Tropical Cyclone Activity in the Northwest Pacific in Relation to the El Niño/Southern Oscillation Phenomenon

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ABSTRACT

The interannual variations in tropical cyclone activity in the northwest Pacific (NWPAC) and their relationships with the El Niño/Southern Oscillation (ENSO) phenomenon were studied using the method of spectral analyses. Time series of a Southern Oscillation Index (SOI, defined as the sea-level pressure difference between Easter Island and Darwin) and tropical cyclone activity in the entire (NWPAC) ocean basin as well as in different regions of the NWPAC were analyzed. Two spectral peaks are apparent in all these time series. One corresponds to the generally accepted Southern Oscillation with a period of ~3 to 3.5 years and another at the quasi-biennial oscillation (QBO) frequency. Cross-spectral analyses between the SOI and tropical cyclone activity show significant coherence in these two spectral peaks. The dominant peak is at the Southern Oscillation frequency with the SOI leading typhoon activity by almost a year. At the QBO frequency, the two series are almost in phase. Cyclone activity in the eastern part of NWPAC, however, is ~180° out of phase with the SOI series at the Southern Oscillation frequency.

It appears that fluctuations of cyclone activity at the dominant Southern Oscillation frequency may be explained in terms of the change in the horizontal and vertical circulations in the atmosphere during periods of low SOI. The establishment of an anomalous Walker Circulation shifts areas of enhanced or suppressed convection, leading to the observed variations in cyclone activity.

1. Introduction

The interannual variation in the number of tropical cyclones within each ocean basin is a well-known phenomenon. Studies in the past have related these variations to changes in the large-scale atmospheric flow features (see the review by Ding and Reiter, 1981). For example, Ding and Reiter observed a decrease in hurricane activity in the Caribbean in the presence of abnormally strong low-level easterlies in the north Atlantic region south of 20°N. This decrease was also related to a shift in the position of the tropical upper tropospheric trough. Physical explanations of these relationships can largely be provided from the generally known conditions favorable for tropical cyclone genesis (e.g., Gray, 1979). Until recently, the causes for the changes in the general circulation which subsequently affect tropical cyclone activity have not been addressed in detail. Angell *et al.* (1969) first pointed out the existence of a quasi-biennial oscillation (QBO) in both the hurricane and typhoon frequencies, although they did not attempt to relate these variations to the QBO in the zonal winds and temperature in the equatorial stratosphere. Using the method of principal component analysis, Shapiro (1982) also found a significant period of about 2.5 years in Atlantic hurricane fluctuations. A possible linkage of such oscillations and the QBO in the stratosphere was proposed by Gray (1983). Gray also suggested that part of the changes in the large-scale atmospheric circulation associated with the variations in hurricane frequency in the Atlantic can be attributed to the El Niño event. These studies have thus provided physical insights into the possible causes of the interannual variability of tropical cyclone frequency.

The present study is an attempt to relate tropical cyclone activity in the northwest Pacific (NWPAC) to the El Niño/Southern Oscillation (ENSO) phenomenon. The relatively narrow scope of this study is mainly a result of data availability (see Section 2), even though ENSO-related events are observed throughout the tropical Pacific Ocean. Such observations include the presence of anomalous equatorial westerlies in the western Pacific and sea-surface temperature (SST) anomalies in the central and eastern equatorial Pacific (see the review by Julian and Chervin, 1978). These anomalies may therefore be associated with part of the interannual variability of tropical cyclone activity in the NWPAC.

Such a possible relationship between ENSO and tropical cyclone activity may be studied in at least two ways. In the first method, the years in which the ENSO event took place are identified and the variations in tropical cyclone frequency before, during, and after these years are then analyzed. If such variations do exist, statistical tests could then be used to test their significance and inferences be drawn.

This was essentially the method used by Gray (1983). A drawback from this method is that ENSO events do not occur at exactly fixed intervals. A spectral analysis of SST anomalies off the coast of South America by Rasmusson and Carpenter (1982) shows a peak between 36.6 and 42.7 months. Therefore, these events are aperiodic and may not necessarily coincide with the calendar year so that this first method may not produce the best correlation.

In the second method cross-spectral analyses is performed between a time series of some index of the ENSO event and the time series of tropical cyclone frequency. If in fact an oscillation in cyclone frequency with a period of ~36–42 months exists, it will show up as a significant peak in the cross-spectrum between these two series. A further advantage of this method is that possible phase shifts between the two events can be isolated. This phase information could provide additional insights into the possible physical links between the interannual variations of tropical cyclone frequency and the ENSO event.

In this study, the first method was used insofar as to provide a preliminary indication that fluctuations in tropical cyclone activity have an apparent relation with the ENSO event. The main part of the paper is devoted to cross-spectral analyses between the tropical cyclone activity series and a time series for the ENSO event. These data sets are described in Section 2. Variations in tropical cyclone activity in the entire NWPAC as well as those in different parts of NWPAC will be investigated. A possible physical explanation of these results will also be discussed.

2. Data and the methodology in the time series analyses

Six-hourly best-track positions of tropical cyclones in the NWPAC (between 100°E and 180°) during the period 1948–82, as determined by the Joint Typhoon Warning Center (JTWC) in Guam, were obtained from the Naval Environmental Prediction Research Facility. Tropical cyclone frequency and the locations of tropical cyclone genesis and development were determined from this data set.

In this study, two main time series of tropical cyclone activity will be considered: the monthly typhoon (TY) series which consists of cyclones having maximum sustained winds of >33 m s^{-1}, and the monthly tropical storm-typhoon (TSTY) series which includes all cyclones with maximum winds > 17 m s^{-1}. If a cyclone had a lifetime that spanned over two months, it was only included in the earlier month.

Each of the two tropical cyclone time series was then correlated with a time series of an index that represents the ENSO event. The index used, the Southern Oscillation Index (SOI), is the monthly mean sea-level pressure difference between Easter Island (27.2°S, 109.4°W) and Darwin (12.4°S, 130.9°E). This time series also runs from 1948 to 1982. Thus, a total of 420 months of data is available.

The annual cycle in the three series is partially removed by subtracting the monthly mean values. Since the interest here is in oscillations with periods of about three years, frequencies of less than 12 months were removed using a low-pass filter. A second-order polynominal was also used to remove the long-term trend in each of the series.

The spectral analysis performed on each of the resulting series contains a maximum lag of 128 months. This gives 6.1 effective degrees of freedom in the cross-spectral analyses (Panofsky and Brier, 1958). The values of the coherence square significant at the 90, 95 and 99% levels are 0.61, 0.67 and 0.77, respectively, (the null hypothesis being zero coherence).

3. Annual variations in tropical cyclone activity in the entire NWPAC

The variations in the annual number of cyclones reaching tropical storm strength and those with typhoon or greater intensity are shown in Fig. 1. A rather large interannual variability is apparent, with the 1960s having the maximum number of tropical cyclones while fewer cyclones were present in the 1950s. The latter might be attributed partly to the inability of detecting some of the cyclones during these presatellite years.

Relative to the mean number of cyclones, tropical cyclone activity does not seem to be suppressed in El Niño years, as is the case for Atlantic hurricanes (Gray, 1983). However, compared with the previous year, a decrease in the number of cyclones reaching at least tropical storm intensity is found for all El Niño years except 1976. A decrease in the number

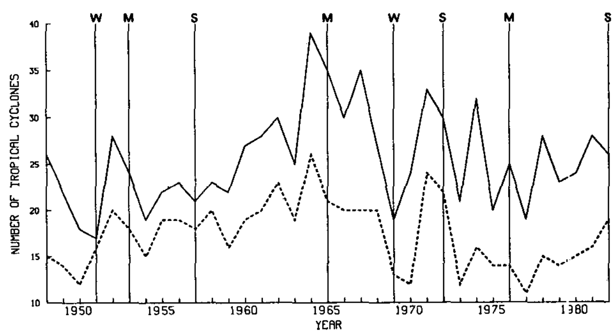

FIG. 1. Annual number of northwest Pacific tropical cyclones (between 1948 and 1982) that reached at least tropical storm (maximum sustained wind > 17 m s^{-1}, solid line) and typhoon (maximum sustained wind > 33 m s^{-1}, dashed line) intensity. The letters *W*, *M*, *S* refer, respectively, to years when a weak, moderate or strong El Niño event took place (according to Quinn *et al.*, 1978).

of typhoons is also apparent for five of the eight El Niño years (exceptions being 1951, 1976 and 1982). Such a decrease in both the number of cyclones, with at least tropical storm intensity, and of typhoons appears to continue in the year following a strong or moderate El Niño event except in 1958. However, these relative decreases in cyclone activity vary among different El Niño years.

The results in Fig. 1, therefore, suggest qualitatively that a decrease in tropical cyclone activity appears to follow the start of the El Niño event. Since the SOI also decreases during an El Niño year, a cross-spectral analysis between tropical cyclone activity and SOI may give a significant peak at the ENSO frequency and a positive phase lag of the tropical cyclone series from the SOI series. Before these relationships are examined, each individual time series will first be analyzed.

4. Spectral analysis of individual time series

a. SOI series

The spectral analysis of the SOI series is shown in Fig. 2. Two peaks in the spectrum are apparent, one with a period between 36.6 and 42.7 months and the other between 25.6 and 23.3 months. The dominant peak occurs at the well-known ENSO frequency which has been widely discussed (e.g., Rasmusson and Carpenter, 1982). The second significant peak appears to be related to the QBO as discussed by Trenberth (1976) and Chen (1982). These results are, therefore, consistent with those from previous studies of the ENSO.

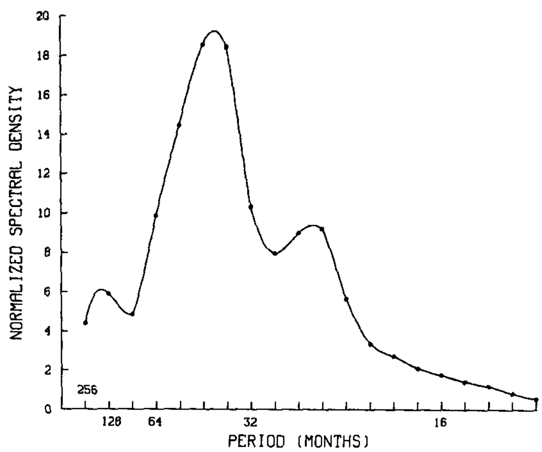

FIG. 2. Spectrum for the monthly anomaly time series of the Southern Oscillation index (Easter Island minus Darwin mean sea-level pressure) for the period 1948–82 (the SOI series). Only the spectral densities at the first 20 frequencies are plotted, from 1 to 20 cycles per 256 months.

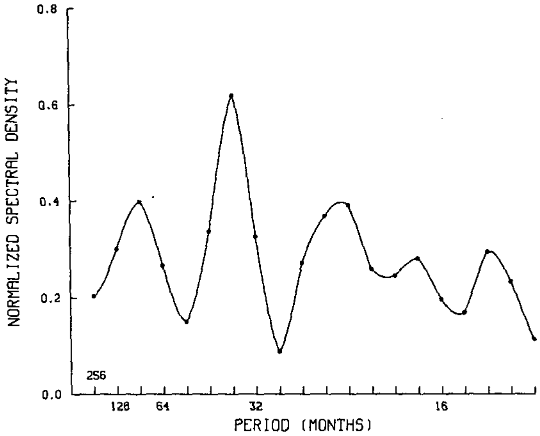

FIG. 3. As in Fig. 2, except for the monthly anomaly time series of the number of typhoons in the northwest Pacific (the TY series).

b. Time series of tropical cyclone activity

Several maxima appear in the power spectrum of the TY series (Fig. 3). The dominant peak has a period of 36.6 months. This peak also appears in the study of Angell *et al.* (1969) although the amplitude in their harmonic analysis with such a period is much less than their QBO signal (Fig. 5 in their paper). This could be due to the way the data were handled. Their harmonic analysis generally shows large amplitudes at low frequencies. This indicates the possible existence of a slow trend in their data. In a discrete harmonic analysis, the leakage from the trend will spread to the lower frequency components and give rise to unpredictable results. This might explain the appearance of a significant peak at ~40 months in their total storm frequency while no corresponding peaks are discernible in two of the individual time series. In the present study, however, such leakage effect is reduced by the appropriate trend-removal technique. Therefore, the significant peak at the three year period is probably real.

One of the other secondary peaks in the power spectrum shown in Fig. 3 has a period between 23.3 and 21.3 months. This appears to be at a slightly higher frequency than that of the QBO described by Angell *et al.* (1969). Although not appearing as a peak, the power at the QBO frequency in the present study does suggest some possible signal. The other secondary maxima in Fig. 3 do not seem to be of physical significance.

The same two major peaks (at 36.6 and 21.3 months) can be identified from the power spectrum of the tropical storm-typhoon (TSTY) series (Fig. 4). However, both peaks have a larger power than their counterparts in the TY series. Possible correlations between these two oscillations in the SOI series and those in the time series of cyclone activity will now be examined.

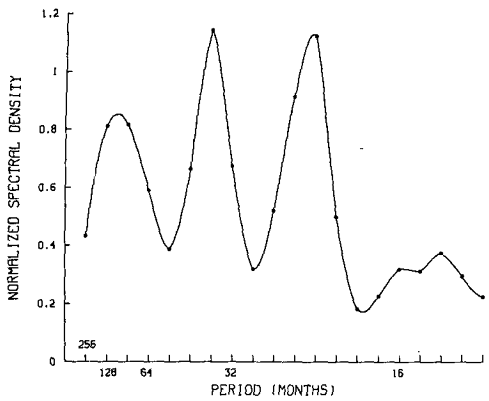

FIG. 4. As in Fig. 2, except for the monthly anomaly time series of the number of northwest Pacific tropical cyclones reaching at least tropical storm intensity (the TSTY series).

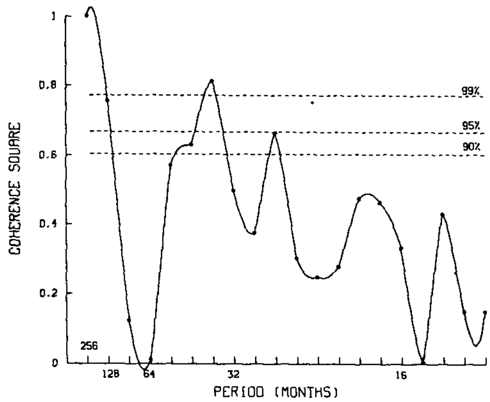

FIG. 6. Coherence square between the SOI and the TY series. Values corresponding to different levels of significance (90, 95 and 99%) for 6.1 degrees of freedom with the null hypothesis of zero coherence are shown by the dashed lines.

5. Cross-spectral analyses

a. Between the SOI and the TY series

The cross-spectrum between the SOI and the TY series is shown in Fig. 5. The most significant peak has a period of 36.6 months while a secondary peak is present with a period of 25.6 months. A low-frequency oscillation (of period 128–256 months) is also present. However, this peak is not pertinent to the objective of this study and will therefore not be discussed. Computations of the coherence square show that the dominant peak at 36.6 months is significant at the 99% level, while the second maximum at 25.6 months has a significance level of 95% (Fig. 6). It may, therefore, be concluded that the SOI and the TY series are significantly correlated at these two periods.

An analysis of the phase difference suggests that the SOI series leads the TY series by 110° or ~11.2 months at the dominant 36.6 month oscillation. From the composite study of Rasmusson and Carpenter (1982), the SOI starts to decrease towards the end of the year before the El Niño and reaches a minimum around the middle of the El Niño year. Therefore, this phase lag relationship between the SOI and TY series suggests that typhoon activity should start to decrease sometime during the El Niño year and be further suppressed in the year after the El Niño event. This result agrees with the qualitative assessment of the annual variations in typhoon activity discussed in Section 3. For the 25.6 month oscillation, the two series are almost in phase, with the SOI leading by 13° or ~0.9 months.

b. Between the SOI and the TSTY series

The cross-spectrum between the SOI and the TSTY series shown in Fig. 7 gives the same general features as the SOI-TY correlation, with a dominant peak at 36.6 months and a secondary maximum at 25.6 months. Again, the low-frequency peak with a period between 256 and 128 months will not be considered in this discussion. The coherence square (Fig. 8)

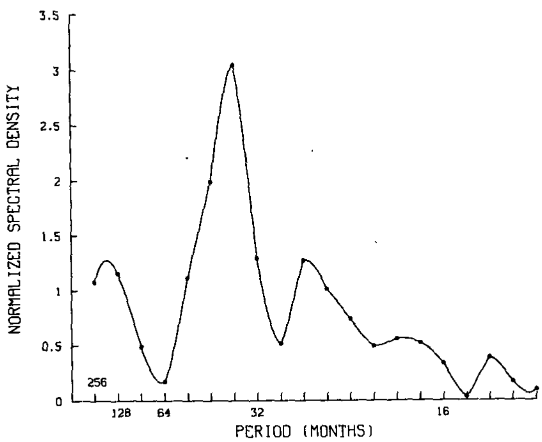

FIG. 5. Cross-spectra between the SOI and the TY series.

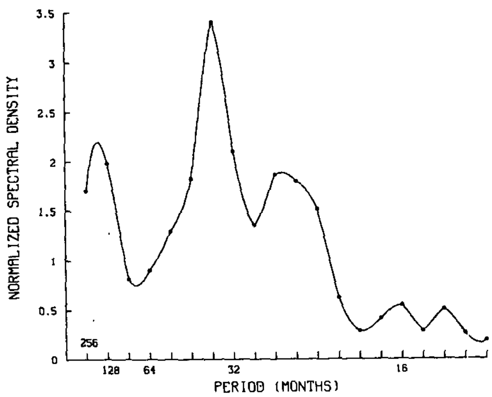

FIG. 7. Cross-spectra between the SOI and the tropical storm-typhoon (TSTY) series.

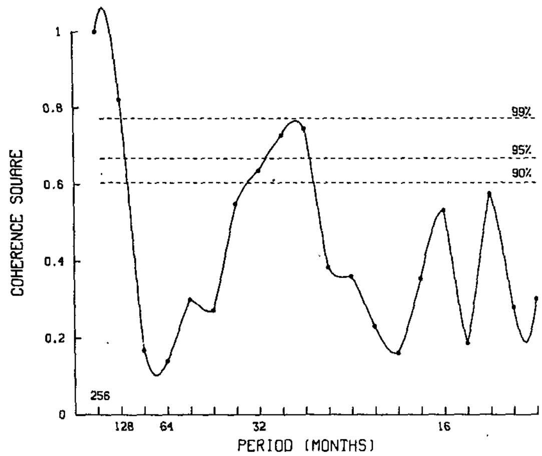

FIG. 8. As in Fig. 6, except for the SOI-TSTY cross-spectra.

surprisingly shows that the peak at 36.6 months is not significant even at the 90% level. It appears that although variations in typhoon activity correlate with those in the SOI at the 36.6 month period, a similar correlation may not exist if weaker cyclones are included. A possible physical explanation of this will be given in Section 7. On the other hand, the secondary peak at 25.6 months has a significance level of over 95%. At this QBO frequency, the SOI series leads the TSTY series by 35°, or ~2.5 months, which is similar to that found for the SOI-TY cross-spectrum.

c. Discussion

The cross-spectrum between the SOI series and each of the tropical cyclone activity series yields rather similar results. In each case, two spectral peaks are present, one at the dominant ENSO frequency (with a ~3 year period) and another at the QBO frequency (with a period of ~26 months). For the longer period oscillation, the SOI fluctuations lead variations in typhoon activity by about a year, but no significant correlation can be established if weaker tropical cyclones are included. For the higher frequency QBO, the SOI seems to vary almost in phase with each of the two tropical cyclone activity series.

Therefore, it appears that two different forcing mechanisms are present. One forcing modulates the sea-level pressure (and thus the SOI) and tropical cyclone activity almost simultaneously at the QBO frequency. This is similar to the findings of Angell *et al.* (1969) and Shapiro (1982). Whether such a QBO is related to the one in the equatorial stratospheric winds is still unclear, although Gray (1983) has suggested a possible mechanism relating the stratospheric QBO to hurricane activity. The other, and perhaps stronger, forcing produces the observed ENSO phenomenon. However, such a forcing operates on tropical cyclone activity in a delayed fashion. It appears that an environment less favorable for tropical cyclone activity is not set up until almost a year after the sea-level pressure difference between Easter Island and Darwin has been below normal.

6. Tropical cyclone activity in the eastern part of the NWPAC

Wyrtki (1975) and Rasmusson and Carpenter (1982) showed that during an El Niño year, the low-level equatorial westerlies in the West Pacific extend eastward to the date line, and sometimes even beyond. These westerlies and the adjacent northeast trades create an environment of low-level cyclonic relative vorticity in the region near the date line. Such a condition has been found to be favorable for the formation of tropical cyclones (e.g., Gray, 1979). Thus, it might be expected that during an El Niño year, an above-normal number of tropical cyclones would develop in this region. Indeed, Atkinson (1977) pointed out that an above-normal number of tropical cyclones developed during 1972 (an El Niño year) in the extreme eastern part of the NWP.

Therefore a preliminary investigation was made on the number of tropical cyclones that formed in a region bounded by (0°, 15°N), (150°E, 180°) for each year in the data sample. This area was chosen because climatologically, the low-level equatorial westerlies do not extend east of 140°E (Palmén and Newton, 1969) and most NWPAC tropical cyclones form south of 15°N (Gray, 1970). The annual variation of the number of tropical cyclones formed (defined as the first warning position given by the JTWC) in this region during 1948–82 (expressed as deviation from the long term yearly mean) is shown in Fig. 9. For all the El Niño years except the weak events (1951 and 1969), the frequency of tropical cyclone formation is above-normal. The other feature to be noted in Fig. 9 is the decrease in the frequency of cyclone formation in this subregion following an El Niño year, although the frequency could still be above-normal.

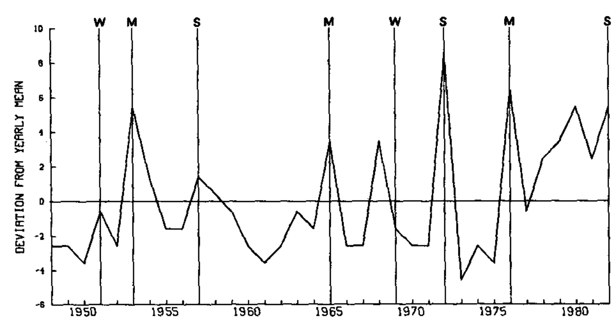

FIG. 9. Yearly number of tropical cyclones (expressed as deviation from the yearly mean) first formed in the region bounded by (0°, 15°N), (150°E, 180°). Letters *W*, *M*, *S* are as in Fig. 1.

These results seem to suggest that some interannual oscillation in the number of tropical cyclones formed in this region may be present. Therefore, a spectral analysis of the monthly anomaly time series of this number was performed (Fig. 10). Indeed, two significant peaks dominate the spectrum, one with a period of 36.6 months and the other 21.3 months. The analyses of the TY and the TSTY series also show peaks with similar periods (see Figs. 3 and 4). The cross-spectrum between the SOI and the TCE series is shown in Fig. 11. The major peak has a period of 36.6 months (the main oscillation of the SOI) with a significance level about 95% (Fig. 12). The other peak, which has a period of 21.3 months, is probably not significant. Although the 36.6 month peak also appears in the time series in the entire NWPAC, the phase relationship here is very different, with the SOI leading by 170° or ~17.3 months. In other words, the two series are nearly out of phase. A low SOI corresponds to a high frequency of tropical cyclone formation in this region.

A similar cross-spectral analysis between the SOI and the frequency of occurrence of cyclones reaching tropical storm intensity or greater was also performed. Although the same two peaks appear, the values of the coherence square show that these peaks are not significant at the 95% level.

To summarize, the results in this section suggest that the forcing which causes the SOI oscillations also produce an opposite effect on the likelihood of tropical cyclone activity in the eastern part of the NWPAC. An increase in the number of tropical cyclone formations corresponds to a decrease in the SOI. Since the minimum SOI value usually occurs in the El Niño year, one would expect an above-normal frequency of tropical cyclone activity in the eastern part of the NWPAC during this year. The relationship was established earlier in this section and is now confirmed from spectral analyses.

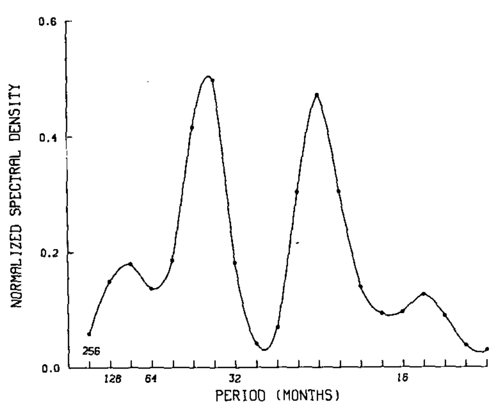

FIG. 10. As in Fig. 2 except for the monthly anomaly time series of the number of tropical cyclones formed in the region (0°, 15°N), (150°E, 180°) (the TCE series).

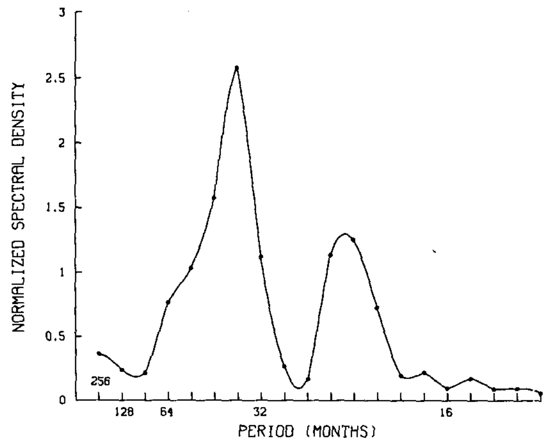

FIG. 11. Cross-spectra between the SOI and the TCE series.

7. Discussion and conclusion

The results obtained in this study show that for all the time series analyzed, two spectral peaks appear. The dominant one is at the generally-accepted ENSO frequency with a period of ~3 to 3.5 years. The other peak, which usually has a lower power in the spectrum, occurs at the QBO frequency. At both frequencies, the ENSO event is significantly correlated with tropical cyclone activity in the northwest Pacific. Gray (1983) also found a similar relationship for Atlantic hurricane activity, although his method was different. The phase relationships for the various cross-spectrum analyzed in this study are shown in Table 1.

Based on previous studies of the ENSO phenomenon, it appears that a physical explanation of the links between oscillations in tropical cyclone activity and those in SOI at the 3–3.5 year period may be established. However, although the QBO in cyclone activity has been established by previous researchers (Angell *et al.*, 1969; Shapiro, 1982; Gray, 1983), how it relates to the QBO in the ENSO event is still not clear. Further studies must be made before a sound

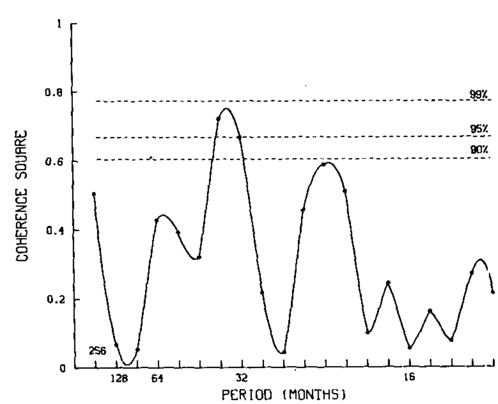

FIG. 12. As in Fig. 6 except for the SOI-TCE cross-spectra.

TABLE 1. Phase relationships between the SOI series and the various tropical cyclone activity time series analyzed in this study.

Tropical cyclone time series	Oscillation Period: 3–3.5 years	Oscillation Period: Quasi-biennial oscillation
I. Entire NWPAC		
a. Typhoon (TY)	SOI leading by ~11 months	in phase
b. Tropical storm and typhoon (TSTY)	*	in phase
II. Eastern part of NWPAC		
a. Tropical cyclone formation (TCE)	180° out-of-phase	*

* The specific cyclone activity series is not significantly correlated with the SOI series at that frequency.

physical explanation of this QBO cycle can be proposed. Therefore, the following discussion will only focus on the possible link between ENSO and tropical cyclone activity at the more dominant period between 3 and 3.5 years.

In a composite study, Rasmusson and Carpenter (1982) showed that the SOI started to fall below normal towards the end of the year before the El Niño, finally reaching a minimum around the middle of the El Niño year. About 10–12 months later, the SOI is again above normal. They also showed that throughout most of the El Niño year, the equatorial westerlies in the western Pacific extend eastward to around the dateline. These westerlies, coupled with the northeast trades to the north, provide some of the necessary ingredients for the formation of tropical cyclones (Gray, 1979). The above-normal SST present in the extreme eastern part of NWPAC (east of ~150°E) may also aid in the process. As a result, a higher number of tropical cyclones is observed to form in this region during El Niño years. Thus, low SOI values are associated with above-normal tropical cyclone activity in the eastern part of the NWPAC, and hence the 180° out-of-phase relationship between the two series.

Corresponding to the decrease in the SOI during the El Niño year, an anomalous Walker Circulation is set up with rising motion in the central part of the equatorial Pacific (near the dateline) and sinking motion in the western part (see Julian and Chervin, 1978). This can also be inferred from the divergence anomalies shown by Rasmusson and Carpenter (1982) and from the outgoing long-wave radiation anomalies (e.g., Heddinghaus and Krueger, 1981; Wagner, 1983). The sinking motion would tend to supress convection, and hence, tropical cyclone activity. The number of tropical cyclones in the central and western part of the NWPAC (west of ~150°E) accounts for almost 90% of the typhoon activity (Gray, 1970). As the SOI value reaches towards its minimum and the anomalous Walker Circulation becomes established, the number of typhoons in the entire NWPAC will begin to decrease. Thus, the SOI series leads cyclone activity by almost ⅓ of the oscillation cycle, or about one year. However, it appears that the suppressed conditions in the atmosphere are not enough to reduce the number of tropical storms significantly and only the most intense systems (typhoons) are affected.

To conclude, interannual variations in tropical cyclone activity in the northwest Pacific seem to be very much related to the ENSO event. The primary forcing that produces the ENSO phenomenon also acts upon cyclone activity, apparently through the modification of both the horizontal and vertical circulations in the region. Gray (1983) has also proposed a mechanism linking the fluctuations in Atlantic hurricane frequency with the ENSO event. Perhaps further studies should be made to determine whether such links can be established for tropical cyclones in the other ocean basins. A physical explanation should also be sought for the QBO in tropical cyclone activity.

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