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Eastern Tropical Pacific hurricane variability and landfalls on Mexican coasts

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ABSTRACT: We investigated composites of sea surface temperature (SST), wind shear (WS) at 850–200 hPa, and zonal winds at 925 hPa during July–September of the hurricane season to determine interannual and decadal differences between weak (categories 1 to 3, HUR1–3) and intense (categories 4 to 5, HUR4–5) hurricanes in the main development region (MDR) of the Eastern Tropical Pacific (EPAC) during 1970–2010. SST in the MDR showed a statistically significant increase of 0.57°C over the whole period, but the frequency of HUR4–5 did not show a significant trend, while the frequency of HUR1–5 significantly decreased (–0.95 % yr^{-1}). This trend is linked to active and inactive hurricane periods which are negatively associated with the Atlantic Multidecadal Oscillation and positively with the Pacific Decadal Oscillation (PDO). The frequency of HUR4–5 also shows a significant positive relationship with PDO and El Niño–Southern Oscillation events. This is likely due to a larger extension of the Western Hemisphere Warm Pool in the EPAC and lower WS values in the MDR during El Niño than during La Niña. Although the mean SST anomalies and WS conditions in the EPAC appear to be more favorable for cyclogenesis and intensification during El Niño, the frequency, duration, and accumulated cyclone energy of HUR4–5 are similar during El Niño and Neutral years, as are the average landfalls of category 1 to 5 hurricanes (HUR1–5). It is hypothesized that a larger size of the North Atlantic warm pool and a weaker Caribbean Low-Level Jet during Neutral years add an extra dynamical mechanism that favors cyclogenesis in the EPAC, which may not be present (or is weaker) during El Niño.

KEY WORDS: Hurricanes · Eastern Tropical Pacific · El Niño–Southern Oscillation · ENSO · Atlantic Multidecadal Oscillation · AMO · Western Hemisphere Warm Pool · WHWP · Mexico

1. INTRODUCTION

The Eastern Tropical Pacific (EPAC) is the second most active tropical cyclone (TC) basin worldwide (Molinari et al. 2000, Camargo et al. 2008, Maue 2011), with an annual average of 8.8 tropical storms (TS) and 7.4 hurricanes (Romero-Vadillo et al. 2007). At intraseasonal time scales, the presence of the Western Hemisphere Warm Pool (WHWP) in the EPAC, characterized by sea surface temperatures (SSTs) >28.5°C, favors a higher frequency of TCs during the summer, when it expands westward (Wang & Enfield 2003), covering most of the TC main development region (MDR; see Fig. 1) of the EPAC. Simultaneously, the expansion and contraction of the WHWP along the equator has an important role in the variability and evolution of El Niño–Southern Oscillation (ENSO) (Wang & Enfield 2001, Wang & Fiedler 2006). The influence of ENSO on the TC activity of several basins is well known (e.g. Kimberlain 1999, Frank & Young 2007, Camargo et al. 2010). The behavior of TCs in the EPAC and their relationship with ENSO is less understood and weaker (e.g. Tang & Neelin 2004, Englehart et al. 2008) than in the North Atlantic (NATL) (Gray 1984, Goldenberg & Shapiro 1996, Landsea et al.

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1998, Frank & Young 2007), due in part to the low number of ENSO realizations for the available TC records (e.g. Kim et al. 2009, 2011). In spite of that, a higher frequency of intense hurricanes have been observed during El Niño (EN) than La Niña (LN) events (Lupo et al. 2008, Frank & Young 2007, Kim et al. 2011). However, changes in the frequency, intensity, and landfalls of EPAC hurricanes during Neutral conditions have been much less documented. Larson et al. (2005) shows that there is significantly less TC-derived rainfall along the Mexican Pacific coasts and the southwest USA during LN than during EN or Neutral conditions, and a similar result was found by Farfan et al. (2013) when evaluating the top 25 landfalling TCs based on accumulated rainfall.

The decadal variation of TCs appears to be modulated by large-scale SST variability associated with the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), and the Atlantic Meridional Mode (AMM). According to Lupo et al. (2008), the TC season in the EPAC tends to be more active during EN of the warm phase of the PDO than the cool phase. Hurricane activity in the NATL basin has been positively correlated with the AMO (e.g. Goldenberg et al. 2001, Trenberth & Shea 2006, Chylek & Lesins 2008), while the opposite has been documented for the EPAC (e.g. Elsner & Kara 1999). Similarly, Wang & Lee (2009) and Maue (2009, 2011), based on accumulated cyclone energy (ACE), found a significant out-of-phase relationship between active and inactive TC periods in the NATL and the EPAC basins, which has been associated with ENSO (Maue 2009) and the AMM (Kossin & Vimont 2007, Vimont & Kossin 2007). Wang & Lee (2009) argue that vertical zonal wind shear (WS) and the size of the warm pools also contribute to the out-of-phase relationship between NATL and EPAC TC activity.

Theoretical and high-resolution modeling studies also suggest that increased surface warming and changes in the thermodynamics state of the tropical atmosphere will lead to an increase in the frequency of stronger TCs (e.g. Knutson & Tuleya 2004, Bender et al. 2010, Knutson et al. 2010), rainfall rates (Knutson et al. 2010), and winds (Elsner et al. 2008). The most devastating impacts derived from TCs on the Mexican Pacific coasts are associated with very extreme rainfall events (some of them >200 mm d^{-1}) (e.g. Romero-Vadillo et al. 2007, Farfan et al. 2013), but not necessarily to intense, i.e. category 4 to 5 hurricane (HUR4–5) landfalls (Farfan et al. 2013), at least not during 1970–2010.

The objective of the present study is to investigate interannual (ENSO) and decadal (AMO, PDO) mechanisms that may help understand possible differences in the variability of the total frequency of intense HUR4–5 and weak, i.e. category 1 to 3 (HUR1–3) hurricanes in the EPAC during 1970–2010. A particular objective is to investigate if there are significant differences between the hurricane characteristics during Neutral conditions, and those occurring during the extreme phases of ENSO. Preliminary results of the mean size of the WHWP derived from 6 general circulation models (GCMs; see Table 1) of the Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor et al. 2012) during the historical period are also discussed.

Section 2 describes the data and methodology used. Section 3 explains the interannual variability and impacts of weak and intense hurricane occurrences in the EPAC, as well as their possible relationship with ENSO and decadal climate patterns. Section 4 discusses the main results and conclusions of this work.

2. DATA AND METHODOLOGY

The focus of this study is on all TCs that reached hurricane strength (categories 1 to 5, HUR1–5) during their lifetime in the MDR of the EPAC (Fig. 1) during the satellite era (after 1970). Satellite imagery and the Dvorak technique to estimate hurricane intensity were not available until 1963 and 1970, respectively (Dvorak 1975, Whitney & Hobgood 1997, Kossin et al. 2007). Kossin et al. (2007) argues that the existing global hurricane records are too inconsistent to accurately measure long-term trends, especially before the satellite era. Thus, hurricane data after 1970 is considered more accurate than before, especially in the Atlantic and EPAC basins (Landsea et al. 2006, Kossin et al. 2007).

Data for the EPAC was obtained from the National Hurricane Center/Tropical Prediction Center Hurricane Best Track Dataset (HURDAT) for the TC season (May 15 to November 30) during 1970–2010. Kossin et al. (2007) have demonstrated the reliability of this dataset when compared with reconstructed data using an algorithm applied to satellite imagery. From HURDAT, we used the hurricane frequency and maximum sustained winds. The annual ACE (Bell et al. 2000) convolves intensity and duration information for each individual TC, and was calculated for the entire hurricane season as the sum of the squares of 6 hourly wind speeds >35 knots (kn) (≈18 m s^{-1}).

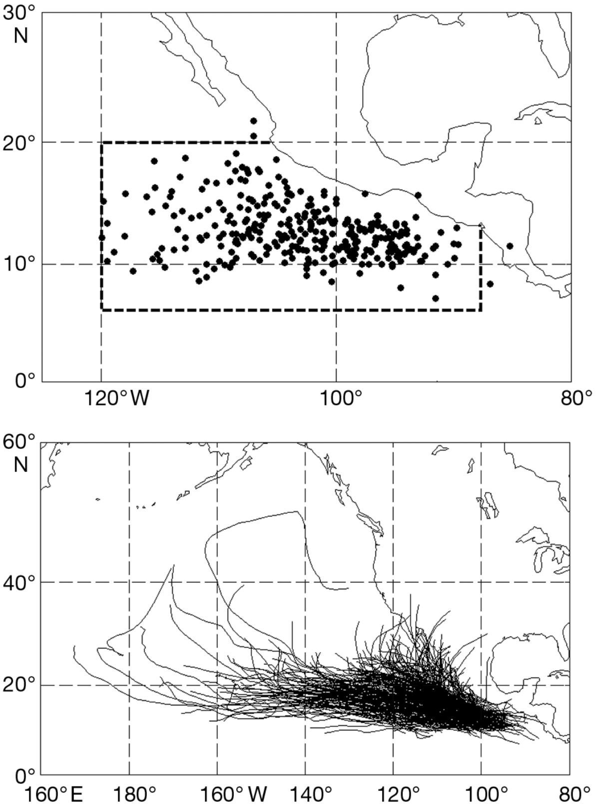

Fig. 1. First position (top) and trajectories (bottom) of all hurricanes (categories 1 to 5) in the main development region (rectangle) of the Eastern Tropical Pacific during May–November of 1970–2010

Hurricane landfalls on the west coast of Mexico were considered at the intersection of the surface center of the storm with a coastline; these landfalls were corroborated with the TC impacts database from the Mexican National Weather Service (Servicio Meteorológico Nacional, SMN) (SMN 2011). A total of 43 hurricane landfalls (8 of categories 3 and 4 HUR1–2, and 35 of categories 1 and 2 HUR3–4) are considered, while the SMN reports 45 landfalls (8 of HUR3-4, and 37 of HUR1-2). No hurricane made landfall as category 5. The discrepancy with the SMN database is that SMN has 2 more HUR1–2 (Orlane in 1974 and Isis in 1998), which both had 2 landfalls; the first landfall in both cases was as a TS and that is what we considered in our counting; the SMN also considered the second landfall, but we did not. Including these 2 extra landfalls in our counting does not change the general results presented here. Weinkle et al. (2012) report 47 landfalls in the same period (9 of HUR3–5, and 38 of HUR1–2).

A generalized Pareto distribution was used to estimate the return levels of extreme winds during hurricane landfalls using the Extreme Toolkit software package in R (extRemes), which is freely available at www.isse.ucar.edu/extremevalues/evtk.html (Gilleland & Katz 2011). The Poisson analyses performed in the present article were also done in R.

A Poisson distribution, which describes the number of independent discrete events, such as small hurricane counts occurring in a period of time, was used to determine the hurricane landfall probability on the Mexican Pacific coasts during the ENSO phases, similar to Bove et al. (1998) and Katz (2002):

$$P(x) = \mathrm{e}^{-\lambda}\lambda^{x}/x! \qquad (1)$$

In this case, x corresponds to the number of landfall hurricanes, and λ (the Poisson parameter) is the average number of landfalling hurricanes during each ENSO phase. A chi-squared goodness-of-fit test was first used to determine if the probability distribution of landfalling hurricanes and the annual frequency of hurricanes during the ENSO phases followed a Poisson distribution (null hypothesis), using $p \leq 0.05$ as the level of significance. The null hypothesis was accepted in all cases.

Nonlinear trends in annual hurricane frequency were obtained using the Poisson regression for the expected number of hurricanes (λ) as a function of time (t = 1 to 41 yr) (Katz 2002, Smith & Katz 2013):

$$\ln \lambda(t) = a + b\,(t) \qquad (2)$$

where a (the intercept) and b (the trend) are parameters to be estimated from the data. The statistical significance of the relationship was obtained with the residual deviance test and a z-test for the coefficients. Trends were also obtained using Sen's slope estimator (Sen 1968), and the statistical significance with the nonparametric Mann-Kendall test (Kendall 1975) with an adjustment for tied observations. The trend results were similar with the 2 tests.

A Mann-Whitney *U* (Mann & Whitney 1947) nonparametric test was used to determine statistically significant ($p \leq 0.05$) differences between the mean annual frequencies of HUR1–3 and HUR4–5 during ENSO phases. To analyze the interannual variability of hurricane activity, the Oceanic El Niño Index (ONI; from the Climate Prediction Center and the Physical Sciences Division of the Earth System Research Laboratory, both at NOAA) in the El Niño 3.4 region averaged during the hurricane season (May–November) was used. EN and LN are defined by an average ONI ≥ +0.5°C and ONI ≤ −0.5°C, respectively, during overlapping 3 mo seasons. Neutral conditions are defined as ONI values between −0.5°C and +0.5°C. Seasonal values of the AMO (www.esrl.noaa.gov/psd/data/correlation/amon.us.

Table 1. General circulation models (GCMs) used in this study. Data available at http://pcmdi9.llnl.gov/esgf-web-fe/

Institute, country	Model ID	Resolution	Realizations	Period available
Canadian Centre for Climate Modeling and Analysis, Canada	CanCM4	3.7° × 3.7°	5	1961–2005
The First Institution of Oceanography, China	FIO-ESM	2.81° × 2.81°	3	1850–2005
Geophysical Fluid Dynamics Laboratory, USA	GFDL-ESM2G	2.0° × 2.25°	1	1861–2005
Geophysical Fluid Dynamics Laboratory, USA	GFDL-ESM2M	2.0° × 2.25°	1	1961–1995
Met Office Hadley Centre, UK	HadCM3	2.5° × 3.75°	5	1859–2005
National Institute of Meteorological Research, Korea	HadGEM2-AO	1.25° × 1.875°	1	1860–2005

data) and the PDO (www.esrl.noaa.gov/psd/data/correlation/pdo.data) indices during the hurricane season were also used. The relationship between hurricane frequency (the response) and each of the independent indices (ONI, PDO, or AMO) was estimated using a generalized linear model with a Poisson regression (e.g. Collins & Mason 2000, Elsner & Bossak 2001). Time (*t*) was included as an independent variable in the model to eliminate any long-term trends. The expected number of hurricanes (λ) based on an individual index (ONI, PDO, or AMO) is given by:

$$\ln(\lambda) = a + b\,Index + c\,t \qquad (3)$$

where *a*, *b*, and *c* are parameters to be estimated from the data. Similar to Collins & Mason (2000), a 2-tailed *t*-test on the ratio of *b* to standard error (*b*/SE) was used to determine the statistical significance of the relationship in Eq (3). For 38 df, $|b/\mathrm{SE}|$ must be greater than 2.02 to be statistically significant at $p \leq 0.05$.

Mean seasonal composites of vertical zonal WS at 850–200 hPa and zonal winds at 925 hPa from the National Centers for Environmental Prediction and National Center for Atmospheric Research reanalysis (Kalnay et al. 1996) were analyzed for the period July–September during the ENSO phases over the Intra-Americas Seas region. Although this dataset has a coarse resolution, Collins & Mason (2000) used it to investigate TCs in the EPAC during the 1972–1997 period, and found physically consistent relationships.

Monthly SSTs from the NOAA Extended Reconstructed SST v3b (ERSST_v3; Smith et al. 2008) and from historical simulations of 6 GCMs (Table 1) of the CMIP5 (Taylor et al. 2012) were used to compute the SST annual cycle in the MDR and the average size of the WHWP during the 1961–2000 historical period. The GCM data is available on the website of the Program for Climate Model Diagnosis and Intercomparison (http://pcmdi9.llnl.gov/esgf-web-fe/).

3. RESULTS

3.1. Hurricane frequency and ACE

Ninety percent of the hurricanes of the EPAC basin originate in the MDR (Fig. 1; 8–20° N, 88–120° W), and the most active months of the season are July, August, and September, accounting for 71% of the total HUR1–5 activity. Forty-three hurricanes (13.5%) landed on the Mexican Pacific coasts (counted according to category at landfall [N_L]; Table 2) in the period August–October.

To compare the descriptive statistics in Table 2, we selected 16 yr of the current inactive period (1995–2010) and 16 yr before that (1979–1994), which are part of the active EPAC TC period that began in 1970 (e.g. Wang & Lee 2009, Maue 2011). A larger

Table 2. Total frequency (N), hurricane days (HDAYS), and accumulated cyclone energy (ACE; $\times 10^4$ kn^2) of weak, i.e. category 1–3 (HUR1–3) and intense, i.e. category 4–5 (HUR4–5) hurricanes during the partial active (1979–1994) and inactive (1995–2010) hurricane periods of the Eastern Tropical Pacific. Also shown is the total frequency of hurricanes that made landfall on Mexican Pacific coasts based on the maximum category during evolution (N_{Lmax}) and the category at landfall (N_L)

Period	HUR1–5	HUR1–3					HUR4–5				
	N (% of total)	N (%)	HDAYS	ACE	N_{Lmax}	N_L	N (%)	HDAYS	ACE	N_{Lmax}	N_L
1970–2010 (41 yr)	319 (100)	230 (72)	7.1	2248	52	40	89 (28)	10.1	2451	18	3
1979–1994 (Active, 16 yr)	150 (47)	106 (71)	7.6	1123	19	17	44 (29)	10.6	1230	7	0
1995–2010 (Inactive, 16 yr)	98 (31)	69 (70)	6.9	611	17	14	29 (30)	9.9	833	9	1

frequency of HUR1–5 (above the upper quartile) occurred during the active period in 1970–1994 in the MDR, followed by a reduced period after 1994 (Fig. 2, Table 2); this later shift is coincident with the transition of the AMO to a warm phase in 1995 and the beginning of an active TC period in the NATL (e.g. Bell & Chelliah 2006, Wang & Lee 2009). The total frequency of all hurricanes (HUR1–5) in the MDR shows a significant nonlinear trend (from Eq. 2) of $-0.95\%\ \mathrm{yr}^{-1}$ at $p \leq 0.05$, which is also observed in the frequency and ACE of HUR1–3. This corresponds to approximately a 39% reduction of the hurricane frequency in the 41 year period.

A total of 319 HUR1–5 ($\sim 7.8\ \mathrm{yr}^{-1}$) developed in the MDR during May–November of 1970–2010, with a consistent proportion of about 70% being HUR1–3 and 30% were HUR4–5, and also, HUR4–5 lasting 3 more days on average than HUR1–3 in any of the periods in Table 2, and in any ENSO phase. Interestingly, even though the inactive period has fewer hurricanes (N = 98; Table 2), it has proportionally slightly more landfalls on Mexican coasts ($N_L = 15$; 15.3% of 98) than the active period ($N_L = 17$; 11.3% of 150), but landfall frequency does not show a significant trend.

In the 1990s, during the transition from an active to an inactive period, there was a significant increase in the number of HUR4–5, with 7 years above the median frequency and 4 years exceeding the upper quartile (1 in a Neutral year and 3 during EN; Fig. 2c). The ACE values of the 1990s are also the largest of the study period, with 2 years characterized by Neutral conditions and 4 by EN conditions. This increase in intense hurricanes in the 1990s has been also identified in other basins (Webster et al. 2005, Kossin et al. 2007, Maue 2011).

Although the study period (41 yr) is not long enough to fully evaluate decadal hurricane variations and trends, Poisson regressions (Eq. 3) were used to determine the significance of the relationship between annual hurricane frequency and decadal and

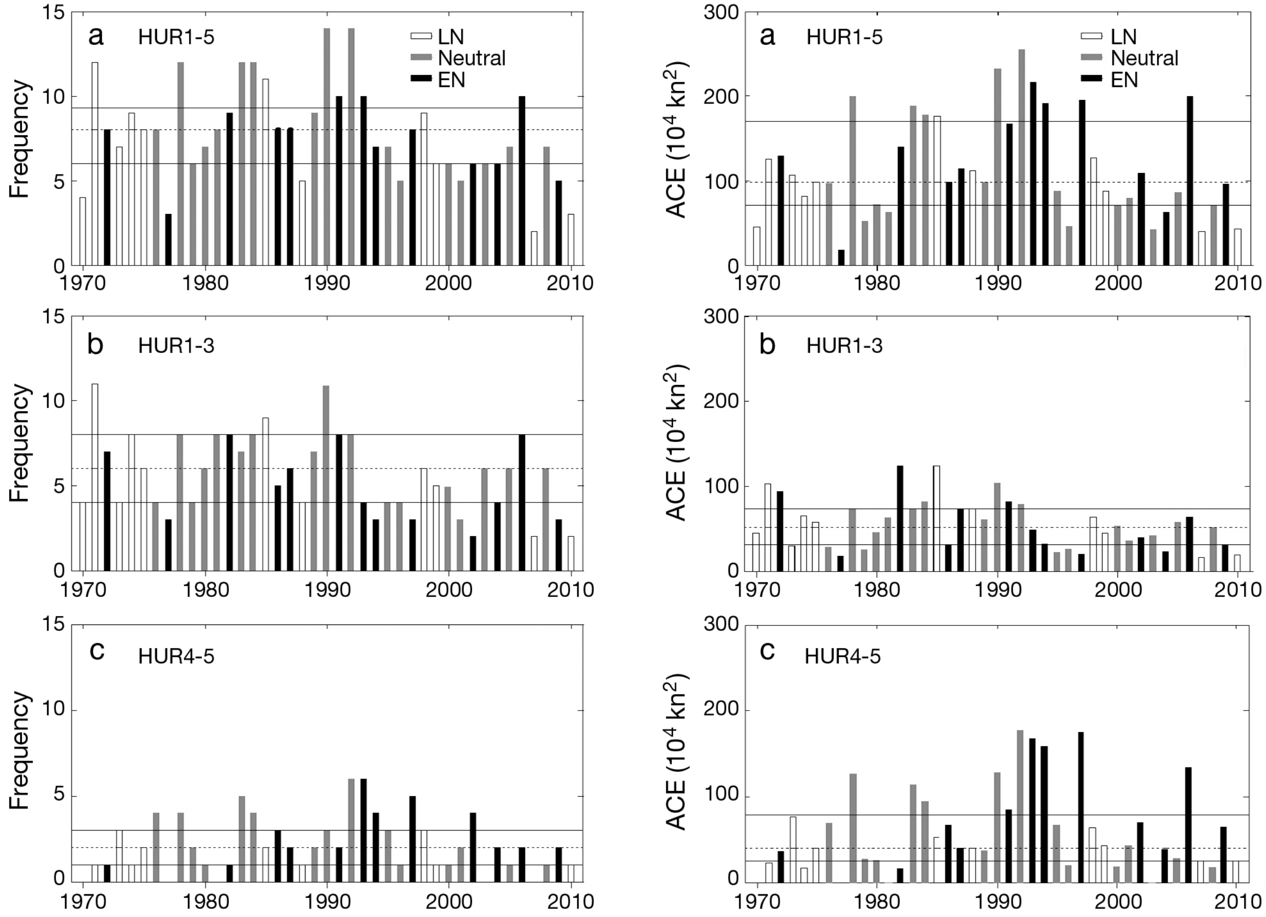

Fig. 2. Annual (May–November) frequency (left) and accumulated cyclone energy (ACE) values (right) of hurricanes in the main development region of the Eastern Tropical Pacific: (a) all, i.e. categories 1 to 5 (HUR1–5), (b) weak, i.e. categories 1 to 3 (HUR1–3), and (c) intense, i.e. categories 4 to 5 (HUR4–5). Solid horizontal lines indicate lower and upper quartiles; middle broken line is the median. LN: La Niña; EN: El Niño

interannual indices. HUR4–5 is negatively associated with AMO (b/SE = –2.2, $p \leq 0.0285$) and positively with PDO (b/SE = 3.45, $p \leq 0.0005$) and ONI (b/SE = 1.92, $p \leq 0.0546$). Similar signs, but weaker relationships ($p \leq 0.1$) were also obtained between HUR1–5 and AMO and PDO. The PDO shifted to a positive phase after 1978 (during an active hurricane period) and to a cold phase after 1999 (4 yr after the inactive period had begun). The mean number of hurricanes per year in the MDR during the last warm (1978–1998) and the current cold (1999–2010) PDO phases are 8.7 and 6.5, respectively. Collins & Mason (2000) performed a similar analysis for the 1972–1997 period; they did not find a significant relationship with PDO (possibly because the current cold phase was not included), but they found a significant relationship between an ENSO index and all hurricanes west of 116° W.

3.2. Hurricane impacts on Mexican Pacific coasts

Almost all hurricane trajectories in the EPAC show a westward displacement, but occasionally re-curve to the east and northeast, affecting the west coasts of Mexico and the southwest USA (Fig. 3). On average, ~1 hurricane yr^{-1} made landfall on Mexican coasts during 1970–2010, consistent with data from Weinkle

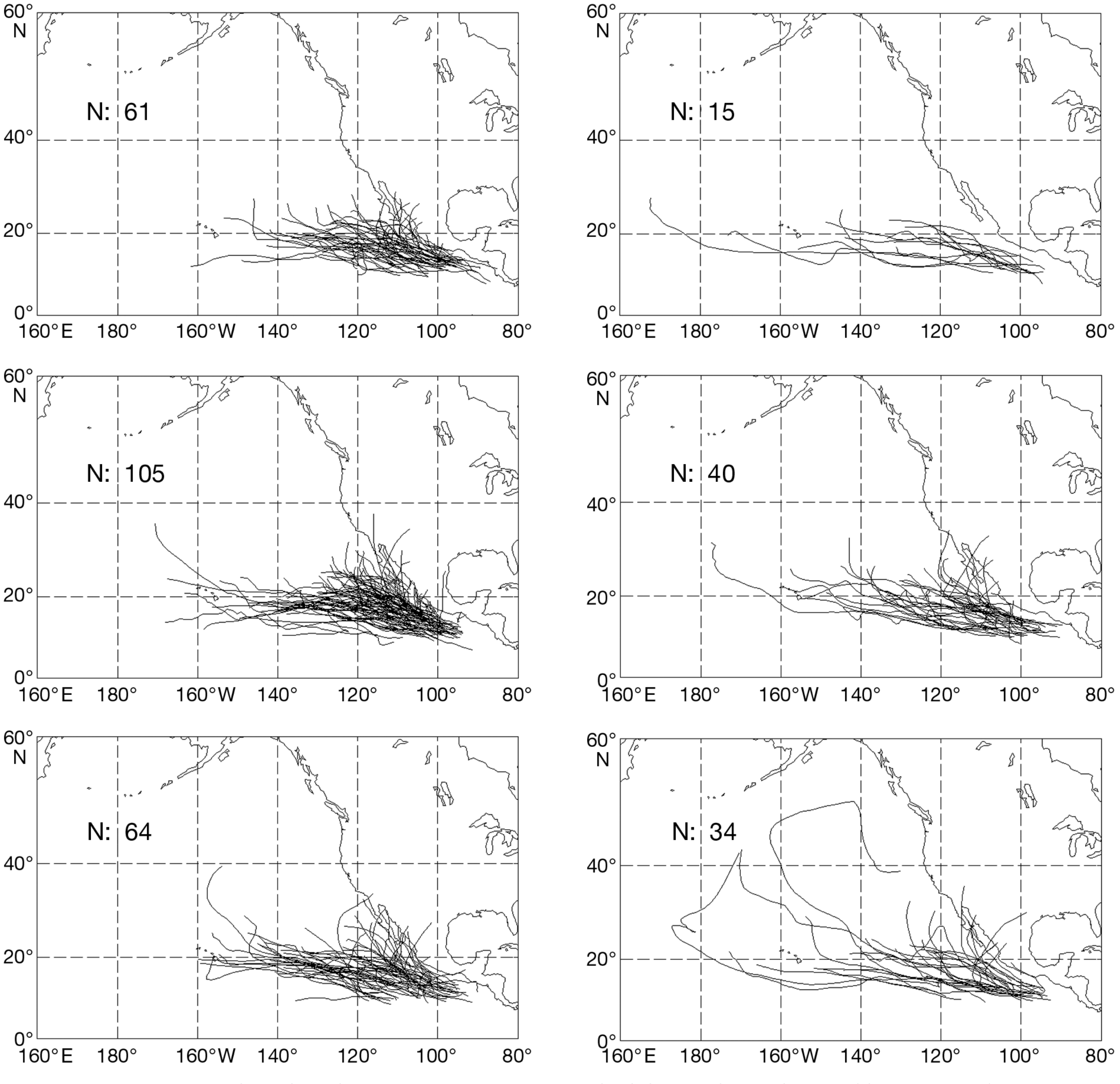

Fig. 3. Hurricane trajectories based on the maximum category reached during the evolution of hurricanes of categories 1 to 3 (HUR1–3; left) and categories 4 to 5 (HUR4–5; right) during 12 La Niña (top), 17 Neutral (center), and 12 El Niño (bottom) events during May–November of 1970–2010. N: total hurricane frequency

Table 3. Total number of tropical depressions/tropical storms (TD+TS), category 1–3 hurricanes (HUR1–3), and category 4–5 hurricanes (HUR4–5) of the main development region that landed on Mexican Pacific states during May–November of 1970–2010, based on the category at landfall (N_L; see Table 2)

Mexican state	TD+TS	HUR1–3	HUR4–5	Total
Baja California Sur (BCS)	17	16	0	33
Sinaloa (SIN)	9	10	0	19
Michoacán (MIC)	5	4	0	9
Guerrero (GRO)	5	2	Madeline, 1976	8
Oaxaca (OAX)	6	2	0	8
Jalisco (JAL)	3	3	0	6
Nayarit (NAY)	2	0	Kenna, 2002	3
Colima (COL)	3	2	0	5
Baja California (BCN)	1	0	0	1
Chiapas (CHP)	3	0	0	3
Sonora (SON)	0	1	Liza, 1976	2
Total	54	40	3	97

Table 4. Total frequency of category 1–5 hurricanes (HUR1–5) that made landfall on Mexican Pacific states based on the category at landfall (N_L; see Table 2), separated by ENSO phases. State codes as in Table 3

State	La Niña	Neutral	El Niño	Total
BCS	4	7	5	16
SIN	3	3	4	10
MIC	1	3	0	4
GRO	0	3	0	3
JAL	1	1	1	3
COL	0	2	0	2
SON	0	1	1	2
OAX	0	0	2	2
NAY	0	0	1	1
Total	9	20	14	43
Average per event	0.75	1.18	1.17	

et al. (2012). The most favorable TC landing area of the EPAC is near the entrance of the Gulf of California (Table 3, Fig. 4), with similar landfall occurrences during Neutral and EN years, and fewer landfalls during LN (Table 4, Fig. 5). Hurricane landfalls are most active in the last months of the TC season, during September (34 %) and October (34 %) (Fig. 5a). The Poisson probability (Eq. 1) in Fig. 5b also shows a greater probability of no hurricane landfalls during LN years and a larger probability of 1 or more hurricane landfalls during Neutral years followed by EN years, consistent with the data in Table 4. Averaged wind speeds at landfall on Mexican coasts are more intense during EN (45 m s^{-1}, category 2) and Neutral (43 m s^{-1}, category 2) years than during LN (38 m s^{-1}, category 1). Average wind speeds greater than 58 m s^{-1} (category 4) at landfall have only occurred during Neutral and EN years, which, based on generalized Pareto distribution estimates (e.g. Jagger & Elsner 2006), show a return period of 10 yr.

3.3. Hurricane characteristics during ENSO phases

According to ONI data, a total of 12 LN, 17 Neutral, and 12 EN events occurred during May–November of 1970–2010. Considering all HUR1–5, Neutral years show significantly more hurricanes (mean annual frequency [F] = 8.7 yr^{-1}; Table 5) in the MDR than EN (F = 7.3 yr^{-1}) or LN (F = 6.9 yr^{-1}) years; however, the mean frequency of intense HUR4–5 is similar during Neutral and EN years (F = 2.5 and 2.3 yr^{-1}, respectively), while it is significantly lower during LN years (F = 1.5 yr^{-1}). On the contrary, Whitney & Hobgood

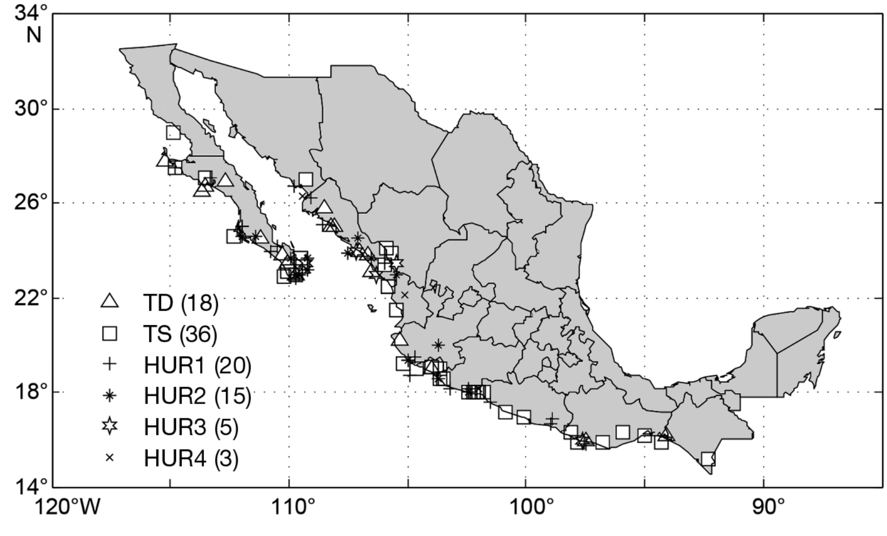

Fig. 4. Total number and position of the 97 tropical cyclones (TCs) that made landfall on the west coast of Mexico during 1970–2010. TCs may land several times with a different category and in different states. The TCs include tropical depressions (TD), tropical storms (TS), and hurricanes (HUR1–4): hurricanes of categories 1–4). See Table 3 for a breakdown by Mexican state

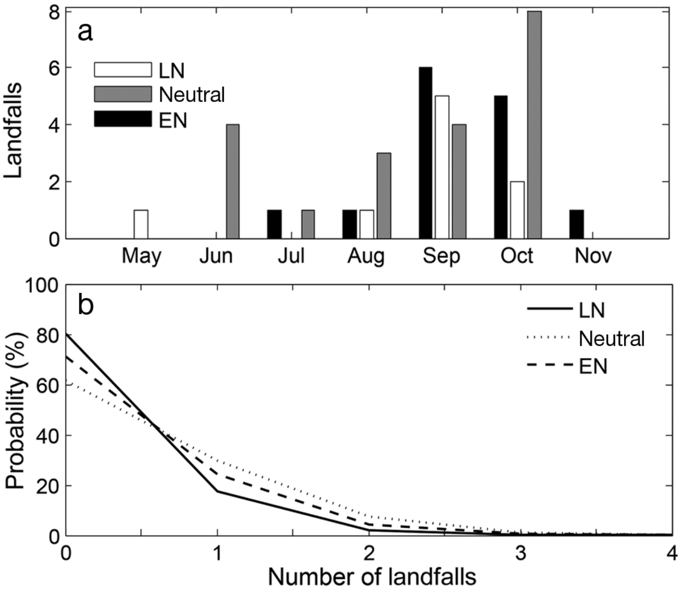

Fig. 5. (a) Seasonal number of hurricanes of categories 1 to 5 (HUR1–5) that made landfall on the west coast of Mexico during La Niña (LN), Neutral, and El Niño (EN) years during 1970–2010, and (b) associated Poisson probability of the number of landfalling HUR1–5 on the west coast of Mexico based on the category at landfall (N_L; see Table 2) for the 3 ENSO phases

(1997) evaluated all TCs (TS, tropical depressions [TD], and hurricanes) during 1962–1993, but found no differences in the frequencies and intensities during EN and non-EN years. The ACE of HUR1–3 is fairly similar during the 3 ENSO phases, but the ACE of HUR4–5 is larger during EN than Neutral and LN events (Table 5), consistent with Camargo et al.'s (2008) results.

Interannually, the MDR of the EPAC is characterized by SSTs between 27.5 and 29°C and WS values between 3.5 and 10.5 m s^{-1} during the peak hurricane season (July–September) (Fig. 6). The transition from cooler SSTs during LN to warmer SSTs during EN shows a weak negative relationship with WS, with the variability of SSTs and WS being larger during LN and Neutral conditions than in EN events (Fig. 6). The hurricane season during LN events are characterized by the smallest WHWP in the EPAC and the largest WHWP in the NATL (Fig. 7 top, Table 6), while EN summers show the opposite, and Neutral years fall in the middle, as expected. These conditions result in large WS in the EPAC and small WS in the NATL during LN (Fig. 7), while the opposite is observed during EN. As a consequence, weaker HUR4–5 activity ($p \leq 0.1$) is observed during LN than during EN and Neutral summers (Table 5). Moreover, there are no HUR4–5 landfalls on the Mexican coasts during LN (Fig. 3), and the hurricane trajectories are farther away from the coast and found at much lower latitudes than those occurring during Neutral and EN summers. Conversely, during EN, HUR4–5 show longer and more extratropical trajectories (Fig. 3) than during Neutral summers, consistent with data in Camargo et al. (2008) and Kim et al. (2011), possibly due to the larger expansion of the WHWP, much weaker WS in the EPAC (Fig. 7 left), and weaker North Pacific anticyclone (not shown) during EN. On the NATL side, the small size of the WHWP during EN summers is accompanied by strong low-level trade winds (<–10 m s^{-1}; Fig. 7 right), typical of a strong Caribbean Low-Level Jet (CLLJ; Mendez & Magaña 2010). The CLLJ in Fig. 7 is ~3 m s^{-1} weaker during Neutral and LN years than during EN.

Seasonal (July–September) conditions in the MDR that favor a higher hurricane frequency (>7.7 yr^{-1} above the average) are WS values between 3 and 7 m s^{-1} (no significant trend) and SSTs between 28 and 28.7°C. Past studies have indicated that strong WS (>8 m s^{-1}) inhibits the development of TCs and may reduce their intensity (e.g. Goldenberg et al. 2001, Camargo et al. 2007). SSTs in the MDR of the EPAC show a statistically significant increase of ~0.57°C during July–September of the study period, consistent with results from Santer et al. (2006), Webster et al. (2005), Elsner et al. (2008), and Ralph & Gough

Table 5. Mean annual frequency (F), lower and upper quartiles (q1, q2), median (m), mean hurricane days (HDAYS), and mean accumulated cyclone energy (ACE; ×10^4 kn^2) of category 1–3 (HUR1–3) and category 4–5 (HUR4–5) hurricanes that formed in the main development region of the Eastern Tropical Pacific during La Niña, Neutral, and El Niño events, based on the maximum hurricane category reached (see Fig. 3) during 1970–2010

ENSO phase	HUR1–5	HUR1–3						HUR4–5					
	F	q1	F	m	q2	HDAYS	ACE	q	F	m	q2	HDAYS	ACE
La Niña	6.9	4.0	5.4	4.5	7.0	7.0	55.2	1.0	1.5	1.0	2.5	10.0	37
Neutral	8.7	4.0	6.2	6.0	8.0	7.2	56.0	1.0	2.5	2.0	4.0	10.2	64
El Niño	7.3	3.0	5.0	4.5	7.5	7.2	52.8	1.5	2.3	2.0	3.5	10.1	74
Average	7.7	3.7	5.5	5.0	7.5	7.1	54.7	1.2	2.1	1.7	3.3	10.1	58.3

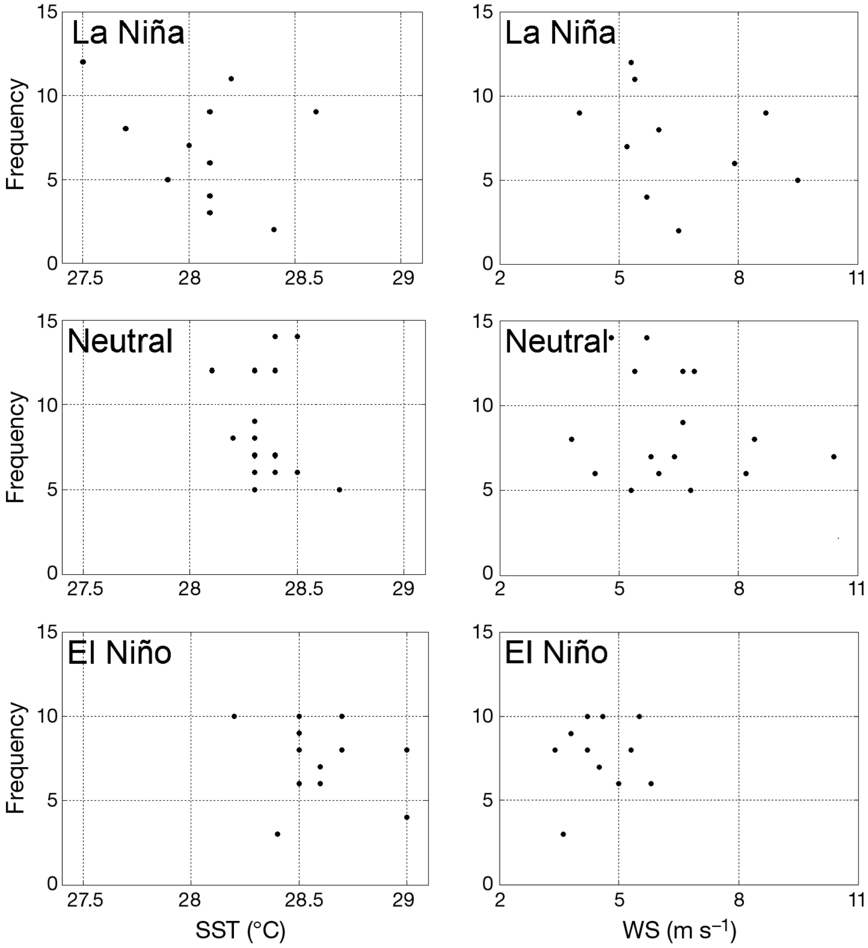

Fig. 6. Annual frequency of hurricanes of categories 1 to 5 (HUR1–5) during May–November of 1970–2010 and their relationship with mean seasonal (July–September) values of sea surface temperature (SST; left) and wind shear (WS; right) in the main development region of the Eastern Tropical Pacific during 12 La Niña (top), 17 Neutral (middle), and 12 El Niño (bottom) events. Some datapoints overlap. WS data is shown until 2007

(2009) for slightly different periods. Future projections based on theory and dynamical models indicate that hurricanes may become more intense under warming conditions (e.g. Knutson & Tuleya 2004, Emanuel 2006, Knutson et al. 2010). The observed frequency of HUR4–5 in the EPAC does not show a significant trend, consistent with what Kossin et al. (2007) found. Preliminary SST results of 6 GCMs of the CMIP5 dataset (Table 1) show that the mean GCM ensemble (ens_GCM) has a weaker WHWP than observed during 1961–2000 (Table 7). Climatologically, the WHWP is larger in the NATL than in the EPAC, but the size varies according to the period analyzed (Tables 6 & 7). The mean ens_GCM greatly overestimates the size of the WHWP in the EPAC but underestimates it in the NATL, producing, on average, an enhanced EN-type WHWP, with a cooler than normal NATL during the TC season. The GCM that best reproduced the size (not shown) and annual cycle of the warm pool in the EPAC (Fig. 8) is the relatively fine-resolution model HadGEM2-AO, which has been found to reproduce well the intraseasonal variability of the EPAC (Jiang et al. 2013), but Sheffield et al. (2013) found that HadGEM2 was unable to reproduce the frequency of TCs, possibly because its resolution is not fine enough (Table 1) and because the model has strong biases in the NATL (e.g. Kozar & Misra 2013).

4. SUMMARY AND DISCUSSION

This study investigated differences and trends in the frequency and ACE of weak HUR1–3 and intense HUR4–5 hurricanes in the MDR of the EPAC and their possible relationship with ENSO, PDO, and the AMO. Since there are few studies focused on the possible role of Neutral conditions on hurricanes of the EPAC, a particular objective was to determine the differences between Neutral conditions, and EN and LN during the peak hurricane season (July–September). The interannual (ONI) and decadal relationships (AMO, PDO) obtained here differ from other studies that have analyzed all TCs, or that have separated the TCs by regions of development and for different periods (e.g. Whitney & Hobgood 1997, Collins & Mason 2000, Gutzler et al. 2013). We considered a single MDR (Fig. 1) where 90% of the hurricanes of the EPAC developed during 1970–2010, with a consistent proportion of about 70% being HUR1–3 and 30% were HUR4–5, and lasting on average 7 and 10 d respectively in any period and ENSO phase analyzed. There is, on average, a higher annual frequency of HUR1–5 during Neutral conditions (8.7), followed by EN (7.3) and LN (6.9), but the frequency of HUR4–5 is similar during Neutral and EN years, and significantly lower during LN (Table 5). There was on average 1 hurricane landfall per year, and most of them occurred during September–October (68%), with larger occurrences during Neutral, followed by EN and LN years. In contrast,

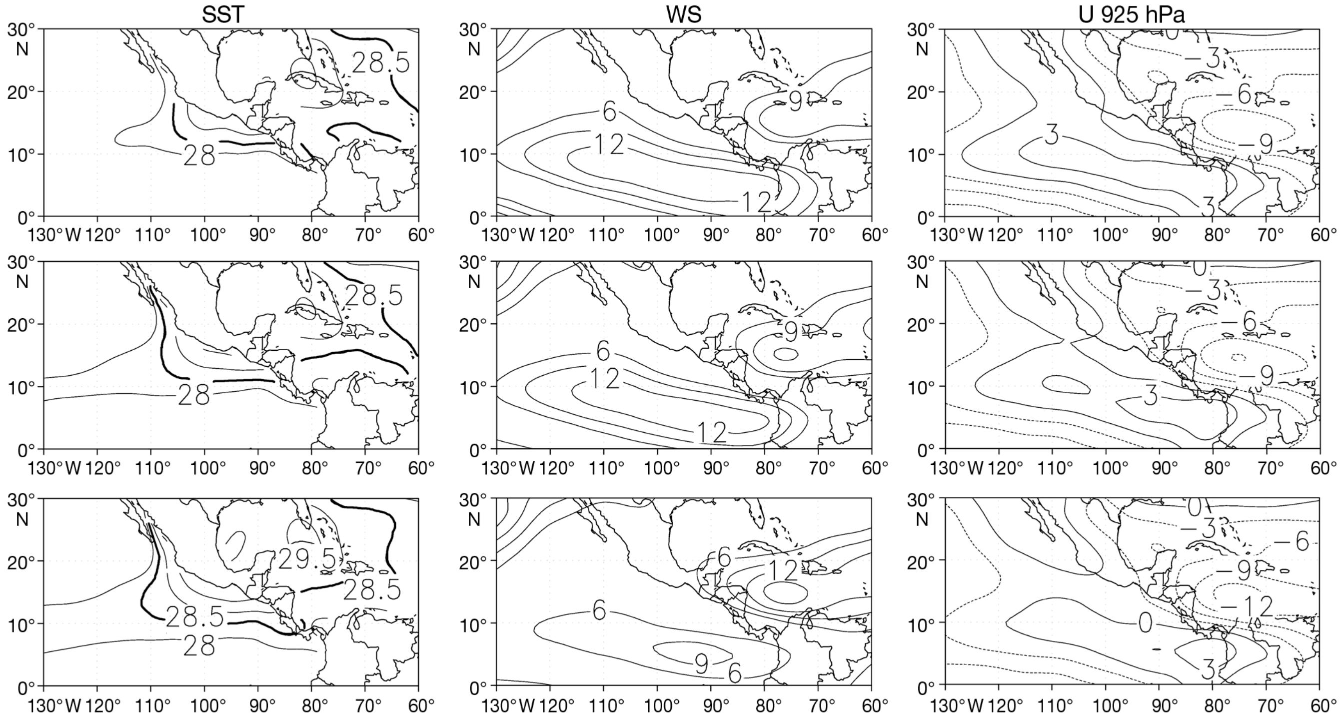

Fig. 7. Mean seasonal (July–September) composites of sea surface temperature (SST; left; °C), wind shear (WS; center; m s^{-1}), and zonal wind at 925 hPa (U 925hPa; right; m s^{-1}) during La Niña (top), Neutral (center), and El Niño (bottom) events of 1970–2010. The 28.5°C isotherm is highlighted. Only contours of SST ≥ 28°C and WS ≤ 6 m s^{-1} are plotted. Broken lines indicate negative values

Table 6. Enclosed area (×10^6 km^2) by sea surface temperatures (SSTs) warmer than 28.5°C, representing the Western Hemisphere Warm Pool, in the Eastern Tropical Pacific (EPAC) and North Atlantic (NATL) basins during July–September of the ENSO phases of study period 1970–2010 (see Fig. 7). (Data from the NOAA Extended Reconstructed SST v3b dataset: ERSST_v3)

Event	EPAC	NATL	Total
La Niña	1.4	6.3	7.7
Neutral	1.8	5.4	7.2
El Niño	2.4	4.6	7.0
Average	1.9	5.4	7.3

Table 7. Same as Table 6, but for the average size (×10^6 km^2) of the Western Hemisphere Warm Pool in the Eastern Tropical Pacific (EPAC) and North Atlantic (NATL) basins according to observed NOAA Extended Reconstructed SST v3b (ERSST_v3) and the mean ensemble (ens_GCM) of the 6 general circulation models (GCMs) in Table 1 for the historical period 1961–2000. SST: sea surface temperature

SST	EPAC	NATL	Total
ERSST_v3	2.1	4.2	6.3
ens_GCM	3.4	2	5.4

Gutzler et al. (2013) found that during the period 1951–2006, near-coastal TCs of the EPAC occurred more often in the period May–July during LN years. Hurricane landfalls account for almost 50 % of all TC landings (Table 3); this, and the different period of analysis, may be responsible for the apparent difference between the 2 studies, which would be worth exploring in the future.

A negative trend of HUR1–5 in the MDR is linked to active and inactive hurricane periods during 1970–1994 and 1995–2010 respectively, which are partially associated with a cold–warm phase of the AMO and with a warm–cold phase of the PDO. The negative trend is consistent with a decrease in the power dissipation index (PDI) documented by Kossin et al. (2007). Maue (2011) also attributes the recent inactive hurricane period in the EPAC to the negative phase of the PDO and the occurrence of several LN events. However, it should be noted that frequency of hurricane landfalls on the west coasts of Mexico during 1970–2010 was independent of the activity period analyzed; an inactive hurricane period does not necessarily mean an inactive landfall period.

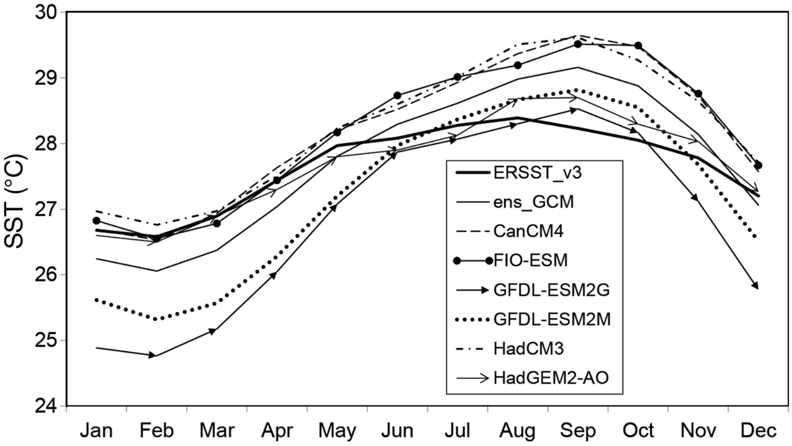

Fig. 8. Mean annual cycle of sea surface temperature (SST) averaged over the main development region of the Eastern Tropical Pacific during 1961–2000 for the observed NOAA Extended Reconstructed SST v3b (ERSST_v3) and the historical simulations of 6 general circulation models (GCMs; see Table 1) and their mean ensemble (ens_GCM)

Zhao & Chu (2006), using a Bayesian multiple point change analysis for the EPAC, proposed slightly different inactive–active–inactive hurricane periods: 1972–1981, 1982–1998, and 1999–2010, respectively.

The frequency and ACE of HUR4–5 do not have significant trends, but show stronger decadal (PDO and AMO) relationships than the HUR1–5. Moreover, the EN also favors the occurrence of HUR4–5 while the LN weakens it ($p \leq 0.0546$), consistent with findings by Lupo et al. (2008), Frank & Young (2007), and Kim et al. (2011). This is likely due to the large expansion of the WHWP in the EPAC and the lowest seasonal vertical WS in the region. In spite of that, the mean frequency of HUR4–5 and the mean number of landfalls of HUR1–5 are similar during EN and Neutral years. According to the ACE values, the most intense HUR4–5 (above the upper quartile in Fig. 2) occurred during 5 EN and 5 Neutral years. Based on maximum accumulated rainfall, Farfan et al. (2013) found that of the top 25 TCs making landfall in western Mexico during 1970–2010, the TCs that had the largest impact on Mexican coasts occurred during 4 EN, 5 Neutral, and 1 LN events. This evidence indicates that the strongest hurricanes (based on intensity or on their impacts) in the EPAC may occur either during EN or Neutral years. Understanding why the HUR4–5 statistics are similar during Neutral and EN years, and why, on average, there is a larger frequency of HUR1–5 during Neutral conditions than during EN years, would be intriguing to study.

Cyclogenesis in the EPAC is modulated by synoptic and intraseasonal mechanisms such as easterly waves (EW) and the Madden–Julian Oscillation (MJO; Collins & Mason 2000, Camargo et al. 2010, Barrett & Leslie 2009, Wang & Lee 2009). Maloney & Hartmann (2000) have shown that the MJO significantly modulates the environmental conditions in the EPAC, with a total frequency of HUR1–5 over 4 times larger during the westerly phases of the MJO than during easterly phases. Our results indicate that at seasonal scales, the mean low-level westerly winds in the EPAC tend to be stronger, and easterly winds in the NATL tend to be weaker, during Neutral conditions than in EN years (Fig. 7), possibly favoring more cyclogenesis in the EPAC than during EN.

Wang & Enfield (2001) argue that small changes in the WHWP during Neutral and EN conditions can induce large effects on tropical convection and cyclogenesis. The mean size of the WHWP in Neutral years is close to the climatological mean in both the EPAC and the NATL (Table 6), while during EN, the WHWP area in the NATL is the smallest of the 3 phases. During Neutral conditions, the 'large' size of the WHWP in the NATL possibly adds an extra mechanism that is not present during EN years. The tropical Atlantic teleconnects with the EPAC through EW activity and moisture fluxes from the Caribbean Sea (e.g. Molinari & Vollaro 2000, Mendez & Magaña 2010, Serra et al. 2010), which favor local cyclogenesis. EW activity is partially modulated by the CLLJ, and, according to Mendez & Magaña (2010), a strong CLLJ inhibits EW activity, while a weak CLLJ allows it, which also corresponds to less or more precipitation respectively in southern Mexico (Salinas-Prieto 2006, Martin & Schumacher 2011). The low-level zonal wind composite during EN (Fig. 7 right) is characterized by stronger low-level easterlies (strong CLLJ <-10 m s^{-1}) in the Caribbean than the Neutral composite (weak CLLJ >-10 m s^{-1}). Amador et al. (2006) also found that EN summers are characterized by a strong CLLJ. Moreover, several studies have also concluded that a strong CLLJ is associated with anomalously cold SSTs and a weak CLLJ with warm SSTs in the Caribbean (Wang & Lee 2007, Rauscher et al. 2011) through interactions with the NATL subtropical high (Wang et al. 2008), which would be consistent with a small WHWP in the NATL during EN and a large WHWP during LN in Fig. 7. Therefore, it is possible that diminished EW activity linked to a strong CLLJ and a small NATL warm pool during EN years may reduce an important dynamical mechanism in the MDR of the EPAC, resulting in fewer hurricane formations during EN compared to Neutral conditions. Therefore, understanding and predicting EPAC hurricane activity appears to depend on both the EPAC and NATL warm pools and intraseasonal variability, as also suggested by Wang & Lee (2009).

Our preliminary evaluation of the size of the WHWP using 6 GCMs of the CMIP5 shows that the majority of the GCMs overestimate the size of the EPAC warm pool and underestimate the size of the NATL warm pool during the summer. In agreement with our results, Kozar & Misra (2013) found that all CMIP5 models have a cold bias in the NATL during the summer, producing a stronger than normal CLLJ. Sheffield et al. (2013), who analyzed TC characteristics using 16 GCMs of the CMIP5, found that the majority of the models greatly underestimated the mean frequency of TCs in the EPAC and the NATL, but finer-resolution models were able to better capture the frequency of TCs. These results have strong implications for future climate projections of TCs and rainfall in the Intra-Americas Seas region. Regional dynamical modeling studies, such as the CORDEX-Centro America initiative (e.g. R. Fuentes-Franco et al. unpubl.), forcing the regional models with observed reanalyses and with GCMs that best reproduce intraseasonal (e.g. Jiang et al. 2013, Kozar & Misra 2013) and interannual (e.g. Sheffield et al. 2013) variability, are required to better understand the role of the different mechanisms involved in the modulation of TCs and rainfall in the region. More research is also needed to fully understand and to predict the important role of Neutral conditions in TC activity.

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