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Enhanced Late Holocene ENSO/PDO expression along the margins of the eastern North Pacific

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ABSTRACT

Pacific climate is known to have varied during the Holocene, but spatial patterns remain poorly defined. This paper compiles terrestrial and marine proxy data from sites along the northeastern Pacific margins and proposes that they indicate 1) suppressed ENSO conditions during the middle Holocene between ~8000 and 4000 cal BP with a North Pacific that generally resembled a La Niña-like or more negative PDO phase and 2) a climate transition between ~4200 and 3000 cal BP that appears to be the teleconnected expression to a more modern-like ENSO Pacific. Compared to modern day conditions, the compiled data suggest that during the middle Holocene, the Aleutian Low was generally weaker during the winter and/or located more to the west, while the North Pacific High was stronger during the summer and located more to the north. Coastal upwelling off California was more enhanced during the summer and fall but suppressed during the spring. Oregon and California sea surface temperatures (SSTs) were cooler. The Santa Barbara Basin had an anomalous record, suggesting warmer SSTs.

Late Holocene records indicate a more variable, El Niño-like, and more positive PDO Pacific. The Aleutian Low became more intensified during the winter and/or located more to the east. The North Pacific High became weaker and/or displaced more to the south. Coastal upwelling off California intensified during the spring but decreased during the fall. Oregon and California SSTs became warmer, recording the shoreward migration of sub-tropical gyre waters during the fall, while spring upwelling (cooler SST) increased in the Santa Barbara Basin. The high-resolution proxy records indicate enhanced ENSO and PDO variability after ~4000 cal BP off southern California, ~3400 cal BP off northern California, and by ~2000 cal BP in southwestern Yukon. A progressively northward migration of the ENSO teleconnection during the late Holocene is proposed.

1. Introduction

Significant progress has been made identifying climatic teleconnections between western North America and the sub-tropical Pacific during the last century at annual to decadal time scales. Identification of ENSO variations at 2–5 year frequencies and corresponding winter Pacific storm tracks has lead to better understanding of spatial Western U.S. precipitation patterns. The Pacific Decadal Oscillation (PDO), a pattern of North Pacific sea surface temperature variability that shifts phases every 20–30 years (Mantua et al., 1997), has also been identified in the North Pacific (>20° N). During a positive PDO phase, sea level pressures are below average over the North Pacific, whereas they are above average during a negative PDO phase. PDO spatial patterns broadly resemble El Niño and La Niña climate patterns (Mantua et al., 1997; Papineau, 2001). Considerably less detail is known about northeastern Pacific climate variations, corresponding teleconnections, and western North American spatial precipitation patterns at century-to-millennial time scales during the Holocene.

Paleoclimatic patterns can be deduced from a spatially distributed network of reconstructions. Such patterns have been estimated for the last 1.5 millennia (Mann et al., 2009) and have been used to propose mechanisms for Holocene changes (Donders et al., 2008). A growing number of Holocene records from the northeast Pacific region, with sufficient temporal resolution and chronological certainty, now provide an opportunity to elucidate spatial climate patterns since the early Holocene. This paper compiles detailed terrestrial and marine proxy records from the margins of the northeast Pacific, from Alaska to southern California, to test the hypothesis that spatial climate patterns of western North American during the Holocene are related to changes in Pacific climate patterns, such as ENSO and the PDO.

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Modern ENSO teleconnections with western North America are spatially and temporally complex (Cayan et al., 1999). Furthermore, a number of high-resolution studies from tropical corals spanning the last millennia have been challenged to clearly identify the roles of ENSO and solar activity during the Little Ice Age (Crowley, 2000; Cobb et al., 2003). The difficulty with identifying North Pacific climate dynamics at sub-decadal scales leads us to avoid interpretations at those temporal resolutions from the data gathered here. Rather, the aim of this synthesis is to contrast the broad, millennia-scale character of climate variability between the middle and late Holocene and elucidate spatial patterns that provide insights on possible synoptic climate patterns. It is proposed that late Holocene climate variability has been primarily driven by west-to-east flow that is influenced by North Pacific ocean-atmosphere dynamics such as ENSO and PDO, and that spatial patterns of middle vs. late Holocene climate of the northeast Pacific can be conceptualized in terms of the North Pacific High and the Aleutian Low.

First, the data for the middle Holocene from western North America is described and compared with northeastern Pacific SSTs. A description of the same regions follows for the late Holocene. There are significant challenges with making a synthesis of proxy records, including varying temporal resolution, chronological control and climate sensitivity. Thus, the focus is on both changes in mean state and variability to describe general patterns and broad changes in state. The qualitative evaluation of temporal and spatial patterns suggests that the expression of PDO-type variations is related to sub-tropical records of past ENSO variability during the middle to late Holocene. Depending on the resolution of record, changes may be manifested either as increased variability between positive PDO and negative PDO phases or by enhanced expression of a positive PDO phase and/or El Niño-like state. The proxy records in the northeastern Pacific and adjacent coastal regions of North America indicate stepwise increases in ENSO variability and strength at ~4200, 3000, and 2000 cal BP.

An important objective of this compilation is to better understand how the evolution of atmospheric and ocean dynamics in the North Pacific can contribute to a better understanding the mechanisms of climate change for western North America. Thus, it will be important that this synthesis be integrated with climate modeling studies, including those of the North American monsoon region as well as the western interior of the US (Harrison et al., 2003; Diffenbaugh et al., 2006). This need highlights the importance of obtaining more records with sufficient length, resolution, and climate sensitivity in western North America.

2. Background

The warm or positive PDO phase occurs when the western North Pacific becomes cool and part of the northeastern Pacific warms (Fig. 1). The opposite pattern characterizes a cool or negative PDO phase. Positive PDO phases resemble El Niño-like North American temperature and precipitation anomalies, while negative PDO phases are more similar to La Niña-like climate patterns (Mantua et al., 1997; Papineau, 2001). During a positive PDO phase, increased winter precipitation occurs in the southwestern US and along the southeastern Alaskan coast, whereas a region of decreased winter precipitation occurs in the northwestern US and southwestern Canada (Fig. 1). These precipitation anomalies are largely reversed during negative PDO phases. The winter precipitation patterns result from the strength and position of the Aleutian Low (AL), which is strengthened and/or located further to the east during a positive PDO phase and weakened and/or located more to the west during a negative PDO.

The North Pacific High (NPH) behaves in a synchronized manner opposite to that of the AL. It is weaker and shifted more to the south

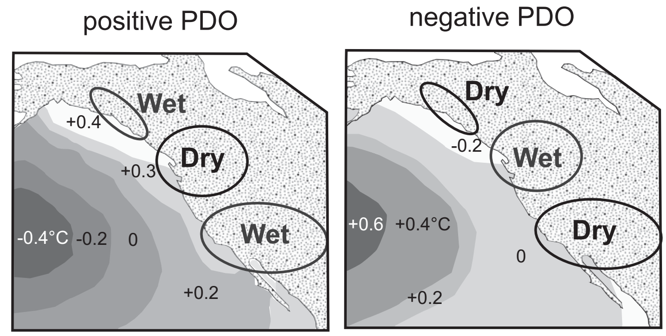

Fig. 1. Anomaly sea surface temperatures (SST) associated with the positive (warm) and negative (cool) phases of PDO in the eastern North Pacific (modified from http://jisao.washington.edu/pdo/) compared with wintertime precipitation changes on adjacent coastal regions. Shading gradient of the SSTs is reversed in sub figures.

in the summer during a positive PDO phase and is strengthened and shifted more to the north during negative PDO. Along the California coast, a positive PDO results in a weakened NPH, suppressed spring-summer coastal upwelling and reduced biologic productivity, whereas during a negative PDO phase, a stronger NPH coincides with increased coastal upwelling and biologic productivity (Mantua et al., 1997). Biologic productivity patterns are reversed in the eastern Gulf of Alaska (GOA), where a more southerly NPH (and stronger/eastward AL) strengthens the Alaskan coastal current, which enhances biologic productivity.

Modeling studies by Clement et al. (2000) argue for insolation-driven suppression of ENSO during the middle Holocene and increased ENSO strength and variability during the late Holocene (Fig. 2c). They imply that ENSO variability was present throughout the Holocene but underwent a steady increase from the middle Holocene to the present. Clement et al. (2000) use a simple coupled ocean-atmosphere numerical model of the tropical Pacific Ocean driven by orbital forcing that suggests that during the middle Holocene, extreme warm El Niño events were smaller in amplitude and occurred less frequently around a mean climate state which included a cold eastern equatorial Pacific Ocean. Cane (2005) emphasizes that the weaker ENSO cycles of the early and middle Holocene were caused by reduced amplification of surface water warming in the western equatorial Pacific during the later summer and early fall in response to increased boreal summer insolation (Fig. 2d).

Proxy evidence from the eastern equatorial Pacific suggests that the middle Holocene, or the interval between ~8000 and 4000 cal BP, was characterized by reduced expression of strong El Niño events and was in general more La Niña-like than the late Holocene (Fig. 2). Koutavas et al. (2006) record cooler than modern SSTs in the eastern equatorial Pacific during the middle Holocene and note that these contrast with warmer SSTs in the western equatorial Pacific (Fig. 2a), a classic La Niña pattern. Detailed studies of El Junco Crater Lake in the Galapagos Islands reveal that past lake level variability was associated with changing seasonal precipitation and ENSO frequency (Conroy et al., 2008). The El Junco Crater record suggests increased precipitation intensity prior to ~9000 cal BP and after ~4200 cal BP, as well as a two-step increase in precipitation at ~3200 and ~2000 cal BP (Fig. 2b). These data are broadly consistent with the ENSO frequency reconstructions from Laguna Pallcacocha, Ecuador that record a long-term increase and millennial scale variability (Moy et al., 2002)(Fig. 2b) and with the observations of Rodbell et al. (1999) in Ecuador.

Donders et al. (2008) proposed that a Pacific basin state change occurred at ~5000 cal BP towards active ENSO cyclicity in the equatorial Pacific. They postulated that after ~3000 cal BP,

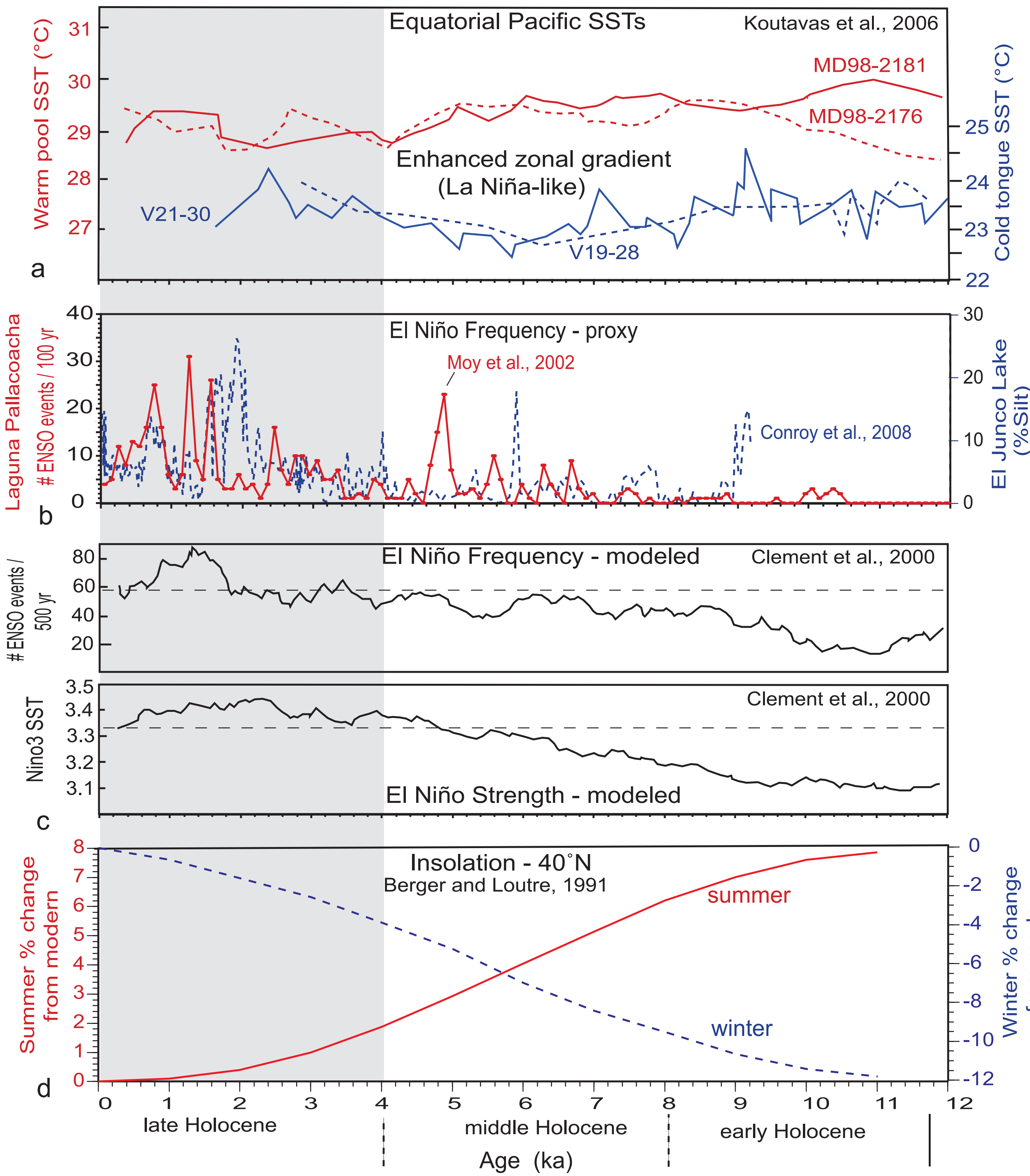

Fig. 2. Holocene Mg/Ca SST reconstructions (*Globigerinoides ruber*) for the western (red) and eastern (blue) equatorial Pacific after Koutavas et al. (2006)(2a), precipitation records of El Niño frequency from the eastern equatorial Pacific (2b), and modeled El Niño frequency and strength (2c) suggest an enhanced expression of ENSO variability and strength in the equatorial Pacific Ocean during the late Holocene that was associated an increase in winter insolation in the Northern Hemisphere (2d). ka = 1000 cal BP.

intensification of ENSO coincided with boreal winter insolation reaching maximum levels, thus allowing enhanced heating of the Indo Pacific Warm Pool, which then spread westward during El Niño events. Wanner et al. (2008) suggested that a progressive southward shift of the Intertropical Convergence Zone (ITCZ) during the middle Holocene was accompanied by a pronounced weakening of the monsoon in Africa and Asia and increasing aridity and desertification on both continents. They argued that summer cooling of the Northern Hemisphere combined with changing temperature gradients in the world oceans, likely led to higher amplitude ENSO cycles.

Previous studies from northeastern Pacific coastal locations have proposed increased El Niño-like conditions between ~4000 and 3000 cal BP (Benson et al., 2002; Barron et al., 2003; Patterson et al., 2004; Fisher et al., 2008). Here, these studies are synthesized with additional proxy paleoclimate data from north to south that are summarized in Table 1. No attempt is made here to discuss the proxy climate records of the more interior regions of the western US such as the Rocky Mountains. Although enhanced expression of ENSO precipitation patterns during the late Holocene has been suggested in these more easterly regions (see Brunelle et al., 2005; Whitlock et al., 2008; Shapley et al., 2009; Shuman et al., 2009), annual precipitation in this region is seasonally derived from numerous sources (Mock, 1996), making detailed ENSO detection more difficult.

3. Middle Holocene (~8000–4000 cal BP)

Middle Holocene climate records in the northeastern Pacific and its North American margins are distinctly different from those of the late Holocene. In general, ENSO-related climate variability including region-wide variation in precipitation and SST patterns was suppressed or more similar to modern day La Niña-like conditions.

3.1. North America

During the latter part of the middle Holocene (~6000–4000 cal BP), a pattern of wetter conditions in the Pacific Northwest (Oregon and Washington) and drier conditions in the southwest US is suggestive of a generalized negative PDO phase in the North Pacific (Fig. 1). In fact, much of interior western North America was characterized by widespread drought between ~8000 and 4000 cal BP (Antevs, 1948; Fritz, 1996; Dean et al., 1996), which is consistent with a reduction of summer insolation and summer precipitation compared to the early Holocene (Diffenbaugh et al., 2006). The dates of onset and termination of this drought vary from region to region, but according to Kennett et al. (2007) western North America experienced a particularly severe dry interval between ~6300 and 4800 cal BP. Although wetter conditions occurred in southern California prior to ~8000 cal BP (Kirby et al., 2004, 2007; Nederbragt and Thurow, 2006), this was likely due to increased vapor advection from the North Pacific that was associated with a weaker, southward-flowing California Current. Indeed, after intensification of the California Current at ~8200 cal BP (Barron et al., 2003), the middle Holocene of southern California was characterized by a long-term drying trend (Kirby et al., 2007).

A dry period in Oregon, Washington, and the Klamath Mountain region of northwestern California was terminated between ~6500 and 4300 cal BP by the onset of cooler and wetter conditions (Briles et al., 2005). Varve studies in Saanich Inlet, British Columbia (Fig. 3) also indicate increasingly wetter conditions between ~6000 and 3250 cal BP (Nederbragt and Thurow, 2001).

Southeastern and interior Alaska and southwestern Yukon were also drier based on pollen, oxygen isotope ratios, and lake level reconstructions (Heusser et al., 1985; Abbott et al., 2000; Barber and Finney, 2000; Anderson et al., 2001, 2005; Mann et al., 2002). Alpine tree line was elevated above present altitudinal limits on the eastern slopes of the St. Elias Mountains, while widespread glacial retreat began by ~6500 cal BP (Denton and Karlen, 1977), as snow accumulation was reduced in the alpine zone of the southwest Yukon between ~7000 and 5000 cal BP (Farnell et al., 2004). Although a diatom-inferred salinity profile in a central Yukon lake (Pienitz et al., 2000) suggests a middle Holocene wet period, it conflicts with lake level reconstructions that indicate warmer and drier conditions prior to 6000 cal BP. Barber and Finney (2000) found that effective moisture (precipitation-evaporation) was 10–20% lower than modern values at ~6000 cal BP based on modeled based on lake level reconstructions. Heusser et al. (1985) estimated that precipitation on the southeast Alaska coast was reduced by 30–50% between 8000 and 5000 cal BP. This spatial climate pattern of drier conditions in southeast and interior Alaska and the southwest Yukon (Anderson et al., 2005) is consistent with more negative PDO conditions in the North Pacific.

Oxygen isotope reconstructions of Gulf of Alaska (GOA) atmospheric circulation also support more negative PDO. Jellybean Lake (Fig. 3) oxygen isotopes record Aleutian Low storm trajectories over

Table 1
Timing of enhanced expression of positive PDO conditions and increased PDO-related climate variability documented in marine and terrestrial proxy climate records from the northeastern Pacific.

Enhanced Variability					
Region	Location	Age (cal ka)	Proxy	Interpretation	Reference
SW Yukon	Jellybean Lake	~1.5	Carbonate $\delta^{18}O$	Aleutian Low	Anderson et al., 2005
SW Canada	Effingham Inlet	3.4	Sediment grey values, fish scales	Productivity	Patterson et al., 2004
N California offshore	ODP 1019	3.4	Pollen	Effective mositure	Barron et al., 2003
W Nevada	Pyramid Lake	~3.5	Carbonate $\delta^{18}O$	Effective moisture	Mensing et al., 2004
S California offshore	Santa Barbara Basin	~4.0	Planktic forams	SSTs	Fisler and Hendy, 2008
S California offshore	Santa Barbara Basin	~4.0	Planktic foram $\delta^{18}O$	SSTs	Kennett et al., 2007
Enhanced + PDO					
SW Yukon	Jellybean Lake	~4.5–3.0	Carbonate $\delta^{18}O$	Aleutian Low	Anderson et al., 2005
SW Yukon	Mt. Logan	~4.2	Ice core $\delta^{18}O$	Sub-tropical moisture	Fisher et al., 2008
SE Alaska	Offshore cores	~4.0	Opal concentrations	Productivity	Addison et al., 2008
S Alaska	Onshore lakes	3.5	Organic $\delta^{18}N$	Salmon abundance	Finney and Addison, 2006
SW British Columbia	Saanich Inlet	3.25	Varve thickness	Precipitation	Nederbragt and Thurow, 2001
S British Columbia	Big Lake	3.6	Diatom lake level	Precipitation	Bennett et al., 2001
N California offshore	ODP 1019	3.2	Alkenones	Winter SST	Barron et al., 2003
N California offshore	ODP 1019	3.2	Tropcial diatoms	Fall SST	Barron et al., 2003
W Nevada	Pyramid Lake	~3.4–2.7	Carbonate $\delta^{18}O$	Lake level	Benson et al., 2002
S California offshore	Santa Barbara Basin	~3.0	Opal concentrations	Spring productivity	Nederbragt et al., 2008
S California offshore	Santa Barbara Basin	~4.0	Planktic foram $\delta^{18}O$	Spring upwelling, stratification	Kennett et al., 2007
S California onshore	Mojave Desert	~4.0–3.0	Lake and flood deposits	Winter moisture	Enzel and Wells, 1997
SE New Mexico	Guadalupe Mnts.	3.3	Stalagmite $\delta^{18}O$	Effective moisture	Asmerom et al., 2007

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Fig. 3. Localities discussed in the eastern North Pacific Ocean and its margins. ML, Mt. Logan; JL, Jellybean Lake; JA, marine cores studied by Jason Addison (2009); BL, Big Lake; SI, Saanich Inlet; EI, Effingham Inlet; TL, Taylor Lake; LL, Little Lake; PL, Pyramid Lake; SBB, Santa Barbara Basin; GM, Guadalupe Mountains.

or around the coastal mountains and indicate a weaker and/or more westward Aleutian Low between 8000 and 4500 cal BP (Anderson et al., 2006). Mt. Logan ice core oxygen isotopes (Fig. 3) from 5300 m a.s.l. (Fisher et al., 2008) reflect zonal-vs.-meridional North Pacific moisture sources and closely resemble the Jellybean Lake data during this interval.

Furthermore, it has recently been documented that the eastern GOA experienced reduced biologic productivity prior to ~4000 cal BP (Addison et al., 2008; Barron et al., 2008; Addison, 2009). Positive PDO phases generally coincide with increased biologic productivity along the eastern coasts of the GOA, whereas negative PDO phases result in reduced biologic productivity (Mantua et al., 1997), another pattern consistent with the presence of a widespread negative PDO phase and/or a more La Niña-like North Pacific during the middle Holocene.

3.2. North Pacific SSTs

With the exception of the Santa Barbara Basin (SBB), cooler SSTs along the Oregon and California coasts during the middle Holocene resemble those of a La Niña and/or negative PDO phase (Barron et al., 2003; Barron and Bukry, 2007). Prior to ~4000 cal BP, the surface waters of the SBB were warmer and more stratified than at present (Friddell et al., 2003; Kennett et al., 2007; Fisler and Hendy, 2008), contrasting with cooler SSTs proposed within the California Current. The SBB lies south of Point Conception (Fig. 3) and is separated and shoreward of the main path of the California Current. The cool waters of the California Current normally only penetrate the SBB during the spring, when they cause upwelling of nutrient-rich waters and increased biologic productivity. During most of the year, SSTs in the SBB are strongly influenced by the warm-water Southern California countercurrent. Diffenbaugh and Ashfaq's (2007) regional modeling study argues that during the middle Holocene, upwelling in the California Current region was seasonally longer than at present with spring upwelling reduced in strength.

4. Late Holocene (~4000 cal BP to present)

4.1. Southeastern Alaska and southwestern Yukon terrestrial records

Low resolution, or discontinuous paleoclimate data of late Holocene climate in Alaska and the Yukon have most often been interpreted in terms of "Neoglacial" cooling (Denton and Karlen, 1977). The Neoglacial refers to a renewed period of alpine glaciation during the later part of the Holocene in Europe and North America that has commonly been attributed to a decline in Northern Hemisphere summer insolation (Clague et al., 2009). High-resolution lake sediment records from interior Alaska and southwestern Yukon indicate that after warmer, drier conditions during the early Holocene, lake levels rose, precipitation increased, and summer evaporation decreased (Cwynar and Spear, 1995; Abbott et al., 2000; Barber and Finney, 2000; Anderson et al., 2005, 2007). Pollen, chironomid, and ostracode data at alpine tree line in the southwestern Yukon Territory also reveal a shift to cool, wet conditions at ~4000 cal BP (Bunbury and Gajewski, 2009). An updated summary of glacier fluctuations in southeast Alaska finds that major glacier advances were underway by ~3000 cal BP, with perhaps two distinct expansions between ~3300 and 2900 and ~2200–2000 cal BP (Barclay et al., 2009). Southeast Alaska glacial activity increased after ~3500 cal BP according to Lamoureux and Cockburn (2005).

Fisher et al. (2008) interpret a large negative excursion in their Mt. Logan $\delta^{18}O$ record at ~4200 cal BP as a major increase in meridional moisture and the onset of the modern ENSO-driven regime (Fig. 4). The Jellybean Lake $\delta^{18}O$ record also indicates an intensified Aleutian Low at ~4200 cal BP (Fig. 4, shaded area) that supports enhanced meridional moisture at this time, which is consistent with more positive PDO conditions elsewhere in the North Pacific (Fig. 1). However, between ~4000 and 3200 cal BP both records trend towards higher $\delta^{18}O$ values that suggest increasing zonal moisture (negative PDO). Yet, they differ slightly, with the Mt. Logan record suggesting more zonal moisture than Jellybean Lake. This implies that regional climate forcing was not strong at this time. Afterwards, between ~3200 and 3000 cal BP, both of the records converge again, consistent with enhanced meridional moisture (more positive PDO conditions) (Fig. 4). Between ~2800 and 1600 cal BP, the records show opposite trends, as Mt. Logan indicates mostly meridional moisture (positive PDO) while Jellybean suggests increasingly zonal moisture (negative PDO conditions). An exception occurs at ~2200 cal BP when both records suggest enhanced zonal conditions. Again, these trends imply that the interval ~2800 and 1600 cal BP was generally characterized by weaker regional climate forcing. By ~1500 cal BP both of the records consistently agree, with abrupt negative $\delta^{18}O$ shifts at ~1200 cal BP and AD ~1800–1850, suggesting strong regional forcing of North Pacific PDO conditions.

Between ~2800 and 1600 cal BP, modeling and tropical proxies indicate a peak in late Holocene ENSO activity that is consistent with a more positive PDO state in the North Pacific. Effective moisture in the Yukon reached a maximum during this interval (Mann et al., 2002; Anderson et al., 2005, 2007). The divergence of the Mt. Logan and Jellybean Lake records (Fig. 4) during this interval could be due to more complex "third" Pacific Ocean climate patterns (Bond et al., 2003) and/or the establishment of blocking atmospheric ridges that effectively channel Arctic airmasses into the interior and lower elevations (Mock et al., 1998). Or alternatively, it could reflect the development of climate patterns related

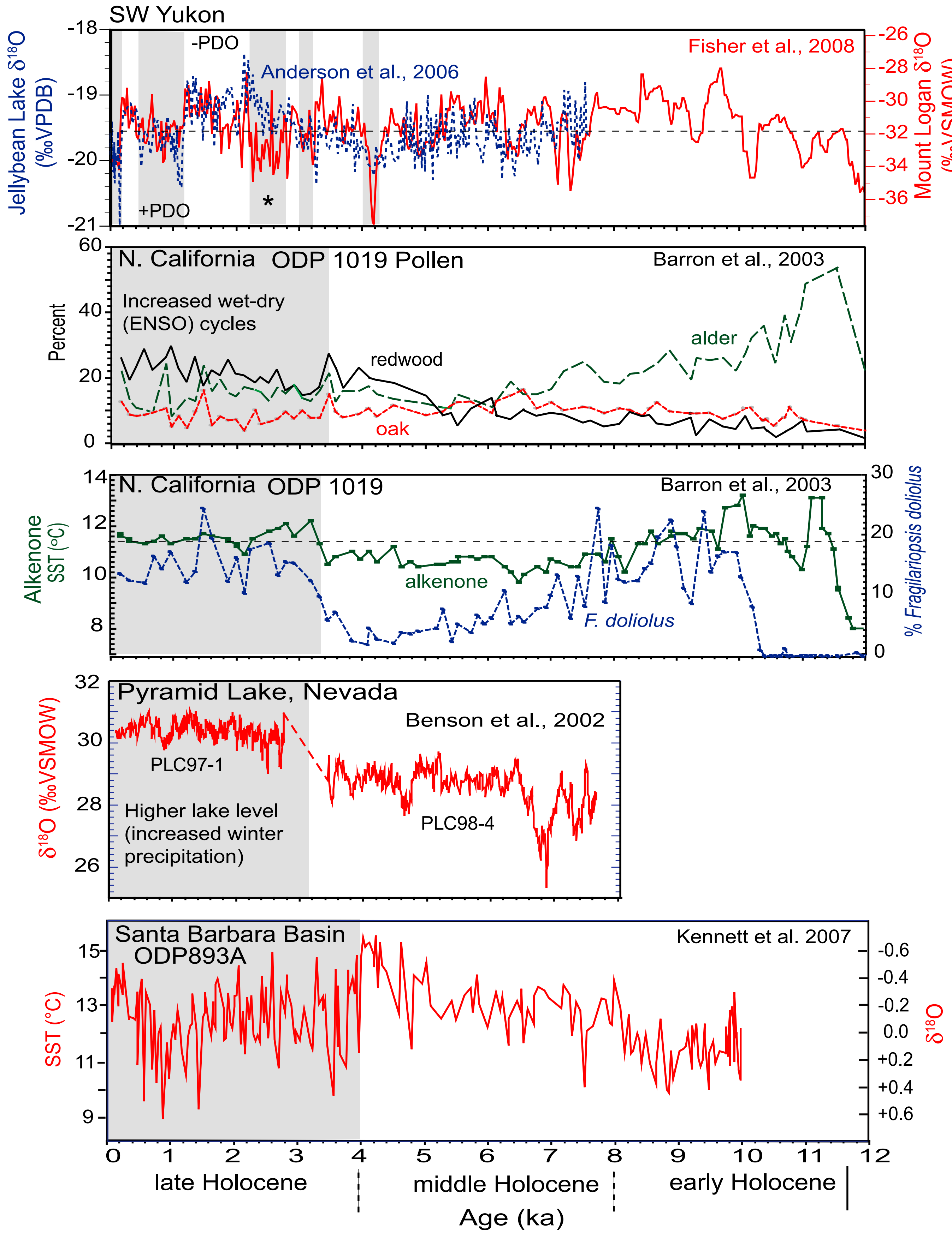

Fig. 4. Comparison of selected high-resolution paleoclimate records along the northeastern Pacific margin. Gray shading illustrates a late Holocene (post 4200 cal BP) increase in ENSO-related climate variability and/or expression of more positive PDO conditions (increased winter precipitation and warmer fall to winter SSTs) compared to middle Holocene climate patterns. * = interval where Jellybean Lake and Mt. Logan proxies indicate different PDO phase ka = 1000 cal BP.

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to reduction in Arctic summer sea ice ~2000 cal BP (Dyke and Savelle, 2001) that may have led to increased Bering and Arctic Sea moisture reaching the interior, where in may be undetected by Mt. Logan.

In general, after ~2000 cal BP, climate variability in Gulf of Alaska region increased and became more like a positive PDO phase. At ~1500 cal BP, the Mt. Logan and Jellybean records indicate an increasingly stronger and/or eastward Aleutian Low, consistent with a more positive PDO state (Figs. 1 and 4). These shifts correspond with increased aridity in the interior, on the rain shadow side of the coastal mountains, and with increased precipitation along the coast (Heusser et al., 1985; Anderson et al., 2007).

4.2. Gulf of Alaska (GOA) marine records

Marine records of biologic productivity along the margins of southeast Alaska indicate increased productivity at ~4000 cal BP (Table 1) (Addison et al., 2008; Barron et al., 2008; Addison, 2009). This is consistent with a greater influence of positive PDO conditions in the North Pacific. Similarly, reconstructions of North Pacific salmon abundance (Finney et al., 2002), using $\delta^{15}N$ in lake sediments of Kodiak Island lakes, suggest an increase after ~1500 cal BP. Finney et al. (2002) argue that Alaskan salmon abundance is greater during positive PDO phases in the North Pacific, so their ~1500 cal BP increase in salmon abundance is consistent with both the Jellybean and Logan $\delta^{18}O$ records (Fig. 4). Longer Holocene sediment records from lakes in southern Alaska and northern British Columbia (Finney and Addison, 2006) indicate that salmon productivity in the GOA increased at ~3500 cal BP following a middle Holocene interval of generally lower productivity.

4.3. British Columbia records

Paleoclimate studies from British Columbia lakes typically identify cooler summer temperatures due to Neoglacial cooling as the major factor responsible for late Holocene climate change in the region (Rosenberg et al., 2004; Hallett and Hills, 2006). Spooner et al. (2003), on the other hand, point out the importance of increasing Pacific moisture based on their compilation of pollen records from 15 lakes in northern British Columbia. They argue that progressive west-to-east increases of western hemlock (*Tsuga heterophylla*) pollen in these lake records between ~4000 and 2000 ^{14}C yr BP (~4500–2000 cal BP) track the increasing inland penetration of warm maritime airmasses that are associated with a strengthened and/or a more easterly position of the Aleutian Low and intensification of ENSO. Bennett et al. (2001) diatom proxy data at Big Lake in southern British Columbia (Fig. 3, Table 1) imply lowered lake levels and a reduction in effective moisture after ~3600 cal BP that is consistent with the development of a more positive PDO-like character in late Holocene climate records of the northeastern Pacific.

Contrary to late Holocene warming trends seen in most North Pacific alkenone records (Kim et al., 2004), Kienast and McKay (2001) found no significant Holocene changes in alkenone-derived SST after 7000 cal BP in sediment core JT96-09, which may be located too far off the British Columbia coast (Fig. 3) to record changes in coastal SST. Diatom records from Effingham Inlet on Vancouver Island, British Columbia (Fig. 3) by Hay et al. (2007) reveal that relatively productive marine conditions between 4850 and 4000 cal BP were followed by a transition to the modern ocean–climate regime marked by decreased siliceous microfossil production after ~2800 cal BP.

Varves in Saanich Inlet, British Columbia (Fig. 3) became thinner at ~3250 cal BP, indicating a general drying of climate in the region (Nederbragt and Thurow, 2001). This is consistent with an enhanced expression of positive PDO conditions in the North Pacific after ~3250 cal BP (Fig. 1). Patterson et al. (2004) high-resolution study of fish productivity in Effingham Inlet also indicates a major shift at ~3400 cal BP after which shorter cycles (>200 y) became more common in both the anchovy productivity data and in the sediment grey scale data. These fish productivity shifts may be evidence of enhanced expression of PDO-like cycles after ~3400 cal BP (Table 1).

4.4. Oregon and northern California margin

The Little Lake (Fig. 3) sediment record from coastal Oregon indicates the onset of modern pollen and plant distributions at ~2800 cal BP (Worona and Whitlock, 1995). In the Klamath Mountain region, the establishment of modern forest conditions is placed at ~2000 cal BP (Briles et al., 2005). At Taylor Lake on the northern Oregon coast (Fig. 3), fire frequency decreased after ~2700 cal BP, possibly reflecting decreased summer drought and increased summer fog (Long and Whitlock, 2002). Fire frequency increased between ~4200 and 3000 cal yr BP in Oregon coastal lakes, possibly due to an increase in summer droughts, which would be expected from increased persistence of positive PDO conditions in the North Pacific (Long et al., 2007).

Off northern California, at ODP 1019, increased amplitude and variability of wet-dry pollen proxies occurs at ~3400 cal BP, which was interpreted as an enhanced expression of ENSO cycles by Barron et al. (2003) (Fig. 4; Table 1). Both alkenone and diatom proxies also suggest a warming of fall and winter SSTs at ~3200 cal BP (Fig. 4; Table 1), consistent with increased occurrence of warm El Niño-like SSTs along coastal northern California. A similar climatic transition after ~3200 cal BP occurs off southern Oregon in core EW9504-17 PC (Fig. 3). Barron and Bukry (2007) hypothesized that this climatic transition reflected narrowing of the California Current with intensified flow occurring closer to the coasts of Oregon and northern California.

4.5. Sierra Nevada

Pyramid Lake (Fig. 3) in western Nevada is fed by the Truckee River, which originates in Lake Tahoe in the Sierra Nevada to the west. Higher sediment $\delta^{18}O$ values from Pyramid Lake indicate lower lake levels between ~6500 and 3400 cal BP that rose after a data gap by ~2500 cal BP (Benson et al., 2002) (Fig. 4). This oxygen isotope interpretation is supported by decreased magnetic susceptibility sediment values after ~3000 cal BP that also suggest higher lake levels and a transition to a wetter, cooler late Holocene climate. Pollen and diatom studies also reveal that the climate in the Pyramid Lake region became more variable after ~3500 cal BP (Mensing et al., 2004).

Glaciers throughout the Sierra Nevada and the more maritime mountains of the western US began to form and advance by ~3300 cal BP (Clark et al., 2005; Clark and Bowerman, 2007). Although this has been attributed to Neoglacial cooling, it can be argued that an increase in winter precipitation associated with the onset of more positive PDO conditions in the North Pacific may have been equally (or possibly more) responsible for late Holocene glacier advances in the Sierra Nevada as well as in southeastern Alaska.

4.6. Southwestern deserts

Enzel and Wells' (1997) review of extensive evidence from diverse environments throughout the Mojave Desert of southern California, including lake, peat, and flood deposits, suggests an

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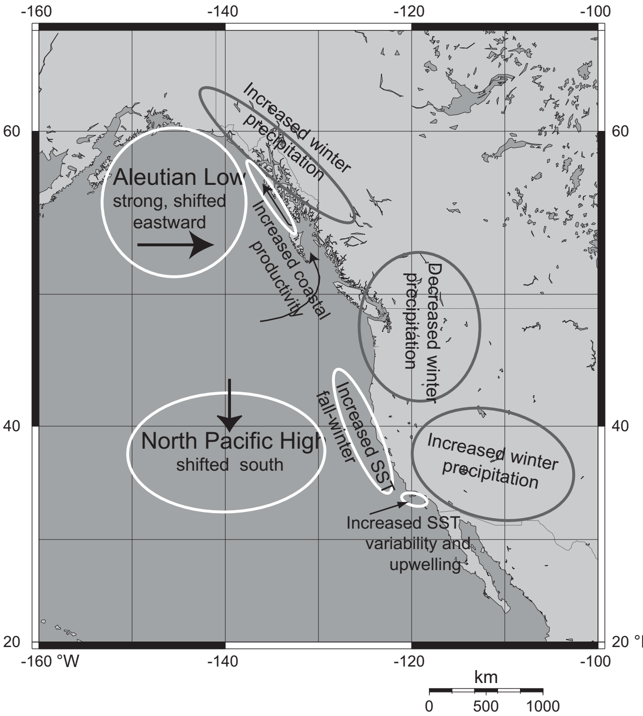

Fig. 5. Proposed late Holocene spatial climate pattern shift relative to the middle Holocene from this proxy record synthesis including 1) Aleutian Low intensification and/or more eastward position, 2) more southern positioned North Pacific High, 3) increased coastal productivity in the Gulf of Alaska, 4) increased fall and winter SSTs along the California margin, 5) increased SST variability and upwelling in the Santa Barbara Basin, and 6) increased winter precipitation in Alaska-Yukon and the southwest U.S and decreased in the Pacific Northwest.

increase in winter storms and flood events occurred between ~4000 and 3000 cal BP. They propose that the onset of a more positive PDO atmospheric pattern in the North Pacific (Cayan et al., 1999) at this time was responsible for these changes.

Increased stalagmite growth and more negative $\delta^{18}O$ values in stalagmites in caves in the Guadalupe Mountains of southeastern New Mexico (Fig. 3) have been related to late Holocene increases in winter precipitation (Polyak and Asmerom, 2001; Asmerom et al., 2007). A shift to more negative $\delta^{18}O$ values beginning at ~3300 cal BP has been interpreted by these authors as increased winter rainfall due to an enhanced expression of ENSO cycles in the region (Table 1).

4.7. Santa Barbara Basin

Cooling of late Holocene SSTs in the Santa Barbara Basin (SBB) has been attributed to a stronger influence of the California Current during the spring, which likely caused an increase in spring upwelling (Barron and Bukry, 2007; Diffenbaugh and Ashfaq, 2007). In particular, the *Neogloquadrina pachyderma* isotope data reflect the penetration of cool waters of the California Current into the SBB during the spring, leading to greater diatom (opal) productivity Kennett et al. (2007).

Increased spring season upwelling is indicated by various proxy records between ~4000 and 3000 cal BP. Kennett et al. (2007) cite oxygen isotope data of planktonic foraminifers to argue for abrupt cooling and increased upwelling beginning ~4000 cal yr (Fig. 4; Table 1). Nederbragt et al. (2008) also note that opal mass accumulation rates, a proxy for diatom productivity and upwelling, increased at ~3000 cal BP. Fisler and Hendy (2008) argue that both planktonic foraminiferal assemblage and oxygen isotope show evidence of enhanced climatic variability beginning at ~4000 cal BP (Table 1). Detailed comparison of SBB isotope data with the bristlecone pine tree ring record from the White Mountains of eastern California, argues for a consistent relationship between cool SBB SST and drier terrestrial conditions during the past 4000 years (Kennett et al., 2007) that is consistent with the modern correspondence of La Niña SST conditions with widespread drought in the southwest US. Although Nederbragt and Thurow's (2006) analysis of varve thickness from ODP Site 893 (Fig. 3) suggests that the amplitude of ENSO scale variability remained constant throughout the past 15,000 years in the SBB, the more recent studies of Nederbragt et al. (2008) reveal that the amplitude or intensity of ENSO variability appears to have increased at ~4000 cal BP (Table 1).

5. Conclusions

This synthesis of northeast Pacific proxy records suggests a general trend since the middle Holocene, from suppressed expression of positive PDO and ENSO to a more variable, more positive PDO-like North Pacific after ~3500 cal BP (Figs. 4 and 5). Most records reflect the influence of increasingly warm ENSO events in the eastern equatorial Pacific after ~4000 cal BP.

In the southwest US and southeast Alaska these trends result in a generalized enhancement of winter precipitation in the late Holocene compared with typically drier middle Holocene conditions. The California Current narrows and changes seasonally, with coastal upwelling enhanced during the spring and suppressed during the fall, characteristics that make it more sensitive to ENSO/PDO variations. Compared with the La Niña-like conditions of the middle Holocene, the fall and winter SSTs of California Current waters appear warmer after ~3400 cal BP. After 4000 cal BP, SST variability and spring upwelling increased in the Santa Barbara Basin. In the Pacific Northwest, a post ~4200 cal BP trend toward drier winter conditions and/or an increased presence of droughts is consistent with a late Holocene expression of more positive PDO state compared with the generalized climate of the middle Holocene (Fig. 5). Northeast Pacific proxy records with higher temporal resolution indicate that El Niño-like and positive PDO-like climate variability was progressively enhanced from south to north in a series of steps at ~4200, 3200, and 2000 cal BP (Table 1; Fig. 4). Although Holocene changes in seasonal solar insolation (Fig. 1) are clearly influential, the proxy records reviewed here also suggest that when the more modern-like ENSO mode of the Pacific turns on, it becomes a primary climatic driver for northeast Pacific region at decade-to-century time scales.

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