SATELLITE OBSERVATIONS OF THE EFFECT OF ENSO ON THE TEHUANTEPEC AND PAPAGAYO UPWELLINGS

RAÚL AGUIRRE-GÓMEZ, OLIVIA SALMERÓN-GARCÍA and ROMÁN ÁLVAREZ

SUMMARY

The effects of El Niño Southern Oscillation 1997-1998 on the Eastern Tropical Pacific Ocean are evaluated for the Tehuantepec (Mexico) and Papagayo (Costa Rica) upwelling regions. The influence of this phenomenon was observed by comparing sea surface temperature anomalies over a 3-year period, from winter 1996-1997 to winter 1999-2000. Satellite observations reveal an increment of 3 and 4ºC during the El Niño year 1997-1998 compared with previous and subsequent years, and the inhibition of upwelling events. It was also observed that during 'La Niña', winter 1998-1999, conditions for upwelling events were re-established.

The continental region under study corresponds to the Eastern Tropical Pacific Ocean (ETPO) and includes the coasts of Oaxaca State, southern Mexico, and the Honduran, Nicaraguan and Costa Rican coasts in Central America. The region (Figure 1) is characterized by three low-elevation gaps in the Sierra Madre Mountains of southern Mexico (Chivela Pass) and Central America (Rivas Channel), including the mountain gap at the Gulf of Panama, not considered in this work. The gaps strongly affect local conditions by channeling winds along their axes, thereby creating exceptional meteorological conditions that result in intense wind jets that blow offshore over the ETPO at irregular intervals of time. The characteristics of the analyzed area have been widely described elsewhere (Love, 1975; Stumpf and Legeckis, 1977; McCreary *et al*., 1989). Hence, we will mention only those aspects relevant to this study.

Thus, masses of cold air originating in north-western Canada move south and east across the North American Great Plains and penetrate into the tropics through the Gulf of Mexico during the autumn, winter, and early spring. The southward movement of polar air creates a strong pressure gradient along the gap axes. Firstly, high-pressure systems, present behind each cold front, create a large pressure difference at sea level across the Isthmus of Tehuantepec, and this generates northerly winds through the Chivela Pass and, consequently, a strong wind jet over the Gulf of Tehuantepec. Wind jets induce strong surface water transport westwards as a major plume, generating upwelling and mixing the water column. These winds are generated by the difference in atmospheric pressure, this being higher over the Gulf of Mexico and the western Caribbean Sea and low over the eastern Pacific Ocean. The pressure gradients drive strong winds through gaps in the Isthmus of Tehuantepec (Hurd, 1929; Stumpf, 1975).

Then, according to the conventional approach, the cold front continues to move south-eastward, creating relatively high surface pressure with a lag of a day or two in the south-western Caribbean Sea. Hence, the pressure difference between the Caribbean and the Pacific triggers a wind jet that blows through the Nicaraguan Lake District. This results in strong easterly surface winds that extend far into the ETPO, west of the Gulf of Papagayo. Winds in the study area are locally known as *tehuanos* at the Isthmus of Tehuantepec and *papagayos* at the Nicaraguan Lake District. High surface pressure over the south-western Caribbean Sea also generates northerly surface winds across the Isthmus of Panama and over the Gulf of Panama in the ETPO. However, Chelton *et al*. (2000) have found that high-pressure systems in the Caribbean Sea are not the only mechanism for the creation of jets in the Papagayo area. They found that

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Caribbean trade winds could also trigger offshore winds in the Gulfs of Papagayo and Panama, since these winds may or may not be statistically related to high-pressure systems.

Average wind speed for *tehuanos* measured at Salina Cruz, Mexico, is $10m·s^{-1}$; however, they may often exceed $30m·s^{-1}$ (Hill, 1969; Stumpf, 1975; Barton *et al*, 1993). *Tehuanos* and *papagayos* blow over ETPO waters characterized by a shallow mixed layer above a sharp thermocline. Consequently, mixing of the upper ocean by the overlying wind can cause a dramatic decrease in sea surface temperature (SST), which can be measured by radiometers on satellites.

The Gulf of Tehuantepec is situated off the Pacific coast of southern Mexico, and centred at 16ºN and 95ºW. Infrared imagery (AVHRR) has been used for studying this area (Stumpf, 1975; Clarke, 1988; Legeckis, 1988; McCreary *et al*., 1989; Lavín *et al*., 1992; Trasviña *et al*., 1995), and major events during winter and spring have been observed as large negative temperature anomalies, extending hundreds of kilometres seaward. This thermal anomaly has been attributed to mixing and upwelling induced by the curl of wind stress (Roden, 1961). The upwelling describes a typical comma-shaped area, whose western edge extends from the head of the gulf southward, roughly along 95ºW following the wind axis. The apparent thermal contrast between some of these features and the waters surrounding them has allowed the study of the mesoscale coastal circulation of the Gulf of Tehuantepec with the support of infrared sensors such as AVHRR (Trasviña *et al*., 1995; González-Silveira *et al*., 2004).

The Gulf of Papagayo is centred at around 11ºN and 85ºW. Winds appear to vary considerably in this region, being stronger at Rivas than at Managua. Rivas is under the influence of winds blowing westward through a mountain gap extending from the Nicaraguan Lake District channel to the Pacific Ocean. On the other hand, the Managua region is influenced by winds blowing northwestward along the long ‘channel’ stretching ~400km northwestward through the Nicaraguan Lake District from the Caribbean Sea to the Pacific Ocean (Rivas Channel). Stronger winds at the Rivas gap are evident as an upwelling in SST images; however, they are more ‘event like’ and weaker than those at Salinas Cruz, Mexico. Wind-induced upwelling in this region has been analyzed through satellite imagery (Brenes *et al*., 2003; Ballestero and Coen, 2004).

The three wind jets have an intense effect on the temperature of the upper layer of the ETPO and, consequently, on the distribution of nutrients, phytoplankton and zooplankton off the Pacific coast of Central America.

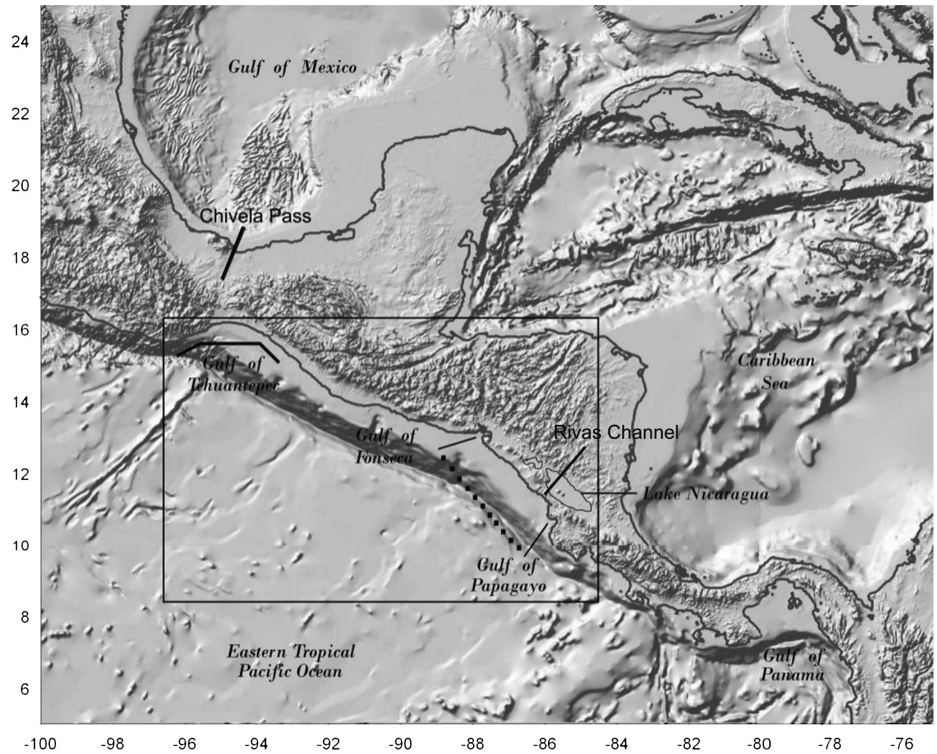

Figure 1. Topographic characteristics of the study area (box) and selected transects at the Gulf of Tehuantepec (solid line) and the Gulf of Papagayo (dotted line).

However, every 3-5 years these conditions dramatically change, (ENSO phenomena), the pressure being higher than normal in the south-western Pacific region (low precipitation) and lower in the south-eastern Pacific (Southern Oscillation). In these years the SST in the central and eastern part of the ETPO area becomes anomalously high. The ENSO phenomenon is associated with the weakening of the tropical trade winds, especially the south-eastern trades over the oriental flank of the South Pacific anticyclonic gyre. Weakening of the trades reduces the upwelling and raises ocean temperature by ~5ºC. This weak atmospheric circulation allows warmer and lighter waters to flow eastward, replacing colder upwelled waters.

The study area is in the Pacific Inter-Tropical Convergence Zone (ITCZ), which migrates northward in ENSO events, covering practically the totality of the ETPO.

TABLE I
CLASSIFICATION OF WIND STRENGTH ACROSS THE GULF OF TEHUANTEPEC AND THE GULF OF *PAPAGAYO*

Year-month	Classification	Comments on year
94-11	M-	
94-12	M+	?
95-01	M+	
95-02	M+	
95-11	M-	
95-12	L	?
96-01	M- in Papagayo, L in Tehuantepec	
96-02	M-	
96-11	M- in Papagayo, S in Tehuantepec	
96-12	M-	Normal
97-01	L in Papagayo, M+ in Tehuantepec	
97-02	M+	
97-11	L in Papagayo, M- in Tehuantepec	
97-12	M-	ENSO
98-01	M-	
98-02	L	
98-11	L in Papagayo, M- in Tehuantepec	
98-12	M- in Papagayo, M+ in Tehuantepec	La Niña
99-01	L in Papagayo, M- in Tehuantepec	
99-02	L in Papagayo, M- in Tehuantepec	

L: low, M: moderate, S: strong. Wind speed ranges are: L<5, 5<M-<8, 8<M+<10 and $S>10m·s^{-1}$.

The invasion of anomalously warm water in the surface layers produces changes in the regional conditions (Robles and Christensen, 1983; Gallegos *et al*., 1984).

The aim of this paper is to show the effect of ENSO on ETPO upwelling areas such as the Gulf of Tehuantepec in Mexico and the Gulf of Papagayo in Costa Rica. This objective has been fulfilled by comparing SST observations made by Advanced Very High Resolution Radiometer (AVHRR) in four consecutive winter periods: 1996-1997, 1997-1998, 1998-1999 and 1999-2000. Winter periods selected are considered as non-ENSO years, except for winter 1997-1998, characterized for being a strong ENSO event. Wind ancillary data show a similar trend as SST, supporting the effect of ENSO in the ETPO.

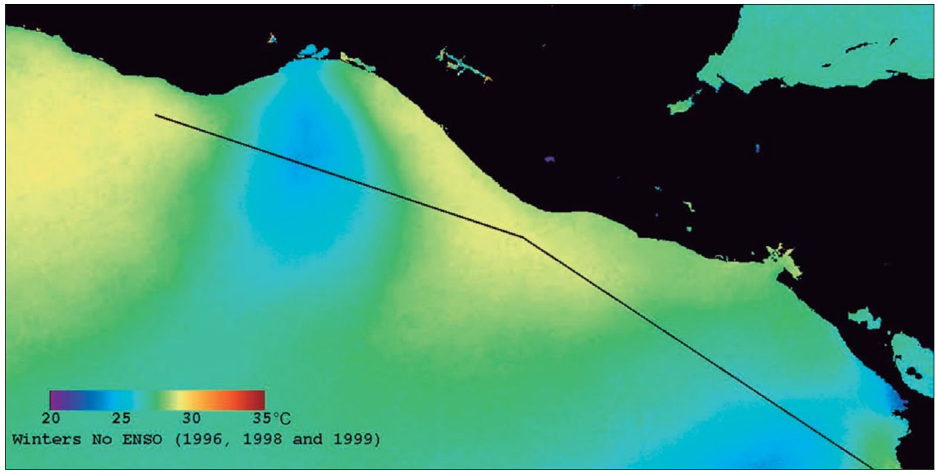

Figure 2. SST composite map of Tehuantepec and Papagayo regions (winter 1996-1997, 1998-1999 and 1999-2000).

Methods

In order to assess the effect of ENSO 1997-98 on the ETPO, SST anomaly maps derived from AVHRR images were compared for the winters prior to, during, and after the 1997-98 El Niño event. Winter was chosen as representative for these events since they mainly occur in this season. Winter periods selected were: 1996-97, considered as a normal year; 1997-98, an ENSO year; and 1998-99, a normal year, (onset of a weak La Niña) and, finally, the winter 1999-2000 taken as a normal year as well.

Satellite observations

AVHRR data were processed using a Terascan System (SeaSpace Corp., USA). SST maps were generated following a multichannel algorithm (split-window) for NOAA-AVHRR daytime images (McClain *et al*., 1985):

$$T_s=1.017T_{11}+2.139(T_{11}-T_{12})+0.779$$

where T_s: SST value, and T_{11} and T_{12}: brightness temperature in the AVHRR infrared channels 4 and 5, respectively. Coefficients appearing in this equation are valid for the split-window algorithm of NOAA-14, which is the satellite collecting data around 20:00 hrs GMT (14:00 local time). Seasonal SST composite maps corresponding to the winters 1996-1997, 1997-1998, 1998-99 and 1999-2000 were subsequently obtained by simply averaging daily SST images.

Thus, SST maps of Non-ENSO winter periods 1996-1997, 1998-1999 and 1999-2000 were averaged to create a 'mean' SST image (Iμ), which was then subtracted from original SST images corresponding to the winter periods under consideration (Aguirre-Gómez *et al*, 2003), emphasizing particularly the ENSO period.

In order to evaluate the thermal differences occurring during each period, two transects were established: one for the Tehuantepec area and the other for the Papagayo region. These transects extend over most of the areas under investigation: the first starts from the east of Salina Cruz, Mexico, and ends close to the coastal area of Chiapas, Mexico; the second transect covers a zone from the Gulf of Fonseca to the north-western Costa Rican coast, crossing the Gulf of Papagayo (Figure 1).

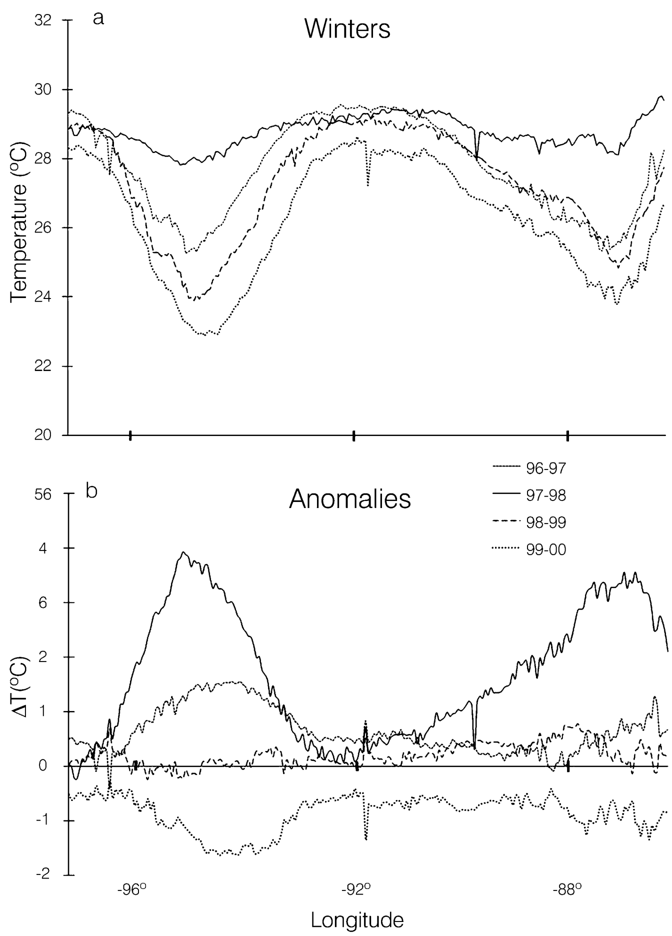

Figure 3. a: SST profiles of Gulfs of transects at the Gulfs of Tehuantepec and Papagayo during 'normal' winters 1996 and 1999, winter 1997 and winter 1998.
b: SST anomalies profiles of Gulfs of Tehuantepec and Papagayo transects during winters 1997-1998 and 1998-1999.

Wind data

Monthly averages of wind direction and strength were obtained from ERS-2 (WOCE, 1998) observations for November-February in 1994-1995, 1995-1996, 1996-1997, 1997-1998 and 1998-99. These data were qualitatively analyzed and compared with SST data. The average monthly wind strength across the two gulfs was roughly categorized as light (L), moderate minus (M-), moderate plus (M+), or strong (S). The corresponding wind speed ranges are: L<5, 5<M-<8, 8<M+<10 and S>10m·s^{-1}.

SST comparisons

Non-ENSO winters. Winters 1996-1997, 1998-1999 and 1999-2000 are considered as non-ENSO years and were selected as representatives for 'normal' SST condi-

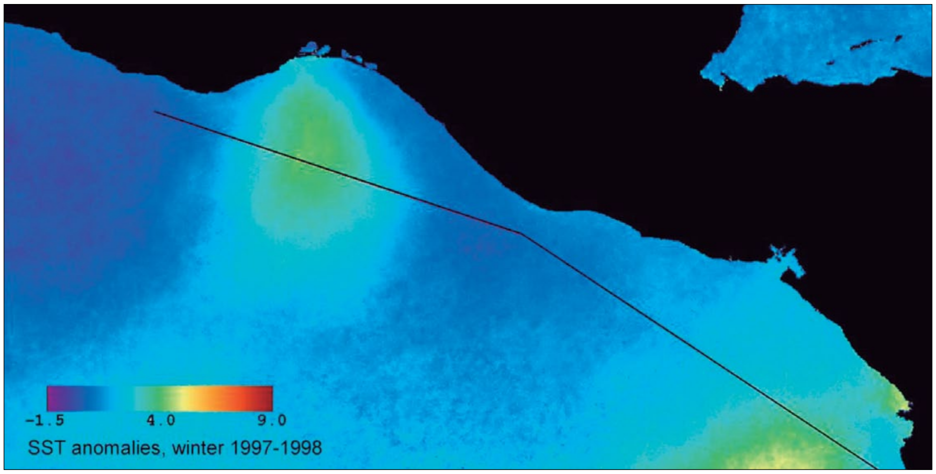

Figure 4. SST anomalies composite map of the Tehuantepec and Papagayo regions (winter 1997-1998).

tions in the Tehuantepec and Papagayo regions and compiled in a SST composite map (Figure 2). It shows the presence of relatively cold waters of ~23ºC (blue tones) associated with winds coming through Chivela Pass and Lake of Nicaragua, extending their effects hundreds of kilometres offshore. Adjacent waters at either side of the upwelling area show warm waters of ~29ºC (yellow tones), which can be associated with the equatorial current. These features are also evident when observing the average profile of SST, corresponding to transect for 'normal' winters 1996, 1998 and 1999 (Figure 3a), whereas that for winter 1997 was rather different. Satellite-derived SST at each end of the transect was, in actual values, ~29ºC decreasing down to 23ºC near longitude 96ºW in the neighbourhood of the Gulfs of Tehuantepec and Papagayo. Thus, in order to emphasize the difference an anomaly analysis was carried out.

Anomalies derived from SST imagery of winters periods analyzed are illustrated in Figure 3b. The transect profile for winter 1996-1997 shows SST anomalies of ~1.5ºC at longitudes 87ºW and 95ºW. This profile shows the presence of typical warmer Equatorial Current waters, whilst sharp anomalies can be associated with the influence of wind on them.

The winter of 1998-1999 is characterized by the onset of a weak La Niña. The anomaly profile for this period oscillates around the mean value (Figure 3b), allowing this year to be considered as the climatological mean of all the winter periods The negative anomaly maximum that was present in the winter of 1996-1997, is now absent. Additionally, SST values oscillate around 29ºC along the transect with a slight decrement in the regions of Tehuantepec and Papagayo.

Finally, for the winter of 1999-2000, the SST anomalies transect shows a dominance of negative values, reaching the lowest anomaly at the Tehuantepec region (97ºW) over -1.5ºC and, for the rest of the profile, oscillations between -0.5 and -1ºC. In the SST profile for this period it is apparent the presence of relatively colder waters over the study area, particularly at Tehuantepec and Papagayo regions with SST values down to 23ºC. It must be noticed that the SST profiles for these three winter periods are similar, which reinforce the fact of considering them as non-ENSO years (Figure 3a).

ENSO winter 1997-1998. Winter 1997-1998 corresponds to a strong ENSO event and the SST anomalies composite map for the study area is shown in Figure 4. Here, the cooling effect of the wind blowing through the mountain gaps at Chivela Pass and Rivas, near Nicaragua's Lake District, is evident. Green and yellow tones are associated with sharp SST anomalies and represent waters travelling offshore of both Gulf of Tehuantepec and Gulf of Papagayo, which extend several hundred kilometres into the ocean. SST anomalies have a fan shape in the composite, reaching a maximum of around 4ºC at the wider south-western part of the fan. Warmer waters of the Equatorial Current, located along the Honduran, Costa Rican and Mexican coasts, are interpreted as positive anomalies (blue tones). The continuity of these positive SST anomalies is broken by the effect of the wind. Noticeable from the map are the anomalous SST conditions compared to those of the previous year. The map shows the dominance of positive SST anomalies in the whole of the region (bluish tones). In the Gulf of Papagayo ENSO is accompanied by nearly isothermal surface waters over the region (green-yellow tones). The SST values indicate a slight variation around 28ºC.

This winter period, when compared with the rest, shows the higher thermal anomalies in relation to the mean, reaching over 3ºC at the Papagayo (87ºW) and near 4ºC at the Tehuantepec (95ºW) regions, as seen in Figure 3b.

Wind data

Twenty ERS-2 wind images were analysed and the resultant classification is show in TableI. Periods 1994-1995, 1995-1996 were included to have a longer sampling period; it is necessary to establish the 'type' of years (i.e. whether these years can be classified as 'normal' or otherwise), in order to extend the comparison period. With this information we can observe that the behavior differs between Papagayo and Tehuantepec about half of the observation period (1996-99), and that the period preceding ENSO (1996-1997) had stronger winds, while ENSO itself shows a decrease in wind intensity. The period 1994-1995 could be classified as similar to 1996-97, while 1995-96 shows weaker wind intensities that are comparable to those of the 1997-1998 (ENSO period).

Discussion and Conclusions

Monitoring upwelling events using satellite information leads to a better understanding of the mesoscale processes occurring in the ETPO. This understanding may influence the economy of the region. For instance, the Gulf of Tehuantepec is economically important because of its fishery and its relatively high levels of biological primary productivity (Robles-Jarero and Lara-Lara, 1993). Such a high productivity is related to these strong winter upwelling events, in which the SST becomes a number of degrees colder than elsewhere along the coasts of the Tehuantepec and Papagayo zones (Stumpf, 1975).

Satellite imagery shows the effect of ENSO on the Tehuantepec and Papagayo upwelling zones; temperatures in the region were higher during the ENSO year 1997-1998, than in previous and subsequent years. The inhibition of upwelling events in the Tehuantepec and Papagayo areas was a remarkable feature of this ENSO year.

High-pressure systems on the Atlantic Ocean, produced by cold air masses, were absent during the winter 1997-1998. Hence, the wind generated by the pressure gradient between the Atlantic and Pacific Oceans did not occur, and both *tehuanos* and p*apagayos* were inhibited. For p*apagayos*, the inhibition can also be attributed to the weakening of trade winds, which is a key characteristic of the ENSO phenomenon.

On the other hand, in the winter 1998-1999, during 'La Niña', conditions for upwelling events were re-established. The jet stream, which during ENSO years remains in Canada, moves further south in La Niña years, bringing cold air to the Gulf of Mexico, and consequently developing high-pressure systems.

Regional environmental changes caused by the variations of the physical parameters during ENSO years can modify the biological processes in the surface layers of the area.

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OBSERVACIONES SATELITALES DEL EFECTO DE EL NIÑO EN LAS SURGENCIAS DE TEHUANTEPEC Y PAPAGAYO

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RESUMEN

Se evalúan los efectos de El Niño Oscilación del Sur en el Océano Pacífico Tropical Oriental sobre las regiones de surgencia de Tehuantepec (México) y Papagayo (Costa Rica). La influencia de este fenómeno fue observada al comparar las anomalías de la temperatura superficial del mar en un periodo de 3 años, del invierno 1996-1997 al invierno 1999-2000. Las observaciones satelitales revelan un incremento de 3º y 4ºC durante el año Niño 1997-1998 comparado con años previos y subsecuentes, y la inhibición de eventos de surgencia. Se observó también que durante el invierno 'La Niña' de 1998-1999 se re-establecen las condiciones para los eventos de surgencia.

OBSERVAÇÕES SATELITAIS DO EFEITO DE EL NIÑO NAS SURGÊNCIAS DE TEHUANTEPEC E PAPAGAYO

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RESUMO

Avaliaram-se os efeitos de El Niño Oscilação do Sul no Oceano Pacífico Tropical Oriental sobre as regiões de surgência de Tehuantepec (México) e Papagayo (Costa Rica). A influência deste fenômeno foi observada ao comparar as anomalias da temperatura superficial do mar em um período de 3 anos, do inverno 1996-1997 ao inverno 1999-2000. As observações satelitais revelam um incremento de 3º e 4ºC durante o ano Niño 1997-1998 comparado com anos prévios e subsequentes, e a inibição de eventos de surgência. Observou-se também que durante o inverno 'La Niña' de 1998-1999 se reestabelecem as condições para os eventos de surgência.
