The 2009 Hurricane Season in the Eastern North Pacific Basin: An Analysis of Environmental Conditions

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ABSTRACT

Despite the presence of an intensifying El Niño event, the 2009 eastern North Pacific hurricane season was near normal when considering overall hurricane activity. This is in contrast to the relative lull in activity observed between 1998 and 2008. Previous research has noted that the eastern North Pacific should be subdivided into two development regions, the western development region (WDR; 10°–20°N, 116°W–180°) and the eastern development region (EDR; 10°–20°N, North American coastline to 115.9°W), when examining interannual hurricane variability. In 2009, the EDR saw below average numbers of tropical cyclones of all intensities, while the WDR saw near-normal activity. However, activity in both regions varied sharply from month to month with periods of high activity in August and October and lower activity in July and September. This monthly variability was also observed in primary environmental forcing factors such as total precipitable water, tropospheric vertical wind shear, and low-level relative vorticity, particularly for the WDR. This variability was obscured by simply examining seasonal means. It is shown that for the 2009 season, large-scale environmental factors forced by the El Niño event and two cycles of the Madden–Julian oscillation contributed strongly to the observed patterns of cyclone activity across the basin.

1. Introduction

When defined by genesis events per unit area and time, the eastern North Pacific basin is the most active region on earth for tropical cyclone formation (Molinari et al. 2000). The 2009 eastern North Pacific hurricane season was notable for a return to near-normal tropical cyclone (TC) activity in the basin; however, this average season was the second most active of the last decade.

The most well-known teleconnection to have an effect on ocean basins is the El Niño–Southern Oscillation (ENSO). Most simply defined as a quasi-cyclic variation in equatorial Pacific oceanic sea surface temperatures (SSTs) and trade winds (Rasmusson and Carpenter 1982) resulting in changes to the intensity and location of the Walker circulation (Wang 2002), ENSO has long been the focus of intense study. However, given its manifestation in multiple forms as a coupled oceanic–atmospheric phenomenon, there is no one universal definition for ENSO (Trenberth 1997). Indices classified by regional sea surface temperature anomalies are popular, specifically in the Niño-3, -4, and -3.4 regions, which straddle the equator from 5°N to 5°S and extend across the Pacific Ocean from 90°W to 160°E. The current National Oceanic and Atmospheric Administration (NOAA) operational index, the Oceanic Niño Index (ONI), is one example of this type of index. The Southern Oscillation index (SOI; Allan et al. 1991) utilizes sea level pressure (SLP), and the Multivariate ENSO Index (MEI; Wolter and Timlin 1993) utilizes SLP and additional parameters to represent ENSO. ENSO events vary in both intensity (Trenberth and Stepaniak 2001) and spatial location. Regardless of the definition used, it is understood that in addition to the direct link to changes in SST, ENSO also affects tropical cyclone variability by modifying the critical atmospheric parameters necessary for tropical cyclogenesis, specifically vertical wind shear, total precipitable water, relative humidity, SLP, and relative vorticity.

It has been found to be beneficial to split the eastern North Pacific basin into two tropical cyclone development regions at 116°W (Collins and Mason 2000). The eastern region, termed the eastern development region (EDR), was found by Collins and Mason (2000) to not exhibit any significant relationships on a seasonal scale

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with key dynamic and thermodynamic environmental parameters (such as ENSO) known to have an effect on the frequency of tropical cyclones in the Atlantic (Gray 1979; Namias 1954). Overall, mean atmospheric and oceanic conditions in the EDR are typically at or above thresholds necessary for tropical cyclone formation (Collins 2007), accounting for the muted link to ENSO. However, the western region, termed the western development region (WDR), was found to have significant interannual variations in tropical cyclone activity that are strongly linked to changes in thermodynamic parameters such as midtropospheric relative humidity, vertical velocity, total precipitable water, and sea level pressure (Collins and Mason 2000).

The Madden–Julian oscillation (MJO; Madden and Julian 1971; 1994) is a primary mode of near-equatorial convective activity directly related to tropical cyclogenesis from easterly waves in the eastern North Pacific basin. The magnitude of the waves entering the region has been deemed irrelevant; instead the phase of the MJO is suggested to be the primary factor in determining whether tropical cyclogenesis occurs (Molinari and Vollaro 2000). When the convectively active phase of the MJO is over the eastern North Pacific basin, easterly waves are able to amplify and undergo tropical cyclogenesis (Molinari et al. 1997); whereas during the inactive phase of the MJO, cyclone formation is at a minimum over the area. Maloney and Hartmann (2000) extensively profiled the impacts of the life cycle of the MJO in the eastern North Pacific by use of an index based on the 850-hPa equatorial zonal wind anomalies. They found that tropical cyclone counts and intensities vary concurrently with the phase of the MJO as a function of vertical wind shear and low-level relative vorticity. These facts were further corroborated by Camargo et al. (2008), who found that the MJO was the primary factor in the variability of tropical cyclogenesis in the eastern region of the basin with near-coastal tracks. While the amplitude of the MJO is at a minimum during the Northern Hemisphere summer (Hendon and Salby 1994), an eastward extension in MJO activity has been shown to occur during El Niño years in the Pacific (Kessler 2001) in association with the expanded oceanic warm pool.

The purpose of this paper is to detail the large-scale environmental factors associated with the variations in tropical cyclone activity throughout the eastern North Pacific basin and its two regions (WDR and EDR) in 2009. First examining monthly activity with respect to major atmospheric forcing mechanisms in each region, this work then expands to assess the impact of ENSO and the MJO on the 2009 eastern North Pacific basin hurricane season.

2. Data and methodology

The source for the tropical cyclone indices used in this study is the official historical tropical cyclone track database obtained from the Tropical Prediction Center (TPC)–National Hurricane Center (NHC) best-track file for the eastern North Pacific (Brown and Leftwich 1982; TPC 1998) basin. These data represent the most complete and reliable source of all eastern North Pacific tropical cyclones. The best-track data records were compiled from various publications and represent a rigorous, post-season analysis of all tropical cyclone intensities and tracks every 6 h. Data are considered reliable since 1972 in the eastern North Pacific when the Dvorak (1975) scheme for estimating the intensity of tropical cyclones was first used operationally (Whitney and Hobgood 1997). Categories of tropical cyclone development considered include tropical storm (17 m s^{-1}), hurricane (33 m s^{-1}), and intense hurricane (50 m s^{-1}) as measured by the maximum 1-min, 10-m sustained wind. As a measure of overall activity, net tropical cyclone activity (NTC) is considered. NTC is defined by Gray et al. (1994) as

$$\mathrm{NTC} = (\%\mathrm{NS} + \%H + \%\mathrm{IH} + \%\mathrm{NSD} + \%\mathrm{HD} + \%\mathrm{IHD})/6,$$

where each season's percentage values from the long period mean (1972–2001) is used for the six measures of seasonal activity [named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), intense hurricanes (IH), intense hurricane days (IHD)]. In addition, monthly and regional NTC are calculated and compared to the monthly and regional climatologies over the same time period. As such, the 1972–2001 average value of this parameter is 100 for both monthly and seasonal measures for the entire basin and its two regions. In addition, we calculate the accumulated cyclone energy (ACE), which is defined by Bell et al. (2000) as the sum of the squares of the maximum sustained surface wind speed (kt; 1 kt = 0.5144 m s^{-1}) measured every 6 h for all named systems while they are at least tropical storm strength and not extratropical in phase.

For tabulation of storm frequency, intensity, and duration statistics, the longitudinal location of each individual observation is the discriminating factor to determine which subregion it belonged to. All observations were divided by longitude along 116°W, the boundary between the EDR and WDR, with all observations and counts occurring in the east (west) counting in the EDR (WDR) for the purpose of NS, NSD, H, HD, IH, IHD, NTC, and ACE. While this does cause some storms that form in the EDR and travel in the WDR to be counted as named storms in both basins, duration statistics are not double counted. Care is taken to remove double counts in storm frequency statistics for full basin statistics.

The National Centers for Environmental Research–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) provides the data for the environmental variables investigated here including layer mean relative humidity from 500–700 hPa, pressure vertical velocity at 500 hPa, total precipitable water, vertical wind shear from 850–200 hPa, relative vorticity at 850 hPa, and SLP. These variables were chosen to examine thermodynamic as well as dynamic factors, and have been shown to have an important influence on hurricane frequency (Palmén 1948; Namias 1954; Riehl 1954; Gray 1979). After checking the distribution of atmospheric parameters for normality, significance testing of the resultant values to the 0.05 level was performed.

The NCEP–NCAR reanalysis project has two unique characteristics, the length of the period covered and the assembly of a comprehensive observational database. These factors make the data ideal for this study. The global data are available on a 2.5° × 2.5° latitude–longitude grid for many vertical levels (the number of which depends on the variable in question) and have a 6-hourly and monthly time resolution. Confidence in these data has been addressed by Collins and Mason (2000) and Kalnay et al. (1996). The monthly environmental data are also averaged over the months from July to October to correspond with peak tropical cyclone activity in the eastern North Pacific. In addition individual months are examined. All climatology values, regardless of dataset used, are calculated from the same 30-yr period: 1972–2001.

3. Results

a. 2009 eastern North Pacific tropical cyclone activity

Overall in 2009 twenty named storms formed in the eastern North Pacific basin, with eight reaching hurricane strength and five becoming intense hurricanes. Individual storm details of duration, peak intensity, and genesis location can be found in Table 1, with storm tracks in Fig. 1. While the overall named storm count ranked as above average, the occurrence of multiple short-lived, weaker storms contributed to the overall activity level of the season as measured by NTC (95.57) and ACE (124.32) to being near to slightly below normal (full storm statistics are in Table 2). These seasonal measures (NTC, ACE) are used to describe the nature of overall activity because of their composition, accounting for and weighting by both storm intensity and duration. Individual statistics such as named storms are not used to characterize the nature of the entire season because of their inability to differentiate between cyclones of different intensities and life spans. In particular, "named storms" equates the short-lived Tropical Storm Maka to one of the strongest cyclones ever observed in the region, Hurricane Rick, and as such clearly cannot be used alone to assess the activity level of a given year. However, 2009 represented a large increase in activity compared to the recent inactive period observed in the basin from 1998 to 2008 (with one active year, 2006, excluded), where on average only 14.2 named storms, 6.8 hurricanes, and 2.6 intense hurricanes formed, with a mean NTC value of 66.8 and mean ACE of 89.7. A histogram of ACE seasonal values from 1972–2009 can be seen in Fig. 2.

TABLE 1. Tropical cyclones which formed in the eastern North Pacific basin during the 2009 season (EDR: 10°–20°N, North American coast to 115.9°W; WDR: 10°–20°N, 116°W–180°). Category refers to maximum intensity reached on the Saffir–Simpson scale. Duration of cyclone refers to the dates during which the cyclone was tropical in nature and of at least tropical storm intensity.

Name	Tropical storm genesis region	Duration of cyclone	Category	Maximum intensity (kt)
Andres	EDR	21–24 Jun	H1	70
Blanca	EDR	6–9 Jul	TS	45
Carlos	EDR	10–16 Jul	H2	90
Dolores	EDR	15–17 Jul	TS	50
Lana	WDR	30 Jul–3 Aug	TS	55
Enrique	EDR	4–7 Aug	TS	55
Felicia	WDR	4–11 Aug	H4	125
Maka	WDR	11 Aug*	TS	35*
Guillermo	WDR	13–19 Aug	H3	110
Hilda	WDR	22–27 Aug	TS	55
Ignacio	WDR	25–27 Aug	TS	45
Jimena	EDR	29 Aug–4 Sep	H4	135
Kevin	WDR	29–31 Aug	TS	45
Linda	WDR	7–12 Sep	H1	70
Marty	EDR	16–19 Sep	TS	40
Nora	WDR	23–25 Sep	TS	50
Olaf	EDR	1–3 Oct	TS	40
Patricia	EDR	12–14 Oct	TS	50
Rick	EDR	16–21 Oct	H5	155
Neki	WDR	19–26 Oct	H3	110

* Maka data limited to observations east of 180°.

The EDR in 2009 saw below average cyclone frequency with respect to named storm, hurricane, and intense hurricane counts. Seasonal activity as measured with NTC and ACE were also well below normal for the EDR, at 73.4 and 52.5, respectively. This is consistent with the observed lull over 1998–2008, where the mean NTC in the EDR was 68.8 and mean ACE was 47.3. In 2009 the WDR saw above average cyclone frequency

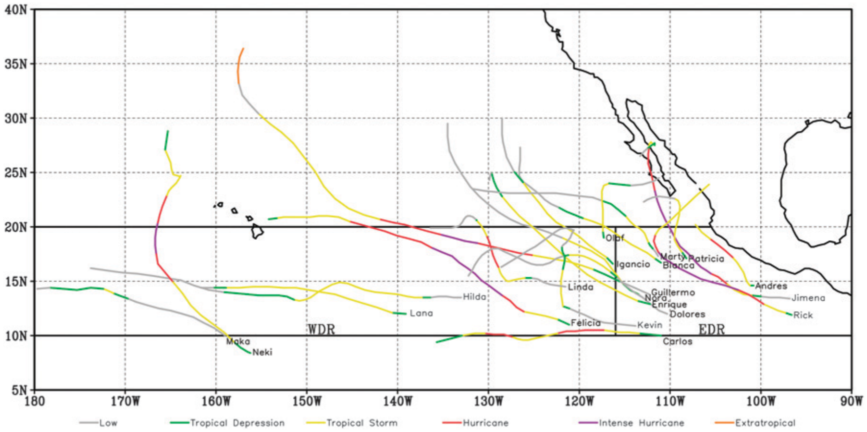

FIG. 1. Eastern North Pacific basin track map for 2009 named storms.

with four more named storms than the long-term WDR mean (15 in 2009 compared to an average of 11.1 for the period 1972–2001). However, hurricane counts were slightly below normal (5 compared to an average of 6.3) and the number of intense hurricanes (3) was normal. Despite the increased number of storm observations in the WDR, when overall activity considering NTC and ACE within the region was calculated (for all observations occurring west of 116°W), for the season it was near normal, not above, at 97.99 and 71.86, respectively. This stands in contrast to the recent lull in overall activity, as during the 1998–2008 period tropical cyclone frequency in the WDR of the eastern North Pacific basin was below average—the lowest for any consecutive 7-yr period since reliable records began in 1972. During the years 1998–2008, there was an average of 7.8 named storms, 4.2 hurricanes, and 1.6 intense hurricanes with a NTC value of 58.9 and ACE of 42.5 in the WDR.

Both NTC and ACE also show the strong monthly variation in activity in both the EDR and WDR, with peaks in August and October and lulls in the normally active months of July and September (Table 3). This is particularly noticeable in NTC values, with the WDR activity in August and October exceeding their monthly means by over 75% while activity in July and September fell short of their monthly means by over 45%.

b. Eastern development region environmental conditions

EDR activity for the season as a whole was below normal; however, significant monthly variation was observed to occur. The months of August and October both featured above normal tropical cyclone activity in the EDR, as evidenced by high NTC and ACE values, while activity reached a minimum in July and was also below normal in September (Table 3). This corresponded well to the favorable environmental conditions found there during August and October (Table 4). Pressure vertical velocity, total precipitable water (Fig. 3), and vertical wind shear (Fig. 4) conditions were significantly favorable for encouraging activity for nearly the entire season, consistent with the findings in Collins (2007). In addition, during the month of August, midtropospheric relative humidity anomalies were significantly above normal. In October favorable significant extrema were observed as well, this time in sea level pressure (-1.83-hPa anomaly) and relative vorticity (4.26×10^{-6} s^{-1} anomaly; Fig. 5). It is posited that the extreme values of these features known to be favorable for tropical cyclone development were responsible for the increase in activity during those two months, while the significant negative anomalies of total precipitable water and relative humidity

TABLE 2. The 2009 TC frequency, duration, and activity statistics for eastern North Pacific basin by month. All climatology figures calculated from a 1972–2001 mean [where abbreviations are as follows: Named storms (NS), named storm days (NSD), hurricanes (*H*), hurricane days (HD), intense hurricanes (IH), intense hurricane days (IHD), accumulated cyclone energy (ACE), and net tropical cyclone activity (NTC)].

		NS	NSD	*H*	HD	IH	IHD	ACE	NTC
Jun	2009	1	2.75	1	0.75	0	0.00	3.18	31.15
	Climo	2.30	8.21	1.17	3.07	0.47	0.87	13.76	100
Jul	2009	4	10.00	1	2.50	0	0.00	11.75	40.54
	Climo	3.97	16.03	2.20	7.22	1.13	2.29	30.51	100
Aug	2009	9	30.50	3	10.00	3	4.75	54.23	175.67
	Climo	4.60	21.29	2.67	8.66	1.20	1.98	36.57	100
Sep	2009	4	12.00	2	3.50	1	1.25	18.41	68.05
	Climo	4.23	18.22	2.57	8.73	1.20	2.68	36.29	100
Oct	2009	4	17.00	2	6.25	2	3.00	36.75	188.47
	Climo	2.53	9.39	1.33	4.30	0.77	1.27	17.69	100
Year	2009	20	72.25	8	23.00	5	9.00	124.32	95.57
	Climo	16.33	76.86	9.47	33.22	4.60	9.52	141.51	100

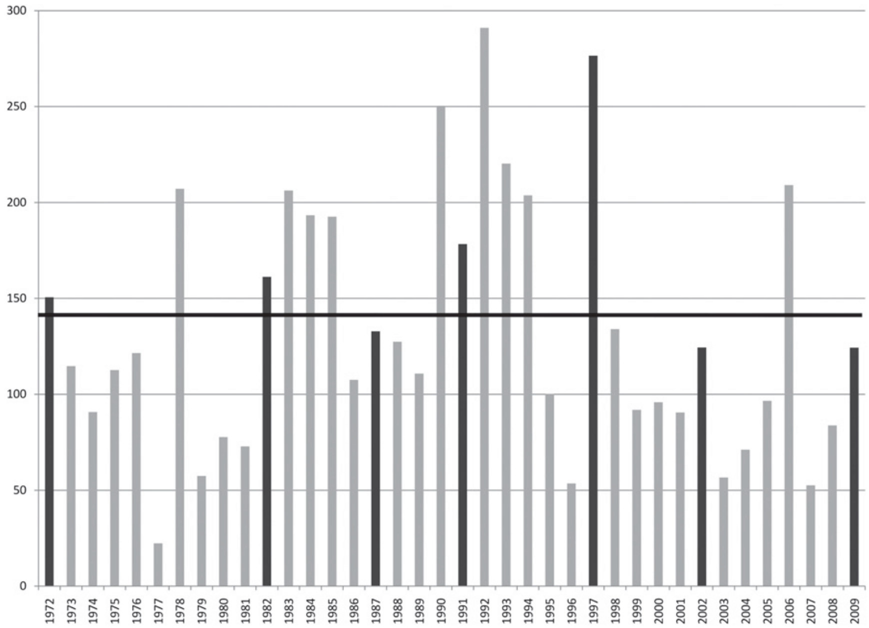

FIG. 2. Eastern North Pacific basin seasonal accumulated cyclone energy (10^4 kt^2) values by year since 1972. Strong El Niño events are highlighted in black; the horizontal black line indicates the long-term (1972–2001) mean.

detrimental to tropical cyclone activity in July contributed to the overall lack of activity in the EDR in that month. Because of the presence of a rare and powerful category 5 hurricane (Rick), October data were also recalculated from daily mean observations with Rick excluded to determine the degree to which the October EDR anomalies were driven by that anomalous event (Table 4; see Oct-R). It can be seen that, with the sole exception of moisture values that were influenced by Rick, most favorable conditions during the month of October were present in the EDR both with and without the impact of Hurricane Rick.

c. Western development region environmental conditions

While seasonal activity was near normal in the WDR (with the exception of tropical storm counts, which was above normal), it was not evenly distributed through the season. Instead, activity was concentrated into the same two hyperactive months as the EDR (August and October) with NTC values in excess of 175 (Table 3), much higher than normal during those periods. Background values of pressure vertical velocity, total precipitable water, sea level pressure, and low-level relative vorticity were significantly favorable throughout the entire season in the WDR (Table 5). Total precipitable water (Fig. 3), a feature previously linked to WDR activity (Collins and Mason 2000), spiked to well above normal values in both active months, especially in August. Relative vorticity anomalies (850 hPa; Fig. 5) exhibited similar behavior by peaking in those two months. In addition, vertical wind shear (Fig. 4) likely played a large role in inhibiting activity during July and September with significant positive anomalies of 4–5 m s^{-1}. In August and October, vertical wind shear anomalies were significantly negative, suggesting favorable conditions for tropical cyclone activity in the WDR. This month to month variation would be missed by standard analysis methods of simply taking a three- or four-month seasonal mean to characterize the atmospheric conditions over the season, and illustrates the need for examination of intraseasonal oscillations within these fields. This is highlighted in the August–October (AO)–June–September (JS) panel in each of Figs. 3–5 (F), where the difference between mean conditions in the active months of August and October and the inactive months of July and September is plotted.

TABLE 3. 2009 TC activity statistics for eastern North Pacific basin by month and region. All climatology figures calculated from a 1972–2001 mean [abbreviations are as follows: Eastern development region (EDR), western development region (WDR), accumulated cyclone energy (ACE, 10^4 kt^2), net tropical cyclone activity (NTC, %)].

		June	July	August	September	October	Season
EDR	ACE	3.18	1.55	12.40	12.05	23.29	52.46
	NTC	35.79	22.11	113.47	74.36	152.59	71.31
WDR	ACE	0.00	10.20	41.84	6.36	13.46	71.86
	NTC	0.00	53.87	177.99	37.46	206.52	97.99

TABLE 4. Atmospheric parameters by month and season in the EDR for 2009. Data obtained from the NCEP–NCAR reanalysis (anomalies based on the 1972–2001 climatology). Oct-R indicates October data recalculated from daily means with Hurricane Rick excluded. JASO indicates the July–October seasonal mean. Underline indicates anomaly significant at $\alpha = 0.05$; bold indicates significant anomaly conducive for TC activity.

	500-hPa pressure vertical velocity (10^{-2} m s^{-1})		Total precipitable water (mm)		500–700-hPa layer mean relative humidity (%)	
	Mean	Anom	Mean	Anom	Mean	Anom
Jul	−3.56	−0.65	44.71	−0.78	51.45	−4.02
Aug	−4.87	**−1.41**	47.74	**1.54**	57.25	**1.68**
Sep	−5.56	−1.09	49.35	**2.47**	59.25	**2.93**
Oct	−5.49	**−3.68**	45.17	**1.32**	47.06	−2.50
Oct-R	−4.73	**−2.92**	44.69	0.94	45.04	−4.52
JASO	−4.87	**−1.71**	46.74	**1.14**	53.75	−0.48

	850–200-hPa vertical wind shear (m s^{-1})		Sea level pressure (hPa)		850-hPa vorticity (10^{-6} s^{-1})	
Mean	Anom	Mean	Anom	Mean	Anom	
Jul	1.47	**−2.42**	1012.10	0.08	−0.81	−0.19
Aug	2.19	**−3.00**	1011.79	−0.14	0.71	0.00
Sep	6.04	**−1.90**	1010.96	−0.32	2.88	−0.63
Oct	2.36	−0.94	1010.10	**−1.83**	3.77	**4.26**
Oct-R	3.07	−0.29	1010.02	**−1.88**	3.73	**4.14**
JASO	3.02	**−2.08**	1011.24	**−0.55**	1.64	0.86

d. El Niño–Southern Oscillation

The La Niña conditions during early 2009 quickly waned and were replaced by an intensifying El Niño event for the eastern North Pacific hurricane season. The 2009 El Niño peaked as a strong event (defined as a three-month mean ONI anomaly of 1.5°C or greater), the seventh since 1972 (CPC 2009) to reach that status. The six prior strong El Niño events (1972, 1982, 1987, 1991, 1997, 2002) and the 2009 seasonal ACE values are highlighted in black in Fig. 2. While the mean strong El Niño event ACE is above normal, this is largely due to the hyperactive 1997 season and there have been strong El Niño events where eastern North Pacific tropical cyclone activity is near or below normal, as occurred in 2009. The mean seasonal (July–October)

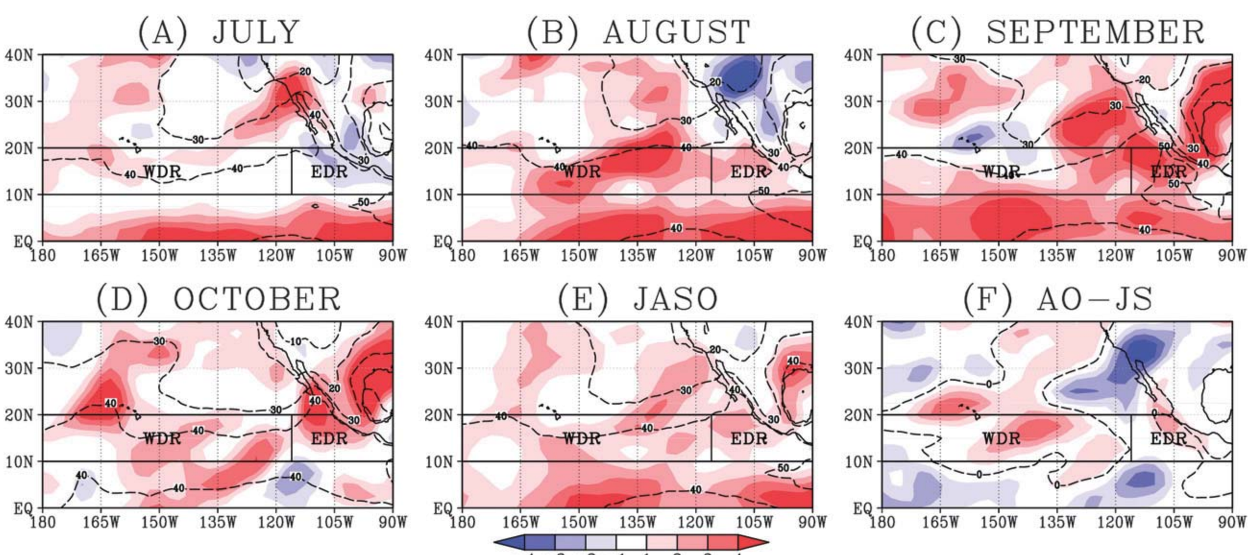

FIG. 3. The 2009 total precipitable water (TWP) anomalies (mm, shaded) and means (contoured): (a)–(d) by month July–October, respectively, (e) July–October mean, and (f) then August–October (AO) and July–September (JS) difference. Data obtained from the NCEP–NCAR reanalysis (anomalies based on the 1972–2001 climatology).

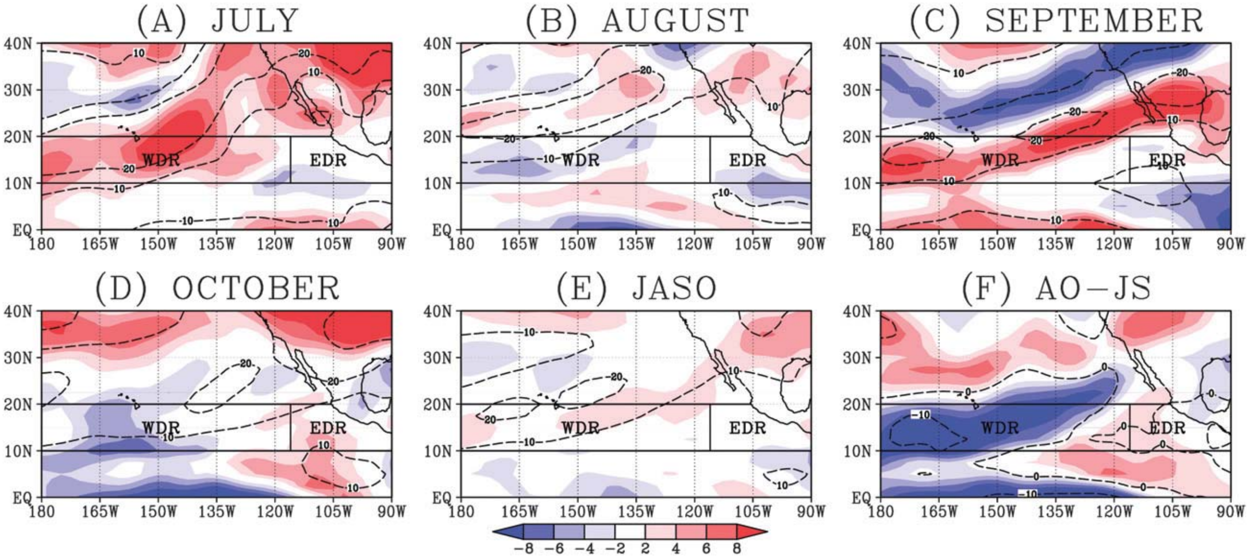

FIG. 4. As in Fig. 3, but for 2009 vertical wind shear anomalies (m s^{-1}, shaded) and means (contoured).

atmospheric values of total precipitable water, vertical wind shear, and low-level relative vorticity during the six strong El Niño events (before 2009) are shown in Figs. 6a–c. Figures 6d–f show the difference between the 2009 strong El Niño event and those shown in Figs. 6a–c. While vertical wind shear values were similar, 2009 exhibited higher levels of total precipitable water and low-level relative vorticity, contributing to the increase in TC activity in 2009 from the recent lull observed from 1998–2008.

e. Madden–Julian oscillation

The MJO is resolved in the eastern North Pacific basin through 850-hPa zonal wind anomalies. A Hovmöller diagram of the *u* component of the wind from 5°S to 5°N over the duration of the eastern North Pacific hurricane season is shown in Fig. 7. The eastward progression of positive anomalies through the WDR (WDR bounds are denoted by vertical black contours; MJO events are highlighted with black ellipses) during most of August and October indicate the presence of the convectively active phase of the MJO, which is associated with increased likelihood of tropical cyclone formation in the eastern North Pacific basin. Further supporting this point were the monthly variations in vertical wind shear and relative vorticity anomalies in the WDR, with favorable conditions peaking concurrently with the

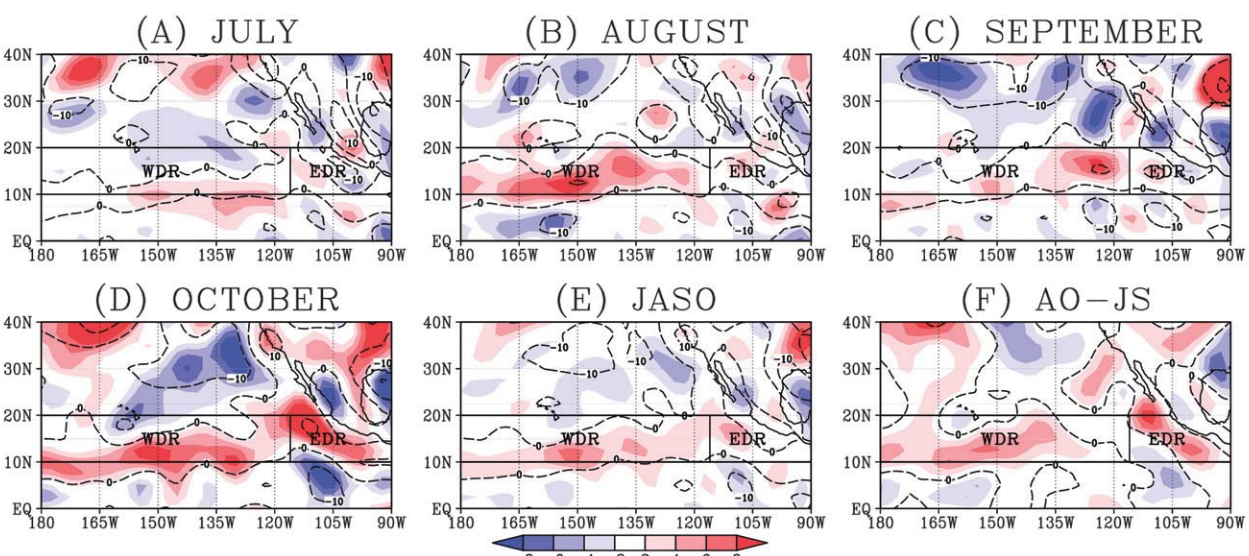

FIG. 5. As in Fig. 3, but for 2009 850-hPa relative vorticity anomalies (10^{-6} s^{-1}, shaded) and means (contoured).

TABLE 5. As in Table 4, but for the WDR for 2009.

	500-hPa pressure vertical velocity (10^{-2} m s^{-1})		Total precipitable water (mm)		500–700-hPa layer mean relative humidity (%)	
	Mean	Anom	Mean	Anom	Mean	Anom
Jul	0.45	0.33	39.75	0.63	36.91	−1.08
Aug	−1.70	−1.39	42.63	2.34	41.81	2.37
Sep	−0.78	−0.58	40.92	1.43	36.63	−0.33
Oct	−1.18	−0.53	40.41	1.59	36.64	1.11
JASO	−0.80	−0.54	40.93	1.50	37.99	0.51

	850–200-hPa vertical wind shear (m s^{-1})		Sea level pressure (hPa)		850-hPa vorticity (10^{-6} s^{-1})	
	Mean	Anom	Mean	Anom	Mean	Anom
Jul	15.23	5.07	1013.14	−0.17	−0.62	0.09
Aug	4.16	**−2.36**	1012.61	**−0.50**	2.70	**3.09**
Sep	10.20	4.45	1012.29	−0.44	1.49	**1.39**
Oct	10.25	**−2.56**	1012.03	**−0.86**	1.67	**2.47**
JASO	9.96	1.15	1012.52	**−0.49**	1.31	**1.76**

presence of the convectively active phase of the MJO in August and October. Less favorable (vorticity) to outright unfavorable (shear) conditions occurred between positive MJO events (values in Table 4). This relationship among the MJO, vertical wind shear, relative vorticity, and tropical cyclone activity in the eastern North Pacific basin is directly in line with prior findings by Maloney and Hartmann (2000).

4. Conclusions

The return of near-normal activity in the 2009 eastern North Pacific hurricane season from the inactive period that began in 1998 was due to multiple factors and primarily driven by activity occurring in the WDR. The development of a strong El Niño event resulted in a large increase in total precipitable water, especially

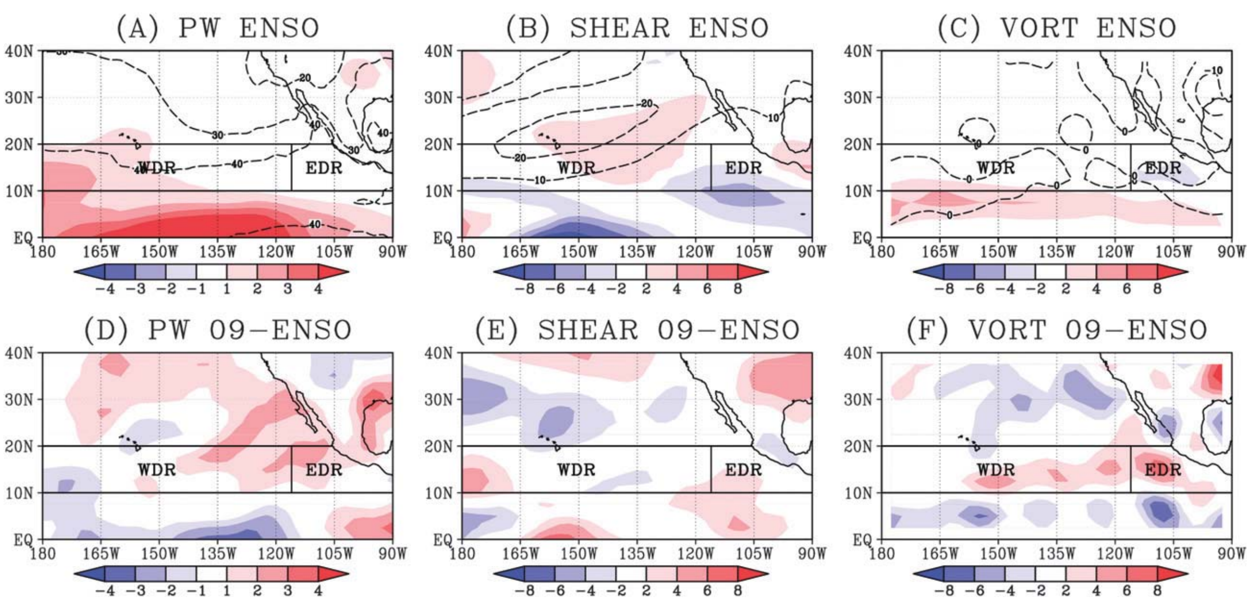

FIG. 6. Mean atmospheric conditions during the past 6 strong El Niño events and the difference between the 2009 and strong El Niño mean conditions for (a),(d) total precipitable water (mm), (b),(e) vertical wind shear (m s^{-1}), and (c),(f) relative vorticity (s^{-1}). Data obtained from the NCEP–NCAR reanalysis (anomalies based on the 1972–2001 climatology).

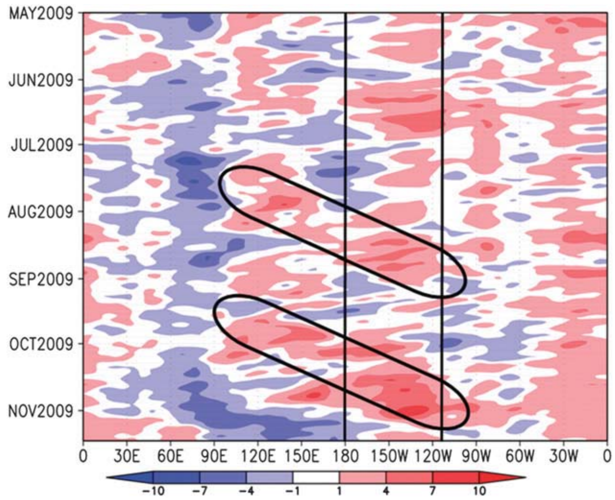

FIG. 7. The 850-hPa zonal wind anomaly (m s^{-1}) Hovmöller diagram, averaged from 5°S to 5°N. Black ellipses highlight eastward progression of the convectively active phase of the Madden–Julian oscillation, vertical black lines indicate the bounds of the WDR. Data obtained from the NCEP–NCAR reanalysis (anomalies based on the 1972–2001 climatology).

during the months of August and October when the majority of tropical cyclone activity occurred. In addition, vertical wind shear and low-level relative vorticity anomalies were strongly favorable for tropical cyclone activity during those months in the WDR. Also of note, vertical wind shear was of opposite sign and unfavorable for tropical cyclone activity during the months of July and September when little activity occurred in the WDR. While the seasonal mean vertical shear anomaly in the WDR was above normal, this clearly was a case where the broader mean was not the best mode of analysis, as the variation in monthly shear values was very large. Prior work by Maloney and Hartmann (2000) has shown that the MJO impacts the eastern North Pacific basin through wind shear and relative vorticity, and when 850-hPa wind anomalies were calculated for the season it was confirmed that the convectively active phase of the MJO was present during those two active periods (August and October).

While EDR activity was below normal for the season, it exhibited similar characteristics to the WDR in October (strongly above normal) and August (above normal). However, activity here was strongly damped during July and September, with most atmospheric conditions not supportive of tropical cyclone activity in July and the inactive phase of the MJO present in September to mitigate storm totals. Overall, it is concluded that a combination of the intensifying El Niño and two distinct MJO events, through amplification of total precipitable water, tropospheric vertical wind shear, and low-level relative vorticity, served as the primary control mechanisms on the 2009 eastern North Pacific hurricane season.

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