fig. 3 caption for further details.

1. PM09 Mean Particle Size

The down-core mean particle-size data from PM09 were analysed to examine the influence of the site of deposition within the barrier estuary on the sedimentary record of barrier integrity. Wavelet analysis of the PM09 mean particle-size trend is not dominated by such a clearly-defined periodicity as that of the PM08 (unpruned) particle-size data but again there are numerous concentrations of power between 4 and 8 years; some of which are denoted by 95% confidence contours (Fig. 8b). Multiple but less consistent concentrations of power are also present between 8-16 years. Two overlapping peaks in variance on the Global Wavelet chart (Fig. 8c) confirm periodicities with ~6-8 and ~8-12 year durations. A tentative 16-32 year periodicity may also be inferred from the Wavelet Power Spectrum and Global Wavelet chart but not with any confidence due to substantial overprint by the COI.

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Fig. 8: (a) PM09 mean particle-size (ⱷ) trend from 70-0 cm. (b) The wavelet power spectrum (the Time axis relates to calendar years calculated from the PM08 core chronology). (c) The global wavelet power spectrum (black line). See Fig. 3 caption for further details.

***Correspondence Across Climate and Particle-size Data:***

Having examined the periodicities present in the climatic and particle-size datasets separately, this section explores the presence of any correspondence across these data – particularly in relation to well-known El Niño years. Figure 9 shows time series for the extended MEI (June-June), the San Francisco mean annual rainfall, and the PM08 down-core mean particle-size plotted according to their known or reconstructed calendar years. The constant sedimentation rate discussed in the chronology section and applied to the core data Wavelet analysis, is used to attribute ages back from 2008 for particle-size data points. Over the period 1971-2004, the extended MEI index values are used to identify major ENSO events. ‘Strong’ and ‘very strong’ El Niño years are labelled, respectively, with light and dark red bands, whilst ‘strong’ and ‘very strong’ La Niña years are denoted with light and dark blue bands. Here, based on the range of the extended MEI, strong events are classified as index values between 1.0 and 2.0 for El Niño and -1.0 and -1.5 for La Niña, with very strong events being those of > 2.0 or < -1.5, respectively.



Fig. 9: Chronological cross correlation of the extended MEI, mean annual San Francisco rainfall (mm), and PM08 mean particle size (ⱷ) between 1871 and 2004. Here the ⱷ scale (larger numbers = small particle sizes) is plotted in reverse order so that peaks in the trend line illustrate coarsening of mean particle size. ‘Strong’ (light red shading) and ‘very strong’ (dark red shading) El Niño events are classified by MEI values of 1.0 to 2.0 and > 2.0 respectively. ‘Strong’ (light blue shading) and ‘very strong’ (dark blue shading) La Niña events are classified as -1.0 to -1.5 and < -1.5. Black rectangles illustrate mean particle size peaks corresponding to El Niño events of > 1.0 MEI; dashed rectangles indicate mean particle size peaks which may relate to more than one El Niño event. In some instances, arrows illustrate temporal offset between MEI and mean particle size peaks. Question marks are placed when > 1.0 El Niño events are present in the MEI but corresponding mean particle size peaks are absent.

Throughout the record, peaks in San Francisco rainfall appear to correspond well with MEI peaks for almost all of the strong El Niño years (Fig. 9). On occasion there is a slight offset which can be accounted for by the MEI annual mean values being calculated from June-June while the rainfall mean values represent calendar years. Despite this, the correspondence between increased rainfall and major El Niño events is clear.

Before moving on to consider correspondence with the PM08 mean particle-size record, it should be stressed that while a constant sedimentation rate very adequately characterises the whole core section, any temporal variation in this rate due to ‘event layers’ or periods of enhanced or reduced sediment accumulation is likely to introduce a non-trivial level of variability, and thus potential offset in the reconstructed and actual age of any sediment sample between dated waypoints within the core (see Fig. 2). With this consideration in mind, on visual inspection of the composite plot (Fig. 9) it is clear that a high degree of correlation exists between the down-core mean particle-size time series and both rainfall and MEI during stronger El Niño events. Black rectangles have been added to the particle-size data to illustrate instances where El Niño events are accompanied by shifts to coarser mean particle sizes. Where the particle–size data is slightly out of step with MEI and rainfall, due to variation in sedimentation rate, the width of the rectangle is extended up- or down-core to encompass the observed peak in particle-size (in some instances an arrow is included to illustrate the ‘direction’ of the temporal offset). Before 1970, correspondence is most obviously apparent between mean particle size and El Niños.

A small number of disparities do merit consideration, most fundamental of which is the lack of a mean particle-size peak associated with the 1925/6 El Niño event. In addition, the mean particle-size peak associated with the 1957-8 El Niño occurs in the particle size record between 1960 and 1961. This offset appears to be significant, but is readily accounted for by a subtle variation in sedimentation rate (see Discussion). After 1970, matching El Niño events to peaks in mean particle size is possible but becomes more problematic. Despite being accompanied by a high mean annual rainfall value of 849 mm and scoring 1.64 on the MEI, the 1972-3 El Niño event appears to be missing entirely from the particle-size data. Following this omission the two strongest El Niño events in the record occur in 1982/3 and 1997/8 peaking at 2.51 and 2.94 on the MEI, respectively. Concurrently, between 1980 and 1998, the mean particle size is dominated by two thick (> 1 cm) and coarse, high energy event layers. The ‘very strong’ 1982/3 El Niño corresponds to the middle of the first and largest of these event layers, whilst the 1997/8 El Niño occurs at the tail end of the second. There were numerous weaker El Niño events between 1982/3 and 1997/8, those occurring after 1990 can be linked to individual peaks in mean particle size within the most recent event layer (see dashed rectangles on Fig. 9). However, this leaves the ‘very strong’ 1997/8 El Niño event, which was accompanied by notably high mean annual rainfall total of 1,071 mm, associated with a relatively limited peak in mean particle size.

Although we do not focus on La Niña in this paper, a high level of correspondence is also evident in the composite plot.

**Discussion.**

It is clear from comparison across the Multivariate ENSO Index, San Francisco annual rainfall and PM08 mean particle-size data that there is a strong correspondence between regional climate forcing, its local expression in rainfall, and barrier estuary particle size for the period 1870-2008 (Fig. 9). Between 1871 and 1970, the cross-correlation across these three metrics is very good; only two strong El Niño events, 1925/6 and 1972/3, are not clearly represented by a marked increase in mean particle size. Although the correspondence between the MEI and San Francisco rainfall remains clear after c.1970, the relationship with particle size persists but becomes somewhat asynchronous (Fig. 9). This recent departure from a good level of co-variance between the climatic, meteorological and granulometric indices may be attributed to non-linear sedimentation at a higher frequency than that resolved by the core chronology.

Where there is sufficient accommodation space, i.e. space for sedimentation beneath limiting tidal levels, neither event-based deposition nor inter-annual variations in sedimentation rate prevent the underlying rate of c.5 mm/yr from being maintained. Consequently, the lower part of the sediment record is characterized by only small temporal offsets the instrumental and particle size record of El Niño and La Niña years. This is in accordance with the regime equilibrium identified in previous work (Clarke et al., 2014a, 2014b). However, when accommodation space becomes more limited, event-based deposition causes significant displacement of ‘background’ sedimentation for a finite number of following years. The presence of high energy event layers therefore offers a partial explanation for the weakening of the El Niño/mean particle-size relationship for the period c.1970-2008.

The coarsening of mean particle size associated with El Niño events is principally envisaged to result from degradation of the coastal barrier system due to coastal erosion coupled with increased streamflow, resulting in sustained periods (months-years) of increased barrier ‘openness’ (Clarke et al., 2014a, 2014b). However, in some instances, notably thick and coarse layers are present due to rapid deposition during high energy events, which may be associated with El Niño winters. One such ‘high energy event layer’ that is > 2 cm thick, with a mean particle size consistently between 4 and 5 ⱷ, is found in the sediment record between 1979 and 1985. This layer is seemingly associated with the 1982/3 El Niño which is well known across the Central Coast due to its marked coastal erosion (Storlazzi and Griggs, 2000). Here, erosion of the sedimentary surface prior to storm deposition causes the 1982/83 storm layer to appear lower in the sediment record and, thus, would have an anomalously ‘old’ bottom contact, i.e. the 1982/3 El Niño layer begins at 1979 in the particle size record. At the same time, the instantaneous deposition of >2 cm of sediment in a single layer occupies the accommodation space for the following 4-5 years or so, i.e. what would have been deposited at an average sedimentation rate of c.5 mm/yr, thus inhibiting depositional evidence of the period up to about 1983-86. A similar potential high energy event layer is present between 1993 and 1997 in the particle size record, although this might equally date from the 1997/98 El Niño winter which, again, is noted in the region for its significant coastal erosion and high sea level (Storlazzi and Griggs, 2000; Allan and Komar, 2006).

By reducing accommodation space due to their instantaneous deposition of the order of 1-2 cm and by potentially eroding the sedimentary surface prior to deposition, these high energy event layers may offset the core chronology and thus account for the difficulty in correlating recent El Niño events with peaks in mean particle size. In light of these considerations, the 1986/7 and 1987/8 moderate El Niño years may be absent from the sediment record due to the thickness of the 1982/3 event layer, or indeed have become incorporated into the upper parts of the layer. Subsequent El Niño events can be linked to coarse mean particle size peaks, with the ‘very strong’ 1997/8 event either represented by a disproportionately small mean particle-size peak at 1998 or being incorporated in the larger high energy event layer found between 1993 and 1996 on the mean particle-size chronology.

A more highly resolved core chronology would overcome the issue of undetected non-linearity in the sediment record. Indeed, an unsupported 210Pb chronology was sought in this respect for the upper part of the record but the determined activities were not sufficiently above background supported 210Pb to provide reliable ages (Clarke, 2011). It is, therefore, apparent that some tuning of the chronology is required where event-based deposition causes the sedimentation rate to vary substantially through time – as one would expect for the most significant El Niños in 1982/83 and 1997/98. Importantly, it is encouraging that no substantial tuning is required for the period c.1870-1970, probably due to there being unrestricted accommodation space and less strong El Niños.

Wavelet analysis of the sedimentary, meteorological and climatic data offers important confirmation of the graphical comparison, particularly in the case of the particle size data where there is a likelihood that the record contains missing data – especially in the upper part of the record under conditions of limited accommodation space. Here, confirmation is sought in the underlying periodicities evidenced in the datasets. First and foremost, a persistent periodicity is identified throughout the PM08 core section; centring between 4 and 8 years for the majority of the record (Figs. 6 & 7). This underlying periodicity is consistent whether or not coarse-grained, extreme event layers are included in the Wavelet analysis. The duration of the periodicity is shortest closer to the present, being slightly longer than 8 years prior to 1890, but remaining closer to 8 years than 4 throughout (Figs. 6b and 7b).

Wavelet analysis of the San Francisco rainfall record (1850-2014), both monthly and annually, also identifies significant periodicity between 4 and 8 years (Figs. 4 & 5). Throughout the PM08 particle size and San Francisco annual rainfall Wavelet plots (Figs. 6-7 and 5, respectively), the 4-8 year periodicities correspond approximately but not directly. Here, small inconsistencies can be accredited to the complex interplay of streamflow, wave climate and sea level with respect to barrier integrity and volume in driving Central Coast barrier dynamics (e.g. Elwany et al., 1988; Rich and Keller, 2013; Behrens et al., 2013). Subtle down-core variation from the linear sedimentation rate applied to the particle size Wavelet analysis may also play a role.

With respect to ENSO, the periodicity has been between 2 and 8.5 years over the last 5,000 years (Rodbell et al., 1999), operating on an average frequency of 3-5 years during recent decades (NOAA, 2010). This is reflected clearly in the Multivariate ENSO Index data (1871-2004), which shows periodicity between 2-8 years when plotted monthly or ~5-7 years when plotted annually (Fig. 3). Identifying ENSO periodicity in the MEI data is to be expected and is not claimed as a finding of this research, rather the MEI analysis is used to demonstrate the validity of the periodicities identified in the other records presented.

Considering the geographical context of Pescadero Marsh, the established periodicity of the ENSO phenomenon, its variable strength and impacts on Central Coast precipitation (Fu et al., 1986; Schoner and Nicholson, 1989; McCabe and Dettinger, 1999), and the known (but not exclusively causal) link between precipitation/streamflow and the opening of coastal barrier systems in California (Elwany et al., 1998; Rich and Keller, 2013), the rhythm of recent ENSO activity is strikingly similar to that of the periodicity observed in the PM08 mean particle-size trend. Indeed, the PM08 trend also evidences a corresponding decrease in periodicity over recent decades. The corresponding periodicity of the San Francisco annual rainfall record further supports the link between the particle-size data and ENSO activity.

Comparing the periodicities apparent in the San Francisco monthly and annual rainfall data (Figs. 4 & 5) with those in present the PM08 record (Figs. 6 & 7) it is evident that the sedimentation rate in the back-barrier of Pescadero Marsh provides sufficient sensitivity to sub-decadal climate variability rather than the pattern of annual rainfall and streamflow. Consequently, as proposed by Clarke et al. (2014b), rather than simply seasonality, the mean particle-size trend is indeed a record of sub-decadal variability in barrier regime ‘openness’.

The PM09 mean particle-size record provides additional support for our interpretations of changes in barrier ‘openness’ driven by ENSO variability. A 4-8 year periodicity is present in sections of the PM09 record and, again, the duration of this is observed to decrease subtly with proximity to the present (Fig. 8). Indeed, the rate of decrease appears chronologically consistent between cores. Appearance of the 4-8 year periodicity is more sporadic in the PM09 record, this is likely explained by an additional influence on sedimentation at the core location. Being marginal to the main Butano Creek channel, PM09 has been subject to a greater influence from day-to-day tidal channel (flood tide) and fluvial (ebb tide) processes than the PM08 location (e.g. Allen, 2000). While the underlying influence of Butano Creek, whether in a barrier estuary or back-barrier setting, can readily account for subtle differences in periodicity (or record sensitivity) between the two records, ENSO activity is still evidenced as an important sub-decadal control on the PM09 sediment record.

While shorter term, multiple, interconnected factors therefore affect barrier opening and closure across a range of temporal scales, it is apparent that ENSO variability has provided the dominant meso-scale control on barrier integrity at Pescadero Marsh during the Euro-American era (~1860 – present). Extending our discussion to multi-decadal climate variability, there is some evidence for PDO-scale variability in San Francisco rainfall, i.e. 12-16 year periodicity, particularly after c.1915 (Figs. 4 & 5). Whilst this is not statistically significant in the MEI, there is an observed increase in Wavelet power at c.14-20 years (Fig. 3). The potential for the back-barrier sediment record to preserve longer-term multi-decadal climate variability (e.g. PDO) is given some support by the longer periodicities centred around 16 years in both the PM08 and PM09 mean particle-size data (Figs. 6-8). However, for periodicities of such duration, considerable caution must be applied due to the length of these records. Furthermore, in both the PM08 and 09 Wavelet plots the c.16 year periodicity components overlap considerably with the cone of influence. The hypothesis of multi-decadal climate variability being recorded in the mean particle-size data from back-barrier sediments thus requires a more robust test than that offered here.

**Conclusions.**

A high level of correspondence is identified in the periodicities present in the sediment record of barrier estuary mean particle size, historical rainfall data and extended Multivariate ENSO Index for California Central Coast. The corresponding ~4-8 year cycle identified in Wavelet analysis of particle-size data from Pescadero Marsh and San Francisco rainfall reflects established ENSO periodicity, as further evidenced in the MEI data, and thus confirms an important ENSO control on both precipitation and barrier regime variability.

Despite the fact that barrier breakdown is linked to the interaction of riverine influences (precipitation, streamflow), coastal erosion (wave energy, sea level, storm surge) and geomorphic resilience (barrier morphology and volume) it is encouraging that considerable correspondence can be observed in the time series of MEI, regional rainfall and mean particle size. This correspondence is, however, weakened by temporal variation in sedimentation rate and event-based deposition, thus compromising a chronology based on linear interpolation across dispersed temporal waypoints. Indeed, the confounding effects of event-based deposition are more prominent in the recent sediment record (post c.1970) when (i) accommodation space may be a limiting factor on post-event deposition, and (ii) particularly strong El Niños in 1982/83 and 1997/98 laid down discrete >cm-thick units during winter storms.

It is evident that the sedimentary record of mean particle size in a barrier estuary or bar-built estuary setting can be of sufficient sensitivity to record changes in barrier inlet condition as a function of sub-decadal ENSO (and equivocally multi-decadal in the case of PDO) climate variability. The efficacy of the sediment record of climate variability appears not to be compromised by location within the back-barrier setting, but it is limited to those El Niños that lead to barrier breakdown, i.e. winters that cause enhanced coastal erosion rather than just higher precipitation and streamflow.

In terms of caveats to consider in the wider application of sediment-based records of barrier estuary particle size for exploring ENSO variability through time and how this this may vary spatially along coastlines, the periodicity of the reconstructed climate variability is strongly dependent upon establishing a well resolved chronology, and the temporal resolution of the record is highly dependent upon sedimentation rate. For example, in the case of Pescadero Marsh, the sediment record is sufficiently sensitive to sub-decadal climate variability rather than annual patterns in rainfall/streamflow. Further, the record of ENSO periodicity and El Niño years may become complicated by reductions in accommodation space and event-based deposition in the upper part of the record. In this respect, thorough reconnaissance of cartographic and photographic evidence of the recent depositional history and exploration of the barrier estuary stratigraphy can act to limit the impact of this on the reconstruction.

It is concluded that despite barrier estuaries experiencing considerable shifts between sediment bypassing and sediment sink characteristics during the year, particle-size data from back-barrier sediment records have proven potential in being able to preserve evidence of sub-decadal climate variability, and perhaps multi-decadal climate phenomena given a sufficient length of record and sedimentation rate. Such sediment records are thus able to provide data *post hoc* for sites and for periods of time for which climate data do not exist. This sediment archive allows researchers to explore temporal and spatial (and temporo-spatial) patterns in phenomena such as ENSO (and maybe the PDO) at much greater resolution than existing instrumental or documentary climate data permit. This is especially the case for Central Coast California where barrier estuaries are located at several points along the coast (approximately every 10-20 km); permitting a study of how the present manifestation of ENSO in California rainfall patterns may have shifted in the past.

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