The Relationship between Sea Surface Temperatures and Maximum Intensities of Tropical Cyclones in the Eastern North Pacific Ocean

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ABSTRACT

An empirical relationship between climatological sea surface temperatures (SST) and the maximum intensities of tropical cyclones over the eastern North Pacific Ocean is developed from a 31-yr sample (1963–93). This relationship is compared with an empirical relationship for tropical cyclones over the Atlantic Ocean and with theoretical results. Over the period of study, the storms over the eastern North Pacific Ocean reached a lower percentage of their empirical maximum potential intensity (MPI) than tropical cyclones over the Atlantic Ocean. At the time of their maximum intensity, only 11% of eastern North Pacific storms reach 80% of their MPI, while 19% of the Atlantic tropical cyclones reach that proportion of their MPIs. Poleward recurvature of Atlantic storms over cooler waters appears to be a major factor in the difference between the two regions. The storms were stratified by latitude, longitude, the phase of the quasi-biennial oscillation (QBO), and the status of the El Niño phenomenon. Tropical cyclones that develop west of 110°W tend to reach a higher percentage of their MPI than storms developing farther east. Tropical cyclones also tended to reach a higher percentage of their MPI and to attain higher maximum intensities when the QBO was in its westerly phase.

1. Introduction

In recent years research has increased into the factors that determine the intensities of tropical cyclones. The external environment appears to be a key ingredient in the intensification of tropical cyclones (Elsberry et al. 1988). The strength of the vertical shear of the horizontal wind may indicate whether a tropical cyclone will intensify or weaken. Molinari and Vollaro (1989) associate eddy angular momentum fluxes in the outflow layers with intensification of hurricanes. Internal factors such as the diameter of the eye (Holiday and Thompson 1979) and concentric eyewall development (Willoughby et al. 1982) may affect changes in intensity. Theoretical studies (Emanuel 1988) and empirical research (DeMaria and Kaplan 1994a) support the concept that the sea surface temperature (SST) may be a factor in the determination of the maximum potential intensity (MPI) of a tropical cyclone.

The SST has historically been mentioned as a limiting factor of the development and intensification of tropical cyclones. Palmén's (1948) study of the Atlantic Ocean proposed that vertical instability was a necessary condition for the formation of hurricanes and concluded that hurricanes only form in regions where the SSTs are greater than 26° or 27°C. Using the assumption of hydrostatic equilibrium, Miller (1958) found that the minimum possible surface pressure in a hurricane was a function of the SST, surface relative humidity, lapse rate, and the height and potential temperature of the top of the storm. More recently Emanuel (1986, 1988) developed a theoretical relationship between the minimum central pressure of a tropical cyclone, the SST, and the outflow temperatures.

Merrill (1987, 1988) compared climatological SSTs with the maximum sustained winds of a sample of Atlantic hurricanes and found evidence of an empirical intensity relationship between the two factors. The relationship suggested that as SSTs increase, the maximum potential intensity also increases. Merrill (1987) suggested that since a wide range of intensities are observed over a given range of SSTs, SSTs were more likely to be a capping function on the intensity of a tropical cyclone, rather than a direct predictor of intensity. Evans (1993) examined the intensities of tropical cyclones that occurred during a period of 20 yr over 5 ocean basins (North Atlantic, western North Pacific, South Pacific–Australia, north Indian, and southwest Indian Oceans). The results of that study also concluded that SST alone was not a sufficient predictor of the intensity, and other factors must affect the intensification of tropical cyclones.

DeMaria and Kaplan (1994a) extended the work of Merrill (1987) by developing an empirical relationship between climatological SSTs and the maximum sus-

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tained winds of Atlantic tropical cyclones that occurred between 1962 and 1992. After subtraction of the translational speed, a function was fitted to the maximum wind speeds of SST groups with a 1°C range. Their result was an exponential function,

$$V = A + Be^{C(T-30°\mathrm{C})}, \quad (1)$$

where V represents the maximum wind speed or MPI in m s^{-1}, T is the SST (°C), and A, B, and C are constants (A = 28.2 m s^{-1}, B = 55.8 m s^{-1}, C = 0.1813 °C^{-1}).

These studies indicate that SST acts as an upper bound on the MPI of a tropical cyclone, but other environmental factors ultimately determine the actual intensity of any given tropical cyclone. This concept is used as the basis for the research described in this article. In comparison to the other ocean basins, relatively little research has been done on tropical cyclones over the eastern North Pacific Ocean. The remainder of this article describes an investigation of the relationship between SST and MPI in the eastern North Pacific and a comparison of tropical cyclones over that ocean basin with those elsewhere. The data used for this study are described in section 2, and the results of the analyses are presented in section 3.

2. Data

a. Tropical cyclone intensities

The data used for this study were taken from the ‘‘best track’’ file compiled by the Eastern Pacific Hurricane Center in Redwood City, California, and the National Hurricane Center in Miami, Florida. The locations and intensities of all known tropical cyclones of the eastern North Pacific Ocean between 1949 and 1993 were recorded at 6-h intervals on the best track file. Storms prior to 1963 were not included in the analysis, because the intensity estimates did not have the benefit of satellite imagery. A 31-yr period for the analysis from 1963–93 was chosen to include the longest homogenous record and to be comparable with the length of the sample used by DeMaria and Kaplan (1994a). The intensities reported in the best track file for the eastern North Pacific were usually estimated from satellite imagery unless aerial reconnaissance or ship reports were available. The intensities in the best track file for the Atlantic Ocean include many more cases determined by aerial reconnaissance and are likely to be more accurate. Gaby et al. (1980) reported an average absolute difference of 3.8 m s^{-1} and an average algebraic difference of -2.4 m s^{-1} between satellite estimates of maximum winds speeds and best track data for the Atlantic during periods when aerial reconnaissance and other data were available. If these results are also representative of satellite estimates of the intensities in the eastern North Pacific, then the maximum sustained winds used in this study probably underestimate slightly the actual intensities of the storms.

Since the focus of this study is the eastern North Pacific Ocean, all storms and observations in the best track file west of 140°W longitude were eliminated. The 140°W meridian was chosen since it marks the western border of the National Hurricane Center’s area of responsibility in the eastern North Pacific. This decision eliminated 1796 of the original 13 068 observations in the best track file between 1963 and 1993. Because the purpose of this research was to determine a relationship between SSTs and the intensities of tropical cyclones, all observations for times when the centers of the storms were over land were also eliminated from further analysis. A distance to land (DTL) was calculated using the method developed by Merrill (1987). A negative DTL indicated that the tropical cyclone is over land and that observation was eliminated. That procedure eliminated another 179 observations. In a few instances the center of a storm moved back out over the water after moving inland. In cases where the storm dissipated without undergoing a period of reintensification, the observations were eliminated from further analysis. The justification for the elimination of these observations was that the circulations were disrupted by movement over land and the intensity of the storm was not related to the SST. Several other minor adjustments were made to the best track data. There are observations with maximum wind speeds of 5 m s^{-1} or less, which seem to indicate that the system had weakened to a tropical disturbance. These observations were dropped from the analysis. Finally, a new longitude was interpolated for Hurricane Dolores (1985) for the 1800 UTC 01 July observation because of an apparent error in the file. The final dataset included 11 062 observations with positions and intensities. The sample included 215 tropical storms and 252 hurricanes. The percentage of hurricanes, 54%, is lower than the 63% DeMaria and Kaplan (1994a) found in their study of the Atlantic.

b. Climatological SSTs

Climatological SSTs developed by Levitus (1982) were used for this study. The climatological SSTs were available at a 1° lat × 1° long resolution. A program to interpolate linearly in time and space to the position and date of each observation was obtained from the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory. The program assumes that the climatological SSTs are valid for the middle of the month. The lowest climatological SST beneath an observed tropical cyclone was 16°C and the highest SST was 29.8°C. The program was able to compute an SST for every observation except the last position of tropical storm Katrina (1967). The position was reported as 30.9°N, 114.6°W, which appears to be very close to land in the northern portion of the Gulf of California. Because of the lack of a suitable SST and the possible influence of the surrounding land, this observation was eliminated from further consideration.

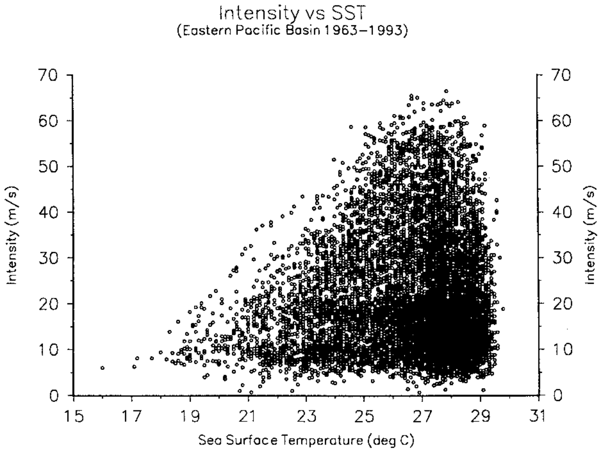

FIG. 1. Scatter diagram with the intensities and SSTs of all 11 062 observations in the 31-yr sample (1963–93). Intensities are corrected for storm translational speed.

TABLE 1. SST group properties.

SST midpoint (°C)	Number of observations	Average SST (°C)	Average intensity (m s^{-1})	Maximum intensity (m s^{-1})
19.0	52	18.8	10.8	20.1
20.0	58	20.0	11.7	26.1
21.0	141	21.0	14.6	36.2
22.0	282	22.0	14.5	39.1
23.0	472	23.0	16.5	43.5
24.0	700	24.0	19.2	51.5
25.0	923	25.0	23.1	58.7
26.0	1256	26.0	24.6	61.1
27.0	2042	27.0	23.7	65.5
28.0	3298	27.9	20.9	65.5
29.0	1838	28.8	19.3	60.7

3. Analyses of intensities

a. Storm-relative velocities

In order to eliminate the influence of the motion of the storm and to make the intensities comparable to those computed by DeMaria and Kaplan (1994a) for the Atlantic systems, the translational speeds of the tropical cyclones were subtracted from the velocities in the historical data tape. For most observations the speed of movement of the system was computed for 12 h centered on the observation. For the first observation of each storm a 6-h movement based on the first two positions in the file was used to compute the translational velocity. For the last observation of each storm a 6-h movement based on the last two positions in the file was used to compute the translational velocity. The average translational speed for the tropical cyclones over the eastern North Pacific Ocean was 4.7 m s^{-1}. This was slower than the translational speed of 6 m s^{-1} reported by DeMaria and Kaplan (1994a) for systems over the Atlantic Ocean. At least part of the difference is the result of the fact that rapid recurvature of tropical cyclones rarely occurs over the eastern North Pacific Ocean. Those few storms that do recurve and begin to accelerate northward usually dissipate rapidly over colder water or over the mountains in Mexico. The translational speed was subtracted from the maximum winds reported in each observation and the storm relative winds were used for the rest of the analysis.

b. Velocities versus SSTs

Figure 1 shows a plot of all of the storm relative intensities plotted according to the SSTs. A strong cluster of observations of relatively weak intensities and high SSTs is apparent. This represents the early stages of many tropical cyclones that were beginning to intensify over the warm water. More relevant to this study are the maximum intensities for each SST, which seem to indicate a roughly linear relationship between maximum sustained winds and SST. The data were stratified by assigning each of the observations to an SST group in the manner specified by DeMaria and Kaplan (1994a). Each observation was assigned to the nearest whole SST number. Since only nine observations had SSTs less than 18.5°C, those observations were included in the 19.0°C category. This reduced the average SST of that group from 19.0° to 18.8°C, but was deemed necessary to prevent a few observations at low SSTs from possibly biasing the rest of the analyses. A separate category was initially created for observations with SSTs greater than 29.5°C. This category contained only 31 observations and many of those intensities were for systems near the coast of Mexico. It was decided to include the 31 observations in the 29.0°C category because of the relatively small number and potential for interaction with land. The average SST of the 31 observations was 29.54°C.

The result was to group the observations in 11 groups of SSTs. The properties of all of the groups of SSTs are shown in Table 1. Approximately three-fourths (76%) of the observations were assigned to SST categories greater than or equal to 26.0°C. That is slightly lower than the 82% found by DeMaria and Kaplan (1994a) for the Atlantic systems. The highest average maximum wind speed was for the 26.0°C group. This is similar to the finding of DeMaria and Kaplan (1994a) that the highest average intensity for the Atlantic occurred in the 25.0°C group. Both of these findings result from the movement of stronger tropical cyclones over colder water, and the lag time until the wind speeds decrease in response to the colder SSTs. The decrease of the average maximum wind speeds at higher SSTs is again due to the large number of developing systems over warmer waters. The most intense hurricane in the record was Trudy (1990) and the peak observation was assigned to the 28.0°C category. The tropical cyclones with the highest wind speeds in each SST group are shown in Table 2. Only one storm, Gwen (1972), was from early in the dataset. Most of the storms were from 1990 or later. Figure 2 shows the curves for the maximum in-

TABLE 2. Eastern North Pacific tropical cyclones with the highest winds speeds in each SST group.

SST group (°C)	Storm name	Year	Lat, Long	Maximum intensity (m s^{-1})
19.0	Gwen	1972	28.9°N, 120.2°W	20.1
20.0	Darby	1992	24.5°N, 122.4°W	26.1
21.0	Darby	1992	23.4°N, 119.0°W	36.2
22.0	Iselle	1990	23.4°N, 119.2°W	39.1
23.0	Orlene	1992	21.0°N, 135.5°W	43.5
24.0	Enrique	1979	19.6°N, 130.7°W	51.5
25.0	Enrique	1979	18.9°N, 129.9°W	58.7
26.0	Tina	1992	17.5°N, 121.1°W	61.1
27.0	Hernan	1990	17.5°N, 117.9°W	65.5
28.0	Trudy	1990	15.5°N, 111.0°W	66.5
29.0	Ignacio	1979	17.0°N, 107.3°W	60.7

tensity, 99th, 95th, 90th, and 50th percentiles of the SST groups. The curve for the 50th percentiles is relatively flat, which is similar to the findings of DeMaria and Kaplan (1994a) for the Atlantic Ocean. The curves for the other percentiles and the maximum intensities all show gradual increases with increasing SST until a decline occurs at the highest one or two SST groups. This is a reflection of the fact that in the eastern North Pacific Ocean, tropical cyclones often develop over the warmest water and then move westward over gradually cooler SSTs. Thus, for many storms the maximum wind speeds do not occur over the warmest waters.

c. Empirical maximum potential intensity function

After a visual inspection of the maximum intensity curve in Fig. 2, it was decided that a least squares linear fit was appropriate. An adaptation of the least squares curve-fitting program listed in James et al. (1985, 337) was used to determine the best-fit line to the maximum intensity curve. The SST midpoints and the maximum intensities of each group were entered into the program and the coefficients specifying the best-fit line were computed. As can be seen in Fig. 3, the initial linear function that included the 29°C category underestimated the maximum intensities of most other SST groups. This was deemed unacceptable and the least squares curve-fitting program was rerun without the data for the 29°C category. The resulting equation for the empirical maximum potential intensity relationship for tropical cyclones over the eastern North Pacific Ocean was

$$\mathrm{EPMPI} = C_0 + C_1(\mathrm{SST}), \qquad (2)$$

where EPMPI is the eastern Pacific maximum potential intensity in m s^{-1}, SST is in degrees Celsius, $C_0 = -79.17262$ m s^{-1}, and $C_1 = 5.361814$ m s^{-1} °C^{-1}. As is evident from Fig. 3, the relationship specified in (2) fits the maximum intensities of the remaining groups much better. Figure 4 shows the line specified by (2) and all of the observations used in the analyses. Although the relationship specified in (2) is strictly only

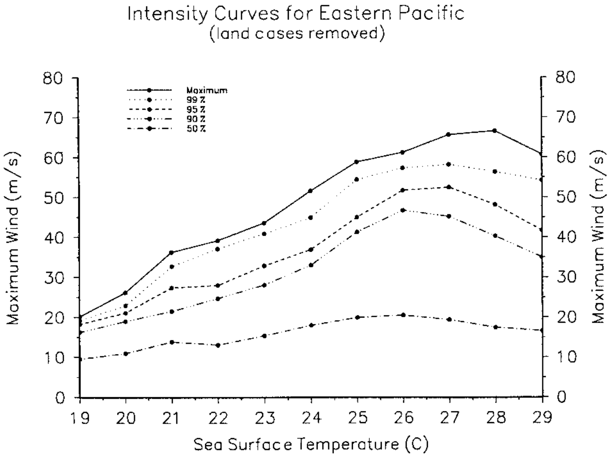

FIG. 2. Intensity curves for the eastern North Pacific Ocean with land cases removed and intensities corrected for storm translational speed.

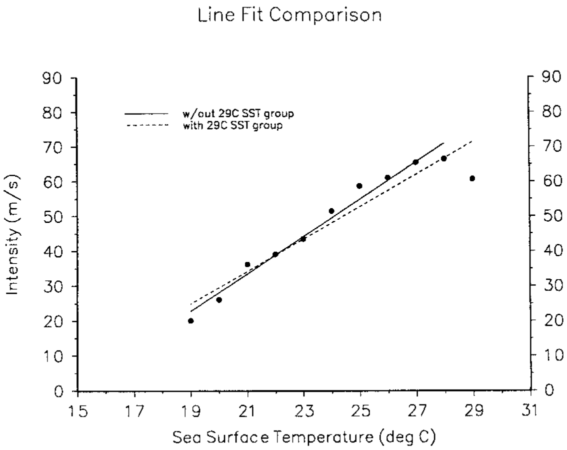

FIG. 3. Comparison of best-fit lines with and without the 29°C SST group and the maximum intensity data.

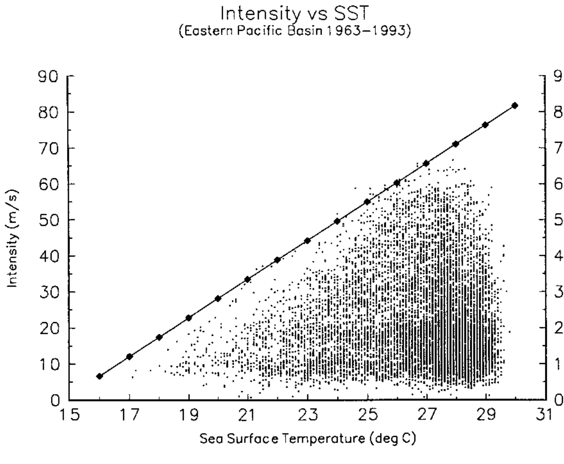

FIG. 4. Comparison of the EPMPI function and all 11 062 observations in the 31-yr sample (1963–93).

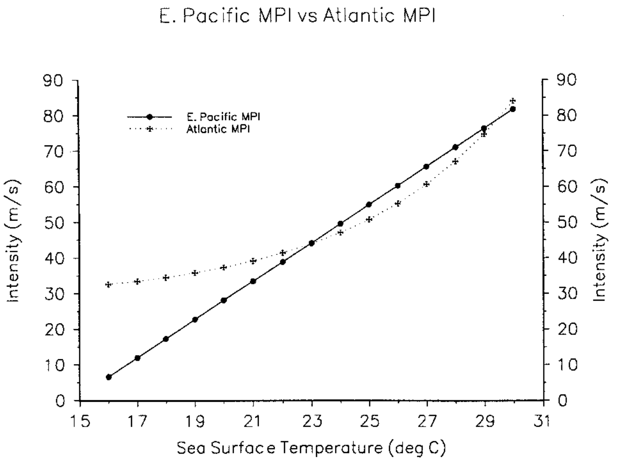

FIG. 5. Comparison of the EPMPI and the Atlantic MPI from DeMaria and Kaplan (1994a).

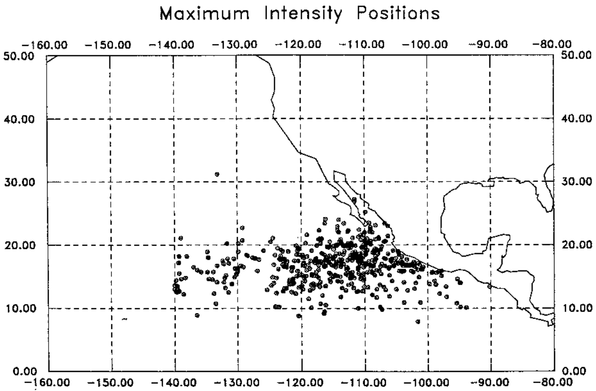

FIG. 6. Position of each of the 467 tropical cyclones in the 31-yr sample at the first time it reached its maximum intensity.

valid for temperatures between 19° and 28°C, the line is extended to show how closely it matches the maximum intensities at other temperatures. The EPMPI seems to provide a reasonable estimate of the maximum observed intensities of tropical cyclones over the eastern North Pacific Ocean. At least part of the reason for the nearly linear relationship between the maximum wind speeds and SSTs may be the almost exclusive use of satellite-derived intensity estimates for the eastern North Pacific region. Unlike in the data for tropical cyclones over the Atlantic Ocean, there are usually no aircraft measurements of maximum wind speeds for the most intense hurricanes.

Figure 5 provides a comparison of the line generated by (2) with the exponential curve computed by DeMaria and Kaplan (1994a) and presented in (1) for storms over the Atlantic Ocean. For SSTs less than 23°C, (1) predicts a higher MPI. This is partially explained by the tropical cyclones over the Atlantic Ocean that rapidly recurve over colder waters. Before they dissipate, these systems have higher wind speeds than would be expected based on the SSTs. Over the eastern North Pacific Ocean tropical cyclones generally move more slowly and dissipate more rapidly as they encounter colder SSTs. Between 23° and 29°C, (2) predicts higher maximum winds for the tropical cyclones over the eastern North Pacific Ocean. This is partially the result of the prevailing westward motion of most systems across the eastern North Pacific, which gradually moves stronger systems over slightly cooler water.

d. Stratified analyses

The data were stratified in various manners to determine the spatial and temporal coherency of the results from the SST analysis. It is apparent from Fig. 4 that most of the observations in the dataset represent situations when the intensity of the tropical cyclone is much less than the EPMPI specified by (2). Several factors account for this pattern. Storms that are just beginning to develop over warm water have wind speeds well below those predicted by (2). Even as storms become more intense, unfavorable environmental factors such as vertical shear of the horizontal wind may keep the intensity beneath the EPMPI. The peak wind speed for each storm is compared to the EPMPI for that observation. In cases where the best track contains multiple observations of the same maximum wind speed for a storm, only the first observation is used in the stratified analyses. Because of the relatively slow movement of tropical cyclones in the eastern North Pacific, the SSTs and EPMPIs change little in the 6 h between observations in the best track data. Thus, the SST beneath the storm at the time of the first observation of the peak intensity is representative of the SSTs for subsequent observations with the same maximum wind speed. The positions where each of the 467 storms reached their maximum intensity are shown in Fig. 6. Because all observations west of 140°W longitude were eliminated, a very small number of storms may have reached their maximum intensity west of the study region. Most of the storms reached their peak intensities between latitudes 10° and 20°N and longitudes 100° and 120°W.

The relative intensity for each observation in the stratified analysis was computed by dividing the maximum wind speed by the EPMPI and expressing the result as a percentage. Figure 7 shows the distribution of the relative intensities for the 467 observations in the stratified sample. Very few of the tropical cyclones over the eastern North Pacific Ocean reach their EPMPI, even when they are at their peak intensity. The average relative intensity for the stratified sample is 49%, which is lower than the 58% average relative intensity found by DeMaria and Kaplan (1994a) for the Atlantic Ocean. Over the eastern North Pacific Ocean, the peak in the distribution of relative intensities was at 30%, while DeMaria and Kaplan (1994a) found a bimodal distribution over the Atlantic Ocean with maxima at 40% and 70%. Figure 8 shows the cumulative distribution of

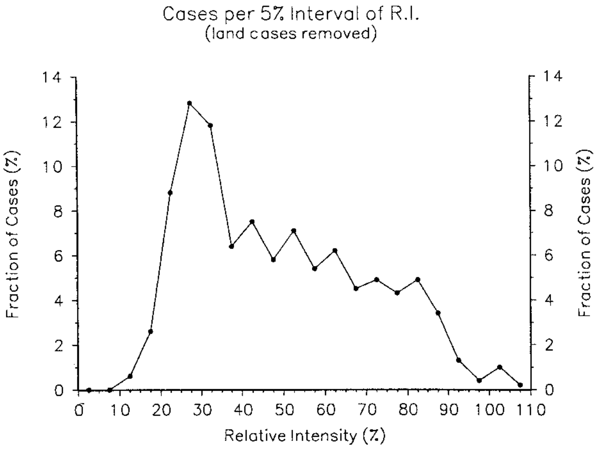

FIG. 7. The percentage of eastern North Pacific tropical cyclones per 5% interval of relative intensity (RI).

TABLE 3. Average relative intensity (RI) of eastern North Pacific tropical cylones (1963–93) stratified by latitude and longitude.

	Location	Number of storms	Average RI (%)
Lat	≥18°N	154	51.2
	<18°N	313	47.5
Long	<110°W	143	41.2
	≥110°W to ≤140°W	324	52.0

the relative intensities. Only 43% of the storms reached 50% of their EPMPI, and only 11% reached 80% of their EPMPI. Over the Atlantic Ocean, DeMaria and Kaplan found that 58% reached 50% of their MPI, and 19% reached 80% of their MPI. It seems clear from these results that tropical cyclones over the eastern North Pacific Ocean are not as intense as one might expect based on the SSTs in that region.

To determine if the relative intensities of tropical cyclones varied by region over the eastern North Pacific Ocean, the average relative intensities were calculated for storms north and south of 18°N latitude and for storms east and west of 110°W longitude. Table 3 shows that the average relative intensity is slightly higher for tropical cyclones north of 18°N. Storms in the stratified sample west of 110°W exhibit a higher average relative intensity than systems farther to the east. Both of the results reflect the typical development and intensification of tropical cyclones over the eastern North Pacific Ocean. Many of the tropical disturbances that develop into tropical cyclones move into this region from the east. As the tropical cyclones develop, the prevailing steering currents move the systems to the north and west. As the storms reach their peak intensities, they gradually move over cooler waters and reach a higher percentage of their EPMPI. Tropical cyclones that reach their maximum intensities east of 110°W are sometimes recurving in southwesterly flow aloft. The combination of increased vertical shear and interaction with land produces lower relative intensities for these storms.

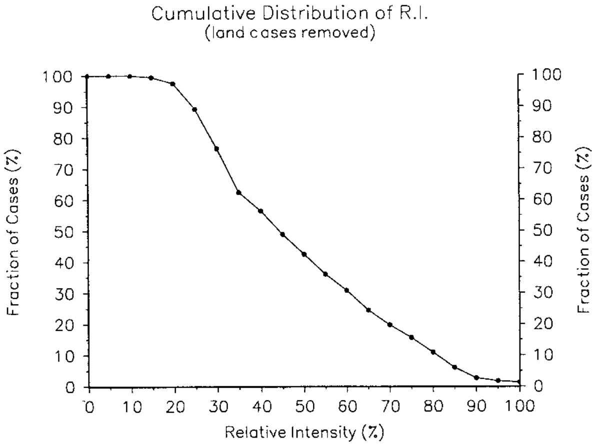

FIG. 8. Cumulative distribution of RI for the eastern North Pacific.

The average relative intensity for each month in which tropical cyclones were observed is shown in Table 4. The number of tropical cyclones peaks during the months of July and August, each of which average around 3.6 storms yr^{-1}. The average maximum intensity and the average relative intensity reach a peak in September, but both of these variables are relatively constant between June and October. These results seem to indicate that the atmosphere over the eastern North Pacific Ocean is generally favorable for the development of tropical cyclones throughout much of the summer and early autumn.

In order to determine the temporal stability of these results, the annual variability of the relative intensities was also examined. The average relative intensities for the years in this analysis are shown in Fig. 9. The relative intensities varied from a minimum of 32.6% in 1964, to a maximum of 63.7% in 1990. The relative intensities exhibit considerable year-to-year variation. However, there appears to be a general upward trend over the 31-yr period. In order to examine this trend further, 5-yr running means were calculated, and these are shown in Fig. 10. This procedure eliminated much of the year-to-year variation, but the general upward trend in the relative intensities remains. Figure 10 leads

TABLE 4. Intensities of eastern North Pacific tropical cyclones stratified by month for the 31-yr sample (1963–93).

Month	Number of storms	Average maximum intensity ($\mathrm{m\ s^{-1}}$)	Average relative intensity (%)
May	11	29.5	42.0
June	61	30.3	46.0
July	112	30.4	48.0
Aug	110	30.8	48.7
Sept	95	34.3	52.5
Oct	68	33.6	49.4
Nov	9	26.7	38.6

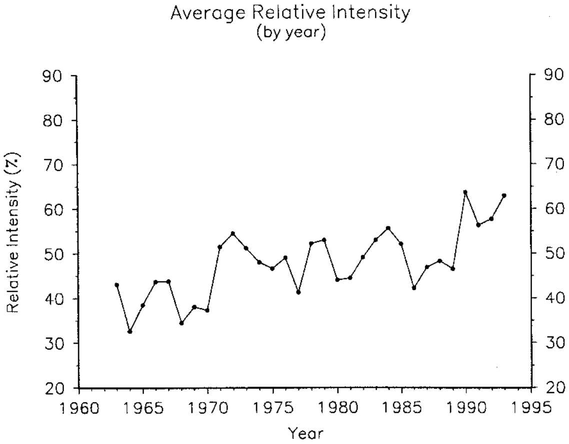

FIG. 9. Average relative intensities of eastern North Pacific tropical cyclones for each year from 1963 to 1993.

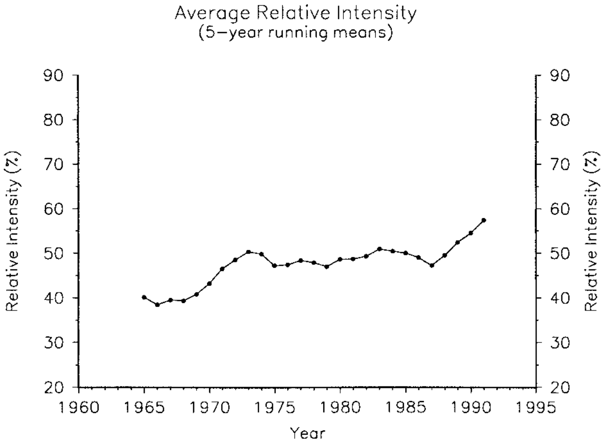

FIG. 10. The 5-yr running means of average relative intensity for the 31-yr eastern North Pacific sample (1963 to 1993).

to the question of whether the intensities of tropical cyclones over the eastern North Pacific Ocean increased between 1963 and 1993, or if the apparent increase is an artifact of changes in procedures used to determine the maximum intensities of these storms.

In the mid-1960s, satellite imagery was still a relatively new technology and methods for the evaluation of intensity of a tropical cyclone based on satellite images were being developed (e.g., Fritz 1966). During the early 1970s, the Dvorak (1975) scheme for the estimation of the intensity of tropical cyclones was developed and used operationally. The implementation of this method may account for the increase in relative intensities between 1965 and 1973. Throughout the period from 1973 to 1987, the average relative intensity remained relatively constant, and this may reflect the consistent analysis of the intensities of the tropical cyclones over the eastern North Pacific Ocean. Between 1988 and 1993 the average relative intensity increased nearly 10%. This may reflect the fact that some of the most intense storms over this region occurred during those years. A bit of caution should be used in the evaluation of this period, since the National Hurricane Center assumed responsibility for the eastern North Pacific in 1988, and some of the increase may be the result of changes in the analysis of the intensities of these systems. At this point, with the lack of aircraft data or other direct measurements of the intensities of these tropical cyclones, it is difficult to fully evaluate the apparent recent upward trend in relative intensities.

Studies by Gray (1984) and Shapiro (1989) discussed the relationship between the interannual variability of tropical cyclone activity over the Atlantic Ocean and large-scale circulation features such as El Niño and the quasi-biennial oscillation (QBO). DeMaria and Kaplan (1994a) found that for the Atlantic Oceans, there were more tropical cyclones per season and that the average annual maximum storm intensity was higher during the years when the QBO was in a westerly phase and in non-El Niño years. Table 5 shows the stratification of the relative intensities by El Niño events and by the phase of the QBO. Only those years in which the El Niño was considered to be of moderate or greater strength were counted as El Niño years. This resulted in the use of the same years (1965, 1972, 1976, 1982, 1983, 1986, and 1991) as were used by DeMaria and Kaplan (1994a) in their study of the Atlantic. With the exception of the removal of 1962 and the addition of 1993 as a west QBO year, the QBO years were also the same as used by DeMaria and Kaplan. Table 5 shows the results of the stratified analyses of the El Niño and QBO years.

There appears to be very little difference in the frequency of tropical cyclones over the eastern North Pacific Ocean between El Niño and non-El Niño years.

TABLE 5. Stratification of the eastern North Pacific tropical cyclones by El Niño and phase of the QBO. El Niño years are the same as in DeMaria and Kaplan (1994a). QBO years are the same as in Shapiro (1989) as updated by DeMaria and Kaplan (1994a). Entries in the five right-hand columns are based on the first time each storm reached its maximum intensity.

Factor	Number of years	Average number storms (yr^{-1})	Average lat	Average long	Average maximum intensity ($\mathrm{m\ s}^{-1}$)	Average EPMPI ($\mathrm{m\ s}^{-1}$)	Average relative intensity (%)
El Niño	7	15.1	16.2°N	116.2°W	32.4	65.9	49.3
Non-El Niño	24	15.0	17.0°N	114.8°W	31.4	65.7	48.6
East QBO	13	15.0	16.8°N	114.5°W	30.4	66.0	46.6
West QBO	14	14.3	16.8°N	115.0°W	32.9	66.2	50.3

There also seems to be little difference in the maximum intensities and the relative intensities of those tropical cyclones. The storms in El Niño years reach their maximum intensities a bit farther south and west than is observed during non-El Niño years. This displacement keeps the storms over SSTs, which are about the same, and produces nearly the same average EPMPIs for the two samples. The displacement is most likely the result of changes in the atmospheric flow over the Pacific Ocean associated with the El Niño phenomenon.

There are slightly fewer tropical cyclones over the eastern North Pacific Ocean when the QBO is in its westerly phase. The storms also exhibit slightly higher maximum intensities and relative intensities during the west phase of the QBO. This result is similar to the findings of DeMaria and Kaplan (1994a) for the Atlantic Ocean. It is also consistent with the work of Gray et al. (1993), which indicated that the formation and intensification of tropical cyclones over the Atlantic Ocean may be linked to the vertical wind shear in the lower stratosphere. The phase of the QBO seems to have little impact on the location at which the the storms reached their maximum intensity.

The decision to analyze data for a 31-yr period was made to have the same length of record as DeMaria and Kaplan (1994a) in order to facilitate comparisons between the eastern North Pacific and the Atlantic. However, it is likely that some of the intensities reported for the earlier years in the analyses are not as accurate as those listed for more recent storms, because of limited aerial reconnaissance and satellite imagery. For this reason, all of the stratified analyses were recomputed for the period from 1972 to 1993, when the Dvorak (1975) method was used to estimate intensity. It should be noted that limiting the analysis to this period does not change the EPMPI relationship, since all the data points used to derive (2) were for storms from 1972 or later, as is shown in Table 2.

The average relative intensity increased to 52% in the reanalyzed stratified sample, but it is still lower than the 58% found by DeMaria and Kaplan (1994a) for the Atlantic. Only 52% of the storms reached 50% of their EPMPI, and only 15% reached 80% of their EPMPI between 1972 and 1993. While these figures are higher than for the 31-yr sample, they are still lower than the comparable figures for the Atlantic. It seems evident that some of the intensities in the best track file are probably underestimated for the years prior to 1972. The pattern of small increases in the relative intensities occurred when all of the other stratified intensities were reanalyzed for the shorter time period. In all cases, the results from the analyses of 31-yr of tropical cyclones were replicated when the data were reanalyzed for the shorter time period. Thus, the results of the stratified analyses do not seem to be affected significantly by the potential underestimation of the maximum wind speeds for the years prior to 1972.

e. Additional analyses

The temperature to which the SST must be cooled in order for the relative intensity to reach 100% was determined for each storm at its maximum intensity. This was computed by solving (2) for the SST when the observed maximum wind speeds were used in place of the EPMPI. The SST computed in this manner was subtracted from the climatological SST in order to obtain the required cooling. Approximately 29% of the cases required cooling of 4°C or less, which is very similar to the 30% of the cases with land cases removed found by DeMaria and Kaplan for the Atlantic basin. Over the eastern North Pacific Ocean, 46% of the storms required cooling of less than 6°C, 71% required cooling of 8°C or less, and no storms required cooling of more than 12°C. This last result is in sharp contrast to the results of DeMaria and Kaplan (1994a), which found that 48% of the storms in the Atlantic required cooling of more than 12°C. This difference is a reflection of the exponential curve developed for the Atlantic basin, which makes it impossible for cooling to produce a relative intensity of 100% for storms with maximum sustained winds below 28.2 $m\ s^{-1}$. Since 71% of the tropical cyclones over the eastern North Pacific Ocean would require a cooling of more than 4°C to attain a relative intensity of 100%, it would appear that other environmental factors limit the actual intensity of these storms.

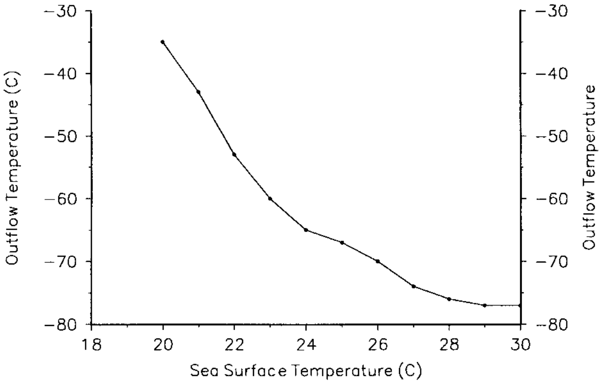

FIG. 11. The required outflow temperature as a function of SST needed to make the theoretical maximum intensity equal to the maximum potential intensity for eastern North Pacific tropical cyclones.

Emanuel (1988) derived an expression that related the minimum central pressure of tropical cyclones to the SST, outflow temperature, and ambient relative humidity. Maximum wind speeds were computed from (2) and then converted to sea level pressures using the Dvorak (1984) empirical relationship between maximum wind speed and sea level pressure for the Atlantic basin. Using the technique of Emanuel (1988) and assuming an ambient relative humidity of 80%, the minimum sea level pressure and the SST were used to estimate the outflow temperatures. The outflow temperatures are shown in Fig. 11. The outflow temperatures are relatively warm at SSTs too low to support normal development of tropical cyclones. The outflow temperatures seem reasonable for the range of SSTs normally associated with the development and intensification of tropical cyclones. The results also show the outflow temperatures remaining constant for SSTs greater than 27°C.

4. Summary and conclusions

The relationship between the maximum intensities of tropical cyclones over the eastern North Pacific Ocean and SSTs was examined for the period 1962–93. After elimination of observations west of 140°W longitude and over land, a dataset with 11 062 observations was developed for the 31-yr period. The final dataset contained positions and maximum sustained winds for 467 tropical cyclones (215 tropical storms and 252 hurricanes). The percentage of hurricanes, 54%, was lower than the 63% found by DeMaria and Kaplan (1994a) in their study of Atlantic systems. The SSTs were determined for each observation from the climatological SSTs developed by Levitus (1982). The storm relative velocities were computed by subtraction of the translational speed from the maximum sustained wind. The average translational speed of 4.7 m s^{-1} was slower than the 6 m s^{-1} reported by DeMaria and Kaplan (1994a) for systems over the Atlantic Ocean. Some of the difference between the two basins is probably due to the fact that few tropical cyclones in the eastern North Pacific Ocean experience the rapid recurvature to the northeast observed in many storms in the North Atlantic Ocean.

The observations were grouped into categories based on the nearest whole SST (in degrees Celsius). The nine observations with SSTs less than 18.5°C were included in the 19.0°C category, and the 31 observations with SSTs greater than 29.5°C were included in the 29.0°C category. Approximately, three-fourths (76%) of the observations were assigned to SST categories greater than or equal to 26.0°C, which was slightly lower than the 82% found by DeMaria and Kaplan (1994a) for the Atlantic storms. A least squares linear fit was performed on the observations of the peak wind speeds in each category. The line with the 29.0°C category systematically underestimated the peak winds at lower SSTs. This result was due to the decrease in the observed maximum sustained wind speeds between the 28.0°C and 29.0°C categories. The location of the warmest SSTs in the eastern portion of the basin and the generally east to west translation of developing tropical cyclones results in the strongest tropical cyclones over the region of 28.0°C water. The least squares linear fit was recalculated without the data from the 29.0°C category, and a much better fit to the other winds speeds was obtained. The linear equation for the eastern North Pacific Ocean produced lower estimates of the maximum potential intensity for SSTs less than 23.0°C than the exponential curve developed by DeMaria and Kaplan (1994a) for the Atlantic Ocean. This result is partly due to the fact that over the Atlantic Ocean some tropical cyclones rapidly recurve over colder SSTs and there is a lag before the circulation spins down. Over the eastern North Pacific Ocean the tropical cyclones generally moved more slowly and the strength of the circulation was more directly correlated with the SST. The linear relationship between maximum intensity and SST over the eastern North Pacific may also be the result of the lack of aircraft observations of extremely high wind speeds.

During the early stages of the development of a tropical cyclone, the system is intensifying and the wind speeds are usually much lower than the empirical maximum potential intensity (EPMPI) based on the SST. At later stages, unfavorable environmental conditions such as vertical wind shear of the horizontal wind may keep the wind speeds beneath the EPMPI. In order to examine some of the spatial and temporal characteristics of the storms over the eastern North Pacific Ocean, the relative intensity, defined as the maximum sustained winds divided by the EPMPI, was computed for the first observation of the peak intensity of each tropical cyclone. The average relative intensity was 49%, which was less than the 58% found by DeMaria and Kaplan (1994a) for the Atlantic Ocean. Only 43% of the storms reached 50% of their EPMPI, and only 11% reached 80% of their EPMPI. These percentages were also lower than the 58% and 19% reported by DeMaria and Kaplan (1994a). The storms that reached peak intensities north of latitude 18°N and west of longitude 118°W exhibited higher relative intensities than storms that developed farther to the south and east. This reflects the pattern of SSTs, which are warmest near the coast of Mexico and generally decrease to the north and west. The average relative intensities were fairly constant between June and October, which indicates that the atmosphere over the eastern North Pacific Ocean is favorable for the development of tropical cyclones throughout much of the summer and early autumn.

Although there was significant interannual variability, the best track data do seem to contain a general trend of increasing relative intensity with time. An examination of 5-yr running means of relative intensity showed an increase in the early 1970s that might reflect the introduction of the Dvorak (1984) scheme for determination of maximum sustained winds from satellite imagery. The average relative intensity remained relatively constant between 1973 and 1987. Between 1988 and 1993 the average relative intensity increased 10%. This may indicate an increase in the intensity of tropical cyclones during those years. However, the National Hurricane Center assumed responsibility for the eastern North Pacific in 1988 and some of the increase in relative intensities may be the result of changes in the analysis procedure. With the lack of aircraft data or other direct measurements it is difficult to evaluate fully the recent upward trend in relative intensities.

There appears to be little difference in the frequencies, maximum intensities, or relative intensities of tropical cyclones over the eastern North Pacific Ocean between El Niño and non-El Niño years. There were slightly fewer tropical cyclones when the QBO was in its westerly phase. The storms also exhibited slightly higher maximum intensities and relative intensities during the west phase of the QBO. This may be the result of decreased vertical shear, but that possibility needs to be investigated further. From the work of Emanuel (1988), outflow temperatures based on the EPMPI were computed. At SSTs that are too low to support the development of tropical cyclones, the outflow temperatures were relatively warm. Over the range of SSTs normally associated with the development of tropical cyclones, the outflow temperatures were reasonable and were indicative of deep convection.

The intensity attained by a tropical cyclone is the result of the complex interaction between the internal dynamics of the system and the environmental factors surrounding the storm. The tropical cyclones over the eastern North Pacific Ocean exhibit an average relative intensity of 49% at their peak intensity. This result is in agreement with previous research that indicates SSTs are a limiting factor, but not the sole controlling factor of intensity. Other environmental factors limit the intensities of tropical cyclones. Strong vertical wind shear disrupts the structure and circulation of a tropical system. Entrainment of drier air and other factors that affect the outflow temperatures limit thermodynamically the potential intensity of a system. Upwelling of colder water in the wake of a tropical cyclone may significantly lower the SST. Price (1981) found the decrease in SST due to upwelling to be enhanced for slower moving storms and storms of greater strength. Schade (1995) used a coupled hurricane–ocean model to show the negative impact of upwelling on intensity. The effects of upwelling should be more significant in the eastern North Pacific because tropical cyclones generally move more slowly over that basin. The impacts of the oceanic response to tropical cyclones over the eastern North Pacific needs to be investigated more thoroughly.

This study represents an analysis of the basic empirical relationship between SSTs and maximum wind speeds of tropical storms and hurricanes over the eastern North Pacific Ocean. The next step is to identify the significant environmental factors that determine the intensities of tropical cyclones over the eastern North Pacific Ocean. The results of this study are being incorporated into a larger examination of the climatological and synoptic factors, including those discussed in DeMaria and Kaplan (1994b), that might affect the maximum wind speeds of tropical cyclones over the eastern North Pacific Ocean.

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