California Current System response to late Holocene climate cooling in southern California

J. Fisler[1] and I. L. Hendy[1]

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[1] New Holocene high-resolution planktonic foraminiferal assemblage data from Santa Barbara Basin, California documents variability in ocean circulation as the California Current System responded to millennial-scale climate change during late Holocene climatic cooling. Climatic variability increased at 4 ka when a series of extreme cool events (notably at 2.2, 1.5 and 0.8 ka) associated with glacial advance in the Pacific Northwest punctuated the predominantly warm Holocene. Simultaneously high subtropical species abundance suggests increased interannual variability (El Niño frequency/severity) or greater seasonality during the late Holocene. Planktonic foraminiferal assemblages indicate that the magnitudes of climatic shifts were greatest after 1.5 ka during an interval of extreme terrestrial hydrological variability in western North America and that the coolest interval of the Holocene in Santa Barbara Basin was coincident with the Little Ice Age. **Citation:** Fisler, J., and I. L. Hendy (2008), California Current System response to late Holocene climate cooling in southern California, *Geophys. Res. Lett.*, *35*, L09702, doi:10.1029/2008GL033902.

1. Introduction

[2] Santa Barbara Basin climate studies paleoclimate studies suggest that the climate of California is already shifting in response to CO_2 induced 20th century warming [e.g., *Field et al.*, 2006]. In the absence of long term instrumental monitoring, the context of this warming within general Holocene climate change is poorly understood. At present, Holocene climate studies in California mostly involve terrestrial precipitation records of the last few millennia that have been linked to Pacific sea surface cooling associated with the Pacific Decadal Oscillation (PDO) [*Larson and Michaelson*, 1989; *MacDonald and Case*, 2005; *Stine*, 1994]. We can now put 20th century warming in the context of changing Holocene climate variability using a high resolution record of marine environmental response to ocean and atmosphere circulation changes on millennial time scales.

[3] Ocean Drilling Program Site 893 (34°17.25′N, 120°2.2′W; 576.5 m water depth), Santa Barbara Basin (SBB) is a prime location to study Holocene atmosphere and ocean circulation due to its high sedimentation rate and position at the confluence of several major currents in the California Current System (CCS). The California Current dominates surface flow above Point Conception advecting cool, low-salinity water into the basin, while the poleward-flowing Southern California Countercurrent brings relatively warm, saline water into SBB [*Reid et al.*, 1958]. The relative influence of these two currents changes seasonally, as a function of the position and strength of the Aleutian Low and North Pacific High (NPH) pressure systems. Northward migration of the NPH during spring and early summer strengthens northerly winds and the CCS. Seasonal upwelling associated with this migration allows nutrient-rich waters to reach the surface [*Hendershott and Winant*, 1996]. Annual sea surface temperatures (SSTs) range from 13°C in the spring to 17°C in the fall, however anomalous interannual variability (i.e. El Niño) can produce temperatures outside this range [*Kincaid et al.*, 2000].

[4] The Holocene planktonic foraminiferal assemblage record from SBB offers a unique marine perspective on regional climate. Planktonic foraminiferal assemblages are highly sensitive to ambient seawater conditions, and clearly record 20th century warming [*Field et al.*, 2006]. Since local surface ocean conditions are intimately tied to North Pacific ocean and atmospheric circulation, the assemblage should reflect CCS characteristics and the influence of atmospheric pressure patterns [*McGowan et al.*, 1998]. The chronology for last 15 ka is based on radiocarbon dating, while details of the last millennia are based on a varve counted chronology (indicated by years AD; see the auxiliary material)[1].

2. Environmental Change in Santa Barbara Basin

[5] Throughout the Holocene the SBB planktonic foraminiferal assemblage varied significantly from that found in the basin today. Maximum accumulation of the dominant species occurred between 8.8 and 10 ka, moderate accumulation (~400 specimen cm^2 yr^{-1}) through to 5.8 ka and low accumulation during the late Holocene. This accumulation decrease through the Holocene corresponds to increasing siliceous biogenic production (see the auxiliary material) because of shifting nutrient availability and/or orbitally forced seasonal changes in upwelling [*Diffenbaugh et al.*, 2006]. These shifts mostly affect *Globigerina quinqueloba* and *Globigerina bulloides* abundances as these eurythermal species (tolerating SSTs of 5–26°C) flourish during high nutrient conditions such as spring upwelling [*Sautter and Thunell*, 1991]. *G. bulloides* responds favorably to high food availability (chlorophyll maxima [*Field*, 2004; *Ortiz et al.*, 1995]) and is abundant throughout the year in SBB [*Kincaid et al.*, 2000]. *G. bulloides* generates 20–45% of

[1]Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan, USA.

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033902.

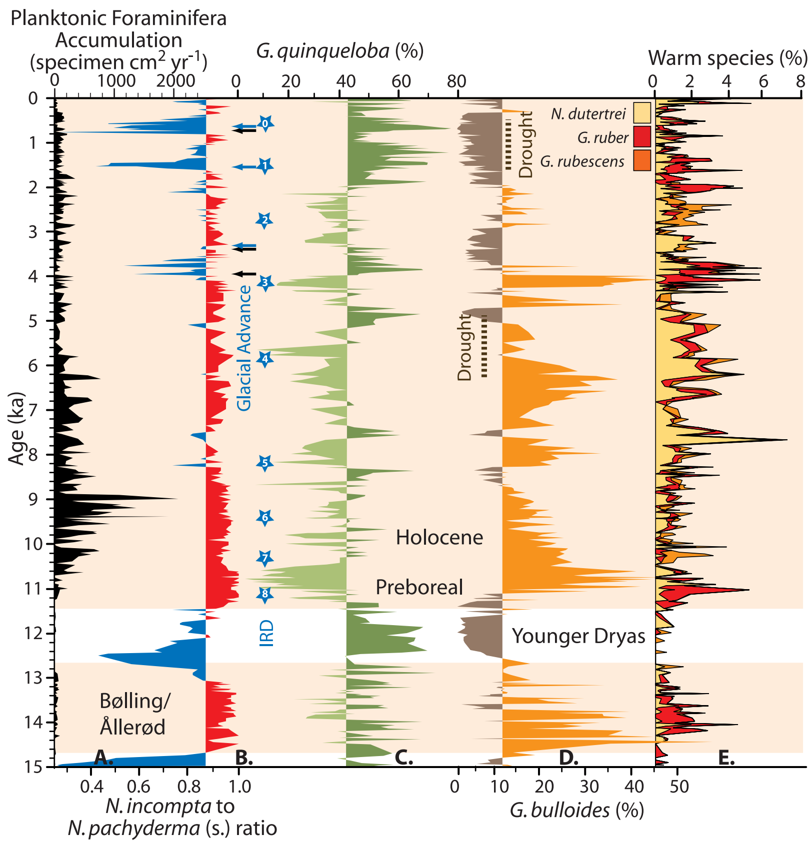

Figure 1. ODP Site 893, SBB, (a) California planktonic foraminiferal assemblage data, (b) foraminiferal accumulation rate in specimen cm^2 yr^{-1} (black), ratio of dextral *Neogloboquadrina incompta*: *N. pachyderma* (s.) (red-blue) and relative abundances of (c) *Globigerina quinqueloba* (green), (d) *Globigerina bulloides* (yellow) and (e) warm species for the last 10 ka. 'Warm species' include *Globogernita ruber* (red), *Globigerina rubescens* (orange), and *Neogloboquadrina dutertrei* (yellow). Relative abundance and ratio data are plotted around mean Holocene values. Arrows represent late Holocene North Pacific glacial advance in British Columbia (blue [*Reyes and Clague*, 2004]) and the Sierra Nevada (black [*Konrad and Clark*, 1998]). Blue stars represent North Atlantic ice rafting (IRD) events associated with a 1500 year Holocene cyclicity [*Bond et al.*, 2001]. Intervals of extended drought are indicated by brown dashed lines.

the total foraminiferal abundance during the Bølling/Ållerød and early Holocene, suggesting high foraminiferal accumulation in the Early Holocene resulted from increased prey abundance. *G. quinqueloba* is common during upwelling [*Sautter and Thunell*, 1991], and precedes spring blooms of *G. bulloides* in SBB [*Kincaid et al.*, 2000]. This species generates 40–80% of the total foraminiferal abundance during the Younger Dryas and late Holocene in association with low accumulation rates and we hypothesize with a High Nutrient-Low Chlorophyll (HNLC) water mass (see the auxiliary material).

[6] In this paper we refer to the morpho-species dextral *Neogloboquadrina pachyderma* as *N. incompta* (see the auxiliary material). The relative abundance changes of dextral *N. incompta* and *N. pachyderma* (s.) produce a sensitive recorder of SST and water column stability in SBB due to the environmental preferences of the two species (Figure 1b). At 50°N sinistral (left-coiling) *N. pachyderma* thrives in cool (6 to 8°C), high nutrient water with a poorly developed thermocline [*Reynolds and Thunell*, 1986], but has been observed in warmer upwelled water (<10°C). This species has not been found in the basin since the 1920s, when the coolest SSTs of the 20th century where recorded in the Eastern North Pacific [*Field et al.*, 2006]. Dextral (right-coiling) *N. incompta* favors 8° to 14°C waters and a more stratified water column [*Reynolds and Thunell*, 1986; *Sautter and Thunell*, 1991]. During the early-mid Holocene the *N. incompta* dominated assemblage (50 to 100 specimen cm^2 yr^{-1} or 30 to 70% of the assemblage with a *N. incompta* (d.): *N. pachyderma* (s.) ratio of ∼>0.8; Figure 1b and auxiliary material Figure S2) indicates a stable stratified water column warmer than 10°C with a well developed thermocline (greater thermal stratification in surface waters), consistent with previous stable isotopic studies in SBB [*Friddell et al.*, 2003; *Kennett et al.*, 2006].

[7] This early-mid Holocene phase closely corresponds with the Holocene Climatic Optimum (∼7 to 4.5 ka) an interval of relative warmth and dry conditions in western North America [*Kennett et al.*, 2006]. Drought conditions during the mid-Holocene [*Kennett et al.*, 2006] appear to be independent of SSTs and driven by large-scale orbital forcing. That is the NPH strengthened during the Mid-Holocene in response to insolation forcing resulting in reduced spring upwelling, warm SSTs and a thermally stratified water column in southern California [*Diffenbaugh et al.*, 2006]. A well-developed thermocline suggests strong anticyclonic atmosphere circulation that increased Southern

California Countercurrent strength allowing warm water to enter SBB depressing the thermocline. The SBB response in southern California differs from sites to the north where strong anticyclonic circulation increased gyral circulation such that cool CCS water prevented warm gyral waters moving onshore [*Barron and Bukry*, 2007].

3. Southern California Climatic Cooling After 4 ka

[8] After ~4.2 ka, the relatively stable warm environment in SBB during the Holocene was disrupted, by cooling events of multi-decadal to multi-century duration as evidenced by increasingly frequent intervals of anomalous high *N. pachyderma* (s.) abundance (notably at 2.2, 1.5 and 0.8 ka) where accumulation rates increase from a background of ~2 specimen cm^2 yr^{-1}, to 10–15 specimen cm^2 yr^{-1} (auxiliary material Figure S2). These coincide with *N. incompta* (d.): *N. pachyderma* (s.) ratio values of 0.4–0.6 (Figure 1b). SSTs must have dropped below 8–10°C during winter through these intervals to provide favorable environmental conditions for *N. pachyderma* (s.) as this species does not inhabit the modern SBB (annual SSTs range from 13°–17°C). The most recent faunal response to cooling was similar in magnitude to that of the Younger Dryas and coincided with the Little Ice Age.

[9] The late Holocene cool events in the SBB foraminiferal record coincide (within dating error; Figure 1) with glacier advance in the Coast Mountain Range, Cascades and Sierra [*Konrad and Clark*, 1998; *Reyes and Clague*, 2004], as well as IRD events in the North Atlantic [*Bond et al.*, 2001] suggesting high latitude cooling occurred at these times. Southward migration of drift ice in the North Atlantic during these events [*Bond et al.*, 2001] would also strengthen the Arctic Low and Siberian High [*Meeker and Mayewski*, 2002] such that the high latitude storm track would penetrate further south into the mid latitudes providing a mechanism for cooling in SBB. Weakening of the NPH would assist the southward penetration of storm tracks increasing precipitation in southern California. Northern Californian diatom assemblages indicate a shift toward modern conditions at 3.5 ka with a warming of SSTs in response to a sluggish CCS [*Barron and Bukry*, 2007] as the NPH weakened.

4. Southern California El Niño Response During the Late Holocene

[10] Subtropical species also do not closely follow the accumulation rate trends as these species are influenced by extreme warm SSTs in SBB. The most common subtropical species, *Neogloboquadrina dutertrei* is found in the basin when the water column is stratified and SST is >13–15°C [*Kincaid et al.*, 2000]. *N. dutertrei* was more abundant during the early-mid Holocene (2–8 specimen cm^2 yr^{-1} or 2–4% of the assemblage), decreasing in abundance at 5.5 ka (Figure 1e; and auxiliary material Figure S2a). *Globigerinoides ruber* and *Globigerina rubescens* persistence after 4.2 ka as climate variability increased is noteworthy (auxiliary material Figure S2a) as it coincides with a 5–10% increase in *N. pachyderma* (s.) relative abundance and 30% decrease in *N. incompta* (Figure 1). These warm tropical species (with SST tolerances of 14 to 32°C [*Kincaid et al.*, 2000]) are not usually present in the basin, however during the 1997–1998 El Niño event, they appeared in sediment traps in significant abundance [*Black et al.*, 2001], advected up the coast in an El Niño-associated kelvin wave.

[11] Subtropical species (*G. ruber* and *G. rubescens)* occur within the same samples (a composite of ~11 years) as *N. pachyderma* (s.) indicating that anomalously warm annual events such as El Niño occurred within intervals when SSTs were generally cooler than the Holocene average. These results corroborate other studies [*Friddell et al.*, 2003; *Moy et al.*, 2002; *Sandweiss et al.*, 2001] suggesting increased interannual (El Niño-Southern Oscillation) variability at ~4.2 ka. The co-incidence of subpolar and subtropical species within the same sample may also represent greater seasonality (stronger upwelling and a well developed thermocline). However, modeling [*Diffenbaugh et al.*, 2006] and paleoclimate studies [*Barron and Bukry*, 2007] suggest the NPH weakened during the late Holocene, implying reduced upwelling and stratification in the basin. Interannual/seasonal variability based on this proxy was pronounced between 4.3–3.6 ka, 2.8–1.3 ka, 1.1–0.4 ka and 0.3 ka to the present and appears associated with millennial scale climatic instability.

5. Santa Barbara Basin Hydrography During the Last Two Millennia

[12] A further change in the planktonic foraminiferal assemblage occurred during the last 2 ka. At this time, in the absence of *G. bulloides* (rarely >5% of the assemblage and <5 specimen cm^2 yr^{-1}) *G. quinqueloba* became the most significant species in the basin (50 to 100 specimen cm^2 yr^{-1} or 60 to 80% of the assemblage), possibly reflecting the presence of HNLC water and subsequently reduced prey abundance. *N. pachyderma* (s.) abundance increased (10–15 specimen cm^2 yr^{-1} or 15–20% of the assemblage) and *N. incompta* decreased (<10 specimen cm^2 yr^{-1} or 20% of the assemblage) between 1.6–1.4, and 0.8–0.6 ka indicating anomalously cool water temperatures (Figure 2 and auxiliary material Figure S2).

[13] The last two millennia were associated with two significant climate events, the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). Though the timing, location, and magnitude of decadal to millennial climate events in western North America differ, most agree that the climate of last 2,000 years was extremely variable [*Larson and Michaelson*, 1989; *Stine*, 1994]. Moreover, 1 to 0.6 ka is consistently described as an epic drought period throughout the region (Figure 2) and has been attributed to both negative PDO cycles [*MacDonald and Case*, 2005] and increased La Niña frequency [*Herweijer et al.*, 2006]. Locally, between 1.5 and 0.65 ka indications of drought conditions include tree rings, low lake levels and high estuarine salinity [*Byrne et al.*, 2001; *Larson and Michaelson*, 1989; *MacDonald and Case*, 2005; *Stine*, 1994], while flood events are evident between 0.8 and 0.2 ka [*Schimmelmann et al.*, 2006].

[14] A further complication to interpretation of this record is that these climatic events are shifted by ~200 years in the last 1000 years if the varve chronology is used rather than the AMS ^{14}C dates for the same interval such that

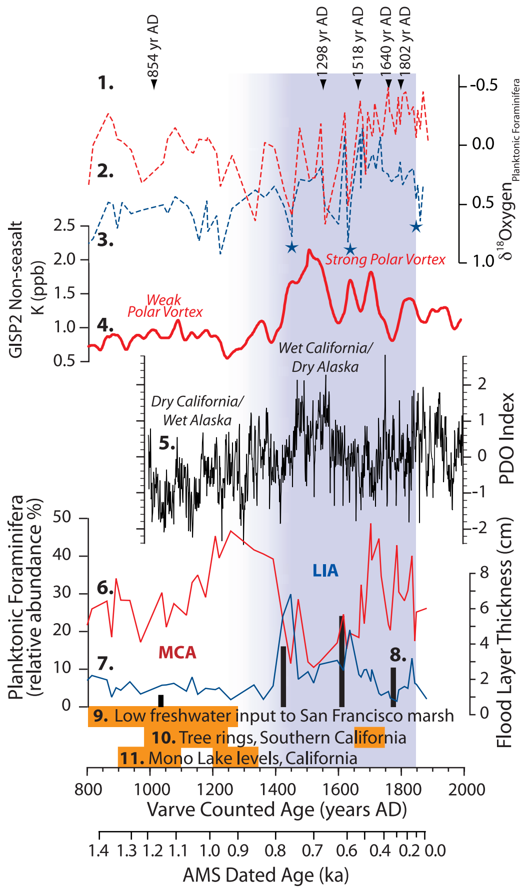

Figure 2. Comparison of climate records for the last two millennia showing (1) position of radiocarbon dates in ODP Site 893 (in calendar years AD); (2) δ^{18}O of *G. bulloides* (red dashed line); (3) *N. pachyderma* (blue dashed line [*Kennett et al.*, 2006]). Stars represent cool events. (4) Estimated polar vortex strength based on GISP2 K ions [*Meeker and Mayewski*, 2002] and (5) Pacific Decadal Oscillation index where negative values represent dry conditions in southern California and positive value, wet conditions [*MacDonald and Case*, 2005]. (6) The relative abundance of *N. incompta* (red solid thick line), (7) *N. pachyderma* (s.) (blue solid thick line), and (8) flood layers [*Schimmelmann et al.*, 2006]. Orange bars represent the temporal extent of California drought indicators including (9) freshwater input to San Francisco Bay [*Byrne et al.*, 2001], (10) southern California tree rings [*Larson and Michaelson*, 1989], and (11) Mono Lake levels [*Stine*, 1994]. Scales represent the two different age models based on varve chronology [*Schimmelmann et al.*, 2006] and radiocarbon dating [*Kennett et al.*, 2006]. Graded blue line represents the duration of the Little Ice Age.

warm SSTs indicated by foraminiferal faunal assemblages associated with the MCA occur between 800–1400 years AD and cool SSTs associated with the LIA, between 1400–1700 years AD (Figure 2) [*Schimmelmann et al.*, 2006]. We assume the varve chronology is more robust for the last 1000 years as ^{14}C reservoir age variability of up to 200 years has been observed in SBB (see the auxiliary material) [*Kennett et al.*, 1997].

[15] SST warming between 1 and 0.8 ka (MCA) in SBB [*Pisias*, 1978] has been challenged by $\delta^{18}O_{planktonic\ foraminiferal}$ data from ODP Site 893 interpreted to indicate cool SSTs during this interval [*Kennett et al.*, 2006]. However, as $\delta^{18}O_{planktonic\ foraminifera}$ reflects both SSTs as well as $\delta^{18}O_{water}$ shifts relating to evaporation/precipitation (E-P) processes, we argue that the isotope record is complicated by regional changes in salinity and water mass. Specifically the low frequency variability in the isotopic record, i.e. the interpreted 'warming trend' from 1200 to 1700 years AD exhibited in both the *N. pachyderma* and *G. bulloides* δ^{18}O records is not reflected in the faunal record (Figure 2). We suggest differences between the faunal and geochemical records indicate a more complicated interpretation of surface water conditions than previously presented, whereby E-P processes dominate over temperature during the Holocene producing low frequency changes in the isotopic record. During the MCA (before 1400 yr AD) low *N. pachyderma* (s.) abundance indicates warm winter SSTs, during an interval of high $\delta^{18}O_{planktonic\ foraminifera}$. Increased *N. pachyderma* (s.) abundance during the LIA (1400–1700 yr AD) occurred simultaneously with decreasing $\delta^{18}O_{planktonic\ foraminifera}$ (Figure 2).

[16] A possible scenario that may explain these discrepancies during the last two millennia, involves the weakening of the Arctic Low during the MWA [*Meeker and Mayewski*, 2002] such that high latitude storm systems remained north of the mid latitudes resulting in glacier retreat in the Pacific Northwest [*Reyes and Clague*, 2004]. It is possible that a weak polar vortex increased the influence of the NPH and Aleutian Low during MWA, such that the PDO exerted considerable influence over the climate of southern California and significant droughts occurred during multidecadal negative or cool PDO events [*MacDonald and Case*, 2005]. However, SST cooling in association with these events in SBB may not have been sufficient to provide the cool environmental conditions required of sinistral *N. pachyderma*. Furthermore, dry conditions could have increased the regional salinity of surface waters (increasing $\delta^{18}O_{water}$ values).

[17] As high latitude cooling intensified the polar vortex during the LIA [*Meeker and Mayewski*, 2002], winter storm tracks penetrated southern California bringing wetter conditions [*MacDonald and Case*, 2005], flood events [*Schimmelmann et al.*, 2006] and unusual seasonal (winter) cooling providing suitable environmental conditions for *N. pachyderma* (s.) (Figure 2). The increased influence of high latitude pressure systems may have muted the expression of the PDO such that severe drought conditions were less likely to develop. Wetter conditions would have freshened surface waters while increased advection of subpolar water could have decreased regional $\delta^{18}O_{water}$.

6. Conclusions

[18] Increasingly variable hydrographic conditions in SBB during the Holocene suggest millennial scale climate change is a feature of the late Holocene climate cooling. While a stable stratified water column and warm SSTs characterized coastal southern California prior to the mid Holocene, North Pacific climatic cooling at ~4 ka resulted in a complex environmental response as indicated by faunal

and geochemical results. The MCA may have been associated with decreased seasonality, high surface water salinity and increased decadal variability (severe drought events indicate intensified cool or negative phase PDO events). The increasingly significant intermittent cool intervals that occurred on millennial scales may be related to changes in the strength of the polar vortex that influenced the expression of decadal (PDO) and interannual climate variability in southern California.

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J. Fisler and I. L. Hendy, Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1005, USA. (ihendy@umich.edu)