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THE RELATIONSHIP OF ENSO AND RELATIVE HUMIDITY TO INTERANNUAL VARIATIONS OF HURRICANE FREQUENCY IN THE NORTH-EAST PACIFIC OCEAN

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1. INTRODUCTION

It has been shown (Collins and Mason, 2000) that there is more than one development region with respect to tropical cyclone (TC) formation in the northeast Pacific basin. Collins and Mason (2003) were able to determine the key environmental factors that are responsible for interannual variations of TC formation in the Western Development Region of the northeast Pacific basin. In contrast to Chu and Wang (1997) and Clark and Chu (2002), who found the dynamic (motion) controls on TC formation (Gray, 1979) to be the major influence on interannual variations in TC frequency in the central North Pacific, Collins and Mason (2003) found that it is typically the thermodynamic controls which show the strongest relationships for the WDR. The strongest thermodynamic control for hurricanes is relative humidity (RH).

This study uses deviance as an alternative test to the *t*-statistic employed by Collins and Mason (2000) to confirm and examine in greater detail the significant relationships found in previous studies of seasonal TC frequency and environmental variables (Collins and Mason, 2000, 2003). With confirmation that the strongest relationship is between RH and interannual variations of hurricane frequency, the influence of the El Niño Southern Oscillation (ENSO) on variations of RH is examined here. With a better understanding of hurricane activity in the northeast Pacific, these results could be applied to improve forecasting.

2. DATA AND METHODS

The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 40-year reanalysis project (Kalnay *et al.*, 1996) was used to obtain monthly environmental data on a 2.5º × 2.5º latitude/longitude grid. Additional monthly data including Wolter's ENSO index (Wolter, 1987), the Pacific Decadal Oscillation (PDO) (Mantua *et al.,* 1997), and the Madden-Julian Oscillation (MJO) (Maloney and Hartmann, 1998) were obtained from other sources. Interannual variations of the average variance of the MJO index for the July-September period are used in this analysis. The TC index used in this study is the official historical TC track database obtained from the Tropical Prediction Center/National Hurricane Center (TPC/NHC) best track file (TPC, 2001). For each category of TC, the location used in this analysis is the point where the storm reached the windspeed appropriate to the category (*i.e.*, 34 knots for a tropical storm, 64 knots for a hurricane and 97 knots for an intense hurricane). Only TCs that began in July, August or September (the peak hurricane season) are included. The same months are used for the environmental parameters.

A deviance analysis of the relationships of TC numbers with the environmental parameters is conducted using a generalised linear model with Poisson errors (Collins and Mason, 2000). Deviance is a measure of fit and its general form is given (McCullagh and Nelder, 1989) by

$$D(y;\hat{\mu}) = 2\{l(y;y) - l(\hat{\mu};y)\} \quad [1]$$

where D is the deviance, y is a vector containing the number of hurricanes, $\hat{\mu}$ is the corresponding vector of fitted y values and l is the log-likelihood function.

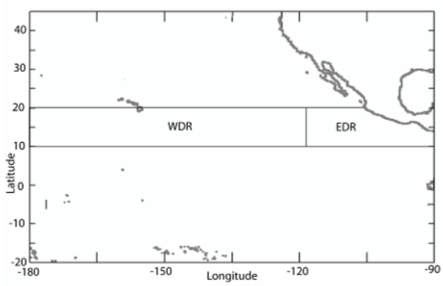
Since the strongest relationship is between RH and hurricane numbers, the latter part of this study concentrates on the hurricane category rather than the other TC categories.

3. RESULTS

3.1 RELATIONSHIPS BETWEEN HURRICANE FREQUENCY AND ENVIRONMENTAL VARIABLES

Relationships between seasonal TC frequency and environmental variables were examined for both the Western Development Region (WDR: 10°N to 20°N, 116°W to 180°W) and Eastern Development Region (EDR: 10˚N to 20˚N, North American coastline to 116˚W) of the northeast Pacific basin (Figure 1). First, the deviance of the null model (the average frequency of hurricanes) is compared to the deviance of a single variable model (when an environmental variable is included). The reduction in deviance between the two models is compared with a chi-squared distribution with 1 degree of freedom to account for the variable. The critical values are 3.84 and 6.64 for 5 percent and 1 percent significance, respectively. Hence, the greater the reduction in deviance, the more significant the result (Table 1).

FIGURE 1
LOCATION OF THE WESTERN DEVELOPMENT REGION (WDR) AND EASTERN DEVELOPMENT REGION (EDR) OF THE NE PACIFIC BASIN



These results compare well to those obtained by Collins and Mason (2000) using the *t*-statistic. For instance, for the hurricane category in the WDR, the model with RH has the largest deviance reduction, 20.65, and thus provides the best model with one variable (see Collins and Mason, 2003). The percentage of variance explained by this model is 54 percent. This study shows a much stronger relationship between ENSO and the frequency of TCs in the WDR than that presented in Collins and Mason (2000), where only one ENSO index was examined. In the current study, additional ENSO indices are examined. Also in agreement with Collins and Mason (2000), there are no significant relationships in the EDR (Table 1).

TABLE 1
THE REDUCTION IN DEVIANCE BETWEEN THE NULL MODEL AND A MORE COMPLEX MODEL, WHEN THE ENVIRONMENTAL VARIABLE IS INCLUDED

	Western Development Region / Eastern Development Region					
Null Deviance	45.02	43.00	54.56	29.06	16.86	15.85
Variable	IH	H	TS	IH	H	TS
RH	**9.68**	**20.65**	**15.88**	0.51	1.56	0.11
SST	**12.57**	**13.98**	6.24	0.96	1.72	0.52
VVEL	**10.01**	**15.50**	**12.63**	0.36	1.06	0.53
PWAT	**10.23**	**18.36**	**12.95**	0.65	1.92	0.32
ULWRF	**8.59**	**13.48**	**9.78**	0.19	1.00	0.67
PRES	4.28	**15.10**	**11.29**	0.18	1.15	0.19
RELV	3.06	3.13	2.63	0.00	0.39	0.00
VZ	2.77	3.46	**10.95**	0.38	0.33	1.29
TMP	1.67	3.51	2.41	0.60	1.36	0.08
ENSO						
(KW)	3.82	6.28	4.14	0.08	0.83	0.19
(SOI)	6.06	**10.48**	**9.51**	0.00	1.15	0.17
(Niño1)	0.75	3.76	3.15	0.02	1.50	0.05
(Niño2)	1.19	3.84	3.72	0.14	0.91	0.00
(Niño3)	1.13	3.27	2.72	0.34	0.50	0.03
(Niño4)	**7.96**	**12.40**	5.72	0.28	1.62	0.23
MJO	3.58	**7.98**	**10.32**	0.17	0.03	0.71
QBO	0.04	1.25	3.59	1.54	1.09	1.14
PDO	2.11	0.45	0.36	1.67	0.55	1.78

Entries in bold face and underlined indicate a significant reduction in deviance to the 1 percent level, and those underlined are significant to the 5 percent level. The environmental variables are relative humidity (RH) at 500 hPa, sea surface temperature (SST), pressure vertical velocity (VVEL) at 500 hPa, precipitable water (PWAT), upward long-wave radiation flux–top of the atmosphere (ULWRF), mean sea level pressure (PRES), relative vorticity (RELV), vertical wind shear (VZ) between 850 and 200 hPa, temperature (TMP) at 300 hPa., ENSO indicies (KW, SOI, Niño1, Niño2, Niño3, Niño4), the Madden-Julian Oscillation (MJO), the Quasi-Biennial Oscillation (QBO) and the Pacific Decadal Oscillation (PDO). The TC categories are intense hurricane (IH), hurricane (H) and tropical storm (TS).

Multiple regressions were carried out to examine the effect of a more complex model with two or more environmental variables to see if these models significantly explained hurricane frequency better than the simple best model containing RH as noted above. Analysis of the results suggest that adding an additional variable does not add significance to the explanation of the variation in hurricane frequency compared to the simpler best model with RH.

An examination of Table 1 reveals that thermodynamic controls necessary for genesis (Gray, 1979) are also relevant in affecting seasonal hurricane frequency in the WDR. Dynamic controls are of less importance and show statisitcally insignificant relationships in the WDR and EDR. The thermodynamic factors such as RH and sea surface temperature (SST), are not independent variables, but operate together to influence instability and the potential for cumulonimbus convection (Gray, 1979). The results presented in Table 1 indicate that variations in the thermodynamic factors are important for the WDR TCs and not important for the EDR TCs.

Longitudinal profiles of RH, and the related variable SST, are shown in Figure 2 for each of the 26 years. Over the EDR (east of 116ºW) where there are no significant relationships (Table 1), for both variables, the values in Figure 2 are consistently high. This result mirrors Chan and Liu (2004), who showed that SST variations in the warm pool of the western North Pacific are not related to the variability in the number of typhoons there. In the WDR, however, there is a marked change in the variables towards lower values. Moreover, in the WDR, active hurricane years are distinct from inactive hurricane years through generally higher values of RH and SST. The effect is shown in Figure 3 when comparing the average values of the variables for the five most active and inactive hurricane years in the period 1972-1997.

FIGURE 2
RH AND SST AVERAGED OVER JULY-SEPTEMBER
(averaged over latitudes 10^{o}N to 20^{o}N) VS. LONGITUDE, 1972-1997

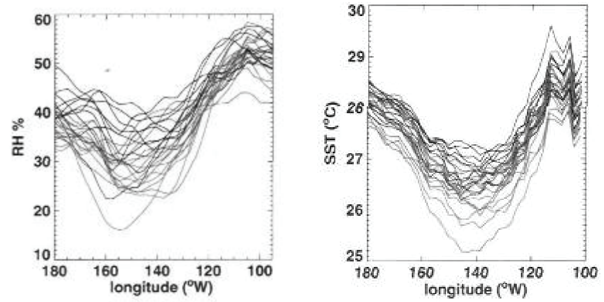
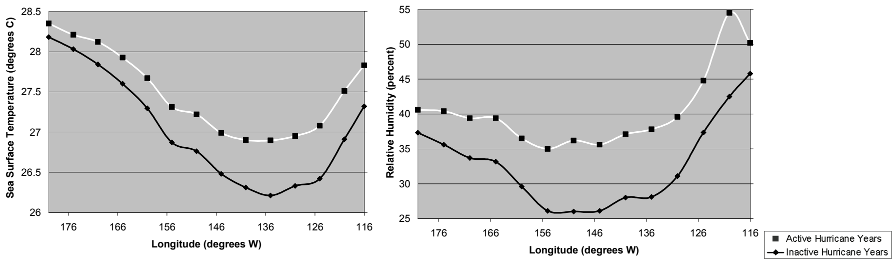


FIGURE 3
RH AND SST AVERAGED OVER JULY-SEPTEMBER (latitudes 10^{o}N to 20^{o}N) VS. LONGITUDE AND AVERAGED FOR THE WDR FIVE MOST ACTIVE (1982, 1994, 1990, 1992 and 1997) AND INACTIVE (1973, 1980, 1983, 1995, 1996) HURRICANE YEARS



According to Gray (1979), cyclone development is assumed not to be possible if the seasonal 500-700 hPa RH is less than 40 percent and the SSTs are less than 26-27˚C. When RH and SST are generally low over a large area, there are no hurricanes in the WDR because the seasonal value is not near the threshold for hurricanes to occur. In the EDR, the RH and SST are typically above these values (Figure 2); the lack of relationships with hurricane frequency there suggests that once the thermodynamic variables have reached their thresholds (*i.e.*, if the SST is sufficiently high and the air is sufficiently humid) then the actual values of SST, and RH are of less consequence. The more favorable values of SST and RH west of about 160˚W might be expected to allow several TCs to form. However, high values of vertical wind shear (VZ) limit TC formation in the area. For the rest of the basin, low values of VZ are present.

Nevertheless, in the WDR, there are still relationships with the spatially averaged environmental variables, not just a step change at a threshold value. A probable explanation of this emerges when we consider what is happening with latitude as well as longitude within the WDR. In less active hurricane years, cooler SSTs and lower RH from the north extend further into the WDR, and conditions are less conducive over a larger fraction of the WDR.

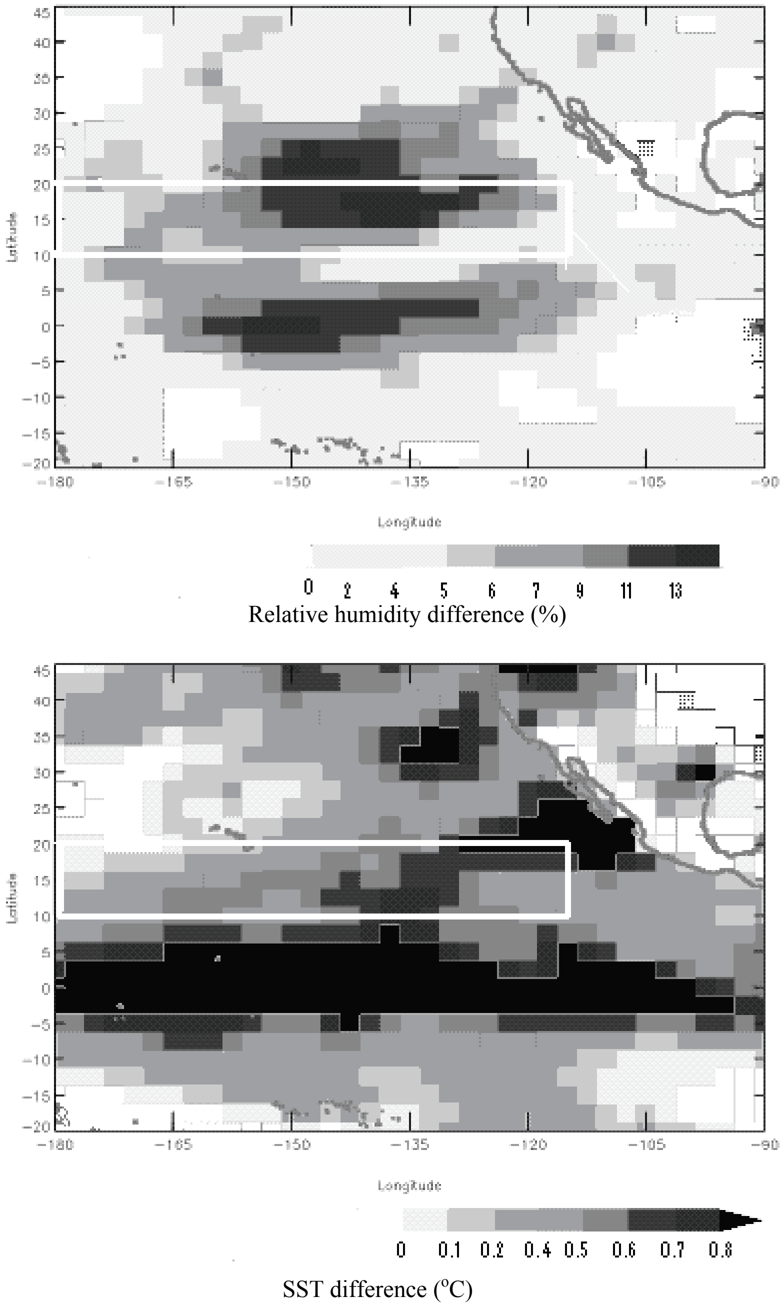
For inactive hurricane years, the far south and east part of the WDR have RH and SST values that are slightly higher than in the main part of the region, and just above the threshold levels of 40 percent and 27˚C respectively. The limited number of TCs can perhaps be explained by the idea that the critical SST threshold of 26-27˚C can in fact vary with position and time (e.g. Royer et al., 1998; Henson, 1998) and may sometimes be higher than 27˚C. In addition, lower than the seasonal climatological average number of triggering disturbances, such as easterly waves, may be occurring in some of the inactive years, independently of the environmental conditions.

Figure 4 shows the differences in RH and SST averaged over the season between the five most active and inactive hurricane years. It can be seen that in some parts of the WDR, RH (SST) differences of more than 13 percent (0.7˚C) marks the difference between an active and inactive season, with active seasons having higher RH and SST values than their inactive counterparts.

Spatial analysis provides a probable explanation of the relationships and generally supports the concept of a threshold in SST and RH for TC genesis, above which the precise local values of SST and RH do not greatly influence their occurrence (supported by Gray, 1979; McBride, 1981; Raper, 1993). In the WDR, relationships between seasonal frequency and SST and RH emerge because of spatial averaging of the variables over the region (larger fractions of the region are above the SST and RH thresholds in years with large spatially averaged values of SST and RH). In the EDR, interannual variations in the values of the environmental variables have no affect on TC frequency, as they are above their respective genesis thresholds.

Saunders and Harris (1997) proposed that the relationship between increasing SSTs and increasing hurricane frequency could be due to increased SSTs helping storms penetrate through the trade wind inversion. If this is the main mechanism in the NE Pacific, one would expect a relationship between SST and hurricane frequency, but not between RH and hurricane frequency (since RH at 500 hPa will be low in the presence of a trade wind inversion, which would generally occur lower in the troposphere than 500 hPa, and so SST should not be strongly correlated with RH). However, there is a strong relationship between RH and hurricane frequency as well as SST and hurricane frequency (Table 1). This proposed "inversion effect" cannot, therefore, be a main factor explaining the correlations observed for the WDR of the NE Pacific.

FIGURE 4
RH AND SST DIFFERENCES IN JULY-SEPTEMBER BETWEEN THE
FIVE MOST ACTIVE (1982, 1994, 1990, 1992, 1997) AND FIVE LEAST ACTIVE (1973, 1980, 1983, 1995, 1996) HURRICANE YEARS IN THE WDR (White box shows the WDR)



3.2 THE INFLUENCE OF ENSO ON THE INTERANNUAL RH VARIATIONS

Landsea and Gray (1989) carried out a preliminary study focusing on the seasonal time-scale in the whole northeast Pacific, and found some indications of an ENSO influence on TC activity. In the current study, when examining the whole region, there is in fact only a weak or insignificant correlation between the ENSO indices and hurricane frequency. This is consistent with the findings of Irwin and Davis (1999), who concluded that the total number of storms in the northeast Pacific does not change with the phase of ENSO. However, when subdividing the basin, strong relationships between hurricane frequency and ENSO emerge in the WDR (Table 1), especially for the Niño4 index (measured by the SSTs in the region 5^{o}S to 5^{o}N, 160^{o}E to 150^{o}W). This index may show a particularly strong relationship due to the proximity of where this index is measured in relation to the WDR region.

Chu and Wang (1997) suggested that there is a relationship between ENSO and frequency of TCs in the central North Pacific, which is related to the location of the monsoon trough and cyclonic horizontal shear and vorticity. In the current study, however, for the WDR (which includes the central North Pacific but also encompasses a larger area) there was no significant relationship on a seasonal time-scale with relative vorticity. Chu and Clark (1999) argue that due to circulation patterns changing during El Niños, the strength of the climatological vertical VZ is eroded in the central Pacific and this may subsequently affect TCs. However, for the WDR, there is no evidence that vertical VZ is significantly reduced in warm ENSO's when average seasonal values of the region are considered (the correlation coefficient between WDR vertical VZ and Niño4 is -0.07).

Instead of the link between ENSO and TC frequency being due to the dynamic variables, it is suggested that the link between ENSO and TC formation in the WDR is predominantly through its connection with the thermodynamic variables, particularly RH, with a warm ENSO phase causing higher values of RH in the WDR, which in turn results in more hurricanes. Table 1 provides evidence that ENSO has an influence on hurricanes in the WDR, though this relationship is not as strong as with RH. In warm ENSO years, the WDR SSTs increase, which means that almost all of the region is conducive to hurricane formation. In La Niña years, the SSTs are at a lower temperature in the WDR, and the central-north part of the region is actually at temperatures which are not conducive to hurricane formation. A similar effect occurs for RH in warm and cold ENSO years.

These relationships between ENSO and SST, and ENSO and RH appear to occur due to a link involving the surface winds. During warm ENSO years, the pressure field in the Niño4 region is modified such that the pressure gradient between the Niño4 region and the WDR is weakened, resulting in weaker trade winds between these regions. During normal conditions, and particularly during La Niña conditions, the stronger winds keep the warm pool of water close to the Equator. When the winds slacken in El Niño conditions, the warm pool is able to spread north and a warm pool of water is evident in the WDR during warm ENSO phases. With weaker trade winds, the area of convection and high mid-tropospheric RH associated with the warmer water spreads from the Niño4 region into the WDR. Hence, the dominant RH control on hurricane frequency results largely from ENSO.

Stronger winds with a northeasterly wind vector (in the western (Niño4) part of the tropical basin and extending into the southwestern part of the WDR) occur in cold phases of ENSO (Collins and Mason 2003). Furthermore, Collins and Mason (2003) show that in the eastern part of the WDR, the wind vector differences, though smaller, are mainly northerly and westerly, showing that the trade winds, which are approximately northeasterly in La Niña years, become slightly less northerly and more easterly during El Niño years, preventing cooler northern water from being driven so far south.

Statistical correlations provide further support for these links. Niño4 correlated with SST averaged in the WDR has an *r* equal to 0.82, again indicating warmer ENSO events are associated with warmer water in the WDR. Wind speed at 10 m between the Niño4 region and the southern edge of the WDR (between 5˚N - 10˚N and 116˚W - 180˚W) vs. SST averaged in the WDR gives an *r* equal to -0.64. This supports the idea that SSTs in the WDR are higher because the high SSTs in the Niño4 region are able to spread into the WDR when there are lower surface winds.

Examining a smaller area, around 5˚N - 10˚N, 150˚W - 180˚W in the west near the Niño4 region, indicates that the individual components for the meridional and zonal winds at the 10 m level are positively correlated with SST averaged in the WDR (*r* values of 0.70 and 0.66 respectively). Thus, when wind anomalies are more southerly (or the actual wind is less northerly), SSTs are higher in the WDR, and when wind anomalies are more westerly (or the actual wind is less easterly), SSTs are higher in the WDR. These relationships between the two vector components offer quantitative support that during El Niño years, the high SSTs from the Niño4 region spread toward the north and the east, which explains why SSTs in the WDR would be increased during El Niño years.

Niño4 SST variations have little effect on variations of hurricane frequency in the EDR. This could be explained by the fact that the Niño4 region is far removed from this region and closer in longitude to the WDR. However, even when other ENSO indices are examined, which are at longitudes closer to the EDR, again no significant effects are found. It is thought that this is due to the reason stated earlier, namely that environmental conditions (*e.g.*, SST, RH) are above critical values in the EDR in all phases of ENSO.

4. CONCLUSIONS

A lack of significant results in the EDR of the northeast Pacific indicate that the variation of hurricane frequency in this region is not influenced primarily by variations in the climatological values of the environmental factors investigated. And, it has been suggested that the climatological values of the varibles examined in the EDR are always above the required threshold and that triggering disturbances are more important for determining numbers of hurricanes per year in the EDR.

However, significant relationships exist between several environmental variables and hurricane frequency (averaged over the peak hurricane season) in the WDR. Important variables for the WDR include RH, SST, VVEL and PWAT. These relationships are not evident when the northeast Pacific basin is treated as one entity, but emerge only when sub-regions of development are identified. While these thermodynamic (and related) variables are important for explaining interannual variations of hurricane frequency in the WDR of the NE Pacific, the dynamic variables are not. RH is the dominant environmental variable affecting hurricane frequency. It has been noted by Gray (1979) that RH affects TCs, although it has not been previously shown to be the *dominant* control on hurricane formation in any basin.

There is an indirect effect of ENSO on the WDR of the northeast Pacific, through RH. The influence of ENSO on the RH in the WDR is shown to occur through the wind field. It is argued that ENSO affects the winds and hence the SSTs in the WDR, where there is an associated effect on the RH. While it has been shown that ENSO plays a major role in causing interannual RH variations, it is also worth noting that there may be other factors which may also affect these RH variations. One of these, namely variations in the thermal low pressure which occurs over the southwest United States, is discussed briefly in Collins and Mason (2003), but is beyond the scope of this paper. With a more thorough understanding obtained in this study of the factors which affect tropical cyclone formation, a forecasting model could be developed for northeast Pacific (WDR) hurricanes and their hazards, and seasonal predictions could be issued similar to those released by various organizations for the Atlantic. Insurance companies in particular require this type of information.

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