GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 23, PAGES 3881-3884, DECEMBER 1, 2000

Local environmental conditions related to seasonal tropical cyclone activity in the Northeast Pacific basin

J.M. Collins and I.M. Mason

Department of Space and Climate Physics, University College London, UK

Abstract. Tropical cyclone formation in the NE Pacific Ocean is poorly understood. We show that by dividing the NE Pacific Ocean into two regions, east and west of 116°W, our understanding is enhanced in terms of which climatological factors are involved. We show that for the period 1972–1997, in our western region, significant relationships exist between several environmental parameters and tropical cyclone numbers on a seasonal timescale, and there is also a significant increasing trend with time. Important parameters common to all tropical cyclone indices examined include relative humidity, sea surface temperature, pressure vertical velocity and precipitable water. The potential for predictability of tropical cyclones in this region is noted.

Introduction

Tropical cyclone (TC) formation is one of the least understood topics of tropical meteorology. In particular, in comparison to the Atlantic basin, there has been relatively little work conducted on the NE Pacific basin, and this generally focuses on genesis (from disturbance to tropical depression) rather than subsequent intensification to tropical storm, hurricane or major hurricane.

Previous work focusing on the seasonal timescale in the NE Pacific includes Chu and Wang [1997] who found that the mean number of TCs within 240 n mi of Honolulu is higher during an El Niño than non-El Niño year. Landsea and Gray [1989] also focus on the NE pacific, examining the El Niño Southern Oscillation (ENSO) and the Quasi-Biennial Oscillation (QBO), to determine their relationship with a TC index for the whole basin. They look at the ratio of the TC index averages in the five strongest and weakest years of each variable. From their results showing a ratio of 1.6:1 hurricanes (2.36:1 major hurricanes) occurring in El Niño compared to La Niña years, they conclude that there is a strong indication for increased TC activity in El Niño years, especially for the strongest storms. They note that there is a slight tendency for the QBO to modulate the numbers of the most intense TCs, with greater activity occurring in the westerly phase.

We extend that work through an in-depth study of the factors that may affect TC formation for the period 1972–1997. We use regression analysis to investigate (a) the relationships between TC numbers and the environmental parameters, and (b) the trends of TCs with time. We also analyze extreme years. However, we do not treat the NE Pacific as one single development region. Rather, we identify sub-regions of development. This has not previously been done for the NE Pacific.

Paper number 2000GL011614.
0094-8276/00/2000GL011614$05.00

Methodology

The NCEP/NCAR 40-year reanalysis project *Kalnay et al.* [1996] provides the data for most of the environmental variables investigated, with the exception of ENSO, where Wolter's ENSO index *Wolter* [1987] is used, the Pacific Decadal Oscillation (PDO) where the PDO index of Mantua et al. [1997] is used, and the Madden-Julian Oscillation (MJO) where the variances are derived from the MJO index of Maloney and Hartmann *Maloney and Hartmann* [1998]. Although the MJO index describes an intra-seasonal oscillation, we examine the inter-annual variations of the average variance of the MJO index for the July–September period.

The source for the TC indices used in this study is the official historical tropical cyclone track database obtained from the TPC/NHC best track file for the NE Pacific basin *Brown and Leftwich* [1982]; *TPC* [1998]. Categories of TC considered include tropical storm, hurricane and major hurricane. For each category of TC the location used in our analysis is the point where the storm reached the windspeed appropriate to the category. We use records from 1972–1997 because major hurricane data in this basin are only considered reliable since 1972 *Whitney and Hobgood* [1997]. We only include TCs that began in July, August or September (the peak hurricane season). The same months are used for the environmental parameters.

From this TC data set the longitudes at which each hurricane forms are established. The longitude distribution is used to identify sub-regions of hurricane formation in the NE Pacific Ocean.

To obtain information about the differences between total TC numbers in the extreme years of particular environmental variables, for each region we compute the probability under a binomial distribution that TC totals did not occur in each extreme group by chance. We calculate the total number of TCs from the six years (approximately a quarter of the total) which provide the upper and lower extreme values. We then test the hypothesis that the probability of a TC occurring in the upper extreme years is 0.5. The use of ratios, though valuable for indicating the variations between extreme years, has limitations when attaching a significance as it appeals to normal distribution theory which is inappropriate for small counts.

Not only do we look at extreme years, but for each subregion identified, an analysis of the relationships of TC numbers with the environmental parameters for all years is conducted. Least squares fitting and the correlation coefficient is not appropriate for small numbers of TCs as the errors are not normally distributed. Therefore we use a generalised lin-

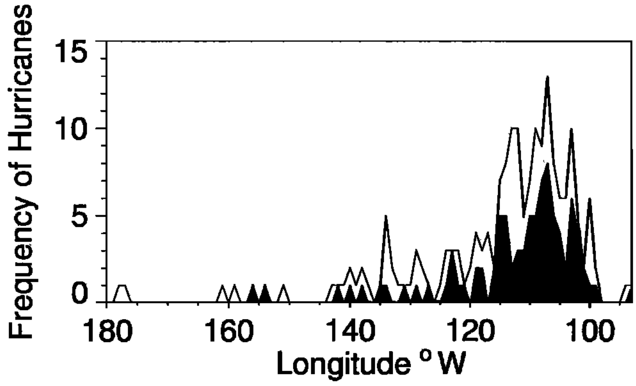

Figure 1. The longitude distribution of all hurricanes (185) for the period 1972–1997 (unshaded plot), and for approximately half the hurricanes (91, from the least active years) (shaded).

ear model with Poisson errors *McCullagh and Nelder* [1989]. Poisson regression is carried out with two independent variables, the environmental parameter and time. Time is included to eliminate any effects of long term trends since we are concerned with interannual variation. Consequently, the fitted model is of the form:-

$$ln(N_{tc}) = a + be + ct \quad (1)$$

where N_{tc} is the expected number of TCs, e is the environmental parameter and t is time (e and t have been standardized to represent a mean of zero and a standard deviation of one to avoid misleading results *Chandler* [1998].)

To assess the significance of the b parameter in equation 1, we conduct a t-test on the ratio $b\ /s_e$, where b is the fit parameter associated with the environmental parameter in the regression and s_e is the standard error of b . If the absolute value of $b\ /s_e$ exceeds 2.07, b is significant at the 95% level.

An analysis of the variations of TC numbers with time is also conducted. We use Poisson regression to obtain a linear relationship between the TC index and time (in contrast to equation 1 where the relationship between the TC index, environmental parameter and time is exponential). These trends are expressed in two ways in terms of (a) the change in TC numbers per year, T, and (b) the relative trend, T_R, given by:-

$$T_R = 100(T(N-1)/\bar{y})\ \% \quad (2)$$

where N is the number of years in the time series and $\bar{y}$ is the mean of the time series under consideration. The significance of the relative trend is expressed by T/s_e (s_e = standard error) *Schonwiese and Rapp* [1997].

Results and Discussion

In Figure 1 (shaded plot) we show the longitude distribution of approximately half the hurricanes (those from the least active years). It can be seen that there are two regimes of hurricane activity, a cluster to the east, with a cut-off around 116°W, and a long tail to the west of 116°W. When all 26 years are considered (unshaded plot), the distribution shows a more prominent tail indicating that the spread of hurricane longitudes is greater for years with a greater number of hurricanes. The percentage of hurricanes to the west of 116°W is 24% (39%) for the least (most) active years, a difference which is significant at the 95% level.

For subsequent analysis we have therefore divided the NE Pacific region into two sub-regions to the west and east of 116°W. The parameters are averaged over the ocean in each area, 10° to 20°N by 93° to 115°W and by 116° to 180°W for the east and the west region respectively. This division into two populations with regard to causal factors is strongly supported by the results of the following regression and extreme year analysis.

Figure 2a shows the time series of seasonal major hurricane numbers for the whole of the NE Pacific basin. An upward trend of 2.4 major hurricanes over the 26 year period (significant at the 94% level) is observed. This value is large compared to the mean of the region which is 3.5 (T_R = 65%). Figures 2b and 2c show that this trend is largely due to the strong upward trend of major hurricanes in the western region of 1.7 major hurricanes over the 26 year period (T_R is 124%). This is significant to the 98% level. In the eastern region, the increase of major hurricanes is only 0.5 for the 26 year period (T_R is 23%) and the trend is insignificant.

Trend analysis is also conducted for hurricane numbers with time for the whole region, where it is found that there

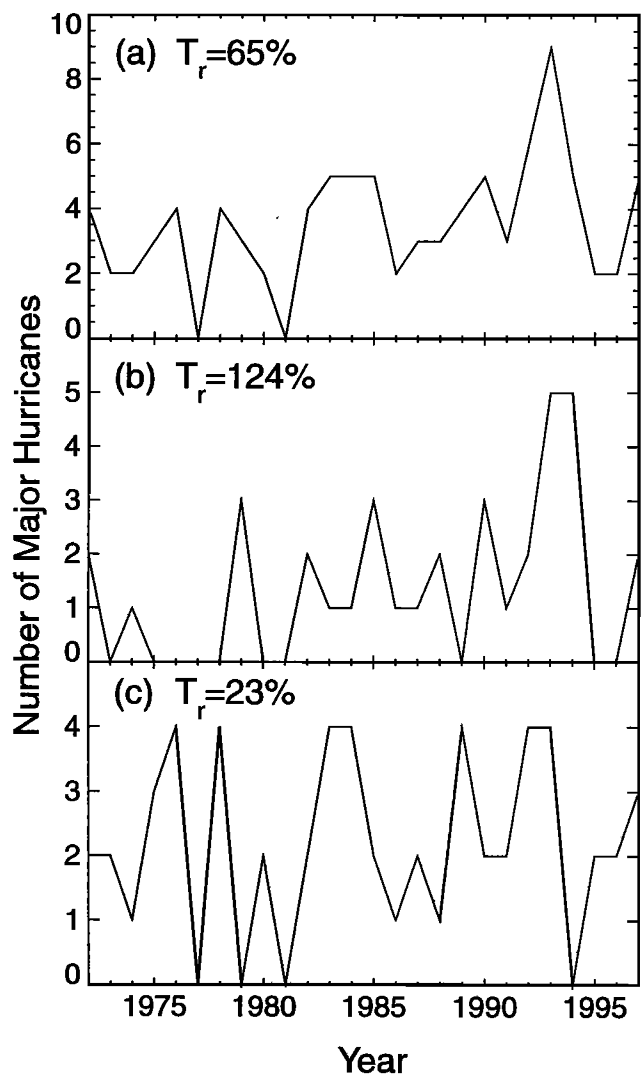

Figure 2. Time series of seasonal major hurricane numbers for the three regions, (a) Whole NE Pacific (b) Western and (c) Eastern, 1972–1997.

Table 1. Extreme value statistics of tropical cyclone indices with several environmental parameters based on binomial statistics

	Western Region			Eastern Region			ALL		
Factor	M	H	S	M	H	S	M	H	S
RH	95	99	99	-	-	-	-	-	-
SST	99	99	95	-	-	-	-	-	-
VVEL	99	99	99	-	-	-	-	-	-
PWAT	99	99	99	-	-	-	-	-	-
ULWRF	99	99	99	-	-	-	-	-	-
PRES	95	99	99	-	-	-	-	-	-
ENSO	-	-	-	-	-	-	-	-	-
RELV	-	-	-	-	-	-	-	-	-
MJO	99	99	99	-	-	-	-	-	-
QBO	-	-	-	-	-	-	-	-	-
TMP	-	-	95	-	-	-	-	-	-
PDO	-	-	-	-	-	-	-	-	-
VZ	-	-	99	-	-	-	-	-	99

Table 1 shows the probabilities that a significant difference in tropical cyclone numbers occurs when the environmental parameters experience extreme years (6 highest and lowest). The relationship is shown for the significances of 95% and 99% and labelled "-" if not significant at the 95% level. The tropical cyclone categories are major hurricane (M), hurricane (H) and tropical storm (S). The parameters are relative humidity (RH) at 500 mb, sea surface temperature (SST), pressure vertical velocity (VVEL) at 500 mb, precipitable water (PWAT), upward long wave radiation flux - top of the atmosphere (ULWRF), mean sea level pressure (PRES), Wolter's ENSO index (ENSO), relative vorticity (RELV) at 850 mb, the Madden-Julian Oscillation index (MJO), the Quasi-Biennial Oscillation (QBO), temperature (TMP) at 300 mb, the Pacific Decadal Oscillation index (PDO) and the vertical wind shear (VZ) between 850 mb and 200 mb. For each significant result, the sign of the relationship is the same as that noted in Table 2.

was no significant trend. However, again hurricanes in the western region show an upward trend of 2 hurricanes over the 26 year period (T_R is 84%). This is significant at the 95% level. These results are consistent with Chu and Clark [1999], who note that in the Central Pacific, TC activity has been increasing from 1966 to 1997. Again there is no significant change of hurricane numbers with time in the eastern region. Therefore there is no consistency in the trends of hurricanes and major hurricanes between the different regions, indicating once again that the two regions should be examined separately.

Table 1 shows the results of examining the extreme years. With a p-value at 95% significance or greater ($p \leq 0.05$) we can reject the null hypothesis that there is no statistical difference between the totals of the two groups. The p-value is doubled to allow for a two-tailed test to account for the uncertainty in the sign of the relationship between the environmental parameters and TC numbers. There are two important aspects of these results. Firstly, it can be seen from the significances above 95%, that there are strong significant relationships between some of the environmental parameters and the TC indices in the western region of the NE Pacific. Conversely, an examination of the eastern region of the NE Pacific shows no significant relationships with any of the environmental parameters studied. Likewise, when investigating the whole NE Pacific basin, the environmental parameters generally showed no significant relationships. Secondly, within the western region of the NE Pacific basin, seven out of the thirteen parameters investigated are significant to at least 95% for all stages of TC activity. These are relative humidity (RH), sea surface temperature (SST), pressure vertical velocity (VVEL), precipitable water (PWAT), upward long wave radiation flux (ULWRF), mean sea level pressure (PRES) and the MJO. Interestingly, the null hypothesis could not be rejected for either ENSO or QBO.

The variation in TC numbers with each of the parameters is indicated by the ratio of the six highest to the six lowest extreme years of the parameter. Ratios of hurricanes (major hurricanes) for all the parameters in the eastern region were low, varying from only 1:1 to 1.5:1 (1.07:1 to 1.73:1). ENSO and QBO in the eastern region gave ratios of 1.06:1 (1.31:1) and 1.33:1 (1.55:1) respectively. This study shows that, by examining the western region only, the ratios are greatly increased.

For the western region, the ratios for hurricanes (major hurricanes) are 6:1 (4:1) for low to high PRES years, 5.2:1 (4.3:1) for high to low RH years, and 4.3:1 (6:1) for high to low SST years, to name a few of the highest ratios. ENSO on the other hand, shows only 2.1:1 (2.2:1) in an El Niño year compared to a La Niña year and QBO shows only 1.21:1 (1.67:1) in a westerly than easterly phase. Therefore, although ENSO gives a higher ratio between extreme years in the western region than the eastern region, this index gives a much lower ratio compared with other parameters.

Table 2 shows the b/s_e values for the environmental parameters versus TC numbers when all years are considered. The parameters that are significant to at least the 99% level are shown in bold face and underlined (95% shown under-

Table 2. Significance of the relationships between the tropical cyclone indices and several environmental parameters, 1972–1997

	Western Region			Eastern Region		
Factor	M	H	S	M	H	S
RH	2.51	**4.05**	**3.61**	1.49	1.74	1.82
SST	2.47	**3.23**	2.10	-0.81	-1.67	-0.91
VVEL	-2.44	**-3.42**	**-3.23**	-0.53	-0.62	0.32
PWAT	2.20	**3.68**	**3.28**	0.44	1.19	0.85
ULWRF	-2.01	**-3.09**	-2.76	-1.15	-1.41	-0.42
PRES	-1.92	**-3.78**	**-3.27**	-0.56	-0.20	0.16
ENSO	1.34	2.09	1.74	0.15	-0.86	-0.12
RELV	1.08	1.31	1.31	1.33	1.91	1.19
MJO	-1.06	-2.19	-2.73	-0.24	-0.29	-0.75
QBO	-0.51	-1.34	-2.05	1.15	1.10	1.02
TMP	0.46	1.28	1.12	-0.60	-0.13	0.06
PDO	0.46	-0.14	0.01	1.19	0.99	1.31
VZ	-0.10	-0.84	**-3.20**	-1.24	0.04	-0.64

Table 2 shows the results from a Poisson regression. The relationships between tropical cyclone numbers and the environmental parameters are shown by the b/s_e values in the table. Entries in boldface and underlined are significant to the 99% level, those underlined to the 95% level. Positive results indicate that more tropical cyclones occur with larger values of the parameter. Negative results indicate an inverse relationship where there are fewer tropical cyclones with larger values of the parameter.

lined only). Again there are no significant parameters in the eastern region. In the western region, however, there are significant relationships. RH, SST, VVEL and PWAT are parameters that are common to all categories of TC which are significant to at least 95%. Therefore the significant parameters in Table 2 include those which are found to be significant for the extreme years only, as shown in Table 1.

The reliability of the NCEP/NCAR data has been considered. A comparison between NCEP/NCAR and ECMWF reanalysis data for 1979-1993, and between ULWRF and NOAA outgoing longwave radiation (OLR) data available from 1974 to 1977 and 1979 to 1995 *Waliser and Zhou* [1997], shows high correlations for all parameters in the western region, and for SST, wind shear (VZ), temperature at 300 mb (TMP), relative vorticity at 850 mb (RELV) and PRES in the eastern region, giving us high confidence in those results. These parameters are also considered most reliable by Kalnay et al. [1996]. In the eastern region, VVEL has a low reliability and ULWRF must be considered unreliable. (By contrast OLR is found to have a significant relationship with numbers of major hurricanes and tropical storms.)

Conclusions and Further Work

We have shown that it is necessary to examine the NE Pacific by sub-regions when investigating the environmental factors affecting TC activity. The longitude distributions, regression and extreme year analysis, provide statistical evidence for two populations of TCs, east and west of 116°W, with regard to causal factors. We show that there is a significant increasing trend of TC numbers with time in the western sub-region. We observe that there are significant relationships between some of the environmental parameters examined and TC activity in the western sub-region. These relationships are absent in the eastern sub-region and the whole NE Pacific when one considers this as one entity. This is because the entire NE Pacific is strongly influenced by the eastern sub-region with its dominance of hurricane numbers. Therefore, without sub-dividing the basin, as this study has shown, important results are obscured, and this may explain why previous researchers have not found strongly significant results for the causes of hurricane formation in the NE Pacific.

For most parameters, the main reason for the large difference between the eastern and western regions may be the longitudinal variation in the significant parameters. In the eastern region, the parameters are generally at a level conducive to TC formation, whereas in the western region there are years when parameters are at a level which is less conducive. Gray [1988] provides insight as to why most of the significant environmental parameters noted herein affect TC activity. However, Gray [1988] notes the importance of some parameters, such as the QBO, which have been shown here to be insignificant in relation to the NE Pacific.

We are currently extending this work to examine (a) other non-local effects and (b) the predictability of TCs in these sub-regions by investigating the significant parameters several months before the TC season.

Our findings offer promise for predicting TCs in the western part of the NE Pacific since we are able to see, for the first time, strong relationships concurrently between TC activity and some observed environmental parameters. This has socio-economic implications primarily for the Hawaiian Islands which are the most at risk from TCs developing in the western region.

Acknowledgments. Jennifer Collins gratefully thanks the Natural Environmental Research Council for sponsorship, and the authors thank Frank Roberts, Richard Chandler, Justin Mansley and Neale Ranns for their valuable comments and help. The ECMWF reanalysis data was obtained from the British Atmospheric Data Centre and the NCEP/NCAR reanalysis data was obtained from the Data Support Section, Scientific Computing Division, National Center for Atmospheric Research).

References

Brown, G. M. and P. W. Leftwich, A compilation of eastern and central North Pacific tropical cyclone data, *NOAA Technical Memorandum NWS NHC*, **16**, Miami, 13pp, 1982.

Chandler, R., Orthogonality. In Armitage, P. and Cotton, T. (eds) *Encyclopedia of Biostatistics*, Wiley, 1998.

Chu, P. S. and J. D. Clark, Decadal variations of tropical cyclone activity over the central North Pacific, *Bull. Am. Meteor. Soc.*, **80(9)**, 1875–1881, 1999.

Chu, P. S. and J. Wang, Tropical cyclone occurrences in the vicinity of Hawaii: Are the differences between El Niño and non-El Niño years significant?, *J. Clim.*, **10**, 2683–2689, 1997.

Gray, W.M., Environmental influences on tropical cyclones, *Aust. Met. Mag.*, **36**, 127–139, 1988.

Kalnay, E., and collaborators, The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteor. Soc.*, **77**, 437–471, 1996.

Landsea, C. W. and W. M. Gray, Eastern North Pacific tropical cyclone climatology—low frequency variations. Report of WG 6.2 (Northeast Pacific Ocean) of IWTC -II, WMO, WMO/TD no. 319, Geneva, 1989.

Maloney, E. D., and D. L. Hartmann, Frictional moisture convergence in a composite lifecycle of the Madden-Julian Oscillation, *J. Clim.*, **11**, 2387–2403, 1998.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteor. Soc.*, **78**, 1069–1079, 1997.

McCullagh, P. and J. A. Nelder, *Generalized Linear Models (2nd ed.)*, 511 pp., Chapman and Hall, 1989.

Schonwiese, C. D. and J. Rapp, Climate trend atlas of Europe - based on observations 1891–1990, *Hurricanes—climate and socioeconomic impacts*, Kluwer Acedemic Publishers. Dordrecht, 1997.

TPC, Northeast Pacific tropical cyclone best-track file: 1998 [Online computer file], 1949– (updated annually). NOAA/NWS/Tropical Prediction Center, Miami, Florida. Available: ftp server: ftp.nhc.noaa.gov.pub/tracks/tracks.epa.

Waliser, D. E., and W. Zhou, Removing satellite equatorial crossing time biases from the OLR and HRC data sets, *J. Clim.*, **10**, 2125–2146, 1997.

Whitney, L. D., and J. S. Hobgood, The relationship between sea surface temperature and maximum intensities of tropical cyclones in the eastern North Pacific ocean, *J. Clim.*, **10**, 2921–2930, 1997.

Wolter, K., The southern oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis, *J. Climate Appl. Meteor.*, **26**, 540–558, 1987.

J.M. Collins and I.M. Mason,Department of Space and Climate Physics, University College London, Dorking, Surrey, RH5 6NT, U.K.

(email: jmc@mssl.ucl.ac.uk; imm@mssl.ucl.ac.uk)

(Received March 16, 2000; revised October 11, 2000; accepted October 16, 2000.)