Decadal surface ocean variability in the lower Gulf of California: Records for the past 300 years

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RESUMEN

Nuevos resultados de estudios observacionales y teóricos sobre la oceanografía del Golfo de California han aportado nuevas ideas y modelos para entender sus estructuras de circulación y controles en escalas interanuales a decadales, reconociendo la importancia del forzamiento de origen tropical y ecuatorial para explicar su variabilidad. El registro instrumental de este mar epicontinental es de corta duración, abarcando sólo desde la década de los 80 a la actualidad, mientras que para años anteriores su pobre resolución limita seriamente la validación de cualquier modelo sobre la variabilidad decadal de esta región. Para superar este problema recurrimos a una reconstrucción de las temperaturas de la superficie del mar (TSM) en el Bajo Golfo de California para los últimos dos siglos a partir de la composición isotópica del oxígeno en los caparazones de un foraminífero plánctico, *Globigerina bulloides* (d'Orbigny), preservados en los sedimentos laminados de alta resolución temporal que se acumulan en el fondo de la Cuenca de la Bahía de La Paz, frente al margen suroriental de la Península de Baja California. El análisis del registro instrumental muestra una variabilidad interanual mayor para las TSM de invierno que en las de verano para las últimas dos décadas. Los registros instrumentales más largos e incompletos muestran un cambio en las temperaturas de las estaciones frías hacia temperaturas relativamente más cálidas a comienzos del siglo pasado, mientras que las TSM de verano no muestran ninguna tendencia. Estas observaciones demuestran la sensibilidad de los meses fríos a la variabilidad interanual en las TSM. Presentamos un registro extendido a los últimos 300 años basado sobre la reconstrucción isotópica del oxígeno en el foraminífero plánctico *Globigerina bulloides* (d'Orbigny) del que sabemos su producción máxima durante los meses invernales en las aguas del Golfo. Este paleotermómetro muestra temperaturas medias de invierno similares a las registradas instrumentalmente para los últimos 170 años, mientras que para el período anterior comprendido entre 1700 a 1830 las TSM derivadas isotópicamente muestran inviernos más fríos alternándose con otros relativamente más cálidos. La variabilidad observada en las TSM de invierno a escalas interanuales a decadales parece ser modulado por las fluctuaciones de baja frecuencia asociadas al fenómeno de El Niño y Oscilación Austral (ENOA), posiblemente por una mayor frecuencia y/o intensidad de los eventos de El Niño y La Niña, que bloquean las TSM del Golfo en períodos cálidos/fríos a escalas decadales, posiblemente como respuesta no sólo al forzamiento ecuatorial introducido por el ENOA como a otros efectos de retroalimentación de origen oceánico.

PALABRAS CLAVE: Variabilidad oceanográfica decadal, variabilidad tropical y ecuatorial, ENOA, ODP, isótopos de oxígeno en foraminíferos plácticos.

ABSTRACT

Recent observational and theoretical studies of the Gulf of California have produced some new ideas and models about its circulation patterns and the controls on interannual to decadal timescales, that call on the importance of the tropical and equatorial Pacific as the main region of forcing. The available instrumental record for this region is of short duration, reaching back only into the early 1980s, which coupled with the poor resolution for previous years limits the validation of these models on longer timescales. To overcome the shortness of this record we resort to a reconstruction of SST variability for the last two centuries with the aid of the oxygen stable isotopic composition of calcitic shells preserved in the high-resolution laminated sediments that accumulate on the sea-floor of the La Paz basin, off the Baja California Peninsula eastern margin. From the analysis of the instrumental record we found that winter sea surface temperatures (SSTs) show greater variability from year to year than summer SSTs. Longer records further show a change in cold season temperatures with a trend towards warmer values at the turn of the last century, while the warm season SSTs show no corresponding trend, which underlines the sensitivity of cooler months to interannual SST variability in this region. We further present an extended SST record for the past three centuries based on a reconstruction from the stable oxygen isotopic composition of the planktic foraminifer *Globigerina bulloides* (d'Orbigny), shown to have its maximum production in the lower Gulf of California during the winter-spring season. This paleothermometer shows mean winter SSTs similar to the instrumentally recorded ones for the last 170 years while for the period between 1700 to 1830 shows cooler winters alternating with relatively warmer ones. The variability in winter SSTs on interannual to decadal timescales seem to be modulated by low-frequency ENSO variability, possibly through higher frequency and intensity of El Niño/La Niña events that temporarily lock surface ocean temperatures into warm/cold decadal periods, thus tracking tropical oceanographic variability on decadal timescales for the past two centuries through ocean driven feedbacks.

KEY WORDS: Oceanographic decadal variability, tropical and equatorial variability, ENSO, PDO, oxygen isotopes in planktic foraminifera.

INTRODUCTION

Monthly sea surface temperatures (SSTs) in the lower Gulf of California show a strong seasonal signal, induceded by the annual insolation cycle of heating and cooling of the atmosphere, by winds and by the tropical Pacific forcing. SSTs reach minimum values (19-23°C) during late winter to early spring associated with a minimum in insolation, while sea surface warming proceeds during late spring and into the summer, reaching maximum temperatures during late summer to early fall (29-31°C). The monsoonal wind regime in the Gulf of California follows this seasonality in a pattern of reversing wind directions responding to the seasonal migration of high and low pressure cells between the North Pacific and the North American continent. (Badan-Dangon *et al.*, 1991; Douglas *et al.*, 1993). Cool months are associated with NW winds, whereas warmest months are weakly related with SE winds (Ripa, 1997; Beier, 1997). Forcing by NW winds during winter and spring favor an anticiclonic circulation in the Gulf and set in motion the upwelling of nutrient rich waters especially off the eastern margin. Advection of these waters within a period of a few weeks over the narrow Gulf to the western coast fertilizes the margin of the Baja California Peninsula, enhancing biological productivity over the entire Gulf. During summer the SE winds force a cyclonic circulation and upwelling of relatively nutrient-poor waters on the western margins which supports lower biological production levels than during the winter spring period (Molina-Cruz *et al.*, 1998; Cortés-Lara *et al.*, 1999).

The opening of the Gulf of California to the south favors the invasion of tropical surface water masses over the temperate California Current waters. These warm water masses are further modified at the surface through atmospheric exchange by evaporation, especially in the upper Gulf of California that results in a net loss of bouyancy and export at upper intermediate depths (Roden, 1964; Álvarez-Borrego y Schwartzlose, 1979; Bray y Robles, 1991). Geostrophic and model calculations of surface circulation show a net inflow of water during summer associated with a mean cyclonic basin circulation and a net outflow during winter driven by an anticyclonic circulation (Marinone and Ripa, 1988; Beier, 1997). The models further show how the observed annual heat storage cycle can be best explained by advection of heat from geostrophic currents that enter the Gulf from the tropical Pacific to the south (Ripa, 1997; Beier, 1997). In contrast to this strong seasonal signal in SSTs, the Gulf's salinity values remain fairly constant, as a result of the combined action of surface heating and evaporation coupled with vertical mixing of subsurface waters and the intrusion of surface equatorial waters.

The combined action of these physical forcings (i) cooling (warming) of surface waters driven by seasonal insolation cycle, (ii) the predominantly NW (SW) wind direction during cooler (warmer) season fueled by the migration of low and high pressure atmospheric cells (iii) the advection of heat by winter (summer) anticyclonic (cyclonic) geostrophic circulation pattern, and (iv) the surface ocean cooling (waming) coupled with the shoaling (deepening) of the thermocline, are responsible for the observed annual oceanographic variability in the Gulf.

Three climatic indices capture the large scale climatic and oceanographic variability for the Pacific: (i) the El Niño and Southern Oscillation (ENSO), an index sensitive to changes in the equatorial and southern Pacific circulation patterns, originally proposed by Walker (1923) to explain the monsoonal temporal and spatial variability, and later interpreted by Bjerknes (1969) in terms of the large scale physical mechanisms centered in the equatorial Pacific that affect the climate and oceanography of the entire Pacific basin and its neighboring land masses; (ii) the Pacific interDecadal Oscillation (PDO), an index based on large scale SST patterns tracking ocean-atmosphere climate variability over the extratropical Pacific (Mantua *et al.*, 1997; Zhang *et al.*, 1997; Gershunov *et al.*, 1999; Bernal *et al.*, 2001); and (iii) the global surface temperature anomalies record, spanning from the mid of the XVII century onto the late XX century, a worldwide compilation of meteorological data originally reported by Jones *et al.* (1986) and of SSTs for the upper ocean by Levitus *et al.*, (2001) that show a trend toward warmer temperatures for the atmosphere and the upper few hundred meters of the water column during the XXth century. This trend towards higher SSTs is thought to be the ocean's response to the widely reported global warming in atmospheric surface temperatures (IPCC, 1992, 2001) whose control is still a matter of intense debate.

METHODS

This work is partly based on the instrumental SST record derived from the COADS database (The Comprehensive Ocean-Atmosphere Data Set, Fletcher *et al.*, 1983) and on the reconstruction of SSTs from an isotopic record preserved in the calcitic shells of the planktic foraminifer *G. bulloides* from a box core retrieved during June of 1996 (BAP96-CM), from 400 m deep waters in the La Paz Bay Basin (also known as Alfonso basin), aboard the oceanographic vessel *B/O El Puma*, and stored under refrigerated conditions since at CICESE. We have cut the core along the depth axis in 1 to 2 cm wide slabs which were X-radiographed at Scripps Institution of Oceanography (SIO). We used the prints for the laminae counting and to draw the template we later use to cut the slab into 1 to 3 mm thick samples. The prints clearly show the continuous nature of laminations downcore, alternating with thin layers of darker homogenous sediments, features that allow us to visually correlate downcore variations in laminae and density contrast between different cores (Bernal, 2001).

The chronostratigraphy is based on laminae counting and radioisotopic determinations of AMS^{14}C on an ensamble of planktic foraminifera in this and on other box cores which were further prepared by Dr. S. Lehmann at INSTAAR University of Colorado and measured at the AMS facilities at Woods Hole Oceanographic Institution. We used these determinations to constrain the sedimentation rates for the core which we further compared with our laminae counts. On average we find each couplet of light and dark laminae spans 2 to 5 years, a number remarkably close to ENSO variability. Although the mechanisms of lamina formation are still under discussion, the multiyear character of each lamina couplet sets a limit on the highest frequencies we can recover from these records.

One of the sampled slabs was used for micropaleontological purposes, mainly taxonomical analysis and characterization of planktic and benthic foraminifera and the picking of planktics for stable isotopic determinations. Samples were washed in Calgon for a few hours and wet sieved through a >63µm opening stainless steel sieve leaving the sand fraction for micropaleontological analysis. They were dried at room temperature overnight and then dry sieved for taxonomical counts and picking for stable isotopes. We selected several specimens of *G. bulloides* from the size fraction >250µm for the stable isotopic determinations, which were carried at the Stable Isotope Laboratory at SIO under the supervision of Dr. C. Charles. All of the samples were heated to 375°C for one hour prior to their insertion into an automated carbonate preparation device Carousel-48 hooked up to a Finnegan MAT252 automated mass-spectrometer were the stable isotopic composition of the resulting gas is measured against a reference gas. The long term precision of the instrument (1s) for oxygen measured on an NBS-19 standard during the time period when these determinations were carried was ±0.06‰.

SST records were obtained from the publicly accesible data base known as COADS for the region between 24–25°N and 109–111°W, and anomalies were calculated by substracting the mean seasonal cycle from each year. Southern Oscillation Index (SOI) for region Niño3.4 was obtained from the NOAA (National Oceanic and Atmospheric Administration of the United States of America, http://www.noaa.gov/) and correspond to monthly data between 1850 and 1998. For the time period between 1850 to 1800 we used the Stahle *et al.* (1998) SOI reconstruction available through http://www.ngdc.noaa.gov/paleo.

RESULTS

Instrumental records

A remarkable feature of the two-decade long SST record in the lower Gulf of California is the relative constancy of summer SSTs with maximum values of 31°C in contrast with the more variable winter SSTs. Bernal *et al.* (2001) explain this observation in terms of the stabilizing effects of latent and sensible heat transport during summer months. The influence of ENSO events in this region, responsible for the largest interanual signal in the regional SSTs, is commonly described as a several months long and extensive northward penetration of warm equatorial surface waters into the Gulf during El Niño years and by the presence of negative sea surface temperature anomalies during La Niña years (Roden, 1964; Baumgartner and Christensen, 1985; Álvarez Borrego y Lara-Lara, 1991; Santamaría del Angel *et al.*, 1996; Lavín *et al.*, 1997; Soto-Mardones *et al.*, 1999).

To show how El Niño events affect our study region we calculated the monthly SST anomalies from the COADS SST compilation, by substracting from each month of the record its monthly mean, basically an annual filter made up of mean monthly climatologies. As anticipated, we found that warmer and cooler anomalies usually appear during late fall to winter months of the year (Figure 1), disappearing during late spring into the summer. On this same figure we further plotted the ENSO anomaly from equatorial regions 3 and 4 (eastern equatorial Pacific), to enhance two important observations (i) both records show a remarkably similar behavior underscoring the importance of the tropical Pacific forcing in the Gulf, and (ii) there is a variable lag of approximately 3 to 6 months between the warm and cool ENSO

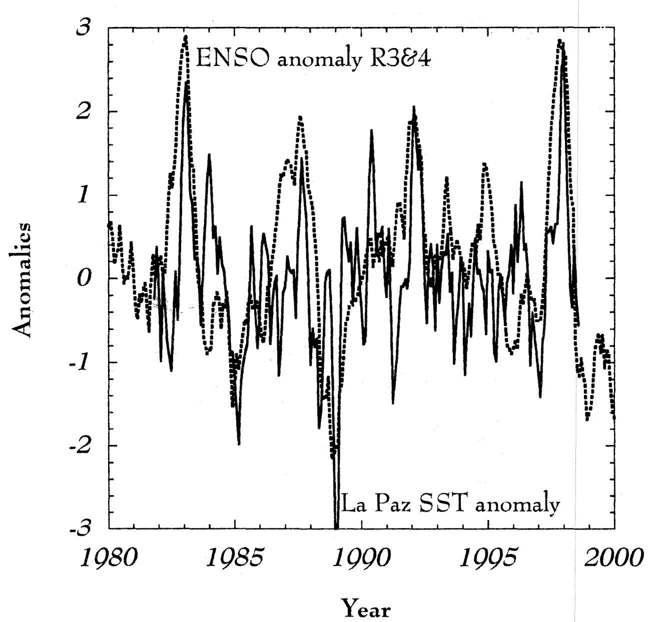

Fig. 1. Comparison between time series of monthly sea surface temperature anomalies (continuos line) obtained by substracting the monthly means for each year of the record and time series of monthly sea surface temperature anomalies for the equatorial region 3+4 (broken line), in this figure the tickmarks on the x axis correspond to the month of January of each year. Notice the good agreement between both records and the 3 to 6 month lag of La Paz basin SST anomalies in respect to the equatorial anomalies

events and its arrival in the southern reaches of the Gulf of California, in a similar fashion suggested by Pavia and Badan (1998) for the northern part of the Baja California Peninsula.

Although ENSO-driven ocean variability is the strongest interannual signal in the Pacific, North Pacific SST records for this last century show another major spatial pattern of variability on longer time scales. The oceanographic variability captured by the PDO index is derived from the leading EOF of the North Pacific SSTs (Zhang *et al.*, 1977; Gershunov *et al.*, 1999). Positive PDO values are associated with cooler than normal SSTs in the central and western North Pacific mid latitudes while the eastern boundary –western coast of North America- shows warm SST anomalies; the reverse SST pattern dominates with negative PDO values. These large-scale spatial patterns are remarkably similar to both ENSO extrema and are thought to respond to the relative position and strength of the seasonally migrating high (subtropical high) and low (Aleutian low) pressure cells over the North Pacific. Nonetheless, little is known about the regional response of the Gulf of California to this interdecadal shifts in the North Pacific ocean mean states. From the comparison between La Paz Basin SST winter anomalies (continuous line) and the PDO index (broken line) (Figure 2), winter SST anomalies in the La Paz region show no apparent response to the mid 70's shift from more negative to positive values, a widely observed phenomenon in numerous indices studied and reported over the temperate North Pacific (Ebbesmeyer *et al.*, 1991). Although we do not rule out the importance of this index to explain a portion of the oceanographic variability in the lower Gulf of California (see Bernal, *et al.* 2001, for discussion)

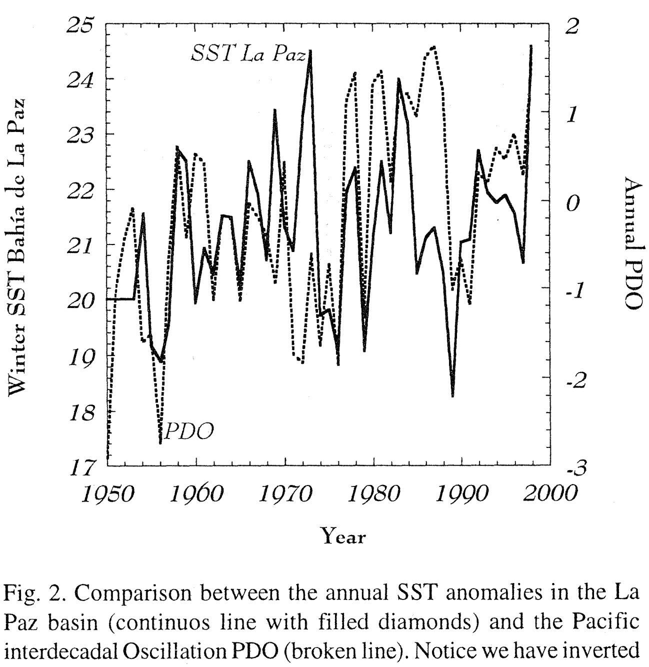

Fig. 2. Comparison between the annual SST anomalies in the La Paz basin (continuos line with filled diamonds) and the Pacific interdecadal Oscillation PDO (broken line). Notice we have inverted the axis for the PDO values to show how both records change during the mid 70's shift.

there is no clear imprint of this large scale interdecadal variability in the SSTs, in part probably due to the short instrumental record available, stressing the importance of longer records to recognize and evaluate this interdecadal variability in our study region.

Stable Isotopic Records

Stable isotopic composition of calcitic shells of these organisms are known to reflect the $^{18}O/^{16}O$ ratio present in sea-water -directly tied to its salinity through evapotranspiration processes- with an offset controled by the sea surface temperature where these organisms precipitate their shells (Emiliani, 1955). Although aware of other biological effects and geochemical properties in the water column and sediment that may alter their isotopic signature, the good preservation of the foraminifer used for the period of this study, the relatively short time span we consider here, and results from other studies showing the reliability of *G. bulloides* to track winter SSTs in the Gulf of California (Thunell *et al.*, 1999) underscore the utility of this planktic foraminifer to reconstruct a high resolution SST record for this region.

Isotopic ratios were converted to SSTs using the empirical equation reported by Bemis *et al.*, (1998), assuming the following empirical relationship between sea surface salinity and the $^{18}O/^{16}O$ ratios -for the upper 200 m of the tropical to subtropical Pacific water column (35°N to 35°S)- derived from reported values by the GEOSECS program (Östlund *et al.*, 1987),

$$\delta^{18}O_w = 0.285*SAL - 9.5\ .$$

Observations of sea surface salinity from the study area shows almost constant values around 35‰, for the instrumental record available, which translates to a value of 0.47‰ for $\delta^{18}O_w$, to which we subtract 0.27‰ to convert from SMOW to PDB values (Hut, 1987). Calculated mean surface water temperature for core BAP96-CM-C is 20.3±.8°C, remarkably close to measured winter SSTs of 20.9±1.6°C, although their standard deviations do show a different scatter. Maximum and minimum instrumental winter SSTs (max: 24.6 and min: 16.8) show a higher amplitude than the isotopically derived ones (2.6°C). This could be explained in part by our constrain on using constant salinity for the entire series analyzed, and probably more important by the smoothing introduced during sampling. The several year span of each lamina couplet and our sample resolution – between 1 to 3mm thick samples- results in the averaging of several years into one sample and a smoothing of interannual amplitude. Nevertheless, the good agreement between the derived and observed winter SSTs underscores the utility of this method to recover mean winter SSTs for this region. In Table 1 we show the mean, minimum and maximum values for *G. bulloides* $\delta^{18}O$, and their calculated SST amplitudes, which we compare with the instrumental record SSTs.

Table 1

$\delta^{18}O$ and instrumental record SST means, maxima, minima and amplitudes

	Mean	Minimum	Maximum	$\delta^{18}O$ Ampl.	SST Ampl.°C
$\delta^{18}O$ *G. bulloides* BAP96-CM	-1.24	-1.57	-0.96	0.61	
$\delta^{18}O$ G. b. BAP96-CM SSTs	20.2	18.9	21.5		2.6
Winter SST COADS	20.9	16.8	24.6		7.8

El Niño events in the lower Gulf of California are associated with positive anomalies in winter SSTs (Figure 1 and discussion in Bernal *et al.*, 2001) while maximum summer SST's remain apparently unaffected probably through changes in the amount of latent and sensible heat lost to the atmosphere and/or heat storage in a deeper mixed layer acting as a negative feedback to sea-surface warming. Cool eastern equatorial conditions during La Niña years are related with negative anomalies in winter SSTs for the short instrumental record available. Here we explore this relationship further back in time, for the last 300 years, with the aid of the isotopically derived SST record and an ENSO index spanning for this same time period. For this end we use the SOI index for the last century available from NOAA (http://www.noaa.gov/) while the XIX century record is a blend of the NOAA record, spanning back into the 1850's and the reconstructed SOI index from Stahle *et al.* (1998). In order to compare both records sampled with different time resolution, the isotopically derived and the SOI index, we smoothed the last one with a Gaussian filter spanning 15 years, a similar result can be obtained applying a Chebeseyev filter with the same time window. This comparison is shown in Figure 3 (SOI index broken line, stable isotopic derived SSTs continuous line with solid triangles), notice we have inverted the SOI scale such that negative values –El Niño- years are plotted upwards and positive values -La Niña- years run downwards. There is a fairly good agreement between years of more frequent and stronger El Niño events and relatively higher winter temperatures in Bahia de la Paz, while cooler winter SSTs seem to be associated with higher occurrences of La Niña events, simple linear correlation results gives an R^2 of 0.39 with a slope significantly different from 0 with a P value < 0.0001.

In addition to the correspondence between SSTs and the smoothed SOI record, the isotopically derived SSTs show an increase in mean winter values at the second third of the XIXth century from 19.8±.5°C to 20.5±.6 (Figure 3) an increase apparently controlled by warmer winter SSTs. These raising SSTs are apparently preceeded by a decade long negative excursion of the ENSO index. Although both chronologies and records, specially the unique Bahía de la Paz one, are subject to errors in both timing and relative amplitudes, if we take both at face value it seems to be the only remarkable decade when the lower Gulf of California cool winter temperatures seem to be independent of the equatorial Pacific forcing. There is also a decade long disruption between the equatorial Pacific forced ENSO and the derived SSts during the 1860s when stronger *La Niña* events have no apparent influence in the relatively warmer lower Gulf of California waters.

We further tested the sensitivity of the Gulf of California to the extratropical North Pacific climate variability by using the PDO index reconstructed by Biondi *et al.* (2001). This recently derived index from a network of tree-ring chronologies from Southern Alta California and Baja California extends the instrumental record into the XVII century and features a prominent bidecadal oscillation. It appears both records are out of phase for most of the record, most prominently during the beginning of the XIX century (Figure 4). Warm decades in the eastern North Pacific during the 1910's,

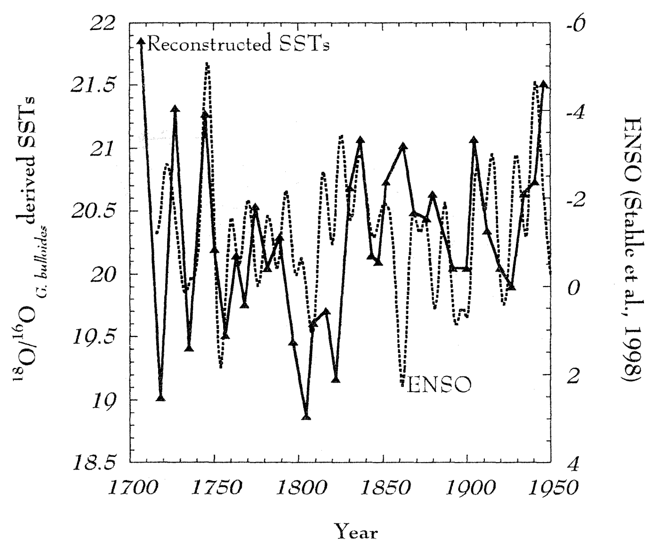

Fig. 3. Time series of $\delta^{18}O$ derived SSTs from planktic foraminifer *G. bulloides* from core BAP96-CM (continuos line with filled triangles) and 10 year long running average of ENSO index Regions 3&4 (broken line).

1890's, 1800's, 1770's and 1720's seem to be reflected in the isotopic record with apparently lower SSTs, while cooler decades in the eastern North Pacific boundary -negative PDO values – are associated with close to mean winter values from the 1830's to the present and with cooler winter SSTs for the period prior to that. These observations seem to confirm the instrumental record ones whereby decades characterized by a positive PDO are not reflected by positive SST anomalies while decades of negative PDO values show winter SSTs around the mean.

DISCUSSION

A. Interannual ENSO timescales

From the comparison between La Paz Basin instrumental record and the SOI anomalies emerge two important observations: (i) both records show a remarkably similar behavior, which we should expect since most of the forcing to the Gulf is generated in the tropical Pacific (Baumgartner and Christensen, 1985) and (ii) there is a consistent lag of approximately 6 months between the warm and cool ENSO events and its arrival in the southern reaches of the Gulf of California. Ocean circulation models for the Gulf of California show the annual heat storage cycle to be mainly controlled by advection of heat by geostrophic currents entering the Gulf from the tropical Pacific to the south (Ripa, 1997; Beier, 1997) while seasonal insolation, wind circulation patterns and surface ocean mixing seem to play a secondary role. Warm winters like 1982-1983, 1986, 1992-1994, 1997, commonly associated with El Niño events, bring warmer SST anomalies usually appearing during late fall to winter months,

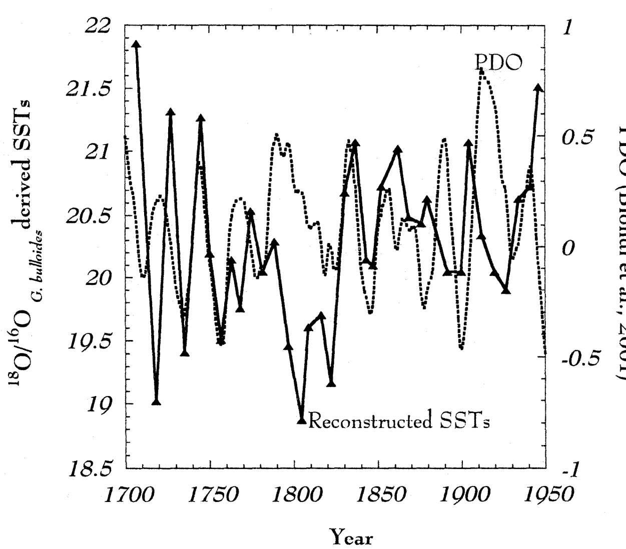

Fig. 4. Time series of $\delta^{18}O$ derived SSTs from planktic foraminifer *G. bulloides* from core BAP96-CM (continuous line with filled triangles) and Biondi *et al.*, (2001) dendrochronological reconstruction of PDO variability in the eastern North Pacific (broken line).

while late spring and summer anomalies appear to show mean values. Cooling of surface waters is associated with La Niña events for the short instrumental record, especially apparent during winter months of years 1985 and 1989 which show negative SST anomalies coinciding with anomalously cool conditions in the Equatorial Pacific. Thus it seems, winter SST anomalies are the most sensitive indicator for a warming/cooling in this region winter SST because they seem to track the input of heat from the tropical Pacific more closely.

Furthermore, from a year to year comparison between winds and ENSO for the period between 1950 and 1997 Bernal *et al.* (2001) point out how winters that follow strong El Niño events like 1966, 1969, 1984, 1992-1994, show positive wind anomalies during that period, while three moderately strong El Niño years 1972, 1977 and 1987 do show mean wind values and only one strong El Niño event during 1958 shows negative wind anomalies. Alternatively, those winters that follow La Niña events like 1956, 1963,1967 and 1970 do show negative wind anomalies and only during winter of 1975 winds appear close to mean values, while another two years with anomalously weak winds 1980 and 1982 are unrelated to La Niña events. These observations emphasize the relevance of the depth of the mixed layer and its heat storage capacity especially during the winter after an ENSO event and winds as a negative feedback to the surface ocean warming. Warm (cold) ENSO events advect excess (deficit) heat that deepens (shoals) the mixed layer during these events, following the relaxation in the advection of these anomalies during winter the differential cooling between ocean and land enhances (reduces) the temperature difference between ocean and continent conducive to a higher (lower) pressure gradient. Interannual changes in this gradient controls the strength of winds along the Gulf's main axis and partially explains heat dissipation patterns and variability in the Gulf of California following equatorially driven advection of warm and cool events.

B. Decadal to interdecadal variability

The observed greater interannual winter SST variability seems to be modulated on decadal to interdecadal timescales by the tropics, showing a significant trend towards warmer values for the last 170 years. Oxygen isotopic SSTs derived from *G. bulloides*, show a mean warming of 0.7°C during the second third of the XIXth century. Furthermore, the close resemblance between the isotopic record from Bahia de La Paz and the ENSOs decadal variability, where decades with warmer winters in the reconstructed record seem to follow higher frequency and intensity of El Niño events, while decades with cooler winters appear to track more frequent and intense occurrences of La Niña years. In this decadal timeband we do not observe leads or lags of the ENSO signal with respect to the reconstructed

SSTs, as we were able to with the monthly instrumental SSTs, in part due to the relatively low time resolution introduced by our sampling techniques which tend to smooth out single year signals, and as we already learned from the previous discussion, ENSO events take only a few months to reach the lower Gulf of California and the warming/cooling introduced by them are going to appear as instantaneous in this time band.

Another remarkable observation is the apparent duration of the warm and cool variability as a several years up to decade long periods which further seem to underlie the lower frequency band of the ENSO variability. A plausible explanation for this correspondence is that a higher frequency in the occurrences of El Niño/La Niña events, and/or higher amplitude of these events will temporarily lock surface ocean temperatures of the Gulf into warm/cold modes. This decadal variability does not appear to closely resemble the North Pacific's PDO, although we cannot rule out the possibility of noise in the Biondi *et al.*, (2001) record, the only PDO reconstruction available to this date to which we would have to add the errors inherent to our chronology which seems to be more finely tuned to the ENSO record. Furthermore, while the instrumental SST time series and the PDO record do show a close agreement on annual time scales, instrumental SST's of the lower Gulf of California lack the shift in values during the mid 70's observed in the rest of the North Pacific (Bernal, *et al.*, 2001). We have not been able at this point to identify an unequivocal mechanism that would produce this apparent lack of response in the lower Gulf of California SSTs to changes in the PDO, but we offer two explanations that may complement each other (i) the relative isolation of the Gulf of California waters from the North Pacific's temperate climate imposed by the Baja California Peninsula to the west and the greater communication through its mouth poised towards waters of tropical and equatorial origin, and (ii) the excess heat advected by surface tropical waters, especially after the intensification of ENSO events since the 80's in addition to the observed past century's long term warming, may be dissipated in part by stronger winds in the Gulf during winter when the land ocean gradients are strongest. These stronger and cooler winds brought by changes in North Pacific's atmospheric circulation patterns and further captured by the positive anomalies in the PDO act as a negative feedback to the warming by dissipating part of the accumulated heat and dampening the increase in SSTs and may partially explain the apparent lack of response to the widely reported mid-70's shift in the eastern North Pacific towards warmer SSTs (Ebbesmeyer, *et al.*, 1991).

The model we propose here to explain the decadal variability in the instrumental and reconstructed SST records calls upon the advection of heat from the tropical western hemisphere warm pool (Wang and Enfield, 2001) into the Gulf of California during warm years - El Niño events- in the Eastern Equatorial Pacific. This warming is effectively capped at 31°C by latent heat exchange with the atmosphere through enhanced evaporation and by a deepening of the surface mixed layer acting as negative feedbacks. Part of this excess heat during El Niño years is stored in the surface mixed layer and becomes a source of latent heat to the atmosphere during late summer and of sensible heat during fall and winter as solar insolation decreases, setting a relatively stronger temperature and pressure gradient with the neighboring and now faster cooling continent. This enhanced pressure field fuels stronger NW winds along the main axis of the Gulf of California acting as a negative feedback to the warming through heat loss at the surface to the atmosphere and by mixing of warm surface waters with deeper cooler ones. All these negative feedbacks tend to cool down SSTs over a time interval which seems to be of annual duration.

To explain the interannual to decadal periods of negative SST anomalies we have to invoke upon a higher frequency in the advection of cooler waters of tropical origin during La Niña years as the main process to cool surface temperatures below mean levels. During these cool years SSTs are probably driven down through advection of cooler waters of equatorial origin that would shoal the mixed layer and decrease the amount of heat stored in the surface ocean. As the cooling season progresses the lower flux of sensible heat to the atmosphere weakens the temperature and pressure gradient with the neigboring cool continent and consequently favors weaker NW winds along the main axis of the Gulf. This model can be further tested against wind and precipitation records for the last century and with sedimentary proxies that are effectively controlled by those two processes, tests that fall outside the scope of this paper.

However, the warming of winter SSTs at the beginning of the XIX century is apparently related to an increase in the amplitude/frequency of El Niño events although after a decade long lag. This warming seems also to follow the last global Northern Hemisphere surface ocean cooling step before the planet steps out of the five centuries long cold period also known as the Little Ice Age from the 1830's into the 1890's (Mann *et al.*, 1998), in contrast the steady surface ocean warming of the XX century is paralleled by an increase in the stable isotopic SSTs as well as in the instrumental record for the past century. These two apparently paradoxical responses bring into question the changing sensitivity in direction and magnitude of the regional oceanographic response to global climate changes. Furthermore, the persistence of the decadal variability in the Gulf of California surface waters, probably sustained by feedbacks operating on timescales longer than the seasonal ones, supports its oceanic origin. The relative importance of these feedbacks to the tropical and equatorial forcing on longer timescales will determine whether the Gulf of California will continue to act as an apparent heat sink for the tropics or whether it is going to reverse its direction and become another feedback to global warming, a balance we should understand carefully if we are to predict the oceanographic and climatic contribution of this region to the observed global climate warming.

Another implication of these observations links the warming of surface waters in the Gulf of California with the biogeochemical cycling of nutrients and carbon in its surface mixed layer. If most of the warming is stored in a deeper warm mixed layer during summer and the following winter cooling and wind mixing does not dissipate it, this deeper and warmer mixed layer will separate more effectively the nutrient deprived surface waters from the nutrient rich at depth and limit the advection of nutrients into the photic zone, a situation leading to lower biological production levels. The few available observations in the lower Gulf of California region show overall lower pigment concentrations during the 82-83 El Niño event than in preceeding and subsequent normal years (Santamaría del Angel *et al.*, 1994) confirming at least the direction of the biological productivity response during warm winters. If true, this model implies the progressive establishment of more oligotrophic conditions in the lower Gulf of California during warm periods with wideranging implications on the regional climate, ocean circulation, nutrient and carbon cycling linked by its biological response. The lower fertility rates that ensue during warmer decades and El Niño events and concomitant changes in the trophic web structure cast an uncertain shadow on the future of traditional fisheries and yields in the region if warming is to proceed at present rates.

CONCLUSIONS

- Instrumental SST records from the Gulf of California and SOI anomalies show a high correspondence with a consistent lag between 3 to 6 months between the equator and the southern reaches of the Gulf of California. Warm/cool winters in the lower Gulf are commonly associated with El Niño/La Niña events bringing relatively warmer/cooler waters of tropical and equatorial origin into this epicontinental sea, a relation that stresses the link between the oceanographic variability in the Gulf of California and the equatorial Pacific. Both warm and cool anomalies usually appear in the Gulf of California during late fall to winter months, while late spring and summer anomalies appear to show mean values.

- From the comparison between the instrumental SST record with oxygen isotopic values determined from *G. bulloides,* thought to have its maximum production in the lower Gulf of California during the cooler season, we found that the mean of the isotopically derived sea surface temparatures agrees fairly well with the instrumental ones, although differing in its total amplitudes. This observation underscores the utility of this planktic foraminifer to track the cool season mean SSTs in this region.

- This paleothermometer shows a warming in winter SSTs during the 1830's, following an increase in the frequency and amplitude of *El Niño* events and in opposite direction than the last step in Northern Hemisphere surface ocean cooling as the planet steps out of the V centuries long cold period known as the Little Ice Age, while instrumental and isotopically derived SSTs during the XXth century seem to parallel the global planetary warming trend.

- The observed interannual to decadal winter SST variability seems to be modulated on decadal to interdecadal timescales by ENSO variability, possibly through a higher frequency in the occurrences of *El Niño/La Niña* events, and/or higher amplitude events that temporarily lock surface ocean temperatures of the Gulf into warm/cold decade long periods through ocean atmosphere driven feedbacks.

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