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Title: Is the ocean responsible for the intense tropical cyclones in the Eastern Tropical Pacific?

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Abstract: The Eastern Pacific (EP) is a very active cyclogenesis basin, spawning the largest number of cyclones per unit area in the globe. However, very intense cyclones are not frequently observed in the EP basin, particularly when the database is constrained to cyclones that remain close to the Mexican coast and those that make landfall. During the period 1993-2007, nine Category 5 hurricanes developed in the EP basin, but only 5 reached maximum intensity while located East of 120W and only one made landfall in Mexico, as Category 4, in 2002. This cyclogenetical area is a favorable region for hurricane intensification, because of the elevated sea surface temperatures observed throughout the year, constituting a region known as the "Eastern Tropical Pacific warm pool", with relatively small annual variability, particularly in the region between 10 and 15N and East of 110W.

In this study we evaluate oceanic conditions, such as sea surface temperature, sea surface height and their anomalies, and relate them to the intensification of major hurricanes, with particular emphasis on those cyclones that remain close to the Mexican coast, including those that make landfall. Our results indicate that there seems to be circumstantial evidence of the presence of warm anticyclonic oceanic eddies impacting positively on the intensification of some of the major hurricanes in the region. However, about half of the major hurricanes that developed in the EP and remained close to the Mexican coast appear to have encountered negative anomalies of both sea surface temperature and sea surface height. These results suggest that the relatively unfavorable oceanic conditions in the EP basin would play an inhibiting role in the development of major hurricanes.Category 5 hurricanes appear to be correlated with El Niño but that is not clear for hurricanes category 3 and 4.

Is the ocean responsible for the intense tropical cyclones in the Eastern Tropical Pacific?

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Abstract

The Eastern Pacific (EP) is a very active cyclogenesis basin, spawning the largest number of cyclones per unit area in the globe. However, very intense cyclones are not frequently observed in the EP basin, particularly when the database is constrained to cyclones that remain close to the Mexican coast and those that make landfall. During the period 1993-2007, nine Category 5 hurricanes developed in the EP basin, but only 5 reached maximum intensity while located East of 120W and only one made landfall in Mexico, as Category 4, in 2002. This cyclogenetical area is a favorable region for hurricane intensification, because of the elevated sea surface temperatures observed throughout the year, constituting a region known as the "Eastern Tropical Pacific warm pool", with relatively small annual variability, particularly in the region between 10 and 15N and East of 110W.

In this study we evaluate oceanic conditions, such as sea surface temperature, sea surface height and their anomalies, and relate them to the intensification of major hurricanes, with particular emphasis on those cyclones that remain close to the Mexican coast, including those that make landfall. Our results indicate that there seems to be *circumstantial* evidence of the presence of warm anticyclonic oceanic eddies impacting positively on the intensification of some of the major hurricanes in the region. However, about half of the major hurricanes that developed in the EP and remained close to the Mexican coast appear to have encountered negative anomalies of both sea surface temperature and sea surface height. These results suggest that the relatively *unfavorable* oceanic conditions in the EP basin would play an inhibiting role in the development of major hurricanes.Category 5 hurricanes appear to be correlated with El Niño but that is not clear for hurricanes category 3 and 4.

Keywords: Major hurricanes, Eastern Pacific basin warm pool, sea level anomaly, warm ocean eddies.

1. Introduction

The Eastern Pacific (EP) tropical cyclone basin covers the region East of 140^{o}W to the coast of the Americas and North of the Equator. Of the approximately 100 cyclones that develop each year worldwide, less than 10% intensify to Category 5 in the Saffir-Simpson scale. Category 5 hurricanes are not frequently observed in the EP basin, and very seldom do they occur close to the Mexican coastline. Before reliable geostationary satellite coverage started in 1966, the number of EP tropical cyclones was very likely underestimated. Between 1959 and 2006 only 11 hurricanes in the EP were assigned Category 5, as listed in Table I. Most of them, though not all, occurred during the warm phase of El Niño/Southern Oscillation (ENSO); while the number of major hurricanes in a season does not show a significant dependence on ENSO (Romero-Vadillo et al, 2007), there seems to be a positive correlation with the number of category 5 hurricanes. On 12 September 1997 Hurricane Linda became the strongest hurricane on record in the EP basin. In other warm years, such as 1994 and 2002, two and three Category 5 hurricanes developed, respectively. However, other years during the warm phase of ENSO, such as 1982 and 1987, presented few major hurricanes and no Category 5 developed. Similarly, none developed in the extended warm period from 1991 to 1993. There seems to be no preferential month for hurricanes to reach Category 5 in the EP, having been observed from June to October.

In general, few major hurricanes (Category 3 to 5) make landfall globally, but even fewer do so in the EP, and a Category 5 hurricane impacting the Mexican coastline is an *extremely infrequent* event. Only two cases have been reported: “Mexico” in 1959 and Kenna in 2002. Actually, the 1959 cyclone was the only one to make landfall as a Category 5, since Kenna had weakened to Category 4 by the time of landfall, being the third strongest to make landfall — the second strongest was Category 4 Hurricane Madeline in 1976. On average, the EP basin has produced 16 named storms and 9 hurricanes each season for the last 40 years. Cyclone activity was slightly below average in 2002 and of the 15 tropical cyclones that formed, 8 became hurricanes, a somewhat higher ratio than usual. Although the total number of hurricanes was below normal, 5 developed into major hurricanes, one more than the long-term average. Kenna was the strongest hurricane of that season, with 270 km/h peak winds. Tropical cyclone intensification involves a combination of different favorable atmospheric conditions such as atmospheric instability to a tropical pre-existing disturbance as well as low vertical wind shear, low level vorticity and good outflow conditions aloft, resulting in enhanced inflow conditions in the surface layer (Emanuel, 1986). A dependence of tropical cyclone on ocean conditions, especially the surface and subsurface temperature is well documented in many observational studies (Leipper, 1967; Perlroth, 1967; Goni et al., 2004). The ocean supplies most of the energy for the development and intensification of tropical cyclones through turbulent heat fluxes at the surface (Marks, 1998). Recently, studies have shown that rapid intensification of tropical cyclones occurred when they encountered oceanic warm features (Hong et al., 2000; Shay et al., 2000; Scharro et al., 2005; Lin et al., 2005; Sun et al., 2007). These warm features, for example the anti-cyclonic rings and eddies shed by the Loop Current in the Gulf of Mexico, are characterized by a deepening of several tens of meters of the thermocline. Observational and numerical studies have supported the fact that tropical cyclone intensity is sensitive to the upper ocean heat content in the region (Mainelli et al., 2008). In turn, tropical cyclones induce modifications of the oceanic conditions after their passage (Brooks, 1983; Shay et al., 1990; 1992; 1998). The observed ocean response includes a significant surface layer cooling to the right of the storm track due to vertical mixing and a cyclonic near-surface current field associated with upwelling just behind the storm, affecting hurricane path and intensity. These features may feedback onto the overlaying storm, or remain as a long-lasting wake to affect other systems that translate over it (Lin et al., 2005).

This study investigates the role of sea surface temperature and sea level height on the intensity of tropical cyclones that developed and remained close to the Pacific coast of Mexico (East of 120W). Section 2 presents the databases and methodology used for the analysis; Section 3 gives a brief description of the major hurricanes of the EP; Section 4 presents the altimetry and sea surface temperature patterns associated with tropical cyclones in the EP. The discussion and concluding remarks are presented in Section 5.

2. Methodology

Sea surface temperature (SST) and sea surface height in the EP are evaluated in relation to hurricane intensification. Anomalies of these variables are calculated with respect to the 15 year climatological mean, for the period 1993-2007, and are denoted sea level anomaly (SLA) and SST anomaly (SSTA), respectively. Temporal and spatial distributions of these anomalies are correlated with the intensity of major hurricanes in the EP, to evaluate the possible role of oceanic features on intensification. For each storm report on the East Pacific tropical cyclone database, it is identified the prior corresponding SSTA and SLA values for the maximum intensity register along the baric path. These observations were systematically integrated in a spread diagram only for all the Major Hurricanes registered east of the 120 W longitude. A previous description of the variability of the East Pacific major hurricane occurrence, SST and SSH, it is included in this research in order to justify the needing of analyze each hurricane independently of each other.

a) Tropical cyclone database

The database of East Pacific tropical cyclones since 1949 used in this study is freely available at: http://weather.unisys.com/hurricane/e_pacific/index.html, courtesy of Colorado State University/Tropical Prediction Center. Latitude, longitude, in tenths of degrees, maximum 1-minute sustained winds and central pressure are given at 6-hour intervals for cyclones from 1949 to 2007. More information on the database and analysis details is found in Landsea et al., (2003). Only data from 1993 onward is here utilized in order to match with the satellite data availability.

b) Sea level height database

The altimetry measurements used here as gridded data of Sea Level Anomaly (SLA) and Absolute Dynamic Topography (ADT), come from the latest merged version provided by the data processing system called Data Unification and Altimetry Combination System Archiving, on the Validating and Interpretation of Satellite Oceanographic (DUACS/AVISO) data products. Merged data from TOPEX, ERS, and Jason are available at 3 different averaging periods: 7 days from 1993 to 2003; 3 - 4 days from 2004 to mid-2006 and more recently, the MSLA product is interpolated to a resolution of 1 day. The latest Merging process performed by DUACS/AVISO is twofold: mapping and generation of by-products. The mapping procedure is based the OI software used for LWE reduction (Le Traon et al., 2003). It is used to merge data from all missions in a single map of SLA. Then this combined map is used to generate by-products such as geostrophic currents or absolute dynamic topography by using a global or regional Mean Dynamic Topography (Rio et al., 2007).

c) Sea surface temperature database

The data were obtained from the one-degree weekly global database available on the NOAA Climate Prediction Center public web site (http://www.cpc.ncep.noaa.gov). Monthly mean SST anomalies were estimated for the period 1993-2007 and the correlation analysis to the East Pacific tropical cyclones database was performed using the optimum interpolation (OIv2) SST data. This interpolation onto a 1 degree regular grid, uses both in-situ SSTs and satellite derived SSTs from the NOAA Advanced Very High Resolution Radiometer (AVHRR). Multi-channel sea-surface temperatures have been computed from AVHRR radiances operationally since 1981. In-situ data are derived from both ships and buoys. The satellite data are adjusted for biases using the method described by Reynolds (1988), Reynolds and Marsico (1993) and Reynolds and Smith (1994).

3. Results

a) Variability of EP Major Hurricanes for 1993-2007

A total of 216 tropical cyclones developed in the EP basin between 1993 and 2007 and 54% of them reached hurricane strength. There is a large inter-annual variability of the total number as well as the fraction that reaches major hurricane intensity (category 3 and above) as seen in Figure 1 (upper panel). Note that before 1999, a larger fraction of cyclones reached hurricane strength, e.g. in 1993, 9 out of the 12 tropical cyclones developed into hurricanes and 8 were major hurricanes. Less favorable conditions for hurricane development appear to be present since 1999: the 2000 season produced only 6 hurricanes of a total of 17 tropical cyclones with only 2 major hurricanes. Zhao and Chu (2006), through a Bayesian analysis, found a decadal variation in the occurrence of tropical cyclones in the EP, with 2 recent change-points: a low activity period from 1971 to 1982, followed by a high activity period from 1982 to 1998 and finally 1999 indicates the change again to a less active period. No major hurricanes developed during 2003, out of a total of 15 cyclones. The 2007 season produced only 4 hurricanes out of a total of 14 cyclones. The observed interannual variability in the number of tropical cyclones does not appear correlated with the variability in the number of major hurricanes.

The intra-seasonal behavior in the monthly occurrence of tropical cyclones by intensity, from May to November (Figure 1, bottom panel) indicates that major hurricanes have been observed in all months from June to October, with no apparent preferred months for their occurrence. The largest number of hurricanes occurs in August and September, but it is in the latter that hurricanes usually reach their maximum intensity closer to the Mexican coastline. While in the weak La Niña year of 2001 a total of 15 storms developed and only 2 became major hurricanes (Category 4), during the weak El Niño year of 2003, a total of 14 storms were observed but none developed into major hurricanes. In the strong El Niño year of 1997, 15 storms formed and 6 developed into major hurricanes in the East Pacific basin as a whole, while in the somewhat weaker El Niño year of 2002 eleven cyclones developed and four became major hurricanes, a year that produced three Category 5 and one Category 4 hurricanes. During the even weaker warm phase of ENSO in 1994, 19 cyclones developed, out of which 5 became major hurricanes. It seems clear that the occurrence of Category 5 hurricanes is correlated with the early warm phases of the ENSO events of 1994/95, 1997/98, 2002/03 and 2006/07 ENSO, however, the occurrence of Category 4 hurricanes seems to be uncorrelated. During the period under study, the largest number of major hurricanes was observed in 1993, at twice the average of the maximum number observed in the rest of the period. While a correlation is apparent with the number of Category 5 hurricanes, Romero-Vadillo et al. (2007) state that no significant correlation is observed between the number of major hurricanes in the EP and ENSO, in contrast to the strong anticorrelation seen in the Atlantic (Landsea, 2005).

Seven Category 5 hurricanes developed in the EP during the period considered in this study, but only one had a trajectory that remained East of 120 °W. Hurricane Kenna developed in late October 2002, explosively intensified from a tropical storm to a Category 5 hurricane in less than 48 hours, weakened and made landfall as Category 4. The best tracks of all hurricanes in the EP in the period 1993-2007 are shown in Figure 2, stratified from June to November. Note that most of the paths are Westward or Northwestward (parallel to the Mexican coastline), with few of them veering toward the coast. The fraction of land-falling cyclones is not uniform during the season, as has been previously reported (Rosengaus et al., 2002, Romero-Vadillo et al., 2007). July and August show predominantly trajectories towards the NW, with the number of land-falling hurricanes reaching a maximum in September. Landfalls occur primarily North of 25°N in September, while landfalls South of 20°N latitude have occurred during June, October and November, even though the fraction of land-falling systems is very small. The trajectory of hurricane Kenna in October 2002 is easily distinguished in the panel corresponding to October in Figure 2.

b) Sea surface temperature and sea level height anomalies

The presence of intense tropical cyclones is well correlated with elevated sea surface temperatures. The EP basin is characterized by a large region of high SSTs with little intra-seasonal variability in the main cyclogenetical region South of 20N. Figure 3a presents the June-to-November average for SST, clearly showing the East Pacific cyclogenetical region coinciding with the warm pool (28°C isotherm). The mean SST shows only small variations inside the warm pool, with the largest variability observed in the region adjacent to the Mexican coast in the Gulf of California, as seen in the spatial distribution of the standard deviation in Figure 3c.. Figure 3b presents the corresponding spatial distribution of the absolute dynamic topography. Several features can be clearly identified: a region of high topography (above 190cm) centered at about 14N and 100W, with temperatures above 28°C. Toward the SE and closer to the coastline, a region of minimum topography is observed, still within waters that are warmer than 27°C. Towards the Central Pacific, there is an area of maximum height (larger than 200cm), related to the dynamics of the Pacific Ocean as a whole. Low topography and cool waters are observed on the West coast of the Baja peninsula. The geostrophic currents associated with the high-low dipole in topography close to the coast correspond to anticyclonic and cyclonic circulations known in the region and discussed in the review study by Kessler (2006). The largest variability relative to the mean topography (Figure 3d) is associated with the large scale features that extend to the Central Pacific, although large variability is also observed near the coast in the Gulf of Tehuantepec which bifurcates in two branches, one of them extending parallel to the coast up to the Baja peninsula.

The spatial distribution of the SST anomalies as a function of the month during the tropical cyclone season (Figure 4) broadly indicates systematic warm anomalies North of 15N close to the Mexican coastline throughout the season. But also it is notable the persistency of warm SST anomalies close to the coastline on the west of the three main mountain gaps of Central American cordillera (erg. Tehuantepec, Nicaragua lowland and Papagayo). It is well known that the winds flowing through these gaps, at the synoptic scale of 5-7 days, generate anti-cyclonic ocean eddies (McCreary et al., 1989; Trasviña et al., 1995). All of those warm anomalies explain very well the observed cyclogenetical activity previously shown in Figure 2, but not at all because they is also cyclogenesis activity during October and November when cold anomalies increase toward the coast south of 15 N. .

The distribution of the sea level anomaly (Figure 5) is characterized by large changes throughout the basin as the season progresses. A positive SLA is related to a warm anomaly in the oceanic mixed layer and higher heat content. Note that in the region to the West of 105W, June and November present an almost mirror image of positive and negative anomalies, with maximum anomalies around 12N and 115W. Near the coastline there is a more complicated pattern of anomalies. The anomaly is negative in June in the waters close to Mexico, from 12N up to the Gulf of California. In July, a positive anomaly is evident "*hugging*" the coastline and becomes larger as the season develops. Nevertheless, the region east of 110W, between 10 and 15N, where a large fraction of tropical cyclones develop, remains with negative anomaly. So even though the mean SSTs (and SSTA) are elevated in this region, the sea level height anomalies suggest that the oceanic heat content to fuel cyclones is reduced. Given than on average the SLAs are negative in the region, there would then be a potential role for transient warm anti-cyclonic oceanic eddies to provide a "boost" for cyclones, if they were to pass over such eddies, as has been shown to be the case in recent studies in other basins.

To further evaluate the relationship between oceanic anomalies and the development of hurricanes in the EP during the period 1993-2007, Figure 6 presents their interannual and intraseason variabilities. The map in the upper right hand corner indicates the region over which the averages and corresponding anomalies have been calculated. Both the SLA (top panel) and SSTA (second panel from top) clearly show the seasonal cycles, with alternating positive and negative anomalies in most of the years. The bottom panel shows the ENSO (JMA) Index, allowing for a visual correlation with SLA and SSTA, for warm and cold phases. Note that the SLA has a larger response to the warm phase of ENSO than the SSTA in this region. The SLA is very large in magnitude during the whole warm phase of 1997-98, while the SSTA has negative anomaly in the winter months. Other warm phase events observed in the 15-year period show smaller signals in SLA, clearly modulating the sea level height anomalies. The third panel from the top shows the number of cyclones (white bars) and major hurricanes (black bars) as a function of the month when they developed, to evaluate the role of the warm ENSO phase on their development. The difference with the data presented in Figure 1 (bottom panel) is that here only the region East of 120W is considered.

c) Correlation between oceanic conditions and selected major hurricanes

The interannual variability in the number of major hurricanes that develop in the region East of 120W may be related to the patterns of SLA and SSTA. Figures 7 and 8 present oceanic conditions observed for the cases of four major hurricanes that made land-fall in Mexico: Category 4 Lidia in 1993, Category 5 Kenna in 2002, Category 4 John in 2006 and Category 4 Pauline 1997. The best tracks for each of these hurricanes have been overlaid on the SSTA (Fig 7) fields corresponding to the daily data prior to the observation of the maximum intensity attained by each hurricane. The size of the circles depicting the best track relates to the intensity of the tropical cyclones as they evolve in time. All four cases shown formed during the warm phases of ENSO (see Fig. 6). Note that Lidia and Kenna developed over cold SST anomalies and in particular, it is noteworthy that Lidia reached Category 4 while still over the large cool anomaly in SST. In contrast, John and Pauline both develop over warm SST anomalies. The corresponding fields of sea surface level anomaly for each of the four cases are shown in Figure 8, where it is clear that all of the trajectories go over positive anomalies. In particular for the cases of Kenna and John, it seems evident that they intensified as they encountered positive sea surface level anomalies.

It is of interest in this study to investigate the evolution of major hurricanes that remain close to the Mexican coast and make landfall, given their potential risk to communities. Note that of the 54 major hurricanes shown in figure 1, only 16 (about 1/3) were observed East of 120W in the 1993-2007 period. The surface oceanic conditions in the region where those major hurricanes developed and evolved were identified for the period when they reached maximum intensity. The conditions were averaged for a circular area of 300km diameter centered on the best track, to take into account the full effect of surface turbulent fluxes on hurricane evolution. We evaluate the Absolute Dynamic Topography (ADT) and the SST as indicators of the potential influence of oceanic conditions on hurricane intensification. The ADT is shown as a function of the SST in figure 9a, where there seems to be threshold values for major hurricanes of 1.78 m for ADT and 27 °C for SST, but it does not seem to be systematic in terms of the maximum intensity attained by the cyclones. Figure 9b indicates that even though there seems to be a general positive correlation between SLA and SSTA, some of the major hurricanes in this region achieved their maximum intensity even though the oceanic conditions were not particularly favorable. In particular, the only category 5 hurricane that developed in this region during the 15 years considered, developed over negative SSTA and only slightly positive SLA (5cm). This would seem to indicate that the ocean was perhaps no the main factor in hurricane intensification.

5. Discussion and Summary

The main tropical cyclogenesis region in the Eastern Pacific (EP) is bounded between the Mexican coast and 120 W. About 53% of the total hurricanes developed in the EP in the 1993-2007 period intensified into a major hurricane, but only 1/3 of those had tracks that remained close to the Mexican coast (East of 120 W). Most of the major hurricanes in this region were classified as Category 4 on the Saffir-Simpson scale. There is a high probability of a major hurricane occurrence between July and September, with most Category 4 hurricanes occurring in September while Category 3 hurricanes are more common in July. Category 5 hurricanes are very infrequent (only about 10% of the number of Category 4) and are as likely to occur in July as in October. The location where major hurricanes reach peak intensity in the EP, changes as the season progresses: it is close to southern Mexico in June, moves outward during July and August and then moves back closest to land during September, but further North (100 -110 W; 15 to 20 N) than in June. Landfall by a major hurricane is more common North of 24 N during August and September and South of 20 N during June and November. During October, landfall has been observed between 20 N and 24 N (such as Category 5, Kenna in 2002.)

Sea surface temperatures are quite high and present little variability in the tropical cyclogenetical region in the EP basin, but there seems to be no clear correlation with the location where major hurricanes reach peak intensity. On average, SSTA are positive (up to 1C) in the region of the warm pool South of 15N from June to September , (Fig. 4). Even though the SST only presents weak intra-seasonal variability during the hurricane season (Fig. 2c), the monthly SLA show a much more pronounced spatial and temporal distribution. The region where most of the major hurricanes reach peak intensity (about 15N and 115-120W) presents a sign reversal from positive sea level anomalies in June to negative anomalies from July to the end of the season (as shown in Fig. 5). As a result from this reversal in the SLA signal, monthly SLA and SSTA fields are both characterized by a meridional gradient between the region of peak intensification (with positive SLA and SSTA) and the cyclogenesis region inside the EP warm pool (with negative SLA and positive SSTA). The average differences between these two regions are of the order of 10 cm for SLA and 0.5 C for SST. The maximum negative anomaly in August-September, corresponding to the middle of the cyclogenesis season in the basin, would suggest that the oceanic conditions would be less favorable for developing strong cyclones in the EP basin. A positive SLA is related to a warm anomaly in the oceanic mixed layer and higher heat content. The presence of a *transient* positive SLA in the cyclogenesis region, would be more favorable toward cyclone intensification. Recent studies of ocean dynamics in the EP region indicate the presence of transient warm anti-cyclonic ocean eddies, generated by various mechanisms and present throughout the year (Zamudio et al., 2006). Tropical cyclones whose tracks intercepted positive SLA anomalies in the Gulf of Mexico (Scharro et al., 2005) and the Western Pacific (Lin et al., 2005) were shown to have received a “boost” that led to the intensification of those systems. Given the average conditions in the EP basin shown in Figures 3, 4 and 5, we explore here if warm eddies could impact cyclone intensification.

The selected cases of land-falling major hurricanes shown in Figures 7 and 8 all developed during the warm phase of ENSO, yet the oceanic conditions (SSTA and SLA) close to the Mexican coast vary widely between these cases. Lidia (1993) and Pauline (1997) developed over cold SSTA, but Pauline encountered early on in its evolution a very large positive SLA that led to rapid intensification to category 4. Lidia reached category 4 in regions of cold SSTA and negative SLA and even though close to the coast it encountered large positive SLA before land-fall, it did not intensify. Hurricanes John (2006) and Kenna (2002) both developed over warm SSTA, but the oceanic mixed layer was very different in each case: John early on encountered a transient positive SLA (warm eddy) while Kenna’s trajectory encountered mostly negative SLA, until reaching a region of positive SLA at 17N, when it re-curved towards the Mexican coast and intensified.

It appears from the isolated cases of major hurricanes described above that their intensification is related to the passage over positive SLA. However, when all 16 major hurricanes observed in the East Pacific basin (East of 120W) during the 1993-2007 period are considered (Fig. 9), there is no apparent correlation between SLA, SSTA and hurricane intensity. This result indicates that the role of the ocean structure may not be as important for the development of major hurricanes in the EP basin but all MH developed in an environment with absolute dynamic topography and SST above 180 cm and 27°C respectively. Recent studies in other basins had indicated a major role of warm SLA in the intensification of Opal (Hong et al., 2000) and Katrina (Scharroo et al., 2005) in the Gulf of Mexico and super-typhoon Maemi (Lin et al, 2005) in the West Pacific. While in some cases we can argue that the oceanic conditions in the East Pacific, particularly the presence of warm anticyclonic vortices, may have contributed to the intensification of major hurricanes, when all 16 cases are considered there is no clear correlation. Furthermore, our results suggest that the major hurricanes that develop in the East Pacific do so even though the oceanic conditions may not be fully favorable, since 50% of the cases shown in Fig. 9b developed over regions with either zero or negative SSTA and negative SLA. The results that we have presented here would indicate that the answer to the question posed in the title: "*Is the ocean responsible for the intense tropical cyclones in the Eastern Tropical Pacific?*", is most likely no, although it may play a role in the evolution of a few selected ones.

While not the main focus of this study, the observed spatial and temporal evolution of the SLA along the coastline merits further discussion here. There are 3 oceanic regions off the West coast of Central America that present positive sea level anomalies during June and September (Fig. 5): close to the isthmus of Panama (~8N), close to Costa Rica (~10N) and in the Gulf of Tehuantepec (~15N), where there are gaps in the mountainous topography. These regions experience enhanced wind speeds during the mid-summer related to large scale variability of the high pressure system in the Atlantic, as discussed in Romero-Centeno et al. (2007). This observed variability in the wind fields seem to affect the sea level height anomalies. During July and August the observed stronger winds through the gaps act to cool the surface waters and to reduce the sea level anomalies.

Another noteworthy observation is the distinct difference in SLA observed very close to the coastline between June and July: a positive anomaly seems to "propagate" northward, reaching even the Gulf of California. This positive SLA spreads away from the coastline as the season advances. In September, the largest values are observed well inside the Gulf of California, coinciding also with the warmest SSTs. The results by Zamudio et al. (2006) of the simulated oceanic evolution corresponding to 1997 resemble the spatial and temporal evolution of the monthly mean SLA near the coastline presented here. The existence of these warm anti-cyclonic oceanic eddies during late summer in the EP has been identified by Zamudio et al. (2001; 2006) in both during warm and non-warm global phases (Kessler et al. 1995). A more in-depth comparison of regional ocean models and SLA observations and the relationship of warm ocean eddies with tropical cyclones is currently the topic of further investigation.

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Figure Captions

Figure 1. Top panel: Interannual variability of occurrence of tropical cyclones (TC, solid black), hurricanes (H, dash with circles) and major hurricanes (MH, solid with stars) in the East Pacific basin (East of 140W) for the period 1993-2007. Bottom panel: Time evolution of the monthly frequency of occurrence of tropical cyclones, stratified by intensity.

Figure 2. Monthly variation of the trajectories of tropical cyclones observed in the Eastern Pacific (East of 120 W) from 1993 to 2007. The size of the different filled circles corresponds to the intensity of the cyclones.

Figure 3 a) Spatial distribution of the June-to-November average of the sea surface temperature observed in the East Pacific, East of 120W. b) Spatial distribution of the June-to-November average of the absolute dynamic topography observed in the East Pacific, East of 120W. Panels c) and d) show the standard deviation of the sea surface temperature and the absolute dynamic topography, respectively.

Figure 4. Monthly mean variability of the sea surface temperature anomaly (SSTA).

Figure 5. As Figure 4, but for the sea surface level anomaly (SLA).

Figure 6. Interannual variability of the sea level anomaly (SLA, top panel) and the sea surface temperature anomaly (SSTA, second panel) in the East Pacific (east of 120 W, as indicated in the box on the upper right corner) for the period 1993-2007. The third panel from the top shows the corresponding Tropical Cyclone frequency, indicated as Hurricanes (H, white bars) and major hurricanes staged by category (H3, H4, H5, color bars), as a function of the month when they were formed. The bottom panel reproduces the ENSO index (taken from ftp://www.coaps.fsu.edu/pub/JMA_SST_Index/), over a similar bar graph of the third panel but for the whole amount of Tropycal Cyclones registered on the East Tropical Pacific (east of 140 W).

Figure 7. Four cases of major hurricanes that made land-fall in Mexico. The contours and shading indicate the sea surface temperature anomaly (SSTA) and the best tracks have been overlaid by color circles. The size and color of the circles depicting the best track relate to the intensity of the tropical cyclones: a) Category 4 Lidia in 1993 b) Category 5 Kenna in 2002; c) Category 4 John in 2006 and d) Category 4 Pauline

in 1997. The SSTA field is the one observed prior to the minimum pressure along the track.

Figure 8. Same as Figure 7, but contours and shading correspond to the sea surface level anomaly.

Figure 9. Major hurricanes observed East of 120W in the period 1993-2007, in terms of **(a)** sea surface temperature (SST) and absolute dynamic topography (ADT), and **(b)** sea surface temperature anomaly (SSTA) and sea level anomaly (SLA).

Table

Table I. Hurricanes that developed in the East Pacific basin since 1959 and reached Category 5. Hurricanes have been grouped into sub-regions where they attained maximum intensity: East Pacific (EP, East of 120W), and West Pacific (WP, West of 140W). Within each sub-region, hurricanes are listed in terms of decreasing maximum sustained wind speed.

Name	Year	Date (Cat 5)	Duration (hrs)	Minimum Pressure (mb)	Maximum sustained wind (km/h)	Comments
Linda [EP]	1997	Sep 12-13	12	902	300	Strongest cyclone in basin, Niño year
Mexico [EP]	1959	Oct 23-29	6	960	280	Uncertain pressure values. ***Landfall*** in Jalisco.
Kenna [EP]	2002	Oct 24-25	18	913	270	***Landfall*** in Jalisco, Niño year
Ava [EP]	1973	Jun 7-8	12	915	260	Earliest in season
Guillermo [EP]	1997	Aug 4-5	12	919	260	Niño year
Elida [EP]	2002	Jul 24-25	6	921	260	Niño year
Hernan [EP]	2002	Sep 1	12	921	260	Niño year
John [WP]	1994	Aug 22-24	42	929	280	Attained Cat 5 W of 140W. Niño year. Minimum pressure not measured at maximum wind speed
Gilma [WP]	1994	Jul 24-25	18	920	260	Niño year
Emilia [WP]	1994	Jul 19-20	18	926	260	Niño year
Ioke [WP]	2006	Sep 24-25	36	915	260	Niño year. Attained Cat 5 in West Pacific basin

Figure1

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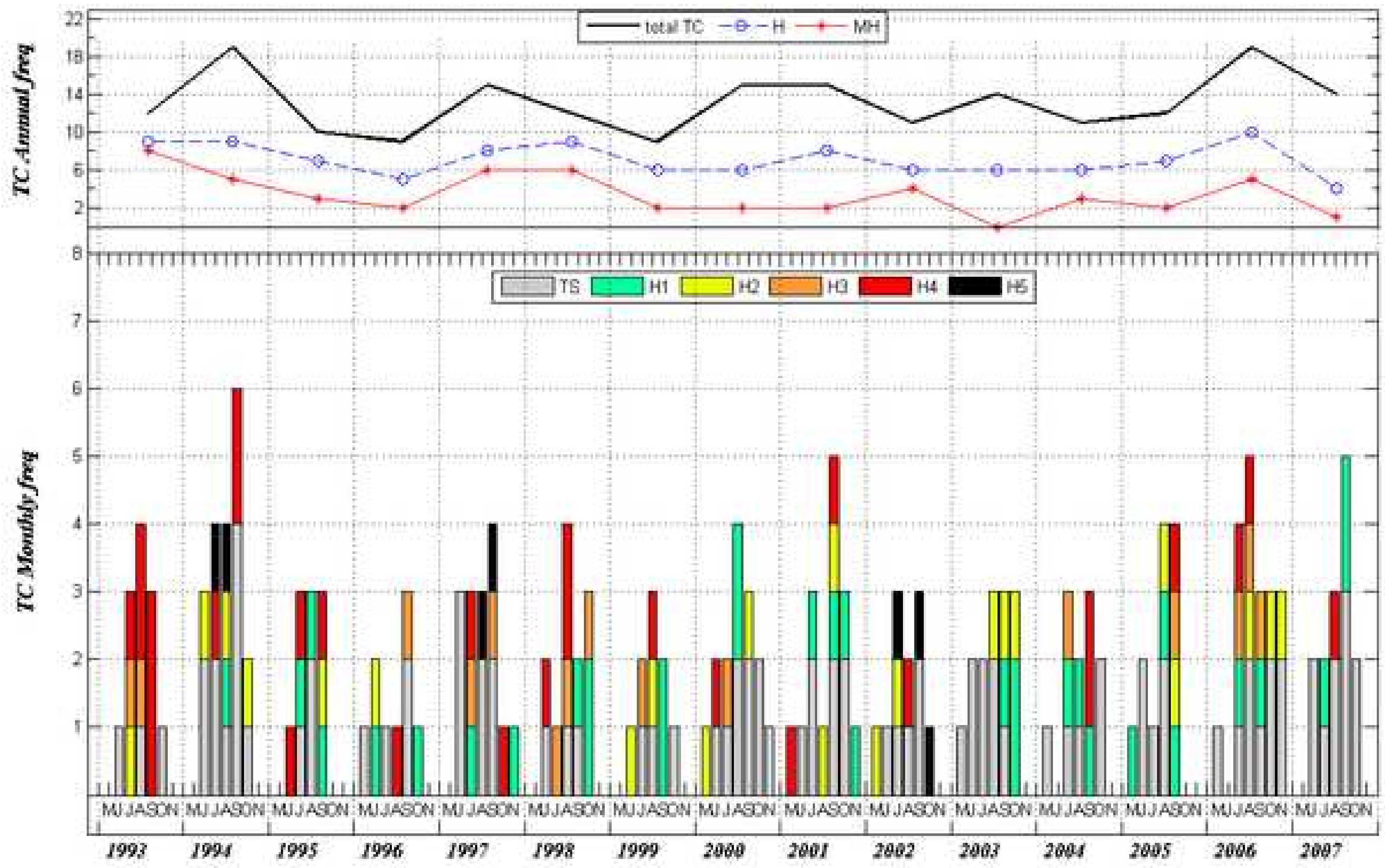

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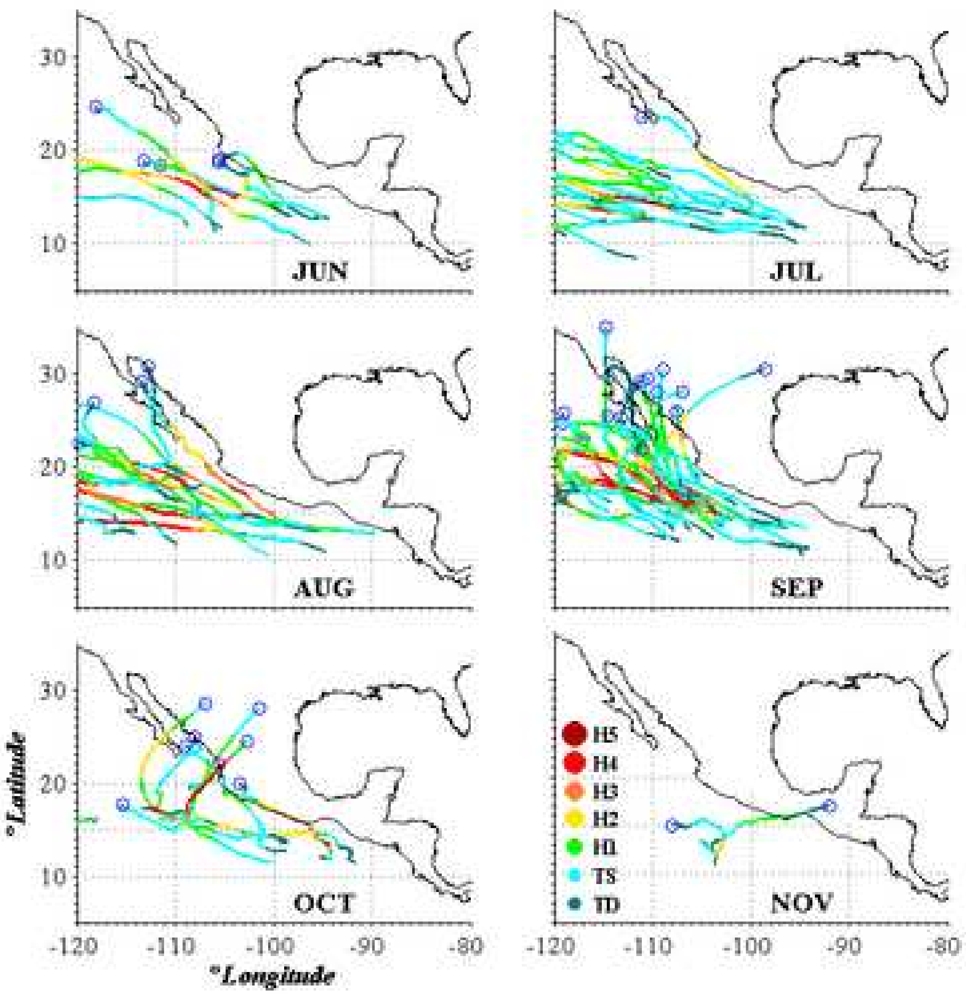

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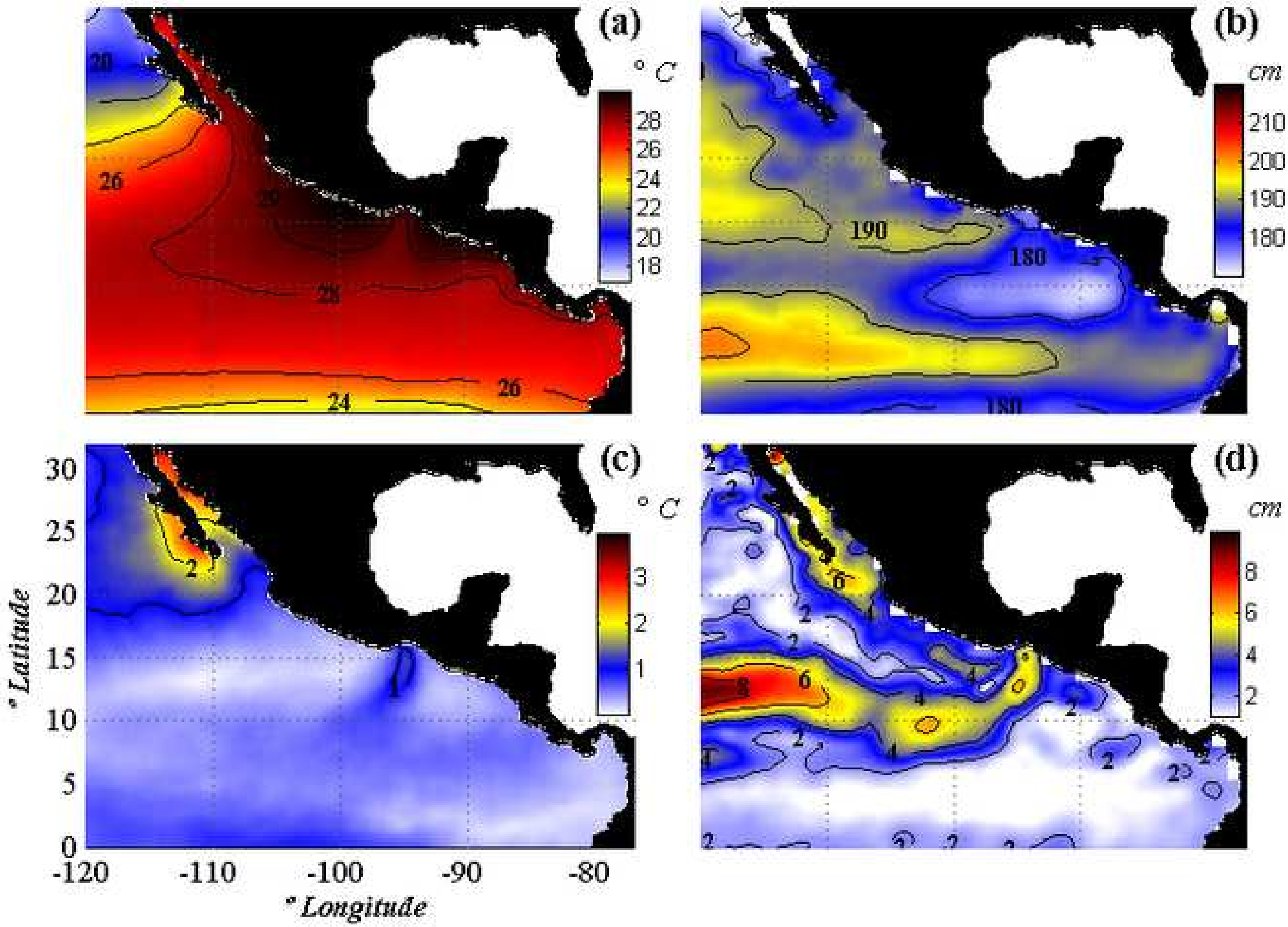

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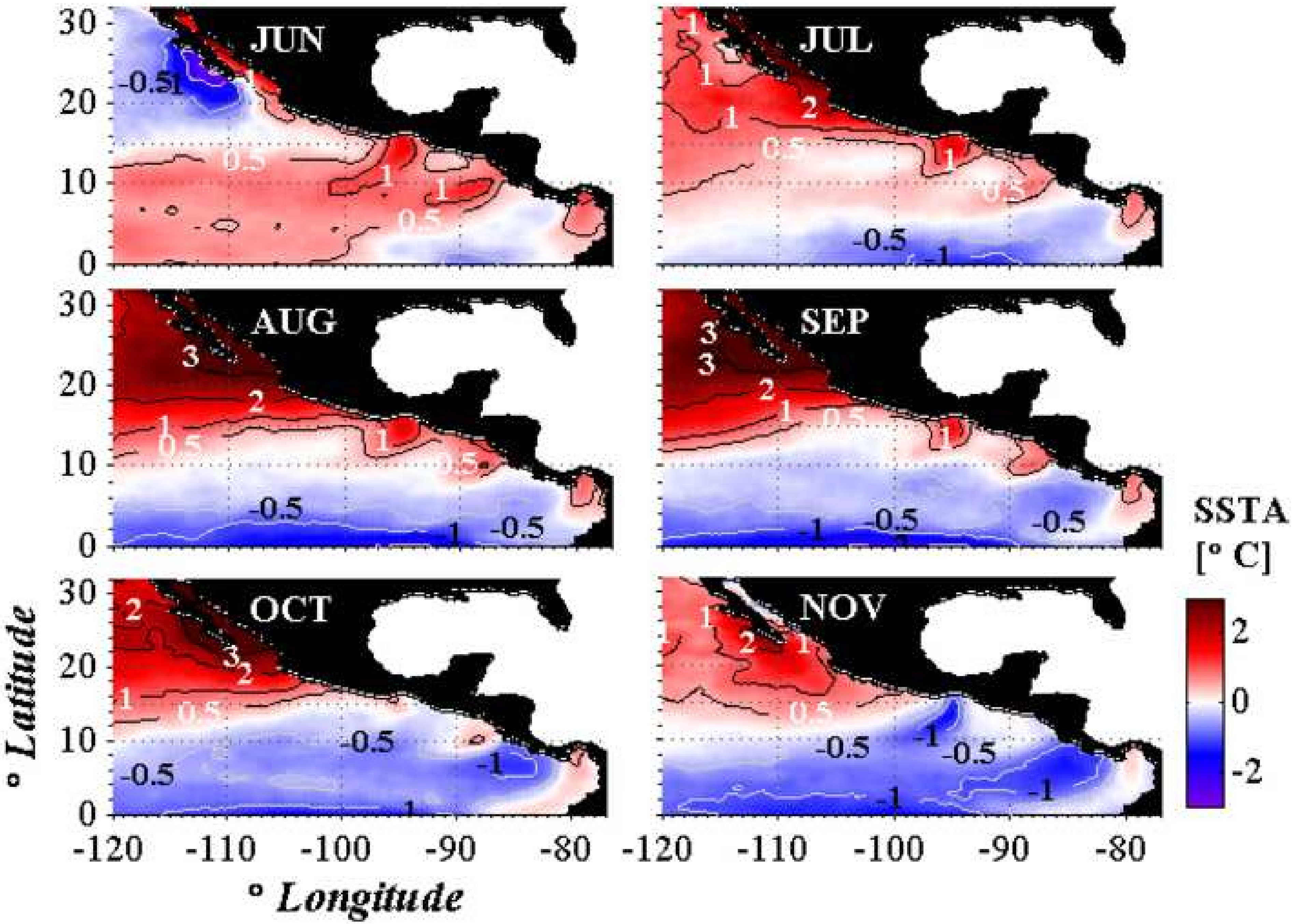

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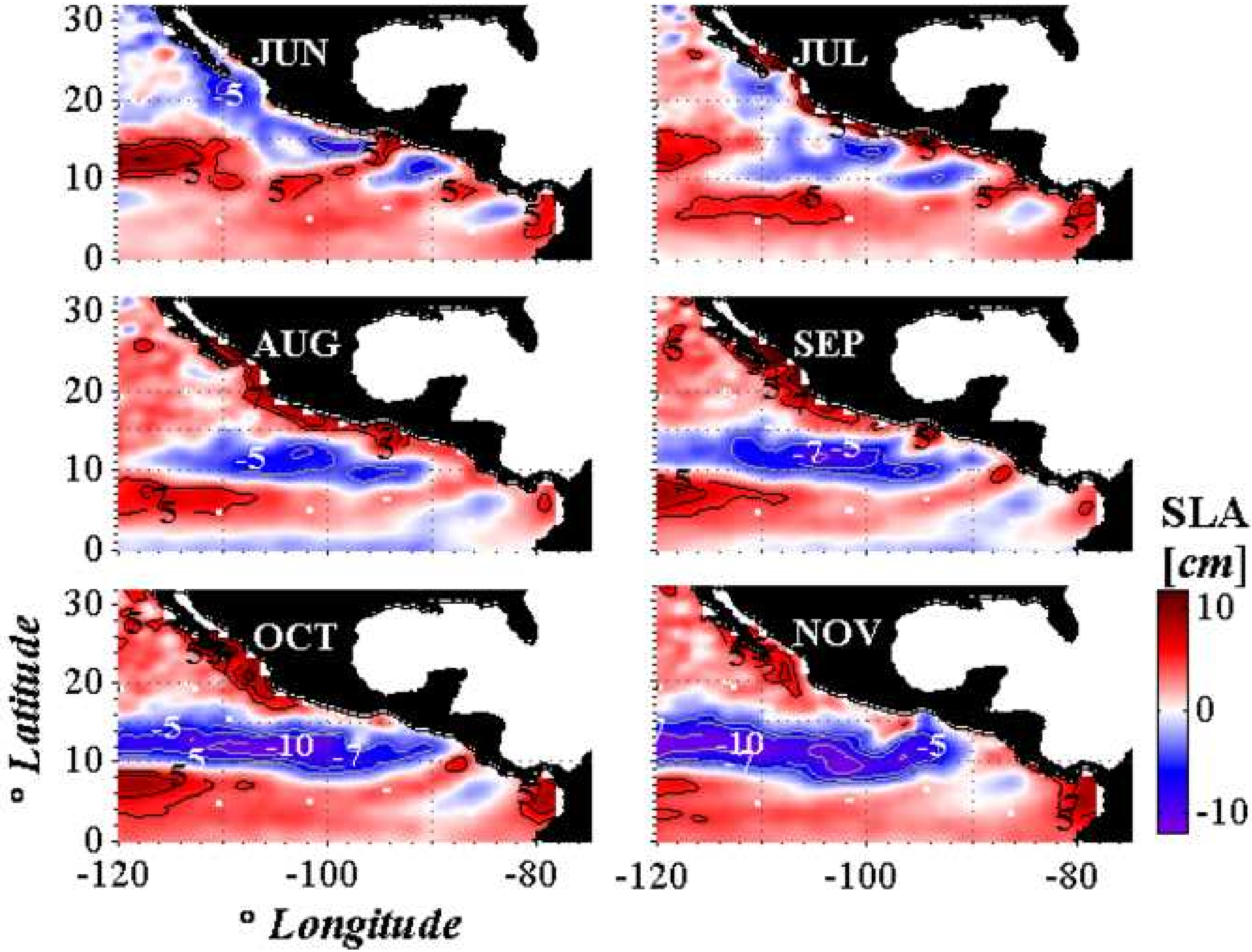

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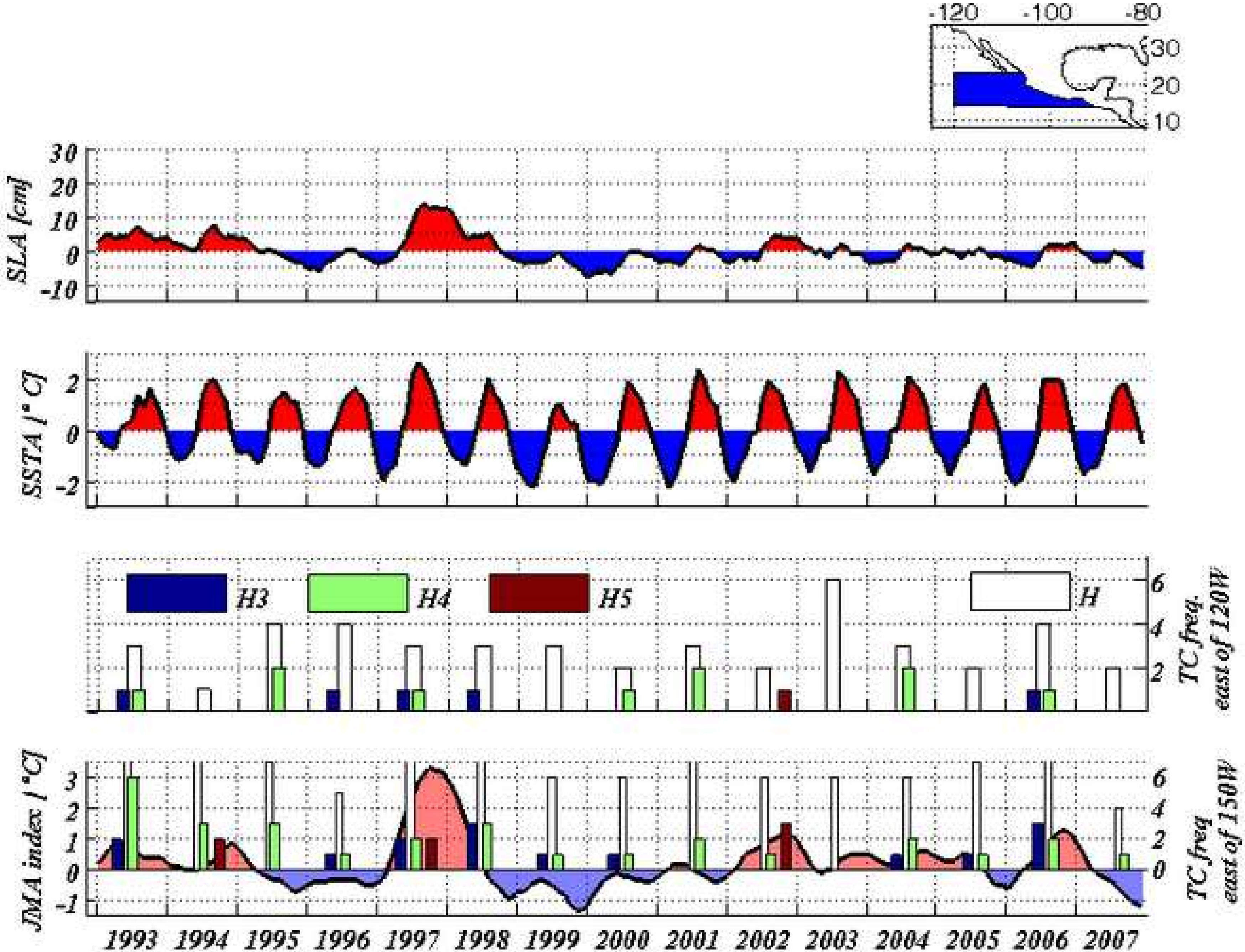

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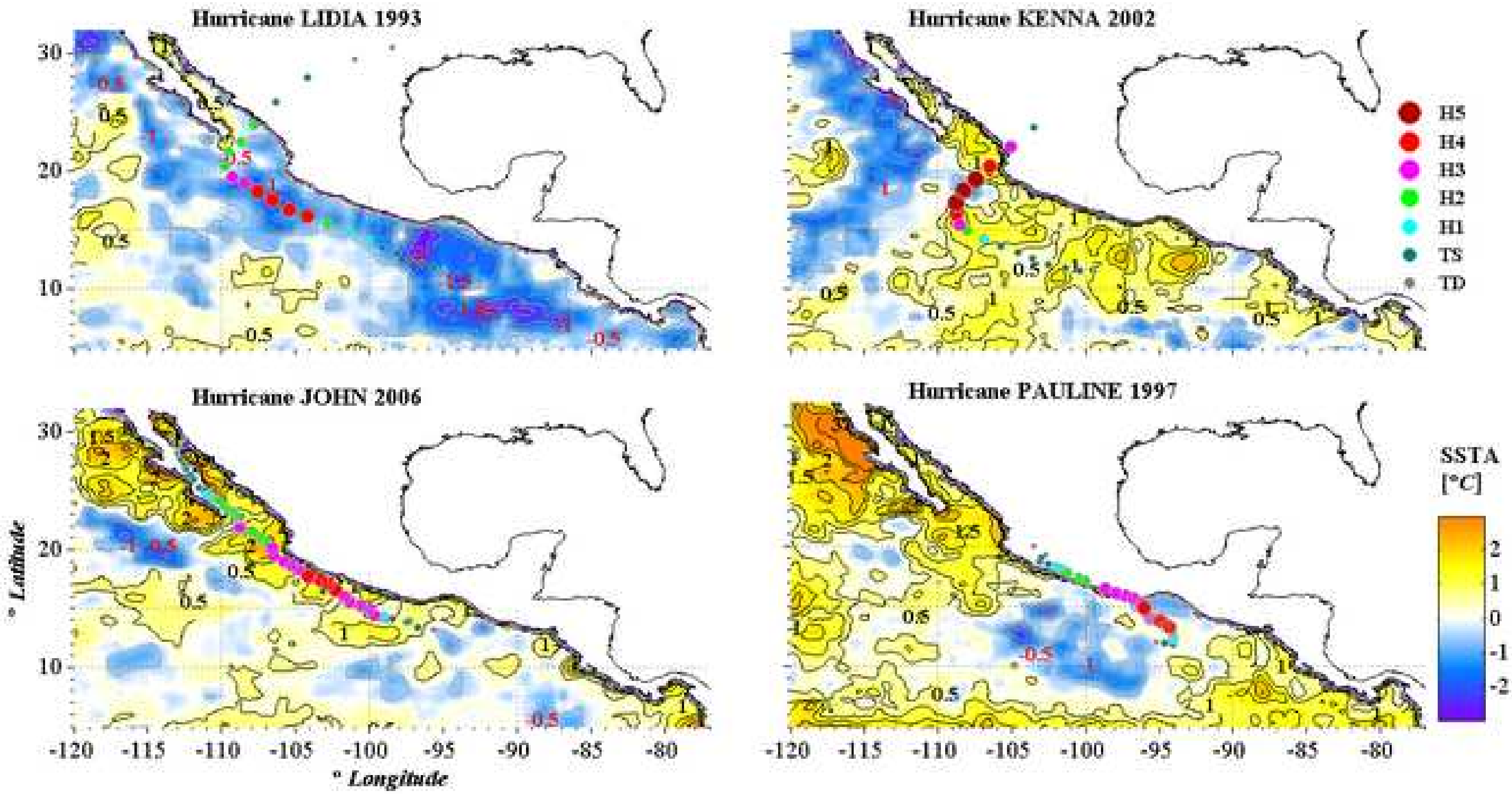

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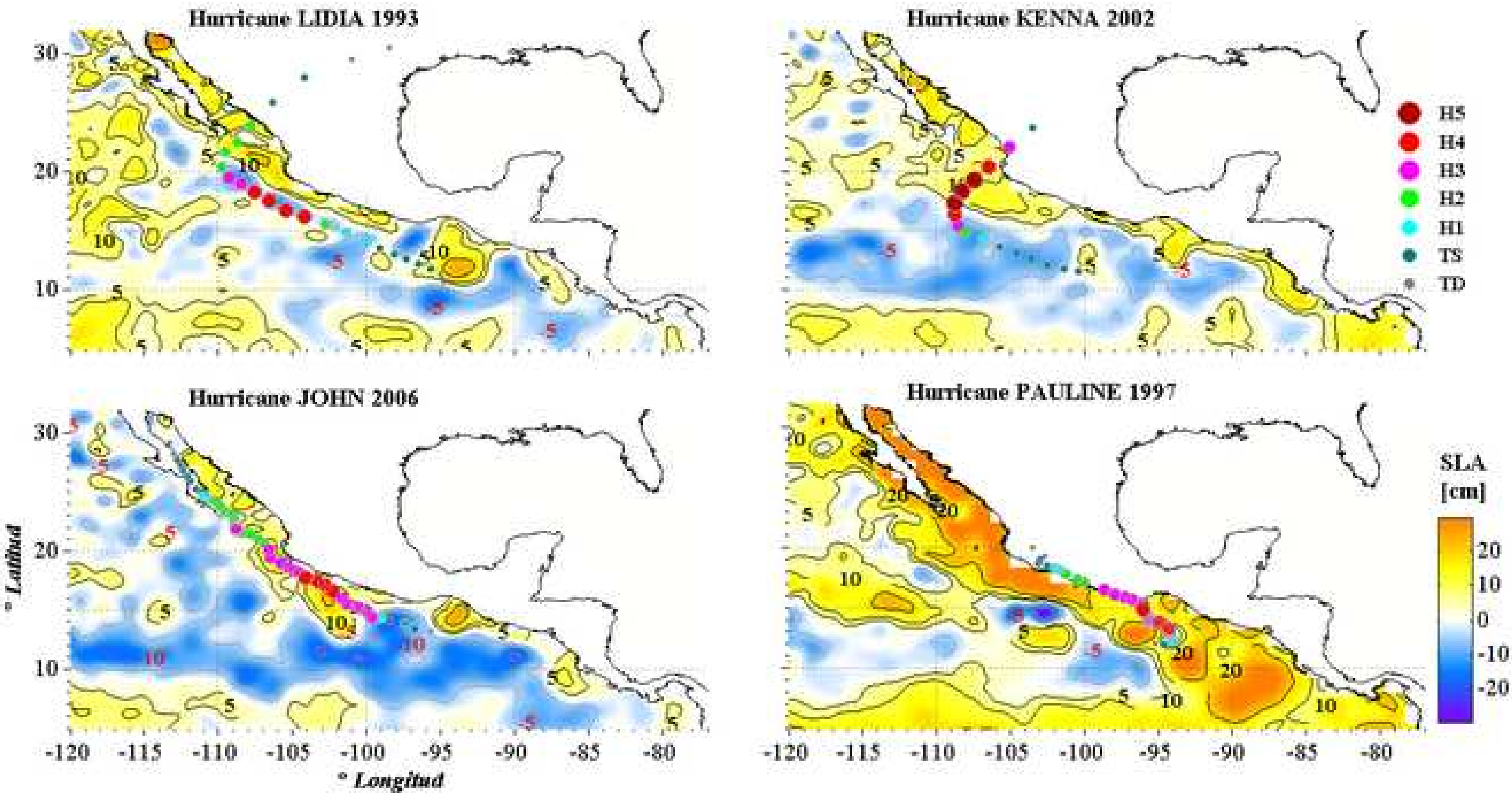

Figure9
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