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P5.10 INTERANNUAL VARIABILITY OF TROPICAL CYCLONE ACTIVITY IN THE SOUTHERN SOUTH CHINA SEA

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1. INTRODUCTION

Tropical cyclones are among the most deadly and destructive of natural disasters in terms of loss of human life and economic destruction (Bengtsson et al., 1996). The 2004 season in the Atlantic Ocean region was one of the most severe in recent memory. Thus, research on tropical cyclones has increased substantially in recent years. This is especially true in examining the intraseasonal and interannual variations in the occurrence of these phenomena, as associated with such phenomena as the Madden Julian Oscillation (MJO – e.g., Maloney and Hartmann, 2001), the Quasi-biennial Oscillation (QBO – e.g., Gray, 1984), the El Nino and Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) / North Atlantic Oscillation (NAO) (e.g., Lupo and Johnston, 2000; Houghton et al., 2001).

Within the Atlantic region, the occurrence and intensity of tropical cyclones have been shown to vary quite strongly with ENSO in general. These studies have shown that during El Nino (La Nina) years, tropical cyclone activity is suppressed (enhanced) and they tend to be weaker (stronger). This does not preclude the occurrence of strong storms like Andrew in 1992. Lupo and Johnston (2000) (*hereafter LJ00*) not only showed the above results, but their study of hurricane activity from 1944-1999 demonstrated that there was an interdecadal variation in the behavior of the ENSO variability. This variability could be associated with the PDO. More specifically, there were more events during one phase of the PDO and little or no ENSO variability. During the opposite phase of the PDO, there was strong ENSO related variability.

While the most extensive studies have been performed in the Atlantic Region, there have been studies demonstrating ENSO variability in Pacific Region tropical cyclone occurrence as well (e.g., Chan, 1985; Wu and Lau, 1992). These studies show similar variations in the Pacific Ocean basin as a whole. However, Ramage and Hori (1981) and Lander (1994) found no variability overall in the region, but large shifts in the tropical cyclone genesis regions.

Recently, there has been concern that tropical cyclone frequencies and intensities may increase due to climatic (greenhouse or anthropogenic) warming. Malaysia, which is located close to the equator, was thought to be generally immune to threats from tropical cyclones. However, in recent years, there have been deadly tropical cyclones which have impacted the Southern South China Sea (SSCS) region, including Malaysia (e.g., Greg – 1996, Vamei – 2001).

Thus, this study will have two objectives and they are; 1) to develop a detailed long-term climatology of tropical cyclone activity for this limited region, the SSCS, and 2) to examine the long term trends and interannual variations as well. The goal is to produce information that will be useful for the long-range prediction of tropical cyclones so that forecasters in Malaysia can advise policy makers.

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2. METHODS AND ANALYSES

2.1. Analyses

The data set used here was acquired from the UNISYS website (http://weather.usisys.com). All tropical cyclones (tropical depressions and storms and typhoons) from 1960 – 2003 were listed on this website and included in this data set. This data was provided to UNISYS by the Joint Typhoon Warning Center.

The sea surface temperature (SST) information and atmospheric variables were provided by the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) gridded re-analyses (Kalnay et al., 1996). These data were archived at NCAR and obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (CDC) website (http://www.cdc.noaa.gov). These re-analyses were the 2.5^{o} by 2.5^{o} latitude-longitude analyses available on 17 mandatory levels from 1000 to 10 hPa at 6-h intervals. These analyses include the standard atmospheric variables geopotential height, temperature, relative humidity, vertical motion, ***u*** and ***v*** wind components and surface information.

2.2. Methods

The region of study is the SSCS which is bounded here by 0^{o} to 10^{o} N and 100^{o} E to 120^{o} E. The monthly tropical cyclone counts include those that develop locally and those that enter the region from the Western North Pacific. The intensity was given as the maximum intensity attained by the storm following LJ00. Categorization and statistical analysis was performed using standard statistical tests found in any standard text (e.g., Neter et al., 1988) and following LJ00.

Many studies such as Gray (1984) have examined the variability in the climatological background state for those quantities that have been associated with tropical cyclone development and intensification. These include the area-averaged monthly; 1) SSTs, 2) the 850 – 600 hPa wind shear, 3) the 850 hPa divergence, and 4) 850 hPa vorticity. These time series were then filtered using the Shapiro (1970) filter as in Kelsey et al. (2005) and then analysed using Fast Fourier Transforms (FFTs) in the MathCad® software package. The significant variability was then identified using statistical tests. These time series were filtered to remove most of the signal on time-scales less than two years including the annual cycle which is the dominant signal. Filtering at this level may also degrade the signal due to the QBO as well.

The vertical wind shear, divergence, and vorticity were calculated by estimating the geostrophic winds using the height fields and using the observed values. Divergence was calculated using the formulation:

$$\nabla \cdot \vec{V} \qquad (1)$$

where the del operator is two dimensional and $\vec{V}$ is the two dimensional wind. If the geostrophic wind is substituted for the real wind and the Coriolis parameter is allowed to vary with latitude, then Eq. (1) becomes:

$$-\frac{\beta v_g}{f} \qquad (2)$$

where β is the variation in the Coriolis parameter with latitude, v_g is the v-component of the geostrophic wind, and f is the Coriolis parameter.

ENSO years were defined using the Japan Meteorology Agency (JMA) ENSO index to classify these as El Nino, La Nina, or neutral years. A complete description of this index can be found at the Center for Ocean and Atmospheric Prediction Studies (COAPS) website (http://masig.fsu.edu) (see also LJ00; Lupo et al., 2004). Briefly, this index classifies each year based on the five month running mean of spatially averaged SST anomalies over the Nino 3.4 region in tropical Pacific Ocean. This value should exceed (be less than) 0.5^o C (-0.5^o C) to be classified as an El Nino (La Nina) year. When the SST anomalies are close to 0^o C, these years are considered neutral years. Table 1 provides a list of these years, and, for example, ENSO year 1970 begins 1 October 1970 and ends 30 September 1971.

Table 1. A list of years as separated by ENSO phase.

El Nino	La Nina	Neutral
1963	1964	1960 - 1962
1965	1967	1966
1969	1970-1971	1968
1972	1973 – 1975	1977 – 1981
1976	1988	1983 – 1985
1982	1998 - 1999	1989 – 1990
1986-1987		1992 – 1996
1991		2000 – 2001
1997		2003
2002		

Finally, the Pacific Decadal Oscillation is a 50 to 70 year basinwide variation in Pacific Region SSTs. This phenomenon is described in Gershanov and Barnett (1998) in more detail, but the positive (negative) phase of the PDO represents the presence of relatively warm (cool) SSTs persisting throughout the eastern portion of the Pacific Ocean Basin. The positive (negative) phase of the PDO persisted during the period from 1977 – 1998 (1947 to 1976), and in 1999 it is believed to have switched phases again (e.g., Kelsey et al., 2005).

3. SSCS CLIMATOLOGICAL ANALYSIS

A total of 46 tropical cyclones occurred within the SSCS region over the 44 year period of study. This sample included nine typhoons, 27 tropical storms, and ten tropical depressions. While this constitutes a very small fraction of the total Pacific Ocean basin activity, these storms have recently had a big impact on the nation of Malaysia. Of the 46 storms observed over the period, 26 of these (57%) were of local origin (Table 2).

Table 2. Total number and annual mean tropical cyclone occurrence by categories over SSCS region during period 1960 – 2003.

	TD	TS	TY	All	Local Origin
Total	10	27	9	46	26
Annual Mean	0.2	0.6	0.2	1.0	0.6

Table 3 demonstrates that the active tropical season for Malaysia persists from October to April. However, most of the activity (79%) occurs in the months of November and December. This represents a sharp peak in the active season and likely is related to the annual migration of the intertropical convergence zone (ITCZ) through the SSCS.

Table 3. Total number and percentage of tropical cyclone occurrence in the SSCS by month during period 1960 – 2003.

	S	O	N	D	J	F	M	A	M	J	J	A	All
Total	0	4	20	16	1	1	1	2	1	0	0	0	46
%	0	9	44	35	2	2	2	4	2	0	0	0	100

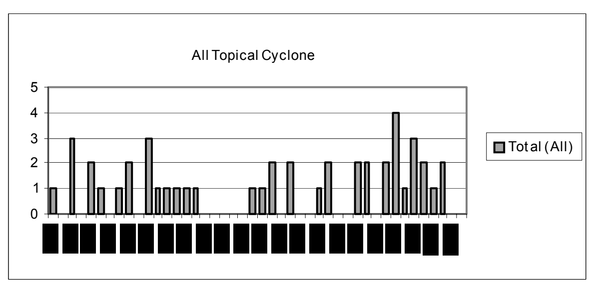

Figure 2. Bar graph of number of Tropical Cyclone over SSCS versus time.

Figure 2 shows a time series of tropical cyclone activity over the 44 year period. With the exception of a quiet period from 1976 – 1980, there has been steady activity in the SSCS during the period. A regression analysis demonstrated that there was a slight upward trend during the period of record. When this trend was tested for significance, however, it was found that the trend was not significant when using the F-test and assuming that there is no trend *a priori*. This agrees with the findings of many other studies in the active tropical regions. Further analysis would demonstrate (not shown) that most of the tropical depressions occurred during the 1990s and there was a prolonged period of local inactivity from 1974-1994.

4. INTERANNUAL VARIATIONS

In order to detect interannual variations in tropical cyclones, the SSCS dataset was partitioned into El Nino, La Nina, and neutral years. Table 4 shows that La Nina (El Nino) years were more (less) active than other years over the SSCS, and this result was significant at the 95% confidence level when testing the means for all events. Since the dataset is small, testing was not carried out for smaller subsets of the data, even though the distribution of tropical storms and events of local origin were similar to the distribution of the total sample. These results are similar to others for the entire western Pacific Region as well (e.g., Wu and Lau, 1992).

Table 4. The mean annual tropical cyclone activity for the total sample and categories including local origin as stratified by ENSO phase.

	All	TY	TS	TD	Local
Neutral	1.1	0.3	0.6	0.3	0.6
El Nino	0.4	0.2	0.2	0	0.3
La Nina	1.6	0.1	1.2	0.3	1.0
All	1.0	0.2	0.6	0.2	0.6

In order to determine which variables in the climatological background could be associated with these statistics, time series of the November and December mean variables which are related to tropical cyclone formation were analysed. These included area averaged monthly mean 1) SSTs, 2) sea level pressure (SLP) 3) 850 – 600 hPa wind hear, 4) divergence (calculated using Eq. 2), and 5) 850 hPa relative vorticity. These time series were correlated versus one another.

As expected there were strong correlations between the SSTs and the SLP, low-level divergence, and the wind shear. These correlations were significant at the 95% confidence level, and were inverse correlations for the former two variables. Only the SLP versus the wind shear showed a weak correlation. Then each time series was filtered and analysed using FFTs (e.g., SSTs Fig. 3). Significant peaks in the periodograms were found in the 3 – 7 year range which is consistent with ENSO variability. Thus, it is likely that ENSO variability in SSCS tropical cyclone statistics is real and due to variability in the climatological background state. That is, during La Nina years, the background state is more conducive to tropical cyclone occurrence than during El Nino years. During neutral years, the mean occurrence was close to the overall means.

In order to test this hypothesis and determine which background variable(s) may be inhibiting tropical cyclone formation in non-active years, the data was sampled by taking the five most active years (Table 5) and comparing these to two sets of non-active years (Tables 6 and 7 – no occurrences). The two sets of non-active years were compared using warm SSTs and cold SSTs. The active sample contained two La Nina and 3 neutral years, while the non-active warm (cold) SST years were predominantly El Nino (neutral) years.

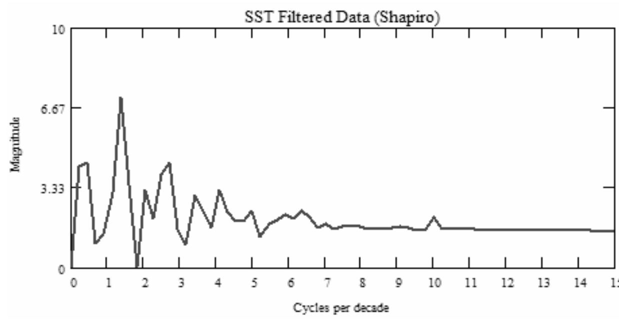

Figure 3. Power spectra of the filtered monthly area average SST time series using Shapiro (1970) filter for the SSCS.

Table 5. The tropical cyclone activity for the five most active years in the SSCS as well as the a) ENSO classification, and b) area averaged SSTs (^oC), c) 850 – 600 hPa wind shear (ms^{-1}), d) 850 hPa divergence (s^{-1}) x10^{-6}, and e) 850 hPa relative vorticity (s^{-1}) x10^{-6}.

Year	tot	a)	b)	c)	d)	e)
1996	4	Neutral	28.6	-1.20	-1.58	-5.86
1998	3	La Nina	28.1	-2.77	-1.35	-8.38
1970	3	La Nina	28.1	-1.60	-0.23	-7.93
1962	3	Neutral	27.7	-0.57	-1.17	-10.10
1995	2	Neutral	28.3	-1.00	-1.08	-9.05
		Means	28.1	-1.43	-1.08	-8.26

This analysis demonstrates that during active years the area average wind shear was of opposite sign to that of the non-active warm SST years. A negative number indicated wind speeds increasing with height. The area averaged low-level wind divergence was only slightly stronger during the warm SST non-active years, while the relative vorticies and SSTs were similar. Thus, it appears that in the SSCS, that even if all other background variables are similar, if the low-level winds decreased with height, then tropical cyclone activity in the SSCS was inhibited.

Table 6. As in Table 5, except for the least active years with warm SSTs.

Year	tot	a)	b)	c)	d)	e)
1987	0	El Nino	29.0	-0.77	-2.07	-6.58
2002	0	El Nino	28.8	0.57	-1.31	-9.14
1966	0	Neutral	28.4	2.47	-0.86	-7.66
1963	0	El Nino	28.4	-0.20	-0.68	-8.11
1986	0	El Nino	28.3	0.70	-2.48	-8.83
		Means	28.6	0.55	-1.48	-8.06

During cold SST non-active years, the low level wind shear was approximately 33% weaker than, but of the same sign as that of the active years. However, the low-level background was distinctly more anticyclonic, and the mean anticyclonic vorticities were 50% stronger during these years. Thus, for the cold SST years, the background is overall more hostile to tropical cyclone development.

Table 7. As in Table 5, except for the least active years with cold SSTs.

Year	tot	a)	b)	c)	d)	e)
1991	0	El Nino	27.9	-0.37	-2.03	-12.60
1977	0	Neutral	27.9	0.33	-0.90	-10.80
1979	0	Neutral	27.9	-1.57	-0.50	-15.10
1978	0	Neutral	27.5	-1.73	-1.76	-11.90
1984	0	Neutral	27.3	-1.37	-1.35	-11.00
		Means	27.7	-0.94	-1.31	-12.30

Finally, in order to assess whether or not significant interdecadal variations were present and could be attributed to the PDO, the total sample was broken down by PDO phase (22 years in each phase). This analysis demonstrated that there was no difference in the total number of tropical disturbances, and little difference in the ENSO-related variability across each phase. During the positive phase of the PDO, the ENSO variability was identical to that of the total sample, while during the negative PDO phase, La Nina and neutral years were equally active. Additionally, no trend or variability could be detected in the intensity of the tropical cyclones in this data set.

5. SUMMARY AND CONCLUSIONS

A detailed analysis of the tropical cyclone activity from 1960 – 2003 in the SSCS was performed here in order to determine whether or not the threat of tropical cyclone activity to the nations of this region, particularly Malaysia was increasing. Malaysia was struck by two deadly events during the 1996 to 2001 period. There has been concern in Malaysia that tropical cyclone activity and intensity may increase in association with observed and expected climate change whether the climatic changes are naturally or anthropogenically forced. The tropical cyclone data was obtained from the UNISYS archive, and the NCEP-NCAR gridded re-analyses available via the world-wide web were used for the climatological analysis of the background conditions.

The important findings resulting from this work were;

- the SSCS experiences one tropical cyclone event per year, whether these were of local origin (about 60%) or they propagated into the region,
- of these, most attain only tropical storm status, and relatively few become typhoons,
- the active season is confined to November and December (79%) as the ITCZ move through the region,
- there was a slight upward trend in the occurrence of these events, but this trend is not statistically significant.

When examining the SSCS sample for interannual variability it was found that;

- La Nina (El Nino) years were more (less) active than other years, and this result was significant at the 95% confidence level. The variability of tropical storms and tropical cyclones of local origin was similar to that of the total sample,
- there was no apparent variability that could be attributed to interdecadal variability such as the PDO,
- there was no apparent trend or variability in the intensity of tropical cyclones in this region.

A spectral analysis of the filtered background variables such as SSTs, SLPs, and wind shear showed that there was significant variability found at the 3-7 year period, which is consistent with the ENSO period. An examination of a subset of the most active years versus those years with no tropical cyclone activity for a) warm SST years, and b) cool SST years yielded some interesting results.

- During warm SST years, tropical cyclone activity was suppressed when the regional low level wind speed decreased with height.
- During cool SST years tropical cyclone activity was suppressed by a background that was considerably more anticyclonic at low levels.

6. ACKNOWLEDGMENTS

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