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Research Article

Assessment of hurricane's effect on the upper mixed layer of the southwestern Mexican Pacific during ENSO 1997-1998: *in situ* and satellite observations

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ABSTRACT. Using data from closely spaced CTD profiles and satellite imagery we investigated the effect of hurricane Rick on the sea surface temperature (SST) and the upper mixed layer of the southwestern Mexican Pacific coast. Effects of ENSO 1997-1998 in this region are also discussed by analysing SST maps. Coincident hydrographic measurements were carried out during an oceanographic campaign over the area in November 1997. Results revealed an increment of SST between 3 to 4°C above the climatological mean temperature ($25^{\circ} \pm 2^{\circ}\text{C}$), in the Mexican Tropical Pacific, during ENSO. *In situ* measurements show instabilities in the upper mixed layer after the pass of the hurricane in oceanic areas. Satellite and historical databases enabled interpretation and analyses of ENSO's effect on the southwest coast of Mexico.

Keywords: hurricane Rick, upper mixed layer, hydrographic measurements, satellite observations ENSO, southwestern Mexican Pacific.

Evaluación de los efectos de un huracán en la capa superior de mezcla en el Pacífico mexicano sudoccidental durante ENOS 1997-1998: observaciones *in situ* y satelitales

RESUMEN. Usando datos de perfiles CTD e imágenes satelitales se analizó el efecto del huracán Rick en la temperatura superficial del mar (TSM) y la capa superior de mezcla en la costa sudoccidental del Pacífico Mexicano. Se discuten los efectos de ENOS 1997-1998 en esta región mediante el análisis de mapas de TSM. Se realizaron mediciones hidrográficas coincidentes con un crucero oceanográfico en el área en noviembre de 1997. Los resultados revelan un incremento de la TSM de 3 a 4°C sobre la temperatura media climatológica ($25^{\circ} \pm 2^{\circ}\text{C}$), en el Pacífico Tropical Mexicano, durante ENOS. Las mediciones *in situ* muestran inestabilidades en la capa superior de mezcla después del paso del huracán en áreas oceánicas. Las bases de datos satelitales e históricas permiten la interpretación y análisis de los efectos de ENOS en la costa suroeste de México.

Palabras clave: huracán Rick, capa superior de mezcla, mediciones hidrográficas, observaciones satelitales, ENOS, Pacífico mexicano sudoccidental.

INTRODUCTION

Sea Surface Temperature (SST) plays an important role in the exchange of momentum, energy and moisture between the ocean and the atmosphere. SST is also crucial in evaluating air-sea interaction and climate variability. El Niño-Southern Oscillation (ENSO) is a manifestation of the coupling of SST to atmospheric circulation and has a great influence on the world's weather and climate. El Niño is the oceanic component while the Southern Oscillation is the atmospheric ele-

ment of the phenomenon (Wells *et al.*, 1996). The surface temperature field influences the development and evolution of tropical storms and hurricanes (DeMaria & Kaplan, 1994) and can be correlated with nutrient concentration and primary productivity (Kamykowski, 1987).

Satellite infrared SST measurements have resulted in a major improvement in oceanography, meteorology and climatology (Legeckis, 1986; Reynolds & Smith, 1994; Monaldo *et al.*, 1997). Cold wakes from storms and hurricanes have been studied by means of infrared

SST, chlorophyll concentration and wind observations (Black & Holland, 1995; Nelson, 1998). For instance, Mitrani-Arenal & Diaz-Rodriguez (2004), presented a study of the oceanic surface layer considering its vertical thermal structure and time-space variability and analyzed the possible connection between the thermal characteristics of the sea surface layer and tropical cyclone activity, considering the presence of ENSO; Shi & Wang (2007), used a combined dataset of ocean surface winds, the SST and ocean color products in order to analyze physical, optical, and biological processes after Hurricane Katrina in 2005, and observed a remarkable phytoplankton bloom in the Gulf of Mexico after Katrina's passing. They attributed the phytoplankton bloom to a big nutrient supply brought up by the wind-driven upwelling and vertical mixing; Han *et al.* (2012), used satellite observations and *in situ* data to investigate the storm-induced changes of sea surface temperature and chlorophyll concentration. They found a decrement of the sea surface temperature and a significant increase of phytoplankton concentration, via satellite data, after the passage of the hurricane Igor, while *in situ* data proved a similar temperature trend and density profiles showed that the mixed-layer depth increased about three times. They suggested that phytoplankton bloom could be triggered by the deepening of the mixed-layer due to the strong wind stirring, by the upwelling associated with the cyclonic wind stress curl, and by the coastal upwelling due to the upwelling favorable alongshore wind. Thus, as may be gathering from these studies, the pass of hurricanes promotes a deepening of the upper-mixed layer due to wind driven upwelling and vertical mixing, generating phytoplankton blooms; hence, their impact on the marine ecosystem is apparent.

However, there are few studies in the eastern tropical Pacific utilizing SST and *in situ* measurements taken before and after the pass of a hurricane. Thus, the aim of this study is to analyze SST observations along a transect of 1165 km (629 nm) with *in situ* measurements carried out prior and after the pass of hurricane Rick in November 1997, coincident with the 1997-1998 ENSO events. Hydrographic measurements were carried out on board the R/V El Puma along the southwest coast of Mexico. We use simultaneous SST satellite-derived observations from the Advanced Very High Resolution Radiometer (AVHRR) and *in situ* measurements, in order to assess the effect of a hurricane pass with two different sources of information. *In situ* observations were coincident with the presence of hurricane Rick forcing the ship to seek shelter in the port of Manzanillo, Mexico, for a number of days. This event allowed for an evaluation of the

perturbations induced by the hurricane in the upper mixed layer.

Study area

The study area is part of the Eastern Tropical Pacific Ocean (ETPO). Specifically, it is located on the southwest coast of Mexico (10-23°N, 90-112°W), which includes both the Mexican coasts of Sinaloa, Nayarit, Jalisco, Colima, Michoacán and Guerrero states and the influence area of the hurricane. Two main superficial currents meet in the Mexican west coast (12-32°N): the California Current (CC) and the North Equatorial Counter Current (NECC). The CC is wide (up to 800 km), deep (about 500 m), slow (typical velocities of 20 cm s⁻¹), and has a persistent movement from north to south, parallel to the western coast of Canada, United States of America and Baja California Peninsula in Mexico (Fernández *et al.*, 1993). In the latter, the CC is characterised by cold water of low salinity (34.5) flowing southwards along the coast. On the other hand, from the Equatorial System formed by currents and counter-currents, parallel to the terrestrial equator only the NECC influences the Mexican southwestern coast (Charnock, 1996). NECC is characterised by temperate waters of intermediate salinity (34.6-34.85) flowing poleward (Badan-Dangon *et al.*, 1989).

These currents meet in a transitional zone and its geographical position seasonally varies (Gallegos *et al.*, 1988). It depends on the relative intensity of each current and on the prevailing surface winds which have occurred during the previous six or eight months, mainly in the northern region. In wintertime, when the California current is more intense, the transition zone is located further south, whilst in summertime, when the counter-current is stronger, the transition zone moves northward. This variation occurs yearly and reaches its extreme positions at the end of these seasons. Thus, the superficial circulation in the Mexican Tropical Pacific region is basically dominated by the meridional displacement of the transition zone. From the oceanographic viewpoint, there is no evidence in this region of any zonal displacement with enough intensity and persistency, allowing it to be considered as a superficial current. Additionally, in the northern part of the study area there is a triangular region formed by Cape San Lucas, Mazatlán and Cape Corrientes. It is a highly dynamic zone due to the confluence of the CC and NECC and also to that of the Gulf of California, which provides warm and highly saline waters (>34.9), flowing southwards through the gulf (Griffiths, 1968). The region has a complex thermohaline structure of eddies, fronts and intrusions originated by the confluen-

ce of these currents (Alvarez & Lara, 1991). Hurricane Rick impacted much of the southern coast of the Mexican Pacific, extending from 105 to 92°W and from 10 to 16°N. Significant ocean responses can be expected following the passage of a hurricane. Indeed, driven by wind stress curl and also due to a longer residence time during this period, an important ocean upwelling was generated by hurricane Rick. Additionally, there were documented storm impacts on reef communities of the eastern Pacific, due to the intensity and high frequency of the 1997 storms that affected the area (Lirman *et al.*, 2001).

MATERIALS AND METHODS

In order to assess the effect of hurricane Rick on the southwestern Mexican Pacific coast, hydrographical data were collected during an oceanographic campaign carried out from November 6th to 13th, 1997. Conductivity, temperature, and pressure were recorded at sixteen hydrographic stations, selected at oceanic and coastal areas, using a Neil Brown Mark-III CTD probe. Thus, the effect of the hurricane could be tracked at some sampling stations before, during and after the event (Fig. 1). Additionally, coincident daily SST maps were derived from AVHRR imagery during the event. This campaign was significant because it occurred during an ENSO year and was affected by hurricane Rick. These facts allow us to analyse the effects of both events, at different timescale, in the Mexican part of the ETPO.

Hurricane Rick sequence

October 15th. The disturbance started as tropical wave moving from Africa to the eastern Atlantic. The wave was unclearly defined on satellite imagery while crossing the Atlantic. Thus, it has to be tracked via continuity for relating to the beginning of Rick.

November 5th. The tropical wave entered the Pacific and part of it generated cloudiness which was clearly seen in satellite imagery extending hundreds of kilometers south of the Gulf of Tehuantepec.

November 6th. The disturbance soon was developing an organization and a characteristic banding cloud pattern. Even though the circulation center was poorly defined satellite tracking started.

November 7th. Rick became better organized and formed into Tropical Depression 19-E, centered at about 900 km S-SW of Acapulco, Mexico. The developing cyclone initially moved toward the NW and then it was turned N by a deep-layer-mean trough.

November 8th. Around noon the cyclone was located about 604 km southwest of Acapulco, deep convection

increased near the center and the depression was upgraded to Tropical Storm Rick.

November 9th. The tropical storm developed a very cold central dense overcast, turned NE, and reached hurricane category. An eye appeared that day, surrounded by a well-center, visible on Acapulco radar. The hurricane reached its peak intensity of 185.2 km h⁻¹ and 973 mbar, making it a low-end Category 2 on the Saffir-Simpson Hurricane Scale.

November 10th. The radar from Acapulco showed the well-defined center of the hurricane moving E-NE until landfall in the vicinity of Puerto Escondido, Oaxaca, after weakening to 138.9 km h⁻¹. around the time of landfall, hurricane force winds extended 56 km and tropical storm force winds extended 185 km from the center, respectively.

November 11th. Rick continued to weaken while moving parallel to Mexico's coast along the northern Gulf of Tehuantepec for another 12 h, before dissipating over central portion of Chiapas. The remnant of the cyclone was visible in satellite imagery as convectionless weak low-level cloud swirl over the southeastern Bay of Campeche (Lawrence, 1999).

Satellite observations

Daily SST maps from November 6th to 13th were initially generated by using the TERASCAN system (SeaSpace Corporation). These maps were produced by applying a multichannel algorithm (split-window) proposed by McClain *et al.* (1985) for NOAA-AVHRR/12 daytime images as follows:

$$SST = 0.963563T_{11} + 2.579211(T_{11} - T_{12}) + 0.242528 * (T_{11} - T_{12}) * (\sec \theta - 1) - 263.006$$

where T_{11} and T_{12} are the brightness temperatures expressed in °K, and SST values are in °C. Brightness temperatures T_{11} and T_{12} correspond to central wavelength of NOAA-AVHRR bands 4 and 5, respectively. Clouds were masked in SST daytime images using an implementation of the Multi-Channel Sea Surface Temperature (MCSST) algorithm (McClain *et al.*, 1985). Brightness temperatures that contain contributions from land and clouds are not used to estimate sea surface temperature. To eliminate this data from the sea surface temperature algorithm, a 3x3 kernel is applied to the entire NOAA-AVHRR image, so all sea surface and cloud-free data must satisfy threshold conditions of maxima in the thermal band (channel 4) and in the near infrared band (channel 2) under user-specified values. Thus, for evaluating the thermal behavior a SST transept was established. This transept extends over the area under investigation including the sampling sites (Fig. 1). It starts from

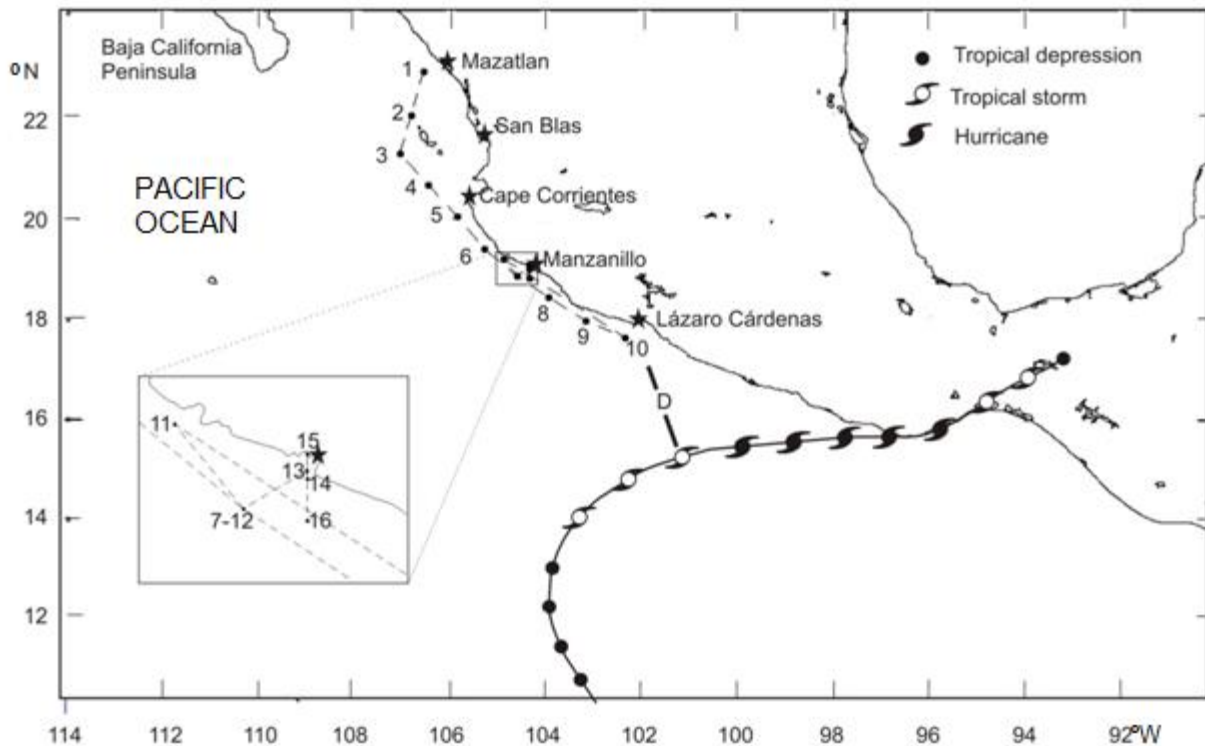


Figure 1. Study area including SST transect crossing over sampling stations (dashed line), hurricane Rick's path (symbol line) and Hurricane-Sampling site distance (D).

Mazatlán crosses areas near sites such as San Blas, Cape Corrientes, Manzanillo, and ends near Lázaro Cardenas (dashed line).

Moreover, Dvorak (1975, 1984) proposed an image processing technique for identifying tropical cyclone development and intensity, based on the degree of spiraling in the cloud bands. This technique combines meteorological analysis of satellite imagery with a model of tropical cyclone development. The model uses a set of curves representing tropical cyclone intensity change in time and cloud feature descriptions of the disturbance at intervals along three curves. The main cloud features are linked in the model to the features of the cyclone and are useful for estimating both its present and its future intensity. Thus, each representative feature is analyzed in a three-stage procedure that assigns a Tropical Number (T-number) or Dvorak's classification to a disturbance by using both the qualitative description of the intensity and a quantitative description. This number rates the intensity of the storm. Usually, a cyclone will exhibit a growth rate of 1 T-number per day. Thus, the initial stage of tropical cyclone development (T1) is first recognized when curved cloud lines and bands define a cloud system center near or within a deep cloud layer. The T2

stage should appear 24 h later and so on. The minimal hurricane stage is attained when the cloud band completely encircles the center and is assigned the value of T4. Once the eye is observed (T4.5), continued intensification is indicated by an increase in eye definition, increasing smoothness of the dense overcast, or embedding of the eye in the dense overcast. Additionally, each T-number can be associated with both a central pressure and wind speeds. Dvorak's technique was applied to thermal bands of NOAA-AVHRR imagery, using a TERASCAN algorithm which is widely described in Dvorak (1975).

In situ data

The sampling transect followed within the campaign is shown in Figure 1. It covered a region between Mazatlán Bay and Lázaro Cardenas (dashed line). Sampling included both oceanic and coastal areas. Hydrographic measurements of temperature, depth and salinity were collected during November 1997. Sixteen sampling stations were chosen along the southwestern Mexican Pacific coast. Twelve stations were located at oceanic sites and the remaining four stations were placed along the coast. The oceanographic campaign was carried out onboard the R/V El Puma from Novem-

ber 6th to 13th, with a break of three days due to the presence of hurricane Rick, which was classified as H2 according to Saffir-Simpson scale.

Vertical profiles of temperature and salinity along with T-S diagrams were obtained in order to observe the physical structure of the study region prior, during and after the event.

RESULTS

Satellite information

Daily SST images were mostly cloudy over the study area. However, there were a number of clear SST patches indicating relative high temperature around 30°C. SST maps and profile transects for days 6, 12 and 13th of November are shown in Figures 2a to 2c. On November 6th, prior hurricane stage, the SST transect varies mostly from 26°C to over 29°C. This interval is higher than the climatological mean of 25°C (Secretaría de Marina, 1984). Relatively colder temperatures appeared at around 17°30'N where sampling sites 9 and 10 were located (Fig. 2a); in the middle of the transect temperature averages 28.5°C. On November 12th and 13th, after the hurricane pass, SST transects show warm profiles with a mean value fluctuating around 29°C. Satellite SST information during the pass of the hurricane was virtually unavailable at sampling sites, due to cloudiness (Fig. 2b), although a number of clear SST patches were observed after the pass of the hurricane (Fig. 2c). Both SST maps and profiles seem to suggest that hurricane Rick had a short time-space impact, mainly close to Oaxaca State as observed in the SST profile at the most southern sampling sites 9 and 10, the nearest to the hurricane and, after few days, SST values were stabilized around 29°C. These SST values are over the climatological mean, which may indicate that ENSO's warming effect on the seawater was the dominant influence over the area. Figure 3 shows a map of SST anomalies for November 1997 which was estimated by subtracting the 25°C climatological mean, as estimated from the sea temperature database, built by Secretaría de Marina (1984). Additionally, and according to the Oceanic El Niño Index (ONI) for the Niño 3.4 region, the measured SST for November 1997 was 29.12 with an 2.38 anomaly (NOAA, 2014). This positive anomaly in ONI information indicates the presence of an ENSO event.

Satellite imagery revealed, using Dvorak's analysis, the development of Rick from its initial stage as tropical depression (06/11/1997), its transformation into tropical storm (07-08/11/1997), hurricane category (09/11/1997) up to its decay as a tropical depression on November 10th, 1997. The sequence of Rick's

development, organization and structure is shown in Figure 4. This structural evolution along with pressure and wind speed data allowed for tracking a T-number sequence (Table 1). Thus, following Dvorak's classification, Rick started as T1 stage, then reached hurricane category T5 (correspondent to H2 in Saffir-Simpson scale) on November 9th 1997, due to its shape, pressure and wind speed characteristics. The main effect of the hurricane, as seen in satellite imagery, is the prevalence of clouds coupled to the storm (Fig. 4). Rick's development can be followed from Table 1 and Figure 4, starting as tropical depression, with a T-number T2, on November 7th (Fig. 4a); passing to tropical storm (T3.5) on November 8th (Fig. 4b); reaching a hurricane stage (T5) on November 9th (Fig. 4c); decaying to tropical storm (T3) on November 10th (Figs. 4d, 4e) and, finally, as a tropical depression (T2) on November 11th (Fig. 4f).

In situ data

In order to properly analyse the hurricane's effect on the upper mixed layer, the results are separated into three groups, based on two criteria: a) firstly, by dates and proximity of the atmospheric perturbation and b) by analysing the water mass variations in the T-S diagram of all the sampling stations (Fig. 5). The whole region is characterized by the presence of typical water masses from the Mexican part of ETPO: Gulf of California Water (GCW) with relatively high temperatures (25-30°C) and salinity values centered at 34.5; Tropical Superficial Water (TSW) characterized by warm temperatures around 30°C and low salinity (34.2-34.4); Sub-tropical Sub-superficial Water (S_tS_sW) characterized by low temperatures (8-12°C) and relatively high salinity waters (34.5-34.7) typical of ETPO (Emery & Dewar, 1982).

Thus, the first group consists of the sampling sites 1-4 located near the port of Mazatlán and far of Rick's influence in distance and time; the second group includes the sampling sites 5-10 located relatively close to Rick, covering its development from tropical depression to hurricane category T4 (H1), particularly site 10; the third group comprises the sites 11-16, sampled a number of days after the hurricane passed (Table 2).

Group 1. Sampling sites 1-4 are here included, located near the port of Mazatlán, and classified as oceanic areas; they were sampled before Rick reached the hurricane category. At this time no coastal stations were measured. Temperature and salinity measurements were carried out for these sites on November 6th, 1997. The vertical temperature profile shows well-stratified layers (Fig. 6a). There is an upper mixed layer, clearly defined from 0 to around 40 m; a thermocline lies

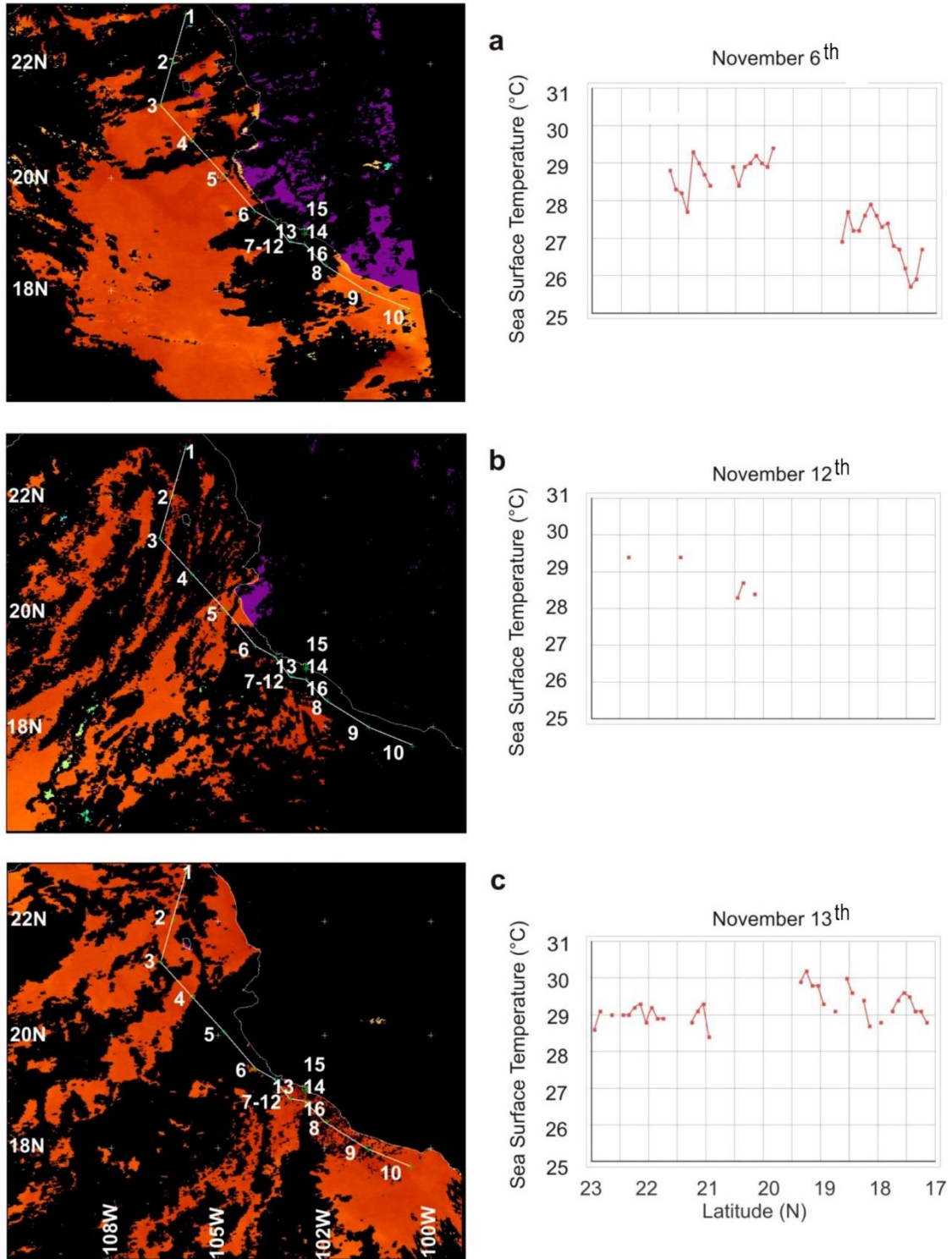


Figure 2. SST maps and profile transects for November a) 6, b) 12, c) 13.

between 44 and 150 m depth, and a deeper mixed layer from 150 m down to the maximum sampled depth. Particularly, the region comprehended by these sites

has been characterised as having a nearly permanent thermocline starting at around 40 m (Wyrki, 1965). Figure 6b shows vertical salinity profile. At the upper

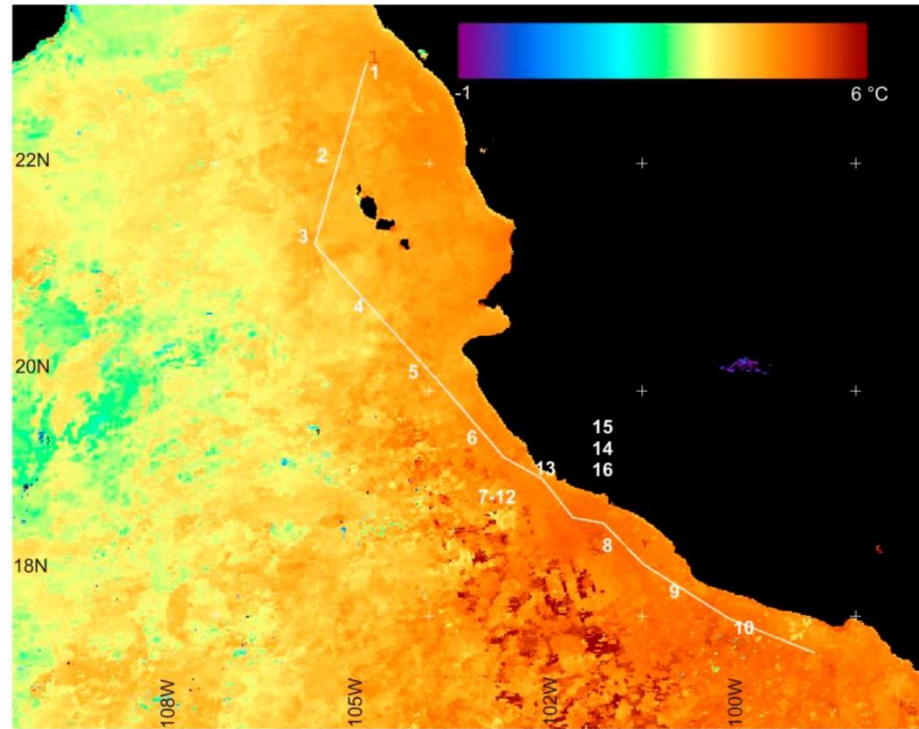


Figure 3. SST map of SST anomalies for November 1997, estimated by subtracting the climatological mean of 25°C from the monthly average.

Table 1. Hurricane Rick development from 6th to 10th November 1997.

Saffir-Simpson scale	T-number	Date (11/1997)	Time (h)	Lat. (°N)	Long. (°W)	Wind speed (km h ⁻¹)	Pressure (mb)	v (km h ⁻¹)
T.D.	T1	6-11-97	1800	09.0	102.5	55.56	1008	-----
T.D.	T2	7-11-97	0000	09.5	102.9	64.82	1008	1.97
T.D.	T2	7-11-97	0600	10.0	103.2	64.82	1008	23.9
T.D.	T2	7-11-97	1200	10.7	103.5	64.82	1007	2.30
T.D.	T2	7-11-97	1800	11.4	103.7	64.82	1006	17.44
T.D.	T2	8-11-97	0000	12.1	103.7	64.82	1005	17.53
T.S.	T2	8-11-97	0600	12.7	103.5	74.08	1004	1.94
T.S.	T2	8-11-97	1200	13.3	102.9	83.34	1002	24.33
T.S.	T3.5	8-11-97	1800	14.2	102.0	111.12	997	18.16
H1	T4	9-11-97	0000	14.9	100.9	138.90	987	33.34
H2	T5	9-11-97	0600	15.3	99.8	185.20	973	24.43
H1	T4.5	9-11-97	1200	15.6	98.6	166.68	977	18.12
H1	T4.5	9-11-97	1800	15.8	97.5	157.42	981	18.3
H1	T4	10-11-97	0000	15.9	96.0	138.90	987	19.89
T.S.	T3	10-11-97	0600	16.3	94.5	83.34	1002	38.36
T.D.	T2	10-11-97	1200	17.0	93.0	55.56	1009	26.34

layer salinity has a variation of 0.4, which can be presumably attributed to the input of freshwater from rain. Salinity values range between 34.1-34.4 between 44 and 60 m, becoming more saline (up to 34.5) at deeper regions.

Group 2. This group is useful for illustrating the hurricane's influence and consists of stations 5-10 which were sampled just before Rick transformed from tropical storm into a hurricane category. Particularly, the sampling stations 7-10 have a rather altered upper

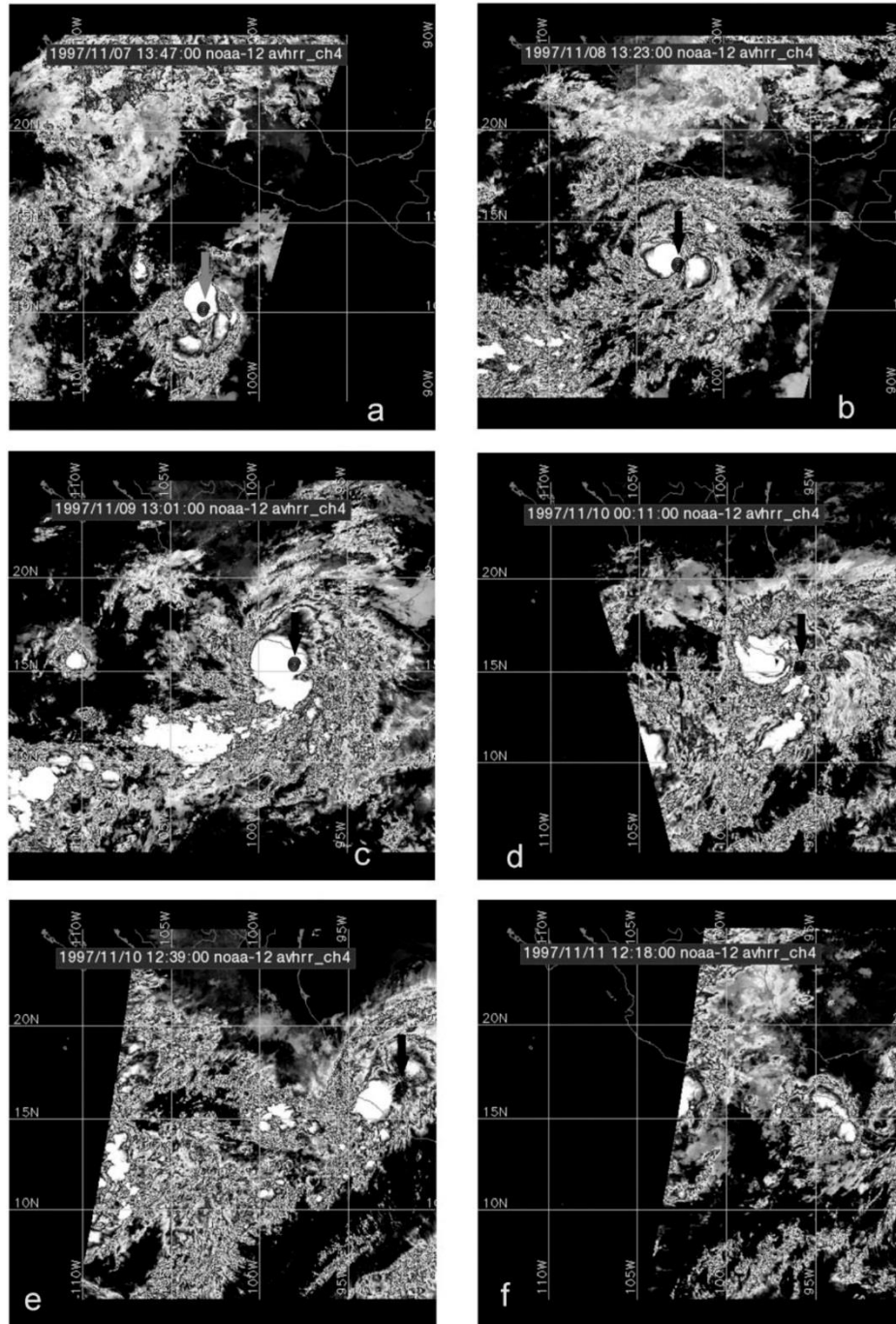


Figure 4. Structural evolution of Rick according with Dvorak's classification (T-number): a) T2, b) T2-T3.5, c) T4-T5, d), and e) T4-T1, f) No class. The eye of the hurricane is indicated by the black arrow.

mixed layer as seen in their temperature and salinity profiles with apparent variations between 25-60 m depth. Since the main effect of the tropical cyclone is in the upper mixed layer, Figures 7a and 7b show the salinity and temperature profiles from the surface down to 150 m depth. The best track position of the hurricane, on November 7th, was located at 500 km from station 7

but the perturbation expanded over a ratio of 250 km. On November 8th the distance between the tropical storm Rick and the sampling station 10 was about 402 km but the ratio of the eye-wall was of 157 km, as estimated from satellite imagery (letter D in Fig. 1).

Particularly, it is evident in the temperature and salinity profiles of station 10 (17.39°N, 102.23°W) loca-

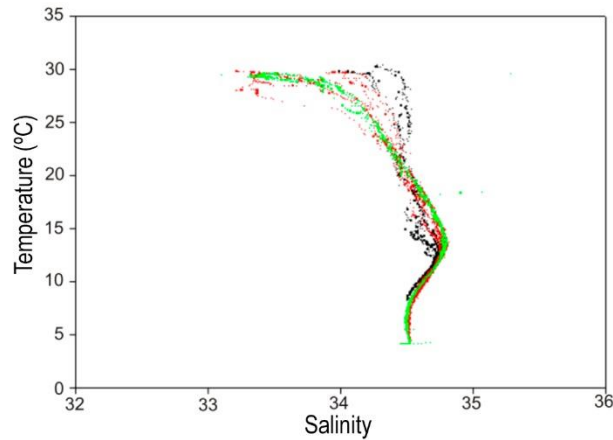


Figure 5. T-S diagram of the 16 sampling stations. Group 1 contains sampling stations 1-4 (black), Group 2 includes stations 5-10 (red), and Group 3 has sampling stations 11-16 (green).

ted close to Lázaro Cardenas, Michoacán (Petacalco's canyon), with Rick hastily approaching to a hurricane rank, and located at around 560 km S-SW from Acapulco, Guerrero. The vertical temperature profile on this date (Fig. 7a) still shows stratified layers but its shape is not as well defined as in the other stations. Thus, the mixed layer between 25 and 50 m is rather altered, especially at 40 m. It has a surface temperature of around 29°C, which decreases about 3°C before reaching the beginning of the thermocline at around 70 m depth. From this depth down to 140 m there is a temperature gradient of about 11°C.

The salinity profile shows variations of about 0.5 from the surface down to 90 m depth (Fig. 7b). Station 10 (solid line) has the lowest salinity values and shows

an intrusion of less saline water around 40 m, which is coincident with the change of temperature observed. Salinity has a slight increment, but still lower than the other sites, down to 75 m. From this depth on, the salinity values increase up to 34.7, matching the rest of the stations. The T-S diagram of this group clearly shows the variations in the upper mixed layer, mainly at the TSW (Fig. 7c). The profile of sampling station 10 (solid line) shows an important anomaly in relation to the remaining stations of group 2, due to the intrusion of fresher water mass.

Even though Rick was a number of kilometers far from station 10, its effect in the upper mixed layer was observed in the first 50 m depth which are in good agreement with the criterion applied by Levitus & Boyer (1994) in the World Ocean Atlas, in which they defined the lower boundary of the isothermal surface layer as the depth where the water temperature is 0.5°C lower than at the surface.

Group 3. The tropical cyclone Rick was quickly transforming into the category of hurricane on Nov 8th. At this date the sea state was rather rough and the oceanographic campaign has to been suspended for two days until November 12th after Rick's landfall on November 10th, near Chiapas. Thus, stations 11-16 were sampled near the port of Manzanillo, at oceanic and coastal points. Temperature and salinity profiles have a typical structure of this region with well-defined layers (Figs. 8a-8b). They show an upper mixed layer from the surface down to 40-50 m depth, a pronounced thermocline from a depth of 45 m down to a depth close to 200 m. Then, steep profiles of temperature and salinity are apparent. These profiles are, in general, similar to the ones of stations 1-4, but are better defined.

Table 2. Information of the stations sampled on the R/V El Puma on November 1997.

Sampling station	Group	Date	Time (h)	Latitude (N)	Longitude (W)	Depth (m)	Category
1	1	06-11-1997	12:03	22° 52.62'	106° 35.46'	540	Oceanic
2	1	06-11-1997	18:00	22° 01.81'	106° 49.79'	400	Oceanic
3	1	06-11-1997	23:30	21° 17.38'	107° 03.93'	400	Oceanic
4	1	06-11-1997	04:56	20° 40.19'	106° 28.81'	980	Oceanic
5	2	07-11-1997	10:15	20° 03.20'	105° 19.08'	1200	Oceanic
6	2	07-11-1997	15:35	19° 25.51'	105° 19.08'	1300	Oceanic
7	2	07-11-1997	21:21	18° 53.30'	104° 38.16'	1100	Oceanic
8	2	08-11-1997	03:00	18° 21.77'	103° 58.99'	1420	Oceanic
9	2	08-11-1997	08:44	17° 58.42'	103° 23.47'	1670	Oceanic
10	2	08-11-1997	15:27	17° 40.41'	102° 23.47'	1350	Oceanic
11	3	12-11-1997	14:17	19° 12.87'	104° 55.49'	200	Coastal
12	3	13-11-1997	01:22	18° 53.21'	104° 38.11'	1100	Oceanic
13	3	13-11-1997	09:14	19° 01.95'	104° 22.97'	95	Coastal
14	3	13-11-1997	10:52	19° 00.02'	104° 21.89'	140	Coastal
15	3	13-11-1997	11:51	18° 55.01'	104° 21.99'	140	Coastal
16	3	13-11-1997	12:57	18° 50.15'	104° 21.82'	880	Oceanic

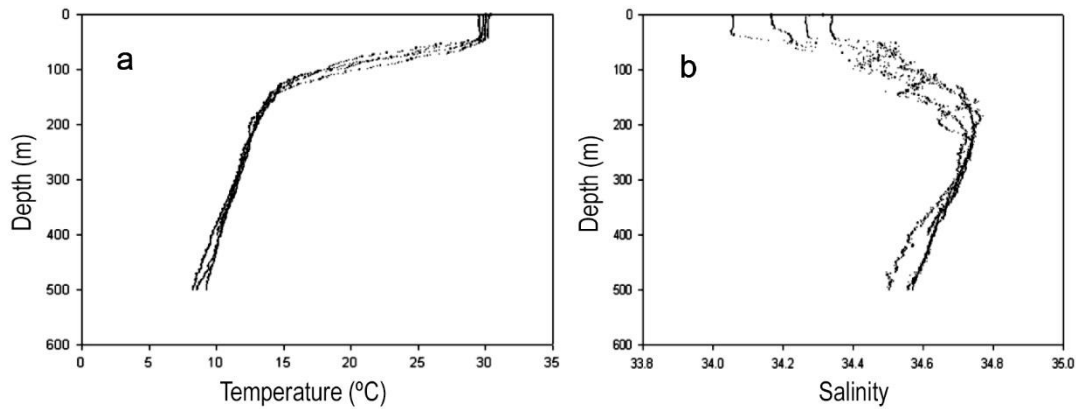


Figure 6. a) Temperature profiles of sites 1-4 sampled on November 6th, 1997, b) Salinity profiles of sites 1-4 on November 6th, 1997.

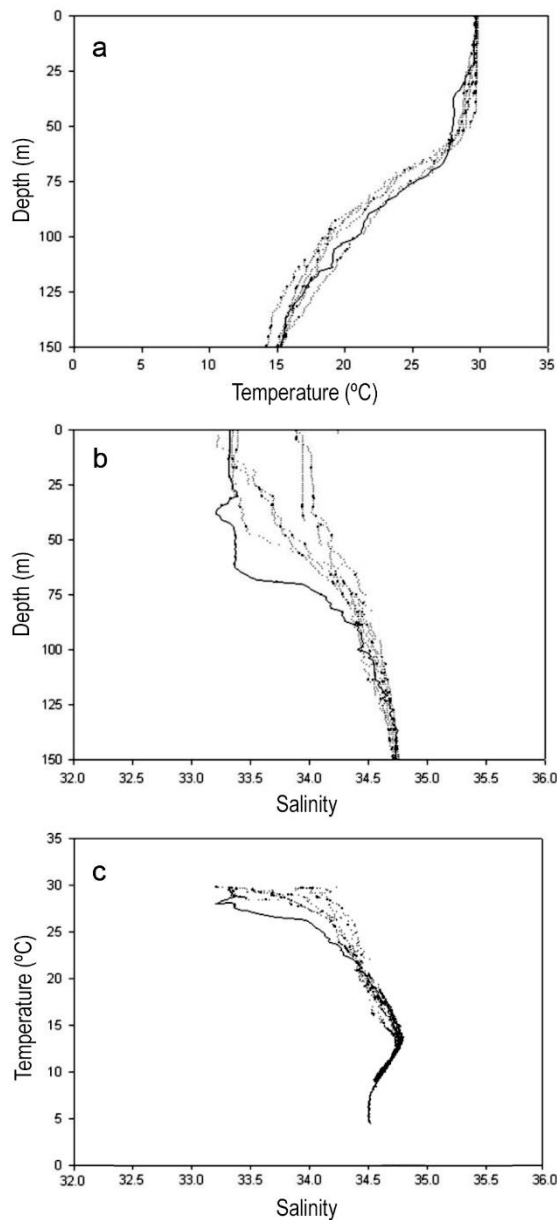


Figure 7. a) Temperature profiles of stations 5-10 sampled during the transformation of Rick from tropical storm into a hurricane (profile of sampling station 10 is shown in solid line), b) Salinity profiles of stations 5-10 sampled during the transformation of Rick from tropical storm into a hurricane (sampling station 10 is shown in solid line), c) T-S diagram of stations 5-10 sampled during the transformation of Rick from tropical storm into a hurricane.

DISCUSSION

One of the most important effects of ENSO on the central Mexican Pacific waters was the presence of the nearly extemporary hurricane Rick, being the last of the 1997 hurricane season. Even though the presence of hurricanes at that time of the year is not rare, there are no reports of them for a number of years prior and after ENSO 1997-1998. Hurricane season in the Pacific was slightly above the annual mean activity. Meteorological reports indicate the absence of hurricanes on the month of November in 1995, 1996, 1998 and 1999 (Servicio Meteorológico Nacional, 2000). The increment on the storm and hurricane activity over the ETPO, as compared with the two previous years, can be partially related to a large area of low values in a vertical shear (wind variation with altitude). As a consequence, a weaker flow from the east was recorded at levels higher than normal crossing the region (Webster *et al.*, 2005).

The primary process responsible for variations in the mixed layer under a hurricane is vertical mixing. This occurs when the hurricane's surface winds exert a stress on the ocean surface, generating, due to friction, ocean currents in the oceanic mixed layer. Vertical shear of the currents in the upper ocean then leads to turbulence. This process mixes and entrains the colder water from the thermocline up into the oceanic mixed layer, thereby thickening and cooling the oceanic mixed

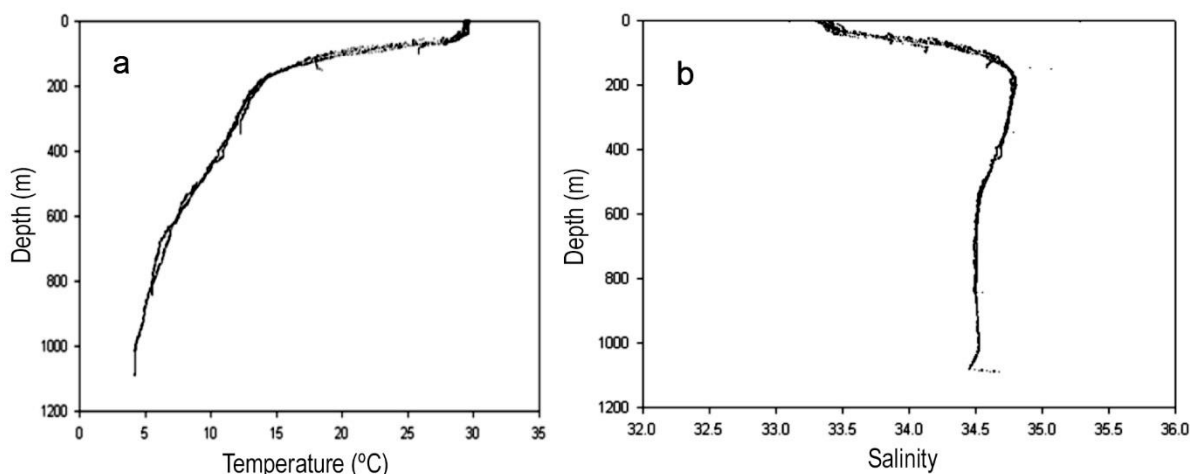


Figure 8. a) Temperature profiles of stations 11-16 sampled after the pass of the hurricane Rick, b) Salinity profiles of stations 11-16 sampled after the pass of the hurricane Rick.

mixed layer. Since this vertical mixing process happens within a few hours, it usually cools the sea surface underneath a hurricane, restricting evaporation and therefore limiting the heat available to the hurricane for intensification and maintenance. On the other hand, the time of residence of a tropical cyclone plays an important role on the perturbation of the upper mixed. This is apparent by observing that the Rick's displacement speed was less than 2 km h^{-1} on Nov 7th allowing a stronger vertical mixing (Table 1).

Satellite imagery shows the effect of ENSO on SST distribution of the area. Even though daily SST images showed a wide cloudiness over the study area, there were several clear SST patches indicating relative high temperature around 30°C . SST profiles suggest that hurricane Rick did not diminish SST values; instead, apparently, ENSO's warming effect on the seawater was the dominant influence over the area. Additionally, Dvorak's classification allowed for both a complementary description of hurricane tracking along with the Saffir-Simpson's, and for satellite analysis.

In situ data show the influence of both wind stress and vertical mixing on the upper mixed layer during the development of a tropical cyclone, particularly in the sampling stations belonging to group 2, when Rick transformed from tropical storm to hurricane H1. The temperature and salinity vertical profiles clearly show the influence of the hurricane as an intrusion in the upper mixed layer. The intrusion of fresher water is apparent around 40 m depth, particularly at the sampling station 10, which was the closest site sampled simultaneously to the tropical cyclone.

The sea temperature database, built by Secretaría de Marina (1984), allowed for averaging a 60-year period of traditional observations, pointed out a climatological

mean temperature of $25^{\circ} \pm 2^{\circ}\text{C}$ in the region and comparing this value with the measured temperature vertical profiles, a temperature increment of about 3°C has been reported during ENSO events. Temperatures measured at the upper mixed layer also show a 4°C increment.

Transects and hydrographic diagrams have proven to be supportive ancillary methods for assessing ENSO effects on Mexican Pacific waters.

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