Sea surface temperature anomalies in the Gulf of California

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RESUMEN

Se utilizan imágenes infrarrojas de satélite de enero de 1984 a diciembre de 2000 para describir las anomalías de temperarura superficial del mar (TSM) en el Golfo de California. Las anomalías positivas predominantes son debidas a El Niño, especialmente el de 1997-1998, con desviaciones de más de 3°C por encima de la climatología estacional. La anomalía negativa más grande (~ -4°C) está asociada a La Niña de 1988-1989. El Niño 1986-1987 tuvo el efecto más débil, con anomalías < 2°C. Las anomalías de TSM tienden a ocurrir primero, y a ser las más fuertes, en la región justo al sur del archipiélago que se encuentra en la parte media del golfo; se propone que esto puede ser debido a la presencia de fuertes frentes de TSM en esa área. Algunas de las anomalías parecen estar conectadas a anomalías del mismo signo en la Alberca Cálida del Hemisferio Occidental en el Pacífico oriental. Procesos locales pueden ser la causa de algunas anomalías, especialmente en la región norte del golfo. El origen de algunas anomalías se desconoce. Se observa un calentamiento estadísticamente significativo de ~ 1°C durante los 17 años de las observaciones, aparentemente debido a la variabilidad interdecadal del océano Pacífico.

PALABRAS CLAVE: Anomalías de TSM, El Niño, interdecadal, Golfo de California.

ABSTRACT

Satellite infrared images from January 1984 to December 2000 are used to describe interannual sea surface temperature (SST) anomalies in the Gulf of California. The predominant positive anomalies are due to El Niño, especially in 1997-1998, with deviations of over 3°C from the seasonal climatology. The largest negative anomaly (~-4°C) was associated with La Niña of 1988-89. The 1986-87 El Niño had the weakest effect, with anomalies < 2 °C. The SST anomalies tend to be earlier and stronger in the region just south of the mid-gulf archipelago; this may be due to the presence of strong SST fronts in that area. Some anomalies appear to be connected to anomalies of the same sign in the Western Hemisphere Warm Pool of the eastern Pacific. Some anomalies, especially in the northern gulf, may be caused by local processes. The origin of some anomalies remain unknown. A statistically significant warming of ~ 1°C during the 17 years of the record was observed, apparently within the interdecadal variability of the Pacific ocean.

KEY WORDS: SST anomalies, El Niño, interdecadal, Gulf of California.

1. INTRODUCTION

At its entrance at 23° N and due to open communication with the Pacific Ocean (Figure 1), the Gulf of California (GC) is strongly affected by El Niño (EN), which is the best identified cause of its interannual anomalies (Baumgartner and Christensen, 1985; Robles and Marinone, 1987; Marinone, 1988; Ripa and Marinone, 1989; Lavín *et al.*, 1997). Baumgartner and Christensen (1985) found that the interannual changes in the ocean climate of the Gulf of California, indicated by sea level and temperature anomalies, are related to the El Niño phenomenon, and they proposed that they result from the intensification of the north equatorial cyclonic circulation composed of the North Equatorial Countercurrent, the North Equatorial Current and the Costa Rica Coastal Current. This intensification leads to increased poleward advection by the Costa Rica Coastal Current, and to its penetration into the GC.

During El Niño, Robles and Marinone (1987) detect warm, low salinity surface anomalies in the hydrography together with positive anomalies in sea surface elevations and in pycnocline depth. The withdrawal phase of this intrusion of warm, fresher surface water of tropical origin is seen in the distribution of surface salinity and temperature at the end of the 1982-83 EN (Figure 1): in March 1983 (Figure 1a), surface water of salinity less than 35.0 psu [Tropical Surface Water, or TSW, according to Torres-Orozco (1993)] was found as far inside as the northern edge of Guaymas Basin (~ 27.5° N), while at the mouth surface salinity was as low as 34.5 psu. In October of the same year (Figure 1b), TSW was still as far inside as in March, but salinities had increased somewhat, probably due to evaporation. By January 1984 (Figure 1c) the TSW had withdrawn to about 25°N and by March 1984 it was almost completely outside the gulf; the difference in surface salinity distributions in March 1983 (Figure 1a) and March 1984 (Figure 1d) is striking. Direct evidence of high surface temperatures and low surface salinities in the southern GC during the 1991-92 EN were obtained by Fernández-Barajas *et al.* (1994) during cruises in February and August of 1992. Castro *et al.* (2000) report deepening of the thermocline and a warming (~ 4°C)

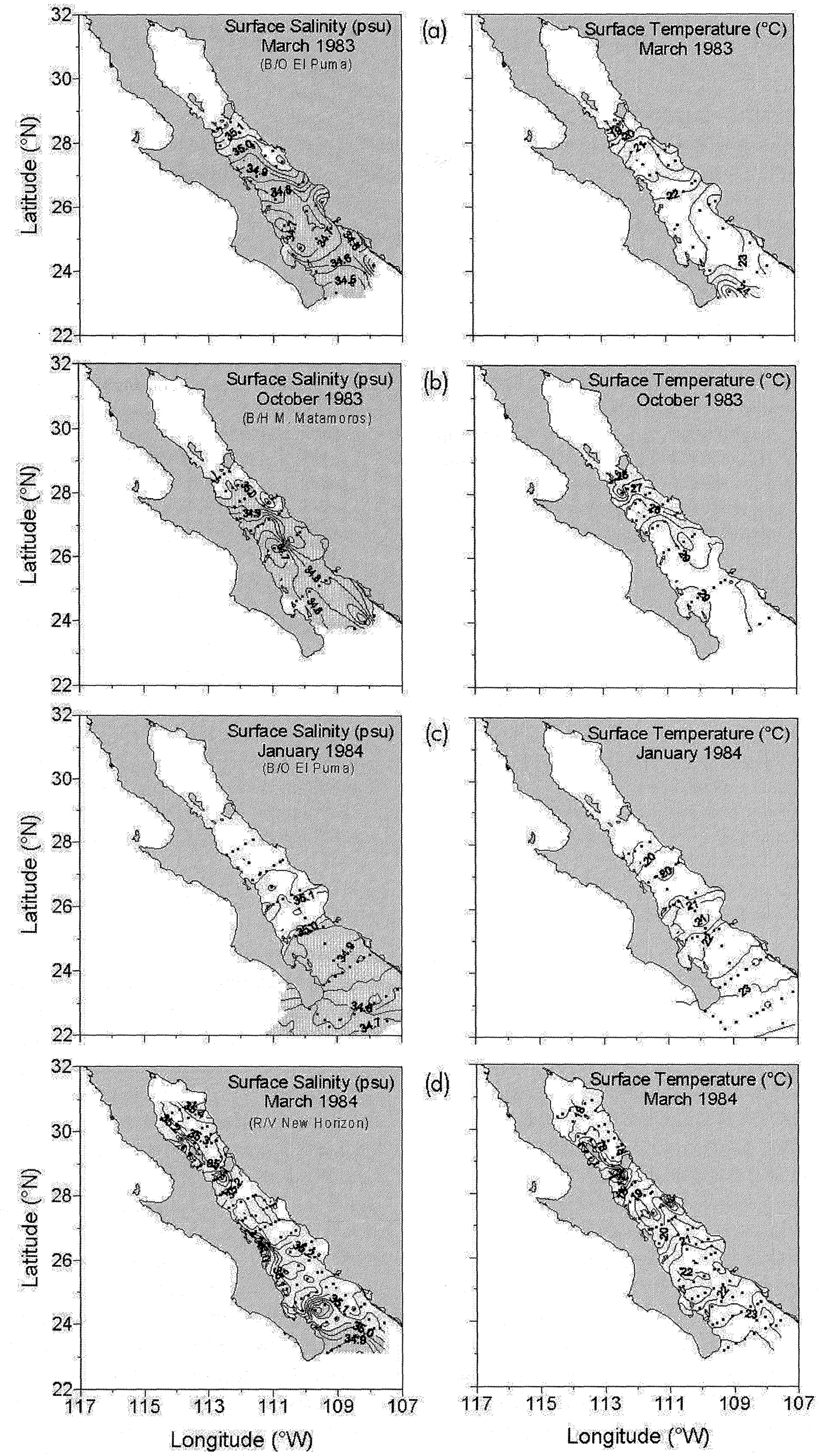

Fig. 1. Distribution of surface salinity and temperature in the Gulf of California during: (a) March 1983, (b) October 1983, (c) January 1984, (d) March 1984.

and freshening (0.1 to 0.2 psu) of the surface layer in the entrance to the GC in November 1997, at the peak of the 1997-98 EN; similar anomalies were observed farther south (19°N), off western Mexico by Filonov and Tereshchenko (2000). During some EN, TSW has been detected as far as the northern gulf (Romero-Centeno, 1995).

Satellite infrared images of the GC were used by Soto *et al.* (1999), hereafter abbreviated S99, to describe the seasonal signal and the interannual anomalies of sea surface temperature (SST) for the period 1984-1995; they showed that the most important interannual SST anomalies are related to El Niño: positive SST anomalies are associated to EN and negative SST anomalies to La Niña (LN). We pursue the work of Soto *et al.* (1999) further, in order to investigate more closely the characteristics and origin of the interannual SST anomalies; it will be shown that SST anomalies apparently unconnected to EN-LN also occur, some of which seem to affect the GC as much as some EN-LN events. Likely origins of these anomalies are proposed.

2. DATA SOURCES

The satellite SST data were obtained from NASA's Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center (PODAAC, webpage http://podaac.jpl.nasa.gov). They are 8-day averages with an approximate resolution of 18km x 18km, covering from January 1984 to December 2000, which is 5 years longer than the data used by S99, and include the 1997-98 EN. Although clouds, gaps and bad data have been eliminated in this data set, a few weeks had to be removed (and filled-in by interpolation), after careful inspection of the strongest anomalies revealed some obviously bad data. The data for the GC were averaged to obtain the monthly means T(x,y,t), where x is distance along the gulf with origin at the head, y is distance across the gulf, and t is the time in months ($\delta t = 1$ *month*) since January 1984.

Indices external to the Gulf of California were used in the search for explanations of the observed SST anomalies. The Southern Oscillation Index (SOI) and the Extratropical Northern Oscillation Index (NOIx), which was recently introduced by Schwing *et al.* (2001), were obtained from NOAA's Pacific Fisheries Environmental Laboratory (http://www.pfeg.noaa.gov /products/PFEL /modeled/indices / NOIx/noix. html). The SOI used here is the difference in sea-level atmospheric pressure anomalies between Tahiti and Darwin, Australia; it reflects the activity in the equatorial region. The NOIx is based on the difference is sea level pressure anomalies in the North Pacific High and in the Low pressure center over Darwin; it reflects the variability in tropical and extratropical teleconnections, and seems to be a reliable indicator of climate change in the NE Pacific (Schwing *et al.*, 2001). SST anomalies were obtained for the El Niño 3 region and the West Coast of the Americas from NOOA's NCEP Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices/index.html).

3. RESULTS AND DISCUSSION

The long-term average SST distribution

$$T_T(x,y) = \frac{1}{N}\sum_{j=1}^{N} T(x,y,t_j),$$

(where $N = 204$ is the total number of months in the data set) is shown in Figure 2a, and its across-gulf average in Figure 2b. The distribution is very similar to that obtained by S99; as these authors noticed, the main features are the difference of some 3°C between the entrance and the head, the minimum (~ 22.75 °C) in the strong tidal-mixing area of the archipelago, and the sharp thermal fronts that surround it (Argote *et al.*, 1995). In the average, the coastal temperatures are lower than in the center (Figure 2a) due, according to S99, to coastal upwelling. A least-squares straight line was removed from the monthly data of each cell, in order to remove the mean $T_T(x,y)$ and the trend $m(x,y)$; this gives the variability signal $T_v(x,y,t)$, which are the data subjected to analysis.

An Empirical Orthogonal Functions (EOF) analysis was performed as in S99 (Barnett and Patzert, 1980; Kelly, 1985). The first mode explains 97% of the variability; the second mode accounts for only 1.6%. The first mode of the EOF analysis is shown in Figures 2c and 2d: these results differ considerably from those presented by S99 (their Figure 13), apparently due to some numerical error, since the product of the time and space components of their first mode do not give reasonable values of temperature. The time evolution of the first mode (Figure 2d) of the EOF analysis clearly shows that although the annual period is dominant, there are substantial interannual anomalies; the largest anomalies are associated with EN- LN, as indicated in the diagram. The annual harmonic of the time component of mode 1 accounted for 96% of its variability, and the semiannual harmonic for only 1%. In this case, the EOF analysis produces a dominant mode which is strongly sinusoidal with annual period, whose physical explanation is clear; this signal also dominates the seasonal heat balance of the upper layers of the gulf (Castro *et al.*, 1994; Beron-Vera and Ripa, 2000).

The annual and semiannual harmonics of the variability series $T_v(x,y,t)$ were obtained by least-squares fitting (S99; Beron-Vera and Ripa, 2000), and the anomaly series $T_a(x,y,t)$ was calculated as

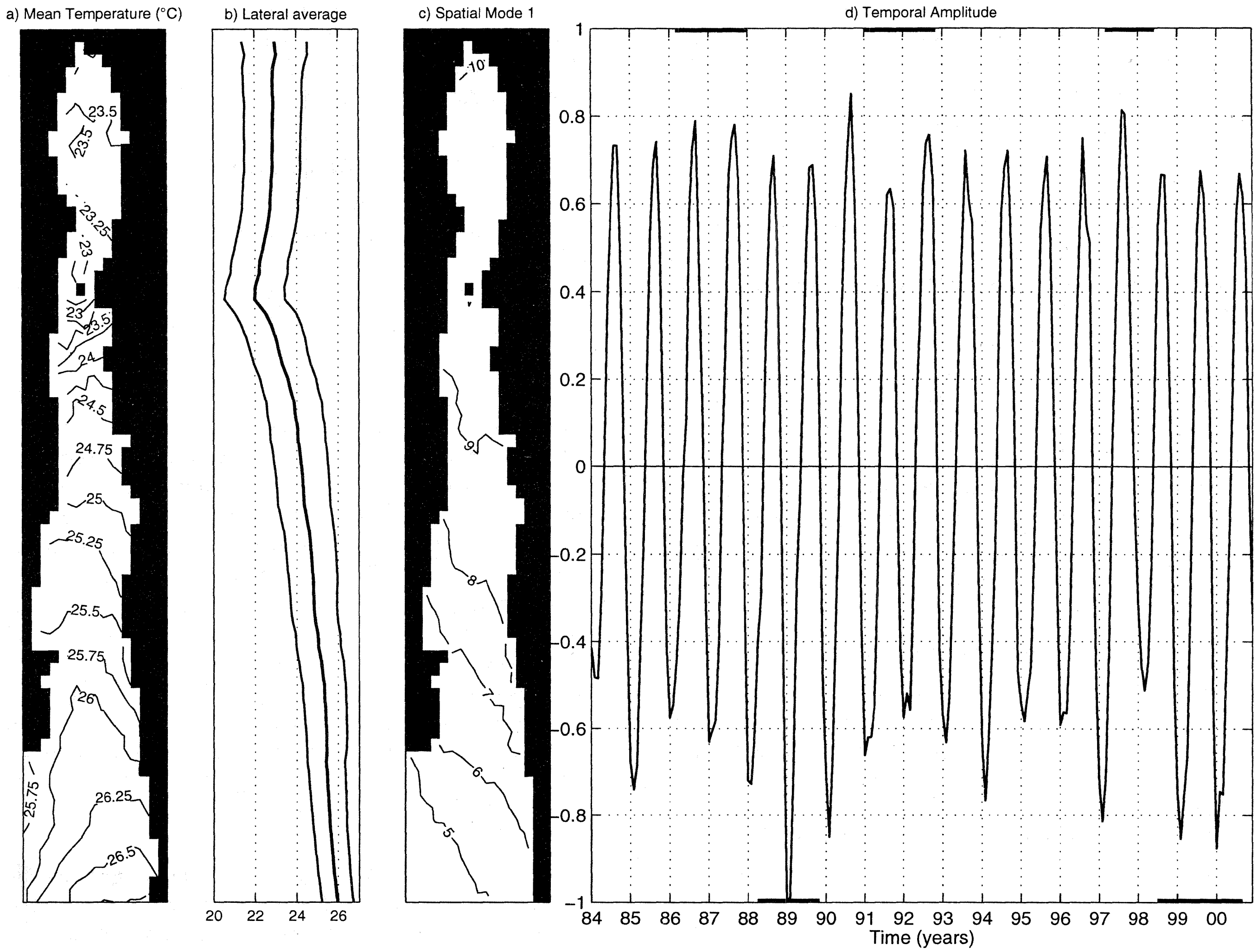

Fig. 2. (a) Long-term mean SST $T_T(x,y)$ (°C) distribution for the period 1984-2000. (b) Across-gulf average of $T_T(x,y)$. Thin lines are the 95% confidence interval, calculated with a normal distribution, and averaged across the gulf. (c) Spatial component of the first EOF mode, (d) its temporal component. Horizontal thick lines mark El Niño (top) and La Niña (bottom) events.

$$T_a(x,y,t) = T_v(x,y,t) - T_1(x,y)\cos(\omega_1 t+\phi_1) - T_2(x,y)\cos(\omega_2 t+\phi_2),$$

where T_1, ω_1 and ϕ_1 are the amplitude, frequency and phase of the annual signal, and T_2, ω_2 and ϕ_2 are the equivalent harmonic properties for the semiannual signal. The annual harmonic (Figure 3) shows that the annual amplitude is larger in the head (~ 7°C) than in the mouth (~ 4°C), and that the maximum occurs at the beginning of August (Figure 3b). In average, the annual harmonic accounted for 92% of the variability, but it reached 95% in most of the gulf (Figure 3c). S99 explain that in the southern part of the gulf the annual amplitudes are larger off the mainland than off the peninsula because NW winter winds are stronger than the SE summer winds, therefore winter upwelling off the mainland coast is more extensive than summer upwelling off the peninsula coast. The distribution of the amplitude of the annual harmonic (Figure 3a) has the same shape as the spatial component of the first EOF mode (Figure 2c), as it should be. The semiannual harmonic explained only 1% of the variability.

In order to show the anomaly series, they were averaged across the gulf,

$$T_A(x,t) = \frac{1}{Y}\sum_{k=1}^{m} T_a(x,y_k,t)\,\delta y,$$

where $Y(x)=m(x)\delta y$ is the width of the gulf at position x. The transversely-averaged, monthly anomalies $T_A(x,t)$ are shown in Figure 4; no smoothing was applied, in order to retain (at the cost of some noise) the abruptness with which some anomalies appear. In order to further synthesize the data and to obtain representative numerical values, the GC was split into the four regions shown in the map in Figure 4, the

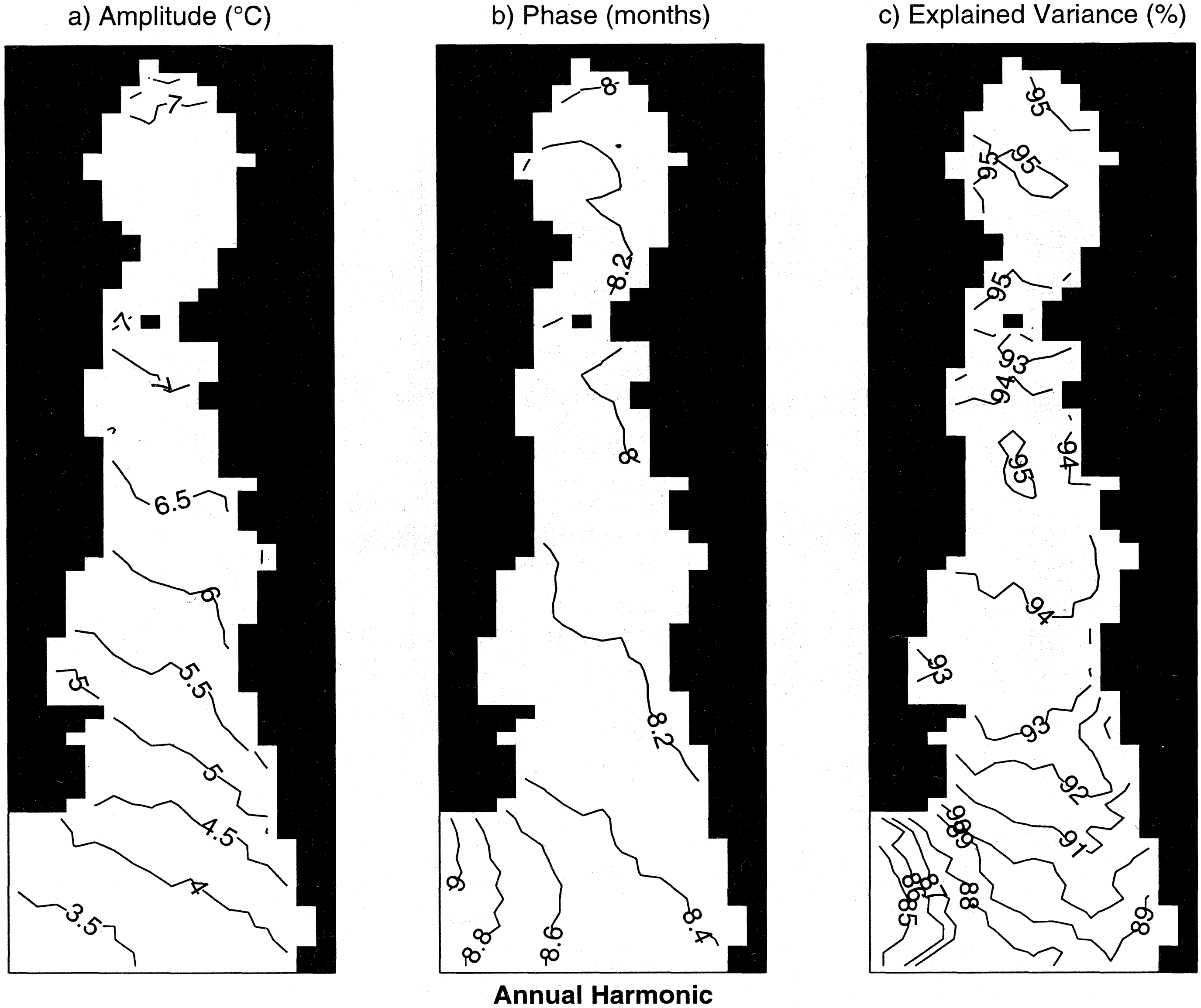

Fig. 3. Annual harmonic of SST: (a) amplitude (°C), (b) phase (months), (c) percentage of explained variability.

monthly anomalies were averaged over those regions, and the resulting time series were smoothed by passing a Hanning filter five times (Figure 5). The gulf-averaged SST anomaly is shown in Figure 6, together with the SOI and the NOIx, in order to investigate the connection between the GC SST anomalies and interannual equatorial and tropical processes; the correlation coefficients between the SST anomalies and SOI and NOIx are, respectively, 0.4091 and 0.4645 (> 99%, 60 effective degrees of freedom).

3.1 El Niño-La Niña anomalies

The close relationship between the largest anomalies and the strongest EN-LN events is apparent in Figure 6. The largest positive anomalies are those associated with the EN events of 1997-98 and 1991-92, with corresponding maxima of ~ 3°C and ~ 2°C (the maximum values of the SST anomalies cited in this section refer to the data of Figure 4, which are not smoothed). The largest negative anomalies are associated with LN of 1988-1989 (~ -4°C) and 1998-2000 (~ -2.5°C). The 1986-87 EN was the weakest in the series, with anomalies < 2°C (Figure 4). This is in contrast with the sustained positive anomaly during the strong 1997-98 EN; even the two-step shape of the SOI that characterized this EN is reflected in the SST anomaly (Figures 5 and 6). Figure 5 shows that the positive anomalies associated to EN are largest in the central gulf, while the negative ones do not have a pattern. The negative anomaly during the 1988-1989

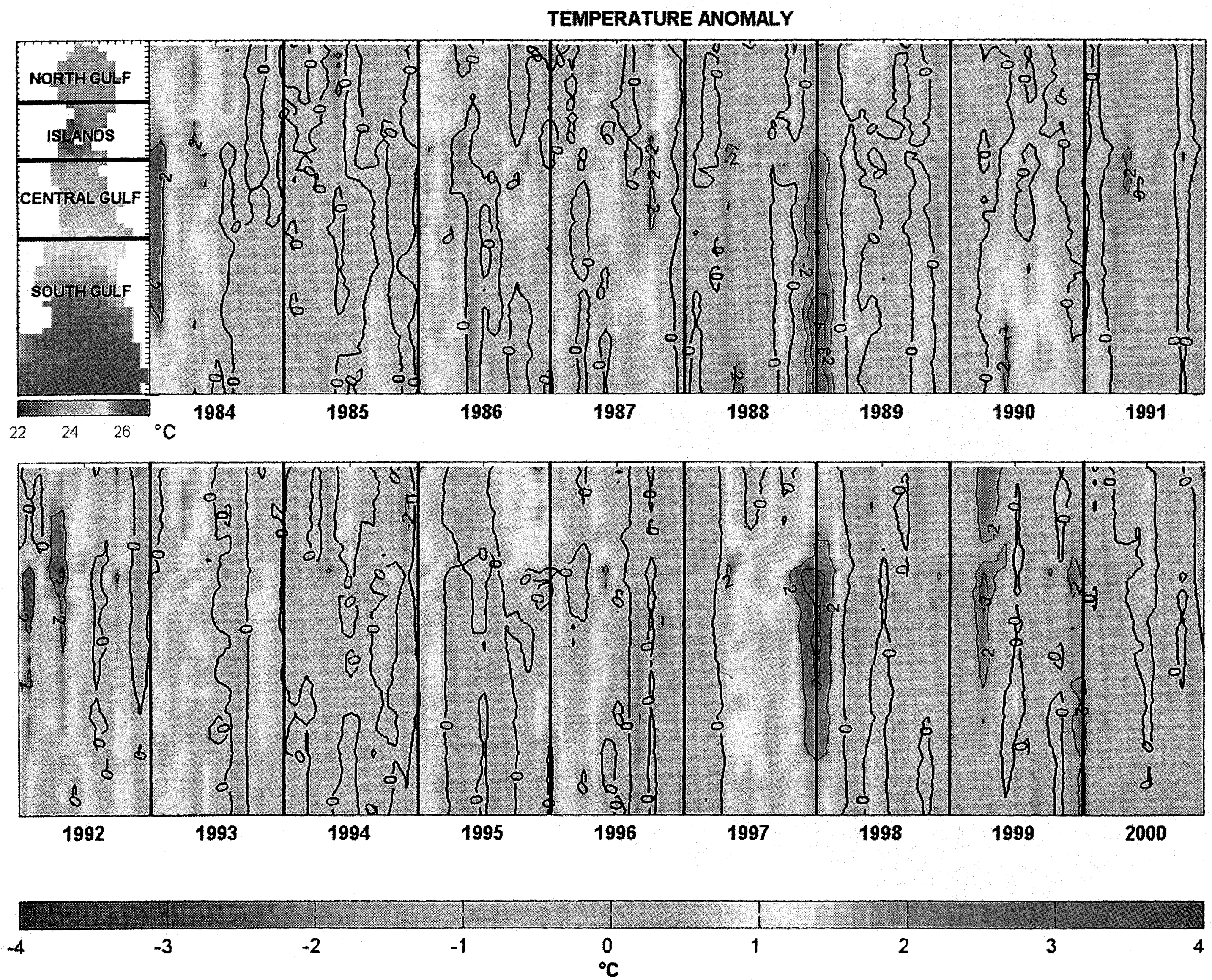

Fig. 4. Time series of the SST (°C) anomalies, averaged across the gulf.

LN was largest in the southern gulf and decreased toward the north (Figures 4 and 5); that of 1991 was uniform, that of 1997 was largest in the central gulf and around the islands. The negative anomaly in the spring of 1999 was weakest in the south, while that at the end of the year was weakest in the north.

A feature that was noticed by S99 is that, sometimes, SST anomalies associated with EN occur first in the mid-gulf archipelago; this is evident in Figure 4. The early "appearance" of EN in the archipelago is especially noticeable in 1992 and 1997 (Figure 4), but there are other isolated positive anomalies there, some of which are not obviously associated to EN. This feature may be explained by EN-induced advection acting on the thermal fronts that surround the SST minimum in the archipelago (Figures 2a and 2b). The position of tidal mixing fronts is very sensitive to even weak advection (Argote, 1983).

A simple way to show this hypothesis at work is by imposing on the long-term mean distribution of SST (Figure 2b) a displacement driven by advection at the gulf's mouth. Figure 7 shows the result of modulating such an intrusion with the SOI (maximum intrusion of 50 km corresponding to the maximum negative value of the SOI in Figure 6a). Comparison against the observed anomalies (Figure 4) show a good agreement during the strongest EN-LN events, and also highlights the disagreements, namely: (a) The 1986-87 EN, which should have affected the GC according to the model, had instead very small anomalies, (b) in 1994 the observations show conditions close to normal, while the model shows EN-like conditions, (c) in 1996, the model predicts cooling, while the data show warming for most of the year, then they agree on cooling in the months prior to the onset of EN 1997-98. This "advective model" of the effects of EN on the GC is inspired on the Baumgartner and Christensen (1985) hypothesis that during EN the Costa Rica

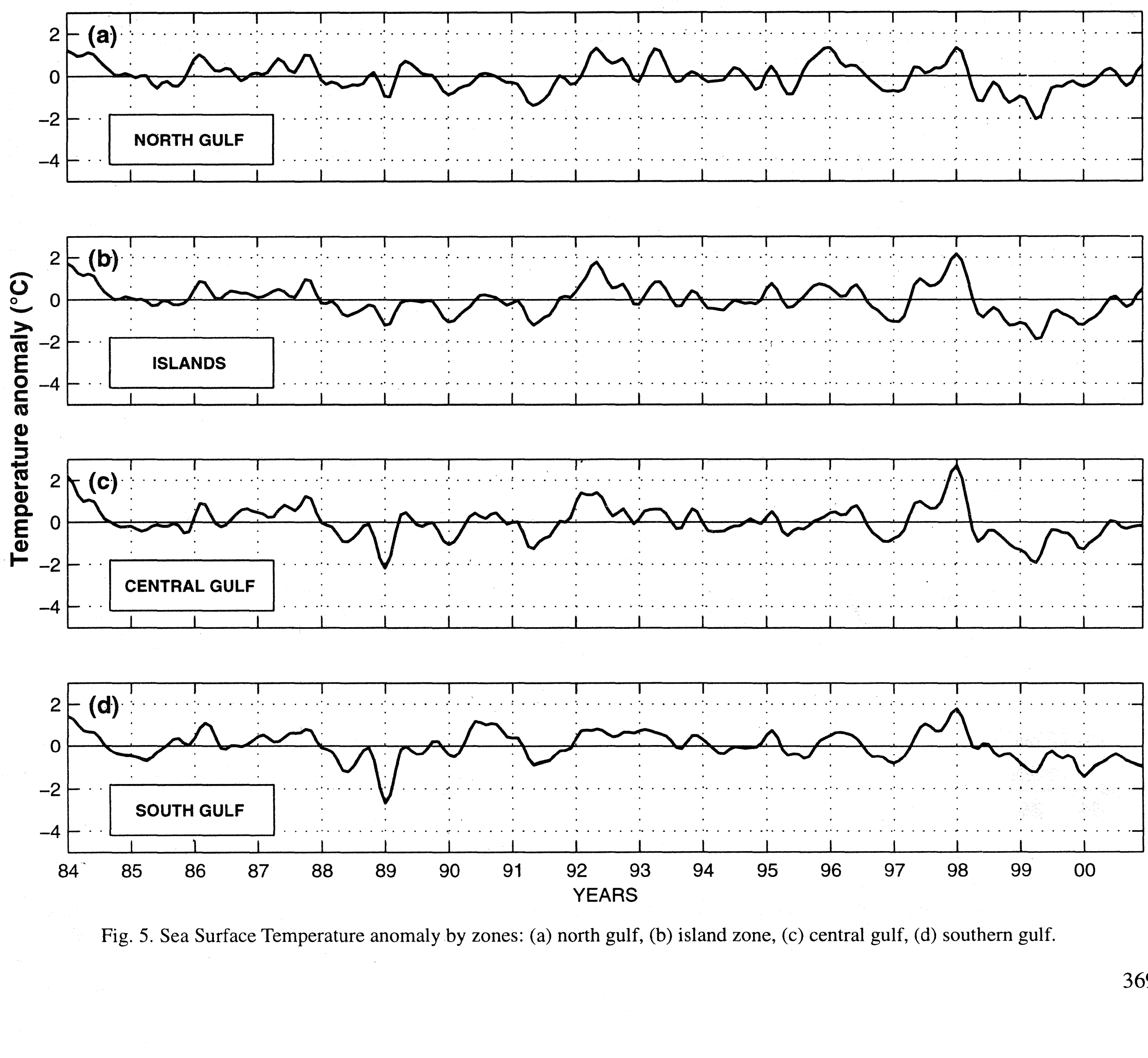

Fig. 5. Sea Surface Temperature anomaly by zones: (a) north gulf, (b) island zone, (c) central gulf, (d) southern gulf.

Coastal Current is strengthened and reaches farther north than usual, affecting the GC. However, the "model" is far too simple, since it imposes instantly a signal that in reality takes some time to reach the gulf from its origin in the equatorial zone. The oceanic signal takes longer than the atmospheric signal, but it can reach the Gulf of California within a month; the speed of travel of the EN signal has been estimated as 100-240 *km day*$^{-1}$(Enfield and Allen, 1980; Chelton and Davis, 1982; Strub and James, 2002). The model is intended only as an illustration of an advective explanation for the outstanding anomalies in the island zone. Deeper understanding of the relative roles played by atmospheric teleconnections and oceanic phenomena on the effects of EN on the GC require further research; unfortunately the required data (sea level, meteorological data, hydrography, currents) remain very scarce.

3.2 Other anomalies

Although the largest anomalies of either sign are associated with EN-LN, there are other anomalies whose origins have not been explored. A slight but prolonged (< 1°C, 16 months) negative anomaly covered the entire CG from mid-1984 until the end of 1985. Although there is a small peak in the SOI early in 1985 (Figure 6), the SST anomaly started before it took place and lasted well beyond it; this disagreement is reflected in the results of the model (Figure 7). The NOIx presents a larger peak than the SOI at this time (Figure 6b), but again it seems to last less than the SST anomaly. To our knowledge, the only reported interannual anomaly for that period that may be connected to that in the GC is the negative anomaly of the SST of the Western Hemisphere Warm Pool (WHWP). The WHWP is defined (Wang and

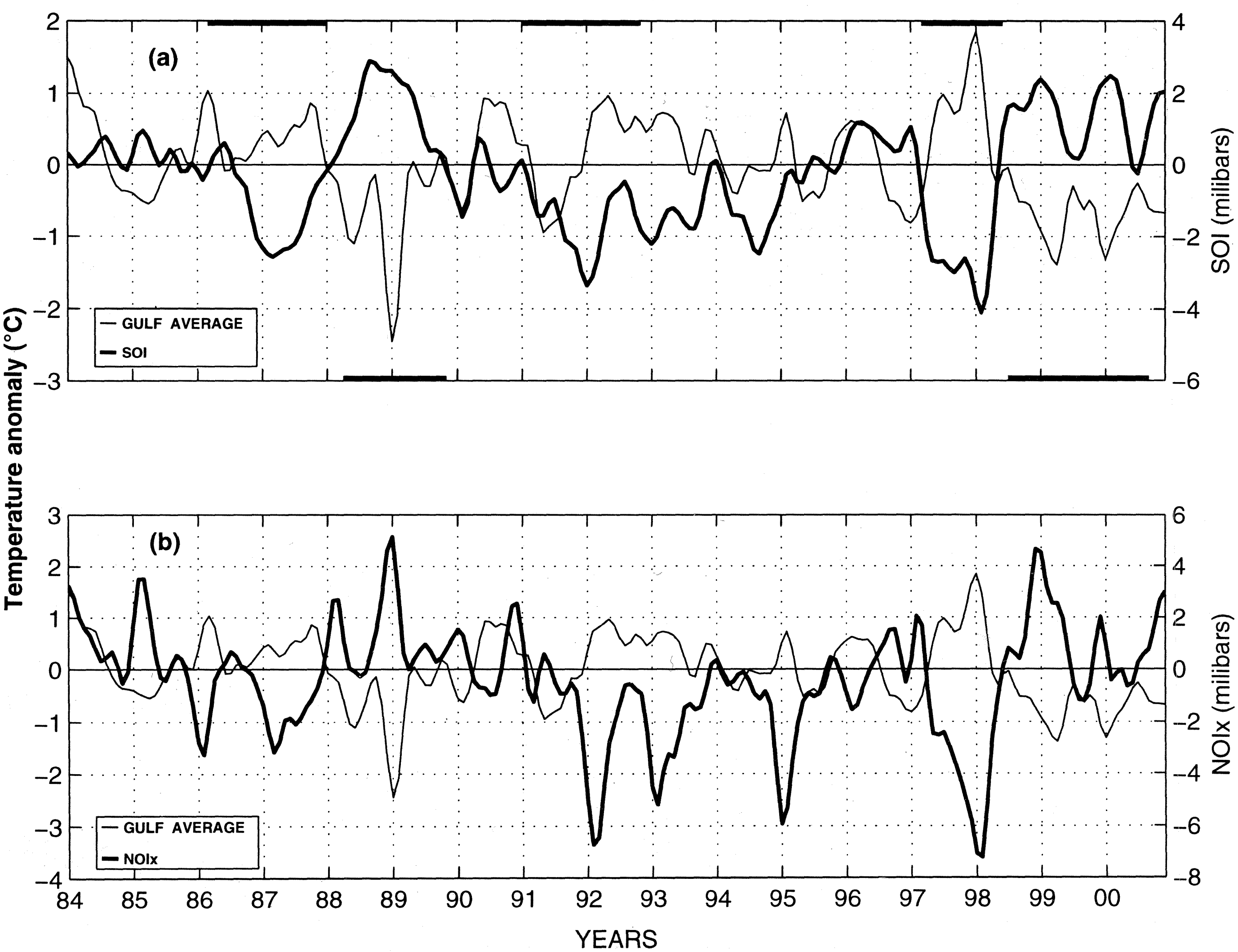

Fig. 6. (a) Average SST anomaly of the entire Gulf of California (thin line) and the SOI (thick line). (b) Average SST anomaly of the entire Gulf of California (thin line) and the NOIx (thick line). Horizontal thick lines mark El Niño (top) and La Niña (bottom) events.

Enfield, 2001) as the region covered by water warmer than 28.5°C, extending from the eastern tropical Pacific to the Gulf of Mexico and the Caribbean. The 1984-1985 cold anomaly of the WHWP is described by Trasviña *et al.* (1999; their Figure 3.19), and is also apparent in Figure 3 of Lluch Cota *et al.* (1997), in Figure 11 of Magaña *et al.* (1999) and in Figure 3 of Wang and Enfield (2001). Lluch-Cota *et al.* (1997) suggest that increased winds and a shallower thermocline may have caused the anomaly.

Also apparently connected to the WHWP is the warm anomaly of 1990 in the southern GC; SST was up to 2°C above normal from about April to November. This anomaly and its effect of increasing rainfall in the south of the Baja California peninsula were described by Salinas Zavala *et al.*(1992). The thermohaline structure in the southern GC was also anomalous, with conditions very similar to those expected during EN, with high surface temperature and low surface salinity (Godínez *et al.*, 1994a, 1994b). The SOI shows a coincident trough, which the model in Figure 7 reflects, suggesting equatorial origin. The NOIx show a peak at this time, but with the wrong sign. The cause of the anomalies in the WHWP have not yet been fully explained (Trasviña *et al.*, 1999; Wang and Enfield, 2001), but they seem to affect the SST and the climate of the GC.

There are other anomalies, which last only a few months, that affect mostly the southern and central parts of the gulf. Warm versions of these anomalies are February-March 1986, January-February 1991 and January-March, 1995; cold versions are May 1988, November 1989-May 1990, May-September 1991. The warm anomalies in early 1986 and early 1995 are similar in that in both cases the SOI shows no anomaly, while the NOIx has pronounced negative peaks; in fact, in early 1995 the NOIx has one of the largest negative values of the entire 1948-2000 series. The warm anomaly in January-March 1995 affected the entire GC; it was very abrupt, involving an SST anomaly change of about 3.5°C in a couple of months (from -2°C to 1.5°C). This year was marked by anomalous oceanic and meteorological behavior in the Pacific shores of NW Mexico; Lluch-Cota *et al.* (1999) reports a positive anomaly in SST (of the order of that of the 1997-98 EN), and it was the wettest (driest) year of the 90's in the south (north) of the Pacific side of the Peninsula of Baja California (Delgadillo-Macías *et al.*, 1999). The authors had oceanographic campaigns in the Gulf of California in December 1994, January, and March of 1995, and an anomalous increase in water temperature was observed (Palacios Hernández, 2001) in the entire Northern Gulf of California (NGC) indicating that the SST anomaly reflects processes affecting the water at least to the depth of the sills in the archipelago (~500 m). No direct ocean data are available to see if the other anomalies reached at depth. Although there is some indication that these anomalies may be connected to the Equatorial system (Figures 6 and 7), local effects (winds, currents) could be at least partly responsible for some of them. More research is needed on these anomalies.

The NGC sometimes presents warm anomalies during summer or autumn, which last a few months. In the spring of 1993 the NGC presents a 2°C anomaly, lasting ~ 4 months. A more extensive anomaly lasted from July of 1995 until October of 1996; this positive anomaly is opposed to what one would expect from the SOI (Figures 6 and 7). These and other anomalies are probably of local meteorological origin; Badan-Dangon *et al.* (1985) and Paden *et al.* (1991) have shown that local weather conditions affect immediately the SST satellite images of the NGC, while Reyes and Lavín (1997) show that interannual meteorological variability can affect the temperature of the NGC.

3.3 Trend

The distribution of the trends $m(x,y)$ that were removed from the time series $T(x,y,t)$ are notably large, especially in the islands zone and in the coastal zone at the head of the gulf. The average over the gulf is 0.0057 °C $month^{-1}$, or an increase of 1.16°C in the 17 years of the record. Although the maximum coastal values suggest that some sampling problems may have occurred along the way from raw data to the data set used here (changes in satellites and orbits, for instance), the signal deserves close inspection.

In order to obtain a statistically reliable estimate of the trend, the monthly SST distribution was averaged over the gulf, to get $T_G(t)$. After removing the mean (25.47°C), this signal was smoothed twice with a 12-month running mean; the smoothed series and the linear trend are shown in Figure 8. The effective degrees of freedom (*edf*), the trend, and the confidence interval were estimated according to Emery and Thomson (1997, pp. 261-263), obtaining $m = (0.0065 \pm 0.0014)$ °C $month^{-1}$ (95%, 13 *edf*); that is, an SST increase of 1.01±0.22 °C in the 13 years shown in Figure 8. The correlation coefficient is $r = 0.8352$, which means that the straight line explains almost 70% of the variability. The observed trend is probably part of the interdecadal variability of the Pacific ocean (see e.g. Miller and Schneider, 2000), which is unresolved by the short length of the record used here (17 years).

The trends for the same period of time (January 1984 to December 2000) were calculated for the (similarly smoothed) SOI, NOIx, El Niño 3 SST, and West Coast of the Americas SST; only the trend of the West Coast of the Americas SST was statistically different from zero (95%, $r = 0.5526$), at (0.0065±0.0023) °C $month^{-1}$ (95%, 13 *edf*). The trend for the NOIx was only marginally significant (95%, $r = 0.4836$), at (0.0092±0.0036) °C $month^{-1}$ (95%, 13 *edf*). Al-

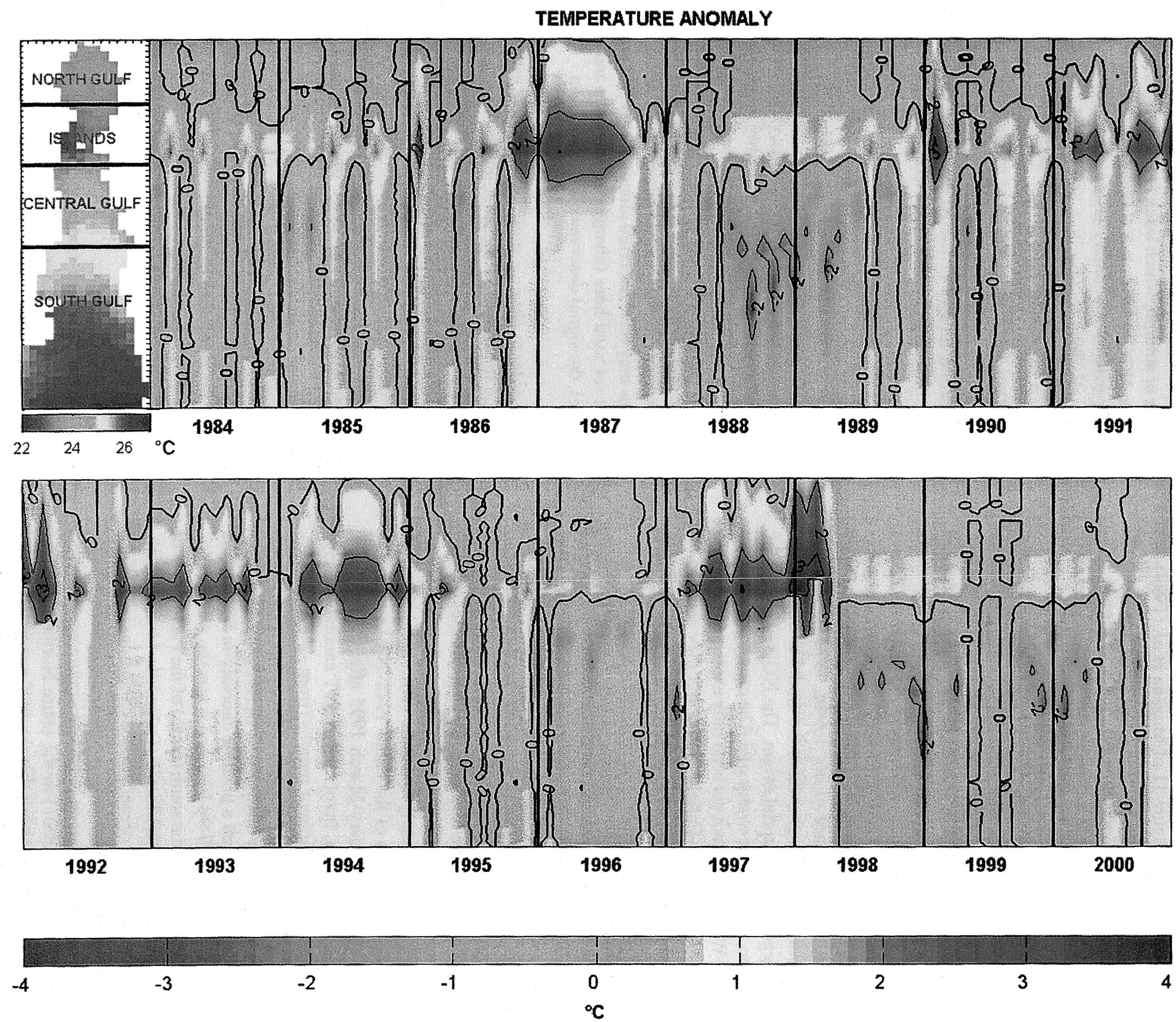

Fig. 7. Simple model of the SST anomalies generated by SOI-modulated shifting of the average SST of the Gulf of California (shown in Fig. 2b).

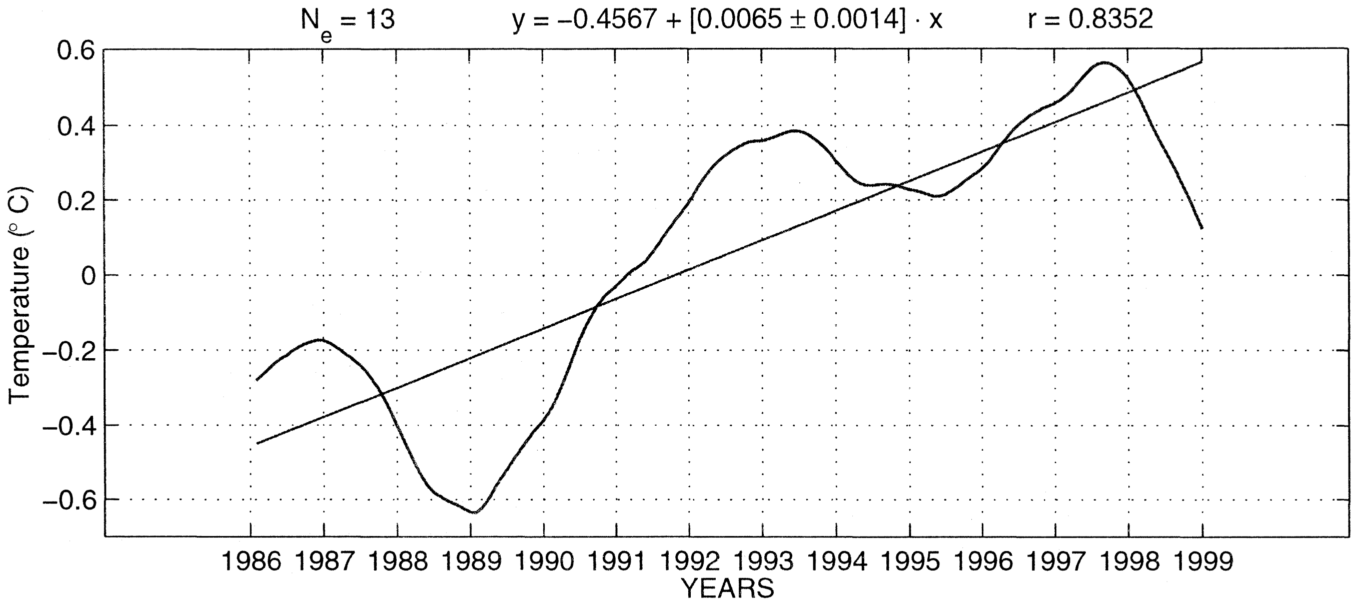

Fig. 8. Low-passed series of average SST of the Gulf of California, after removal of the mean. A 12-month running mean was passed twice. The least-squares linear fit is also shown.

though the presence of the cold anomaly associated to LN of 1988-89 combined with the warm anomaly due to EN of 1997-98 near the end of the record also help in producing the large observed trend, there is a non-EN interdecadal signal of SST in the Eastern Equatorial Pacific that shows an increase from the late 80s to the late 90s (Mestas-Núñez and Enfield, 2001; their Figures 2 and 3). Between the 1970s and 1990s, the SST of the Equatorial Pacific increased by about 0.8°C, as shown by McPhaden and Zhang (2002), whose record of equatorial SST anomalies is very similar to Figure 8 for the period studied here (Figure 2b of McPhaden and Zhang, 2002). Therefore, the observed trend of the Gulf of California SST is driven by interdecadal changes in the Pacific ocean.

4. CONCLUSIONS

Satellite infrared images of the GC from NOAA satellites from January 1984 to December 2000 are used to describe interannual anomalies in SST. The most noticeable positive anomalies are due to EN, especially that of 1997-1998, with deviations over 3°C from the climatological seasonal behavior. The largest negative anomaly was due to LN 1988-89. The 1986-87 EN had the weakest effect on the GC, with anomalies < 2°C. It is proposed that EN induced advection of thermal fronts is the cause of the observed early and maximal anomalies just south of the mid-gulf islands. Other anomalies are connected to anomalies in the warm water pool of the eastern Pacific, whose origins in turn are not clear. Local effects may cause some of the anomalies, especially those in the Northern GC. A statistically significant positive trend was observed, probably due to the interdecadal variability of the Pacific ocean, which is not resolved by the 17 years of the record. More research is needed to explain all these anomalies.

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