The Interannual Variability of Tropical Cyclone Activity in the Southern South China Sea

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Abstract

A study of tropical storm activity in the Southern South China Sea region was carried out for the period of 1960 to 2006 using data obtained from the UNISYS website archive, which was provided to them from the Joint Typhoon Warning Center (JWTC) best track data. This study was motivated by two particularly costly storms that impacted Malaysia during the 1996 – 2001 period. This study demonstrated that November and December were the most active months for tropical cyclone activity in this region. A majority of these storms attained tropical storm intensity. Also, a majority of the tropical cyclones originated within the study area near Malaysia as opposed to moving into the area. The long term trend showed that there has been a slight increase in tropical cyclone activity in the region, but the trend was not statistically significant. A study of the interannual variability revealed that there was more (less) tropical cyclone activity in the region during La Niña (El Niño) years. Longer term variability, such as that related to the Pacific Decadal Oscillation, was not found in the analysis here. Using spectral methods confirms that there was significant El Niño-related variability in climatological quantities such as monthly sea surface temperatures or pressures. Finally, the background climatological state was examined in order to determine whether or not the atmosphere in the region was more conducive to tropical cyclone formation or maintenance during active years. It was found that the most active years were associated with warmer SSTs in the study region, relatively weak 200 – 850 hPa wind shear, a warm-core structure, more water vapor, and more cyclonic low-level relative vorticity, and these were all La Niña-type years. Non-active years were associated with weaker wind shear, less water vapor, and a more anticyclonic (vorticity) background, regardless of whether the SST's were warmer or cooler, and most of these were El Niño-type years.

1. INTRODUCTION

In recent years, there have been deadly tropical cyclones that have impacted the Southern South China Sea (SSCS) region, including Malaysia. Malaysia suffered direct strikes from tropical storm Greg on 25 December 1996 and tropical storm Vamei on 27 December 2001 (Chang et al. 2003). Furthermore, Vamei had reached typhoon intensity before it reached Malaysia near 1^{o} to 2^{o} north latitude, which made such an occurrence unusual (Chang et al. 2003). The previously recorded lowest latitude for a typhoon was Sarah (3.3^{o} N) in 1956 (Fortner, 1958). Additionally, Greg caused 238 deaths and economic losses of $52 M in US dollars (Ooi and Ling, 1996). These storms have caused concern in Malaysia as to whether or not this was part of a long-term trend toward more frequent tropical cyclone strikes.

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 and 2005 seasons in the Atlantic Ocean basin region were two of the most severe in recent memory for the nations bordering the region. Thus, interest in research on tropical cyclones has increased substantially in recent years (e.g., Emanuel, 2005). This has been especially true regarding the study of intraseasonal and interannual variations in the intensity and occurrence of tropical cyclones, as associated with such phenomena as the Madden Julian Oscillation (MJO – e.g., Maloney and Hartmann, 2001; Chang et al. 2005b), the Quasi-biennial Oscillation (QBO – e.g., Gray et al., 1984a,b; Chan, 1995), the El Niño and Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) / North Atlantic Oscillation (NAO) (e.g., Gray et al., 1984a,b; Chan, 1985; Wu and Lau, 1992; Lander, 1994; O'Brien et al., 1996; Bove et al., 1998; Landsea et al., 1999; Pielke and Landsea, 1999; Lupo and Johnston, 2000 *hereafter LJ00*; 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 (see references above). These studies have shown that during El Niño (La Niña) years, tropical cyclone activity is suppressed (enhanced) and they tend to be weaker (stronger). This does not preclude the occurrence of strong storms during relatively quiet years, such as hurricane Andrew in 1992.

LJ00 not only found results similar to those discussed above, but their study of hurricane activity in the Atlantic region from 1944-1999 demonstrated that there was an interdecadal signal in the behavior of the ENSO response. This variability could have been associated with the PDO. Specifically, that there were more hurricane events per year during one phase of the PDO (e.g., 1947-1976), but little or no statistically significant ENSO variability. During the opposite phase of the PDO (1977 – 1998), there was strong ENSO-related variability in the intensity and number of Atlantic storms.

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 showed similar results for the Pacific Ocean basin as a whole. However, Ramage and Hori (1981) and Lander (1994) found no ENSO variability in the overall tropical cyclone numbers throughout the North Pacific as a whole, but significant variability in the primary tropical cyclone genesis regions. Since then, studies have shown that the focus of tropical storm activity moves southeastward (northwestward) during El Niño (La Niña) years (e.g., Chan, 1985; Wu and Lau, 1992; Lander, 1994; Wang and Chan, 2002).

Recently, there has been concern that tropical cyclone frequencies and intensities may be increasing due to climatic (whether attributed naturally forced or anthropogenic) warming, and several studies have investigated the issue (Henderson- Sellers et al., 1998; Houghton et al., 2001; Pielke et al., 2005; Emanuel, 2005; Webster et al., 2005). These studies, however, have shown inconsistent results. Malaysia, which is located close to the equator, was thought to be generally immune to the threat of tropical cyclones. Gray (1968) found that for tropical cyclone development, the disturbance should be approximately a minimum of 5 degree latitude from the equator, generally.

There has also been some disagreement in the literature regarding the relationship between the QBO and tropical cyclone activity over the western north Pacific. Chan (1995) found that the westerly phase of the QBO was positively correlated with increased tropical cyclone activity over the western north Pacific, which is similar to the results of Gray (1984a) for the Atlantic Ocean basin. However, Lander and Guard (1998) showed that the global tropical cyclone activity was not significantly correlated to the QBO.

Thus, this study will have three objectives and they are; 1) to develop a detailed long-term climatology of tropical cyclone activity in the SSCS region, 2) to examine the character of the long-term trends and interannual variations in tropical cyclone activity, and 3) to examine variations in the background atmospheric and surface environment in the SSCS (especially in the active season – November and December). In order to accomplish the second objective, we examined whether or not there were significant ENSO or PDO related variations in the SSCS tropical cyclone climatology. Other recent studies have examined the regional climatological character of tropical cyclones and the background climatological state in which they occur (e.g., Tonkin et al. 2000; Dare and Davidson, 2004; Paterson, et al., 2005). One outcome of this study will be to produce information that may provide useful guidance for the long-range prediction of tropical cyclone occurrence for tropical weather forecasters in the SSCS region (Malaysia and adjacent nations). This will include information for advising policy makers regarding future tropical cyclone occurrences.

2. METHODS AND ANALYSES

a. Analyses

The data set used here was acquired from the UNISYS website (http://weather.usisys.com). All tropical cyclones (tropical depressions, tropical storms, and typhoons) from 1960 – 2006 were listed on this website and included in this data set. These data were provided to UNISYS through the Joint Typhoon Warning Center (JTWC) best track data set. The data set contains tropical cyclone categorization, name, life span, maximum wind speed, and track information. As stated in Lander (1994), tropical cyclones in the western North Pacific Ocean have been monitored by the United States Navy since 1945 and by the United States Air Force since 1947 using aircraft reconnaissance. In 1959, these entities were combined under one command, the JTWC, to track tropical cyclones over the western North Pacific. Weather satellite observations became routine in 1965, and these observations contributed to the data set as well.

The monthly 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; Kistler et al., 2001). These data are archived at NCAR and obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (CDC) website (http://www.cdc.noaa.gov/cdc/reanalyses/). These re-analyses are displayed on a 2.5^{o} by 2.5^{o} latitude-longitude grid available on 17 mandatory levels from 1000 to 10 hPa at 6-h intervals.

These data included standard atmospheric variables geopotential height, temperature, relative humidity, vertical motion, ***u*** and ***v*** wind components, and surface information.

b. Methods

The region of study was the SSCS, and it is bounded here by 0^o to 10^o N and 100^o E to 120^o E (Fig. 1). The monthly tropical cyclone counts include those that develop locally, as well as those that enter the region from the Western North Pacific. The intensity was given as the maximum intensity attained by the tropical cyclone following the methodology of LJ00. Briefly, central pressure data were not always available for each storm in the earlier years in the period described above and were not used. In the Atlantic, maximum wind data have been shown to contain biases (e.g., 1944 - 1969). Landsea (1993) discusses the 1944 - 1969 bias in maximum wind speeds (as much as 5 kt or 2.5 m s^{-1}) at some length. To reduce the influences of these biases in maximum wind speed, hurricane intensity was assigned based on the maximum Saffir-Simpson intensity attained by the storm. Thus, only storms which reported maximum wind speeds close to the limits of a particular Saffir-Simpson category would have been vulnerable to being improperly classified. The statistical analysis of trends and distributions were performed using the standard statistical tests found in any standard text (e.g., Neter et al., 1988) and also follows those used in LJ00.

Many studies, such as Gray et al. (1984a), have examined the variability in the climatological background state for atmospheric quantities that have been associated with tropical cyclone development and intensification. Such variables used in other studies (e.g., Tonkin et al. 2000; Chang et al. 2005b) and included here were the area-averaged monthly; 1) SSTs and sea-level pressure (SLP), 2) the 850 – 200 hPa wind shear, 3) the low-level divergence, and 4) low-level vorticity.

i. The analysis of SST and SLP

The method of cycles as described by Mokhov et al. (2004) and modified by Lupo et al. (2007), was used to extract interannual and interdecadal variability from a one-dimensional time series in this study. It is based on the analysis of simple phase plots of the first derivative of the time series versus the time series itself. For a function that is represented by a cyclic time series, or one that is sinusoidal or nearly sinusoidal, we can use;

$$X(t) = A(t)\sin\left[\omega t + \phi_o(t)\right], \quad (1)$$

where X(t) represents the time series of some variable, A(t) is the amplitude, ω is the frequency, and ϕ(t) is the initial phase. Then, X(t) represents a general solution for differential equations of form;

$$\ddot{X} + \omega^2 X = 0. \qquad (2)$$

The time series in this study were also filtered to extract periodicities on the interannual and interdecadal timescale, or time scales of two years or longer following the procedure in Mokhov et al. (2004). However, their publication used a two-year running mean in order to filter out the higher frequency noise. Lupo et al. (2007) modified this technique by using a Shapiro (1970) filter. This technique has the advantage of retaining the original length of the data set and can be applied a successive number of times in order to control the retention of signal versus noise. This filter also; a) preserves some of the annual cycle, b) does not result in a phase shift in the low-order variability, and c) does not introduce significant aliasing error. Finally, Fast Fourier Transforms were used in order to extract significant interannual and interdecadal variability. Unfortunately, the methods used here filter out the signal induced by such phenomena as the MJO. Phenomena on these smaller timescales, however, are beyond the scope of our analysis here and are influenced likely by phenomena such as ENSO and the QBO.

ii. Analysis using quantities at the 850 hPa and 200 hPa geopotential height level

Winds at the 850 hPa and 200 hPa geopotential height surfaces were used to generate the quantities described below. The monthly mean vertical wind shear (850 – 200 hPa), the 850 hPa vorticity and divergence were calculated using the observed winds. The wind shear was calculated using the formula:

$$W_{shr} = \vec{V}_{200} - \vec{V}_{850}, \quad (3)$$

where $\vec{V}$ is the observed horizontal wind vector. Wind shear is a measure of baroclinicity in the atmosphere, and many researchers and forecasters have shown that tropical cyclone development or intensification is not favored in a strong wind shear environment (e.g. Fitzpatrick, 1997). Wind shear was used, for example, in the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (e.g. DiMaria et al, 2005). SHIPS is an operational model using environmental conditions in order to forecast hurricane intensity. The 850 hPa divergence and relative vorticity were calculated using;

$$DIV = \nabla \cdot \vec{V} \qquad (4a)$$

$$VORT = \nabla \times \vec{V} \qquad (4b)$$

where positive (negative) values represent divergence (convergence) in 4a, and ∇ is the three-dimensional del operator applied to a similar wind vector. The horizontal component of the divergence and the $\hat{k}$-component of the vorticity were then used here, as has been done commonly in standard meteorological analysis. Also, these calculated quantities were averaged over the period of 1 November to 31 December (the active SSCS tropical season), as well as area-averaged over the study region (see Fig. 1). These variables were chosen since tropical cyclone formation generally requires pre-existing low-level cyclonic disturbance for formation. These variables were also used in the study of Chang et al. (2005b) as they studied convective activity over the SSCS. We used these months because such a large fraction of the tropical cyclone activity in the SSCS occurred in these two months. While the time compositing was performed using the CDC website, the area averaging was carried out by downloading the data and integrating over the area using mean-value theorem (see Burkhardt and Lupo, 2005).

c. ENSO and PDO definitions

ENSO years were defined using the Japan Meteorology Agency (JMA) ENSO index to classify these as El Niño, La Niña, or neutral years. A complete description of this index can be found at the Center for Ocean and Atmospheric Prediction Studies (COAPS) website (http://www.coaps.fsu.edu). Briefly, this index classified each year based on a five month running mean of spatially averaged SST anomalies over the Niño 3.4 region in tropical Pacific Ocean. This value should be equal to or exceed (be less than) 0.5^{o} C (-0.5^{o} C) for six straight months to be classified as an El Niño (La Niña) year. When the SST anomalies were close to 0^{o} C, these years were considered neutral years. Table 1 provides a list of these years, and, for example, the ENSO year 1970 begins 1 October 1970 and ends 30 September 1971. This definition of El Niño has been used by several studies which have examined the interannual variability of atmospheric phenomenon (e.g., Bove et al., 1998; LJ00; Smith and O'Brien, 2001; Weidenmann et al, 2002), and is similar to other definitions used by other investigators (e.g., Pielke and Landsea, 1999).

Finally, the Pacific Decadal Oscillation is a 50 to 70 year basinwide variation in Pacific Region SSTs. This phenomenon is described in, for example 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[1] (Table 2) persisted during the period from 1977 – 1998 (1947 to 1976), and in 1999 it was believed to have switched phases again (e.g., LJ00; Houghton et al., 2001; Lupo et al. 2007).

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[1]See also the Joint Institute for the Study of the Ocean and Atmosphere at the University of Washington (http://www.jisao.washington.edu/data_sets/)

3. SSCS CLIMATOLOGICAL ANALYSIS

A total of 50 tropical cyclones occurred within the SSCS region over the 47 year period of study (Table 3). This sample included 11 typhoons (TY, ~20%), 29 tropical storms (TS, ~60%), and ten tropical depressions (TD, ~20%). While these events constituted a very small fraction of the total Pacific Ocean basin activity (3%), two of these tropical cyclones have had recently a major impact on the nation of Malaysia. Of the 50 tropical cyclones observed over the period, 27 of these (54%) were of local origin (Table 3). Local origin here refers to storms developing within the study area shown in Fig. 1.

Table 4 demonstrated that the active tropical season for Malaysia persists from October to April. However, most of the activity (78%) occurred during the months of November (42%) and December (36%). This represented a sharp peak in the active season and likely is related to the annual migration of the Intertropical Convergence Zone (ITCZ), and the associated convection, through the SSCS (e.g., Hurrel et al., 1995; Chang et al. 2005a). This seasonal peak seemed to exist regardless of whether the tropical cyclones were of local origin or they migrated into the area from the adjacent area to the east. While tropical cyclones have occurred in all months in the greater western North Pacific in general, the poleward portion of the greater Pacific region is climatologically more active from July to October (Yumoto and Matsuura, 2001). Thus, the peak of the tropical season for the SSCS followed that of the greater western North Pacific.

Tropical cyclones in the SSCS region tended to move from east to west and more of these tended to move across the poleward portion of our study domain. Tropical cyclone Vamei is an example of this type of behavior (Fig. 2b). Vamei developed rapidly off the coast of Malaysia and was classified as a typhoon early on 27 December 2001 (http://weather.unisys.com/hurricane/w_pacific/2001H/VAMEI/track.dat) (see also Chang et al. 2003). The storm then moved inland and decayed quickly over land, but not before causing widespread flooding in Malaysia and neighboring nations. However, some storms did move west to east (Fig. 2a) and tropical cyclone Greg is an example of this type of behavior. Greg developed out of a tropical depression on 24 December, 1996 and became a tropical storm just before striking northern Malaysia and then moving out of the SSCS. Following the move out into the SSCS, Greg was downgraded to a tropical depression again. Additionally, locally developing tropical cyclones tended also to have a short track, while most of the typhoons were storms that have migrated into the region.

Figure 3 shows a time series of tropical cyclone activity over the 47 year period. With the exception of the 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 in the number of tropical cyclones during the period of record overall (Fig. 3a). However, when this trend was tested for significance, it was found that the trend was not statistically significant at even the 90% confidence level by using the F-test and assuming that there should be no trend *a priori*. This agreed with the findings of many other studies of the active tropical regions (e.g., Free et al. 2004). There was a prolonged period of inactivity for tropical cyclones developing within the SSCS from 1974-1994 (Fig. 3b). The relatively active period since 1995 has been the result of an increase in tropical depressions developing in the SSCS. The observations for the period during the 1974 - 1994 would coincide with the fact that there were more and stronger El Niño events. The observations also support the assertion of the studies cited in the reference section, mainly, that during El Niño years, the focus of tropical storm activity was located further east. Regardless, this would favor the migration of tropical cyclones into the region if there were no locally developing storms during years where one storm was observed. Alternatively, the noted increase in the climatological trend noted above could be the result of better satellite identification techniques. However, more observations (and/or reanalysis of previous records) would be needed to confirm this hypothesis, and the satellite record may also provide better insight into trends in tropical cyclone intensity.

In order to detect interannual variations in tropical cyclone occurrences, the whole SSCS dataset was partitioned into El Niño, La Niña, and neutral years. Table 5 shows that La Niña (El Niño) 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 of these years against the mean of the entire sample using the z-score test (Neter et al., 1998) using the null hypothesis. It should be noted that since the dataset is small, statistical testing was only carried out on the complete dataset and not 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, however, were similar to the results of other studies for the entire western Pacific Region as well (e.g., Wu and Lau, 1992). Finally, an examination of the variability with respect to the predominant phase of the PDO (not shown) demonstrates that there was little or no difference in the relative annual distribution of tropical cyclones. Additionally, there was no change in the interdecadal character of the ENSO related variability as found, for example, in the Atlantic by LJ00. It was not clear whether this result was a function of the small area included in the study, the small data set, or other real factors.

4. INTERANNUAL VARIATION IN THE SSCS BACKGROUND STATE

One goal of this study was to examine whether the tropical cyclone activity in active and non-active years could also be associated or correlated with variability in meteorological parameters related to tropical cyclone formation in the climatological background of the SSCS region. In order to accomplish this, the time series of the November/December mean variables were analyzed. These included SSCS area-averaged monthly mean 1) SSTs, 2) sea level pressure (SLP), 3) 850 – 200 hPa wind shear, 4) divergence (calculated using Eq. (4a)), 5) 850 hPa relative vorticity (Eq. 4b), 6) 500 hPa heights, 7) precipitable water, and 8) lifted index. The time series of variables 1 - 5 were then correlated with one another. We examined the background climatological state of the SSCS as a study of the general circulation of a much wider region is beyond the scope of this study. There are many available studies in the literature on this topic (e.g. Hurrell et al., 1995; Houghton, et al., 2001).

As expected, there were strong correlations between the SSTs and the SLP, low-level divergence, vorticity, and the wind shear (Table 6). Some of these correlations were significant at the 95% confidence level, and only the SLP correlated with the wind shear and SST correlated with vorticity showed weak correlations. Then some of these time series were filtered following the procedures in section 2 and analyzed using FFTs (e.g., SSTs were representative of the other variables and shown in Figs. 4, 5). A significant peak in the periodograms was found in the 3 – 7 year range (peak near two cycles per decade in Fig. 5) which is a time period consistent with ENSO variability. A cross-spectral analysis was then performed using, for example the SST and SLP time series (not shown), and the results were consistent with the observations in Fig. 5. Thus, it is likely that variability in SSCS background climatological state was real, and may have been due to (or at least associated with) the ENSO. Thus, the next step would be to demonstrate that during active years, the atmospheric background state must be more conducive to tropical cyclone occurrence than during non-active years. It must also be shown that the active (non-active) years were associated with La Niña (El Niño) years. Additionally, an analysis of long term trends in the SSTs (Fig. 4) and SLP (not shown) revealed that there was no statistically significant secular trend in the SSCS region.

Then, in order to test further the hypothesis (objectives – section 1, and elucidated above) and determine which primary and calculated variable(s) may have been encouraging or inhibiting tropical cyclone formation and maintenance in the SSCS, the SSTs, 200 – 800 hPa wind shear, and the 850 hPa divergence and relative vorticity were examined, and these were calculated as discussed in section 2. In order to sample these data objectively, the five most active years were chosen (Table 7) and then compared to two sets of non-active years (Tables 8 and 9 – no occurrences). The variables displayed in Figs 6-8 are the mean 1 November – 31 December SLP, 500 hPa height, precipitable water, and lifted index (stability) in the SSCS region. These data were composites of the conditions within the samples shown in Tables 7-9 and these groups overall. The two sets of non-active years were compared by using the five years with the warmest SSTs and the five years with the coldest SSTs in order to generate objective samples of years with no activity and to determine the possible impact of SSTs in the SSCS. The mean SSTs for the warm (cold) non-active years was about one standard deviation (0.45^{o} C) greater (less) than the 45 year mean (28.14^{o} C).

The active sample contained two La Niña and three neutral years, but these three neutral years were "cold" neutral, that is SST anomalies close to La Nina conditions during the October – January period. The non-active warm SST years were predominantly El Niño, but one year was a cold neutral year. The non-active cold years included one El Niño year and two "warm neutral" and one year with SST anomalies very close to zero. However, when examining all 18 years in which there was no tropical cyclone activity, 12 years were El Nino or warm neutral and two were years with SST anomalies very close to zero. The three groups described above together represent almost one third of the total number of years.

This analysis demonstrates that during the active years, the area averaged 200 – 850 hPa wind shear was of similar magnitude to that of the non-active warm SST years (Tables 7, 8) and close to the overall mean. A positive number indicated wind speeds increasing with height. The mean value for the five active years in Table 7 was smaller compared to mid-latitude values of 15 – 30 ms^{-1} found by taking several random samples of mean November/December wind shear within the mid-latitude region approximately 30 degrees latitude poleward of the study area. The wind shear values in Tables 7-9 were lower than 15 ms^{-1}, and these values are generally accepted as being supportive of tropical cyclone formation and maintenance. The relatively low tropospheric wind shear in the SSCS indicated a less baroclinic environment, especially when compared to the mid-latitudes. Additionally, an examination of the low-level relative vorticity for the active seasons demonstrated that the lower troposphere was dominated by cyclonic relative vorticity (Table 7), but the value in Table 7 was only slightly greater than the sample mean. The active year composites in Fig. 6 support the discussion above as it showed that there was relatively low SLP in the SSCS (Fig. 6a, d), and there was also ridging in the mid-troposphere (Fig. 6b), especially over the eastern portion of the SSCS. This would suggest an SSCS atmospheric environment that was more cyclonic near the surface, and the troposphere was warmer than the samples from the other group. This atmosphere would also be supportive of warm core disturbances such as tropical cyclones. Additionally, the SLP was significantly lower (at the 95% confidence level, for the whole sample $\sigma = 0.40$ hPa) than the long term mean across the SSCS, except along the equator.

However, in the non-active years with warm SSTs (Table 8), factors other than SSTs, such as the more anticyclonic environment seemed to differentiate the active-year sample from the inactive years. The SSTs from this sample were actually warmer than those for active years, but not at any accepted level of statistical significance. The area averaged low-level vorticity was the more anticyclonic (lower than the mean at the 95% confidence level) for this group (Table 8) than the two groups in Tables 7 and 9. The low-level divergence was similar to that of the active year sample. The composites of the years shown in Table 8 are given in Fig. 7. The near surface environment was clearly more anticylonic for the non-active years (Fig. 7a), but not different significantly from the long term mean (Fig. 7d). In the mid-troposphere there were stronger height gradients over the region (Fig. 7b), and the flow was nearly zonal or showed weak troughing over much of the domain. This atmospheric configuration is similar to results found by Chang et al. (2005b) who found that convection was suppressed over the SSCS when the near surface environment was more anticyclonic (or as stated in their work, the ‘Borneo vortex’ was not present).

Additionally, an examination of the precipitable water suggests that the SSCS environment in these non-active years (Fig. 7c) was clearly drier than for the active year sample (Fig. 6c). Thus, it is suggested here that there was more low-level atmospheric water vapor available to potential tropical cyclones in the active years. Latent heat release has been identified as an important thermodynamic process in tropical cyclone intensification (e.g, Holland, 1997). Since climatologies of the tropics (e.g. Hurrell et al., 1995) demonstrated that most atmospheric moisture is contained in the boundary layer, the precipitable water here was taken to represent low-level moisture available for possible ingest into convective systems.

In the SSCS, it appears that even if the other background variables were similar (e.g., wind shear, low-level divergence, SSTs), the tropical cyclone activity in the region was inhibited during seasons when the relative vorticity was more anticyclonic (even though the low-level wind shear was favorable). The variables shown in Fig. 6 (Fig. 7) and Table 7 (Table 8) suggest a more (less) cyclonic and warm core background climatological state for the active (inactive) warm SST years. These results also suggest that in the SSCS, this set of El Niño years with warm SSTs may have been more hostile to tropical cyclone development as a result of the atmospheric conditions, and not necessarily because of cooler SSTs. Many studies have shown for different regions that, in addition to warm SSTs, the atmospheric background state was also a critical factor in contributing to tropical cyclone activity, (e.g., Holland, 1997; Tonkin et al, 2000; Dare and Davidson, 2004; Paterson et al. 2005). Free et al. (2004) also demonstrated that SST was not always associated with a higher potential intensity for tropical cyclones.

During the warm SST years (Table 8) in which no storms occurred in the SSCS, it is clear that the wind shear was similar to that of the active years. During the cold SST non-active years (Table 9), however, the low-level wind shear was even weaker than that of the samples in Tables 7 and 8. Nonetheless, the low-level background was also more anticyclonic (again, at the 95% confidence level) when comparing the low-level vorticities (anticyclonic relative vorticity) to those of the warm active years (Table 7). A composite map of the SLP (Fig. 8a), however, showed that in spite of weak cyclonic conditions over the ocean, similar to the active years (Fig. 6a), these values were higher than that of the long term mean (but not at the 90% confidence level). But, there were strong height gradients and troughing over the much of the SSCS region and weak ridging over the east side (Fig. 8b), which was more similar to the warm non-active years (Fig. 7b). This was also a season in which the tropospheric moisture was comparable to that of the active years (compare Fig. 8c to 6c), but more than that of the warm non-active years (Fig. 7c). Thus, in addition to the cooler SSTs, the non-active years sampled in Table 9 presented a less favorable atmospheric background environment for tropical storm formation than that of the active years. Additionally, for Tables 8 and 9 (not shown), adding the next three years to these samples in which no tropical cyclone activity occurred did not change the interpretation of the results discussed here in section 4. Adding those years represented a total of 21 years sampled from the 47 year period.

5. SUMMARY AND CONCLUSIONS

An analysis of the interannual variations and long term trends in tropical cyclone activity from 1960 – 2006 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, has increased in a detectable fashion, or whether the active period of the last decade was due to natural cycles. Malaysia was struck by two deadly tropical cyclones during the 1996 to 2001 period. There has been concern in Malaysia that tropical cyclone activity and intensity may increase in association with the expected climate change whether or not the climatic changes are naturally or anthropogenically forced. The tropical cyclone data was obtained from the UNISYS hurricane archive, and the NCEP-NCAR gridded re-analyses available via the world-wide web were used for the analysis of the climatological background conditions.

The important findings resulting from this work were;

- the SSCS experiences about one tropical cyclone event per year, whether these develop locally within the SSCS (about 54%) or they propagate into the region,
- of these, most attain tropical storm status, but relatively few become typhoons,
- the most active part of the season was confined to November and December (78% of all activity) and was likely associated with the ITCZ as it moves through the region,
- there was a slight upward trend in the occurrence of these events, but this trend was not statistically significant.

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

- La Niña (El Niño) years were more (less) active than other years, and this result was significant at the 95% confidence level when examining the total sample. The variability of tropical storms and tropical cyclones of local origin was similar to that of the total sample,
- there was no apparent climatic variability (statistically significant) in the SSCS that could be attributed to interdecadal variability such as the PDO,

A spectral analysis of the filtered climatological background variables such as SST, SLP, 200-850 hPa wind shear, 850 hPa divergence and 850 hPa vorticity showed that there was significant variability found in the 3-7 year period, which is consistent with that of the ENSO period. Examining a subset of the most active years (all La Niña and "cold" neutral years) versus those years with no tropical cyclone activity for the five years of a) warmest SSTs (predominantly El Niño years), and b) coolest SSTs yielded some interesting results (mostly El Nino or "warm" neutral). First, during warm non-active SST years, tropical cyclone activity was likely suppressed as the low-level relative vorticity was considerably more anticyclonic, even though SSTs were about one standard deviation warmer and wind shears were similar to those of active years. The SSCS atmospheric environment for warm SST non-active years was drier than that of the active years, and did not exhibit a surface – 500 hPa structure that would be as supportive of warm-core tropical cyclones. Most of these years were also ENSO years, and two thirds of all years with no activity were El Niño or warm neutral. These results may indicate that, in the SSCS region, it was atmospheric conditions that were unfavorable to tropical cyclone development during El Niño years with warm SSTs.

During cool SST years, tropical cyclone activity was suppressed by a climatological background that was more anticyclonic at low levels than that of active years, even though the wind shear was even more favorable. The background climatological state was more similar to that of the warm SST non-active years. These results should provide forecasters in the SSCS region with guidance regarding the type of background conditions that are favorable for the occurrence of tropical cyclones. The majority of these were also El Nino and "warm" neutral years.

6. ACKNOWLEDGMENTS

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Table 1. A list of years examined in this study separated by ENSO phase.

	El Niño	La Niña	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		2003-2005
	2002		
	2006		
Total Years	12	10	25

Table 2. The phase of the PDO.

PDO Phase	Period
Phase 2 (negative)	1947 – 1976
Phase 1 (positive)	1977-1998
Phase 2 (negative)	1999-2006

Table 3. Total number of tropical cyclones and annual averages over the SSCS region from 1960 – 2006.

	TD	TS	TY	Total	Local Origin
total	10	29	11	50	27
Annual avg	0.21	0.62	0.23	1.06	0.57

Table 4. Total number (top row) and percentage (bottom row) of tropical cyclone occurrence in the SSCS by month for the period 1960 – 2006, following the ENSO year definition used here (beginning with October).

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Total	4	21	18	1	1	1	2	2	0	0	0	0	50
%	8	42	36	2	2	2	4	4	0	0	0	0	100

Table 5. The average annual tropical cyclone activity separated by a) El Niño years for all tropical cyclones (All), typhoons (TY), tropical storms, tropical depressions (TD), and tropical cyclones of local origin.

	All	TY	TS	TD	Local Origin
Neutral	1.1	0.3	0.6	0.3	0.6
El Niño	0.4	0.2	0.2	0	0.3
La Niña	1.6	0.1	1.2	0.3	1.0
All Years	1.0	0.2	0.6	0.2	0.6

Table 6. The correlation between SSTs, SLP, geostrophic wind shear, wind divergence, and vorticity. The asterisk denotes a correlation at a 95% confidence interval.

Parameter	SST-SLP	SST-Div	SST-Shear	SLP - Div	SLP- Shear	Div-Shear
Correlation	-0.59*	-0.70*	0.29	0.55*	-0.10	-0.23

Parameter	SST-vor	Div-Vor	Shear – Vor
Correlation	0.15	-0.53*	0.35

Table 7. The area-averaged November and December means for the five most active tropical seasons in the SSCS.

Year	Total TCs	ENSO Year	SSTs (^oC)	wind shear (ms^{-1})	divergence ($x\ 10^{-6}\ s^{-1}$)	relative vorticity ($x\ 10^{-6}\ s^{-1}$)
1996	4	Neutral	28.6	11.4	-2.26	5.70
1998	3	La Nina	28.1	12.4	-2.49	10.00
1970	3	La Nina	28.1	12.0	-2.22	-2.35
1962	3	Neutral	27.7	9.8	-0.03	-2.10
1995	2	Neutral	28.3	9.4	-2.44	5.85
		means	28.1	10.1	-1.88	3.42

Table 8. As in Table 7, except for five non-active years with the warmest SSTs.

Year	Total TCs	ENSO Year	SSTs (^oC)	wind shear (ms^{-1})	divergence (x 10^{-6} s^{-1})	relative vorticity (x 10^{-6} s^{-1})
1987	0	El Niño	29.0	9.2	-1.95	0.90
2002	0	El Niño	28.8	2.7	-1.31	-0.90
1966	0	Neutral	28.4	12.8	-2.62	-2.25
1963	0	El Niño	28.4	7.5	-0.08	-4.95
1986	0	El Niño	28.3	5.8	-2.94	1.55
		Means	28.6	8.5	-1.78	-1.13

Table 9. As in Table 8, except for five non-active years with the coldest SSTs.

Year	Total TCs	ENSO Year	SSTs (^{o}C)	wind shear (ms^{-1})	divergence (x 10^{-6} s^{-1})	relative vorticity (x 10^{-6} s^{-1})
1984	0	Neutral	27.3	4.9	-1.44	-0.75
1978	0	Neutral	27.5	6.2	-0.35	0.16
1979	0	Neutral	27.9	7.1	0.37	-0.49
1977	0	Neutral	27.9	4.8	0.16	-1.40
1991	0	El Niño	27.9	2.9	-0.02	-0.68
		Means	27.7	5.2	-0.26	-0.63

Figure Captions

Figure 1. A map of the South China Sea and part of the West North Pacific Ocean. A map of the study area and Malaysia are indicated in the inset.

Figure 2. Tracking information for a) Tropical Storm Greg (24 – 31 December, 1996), and b) Typhoon Vamei (27-28 December, 2001). The mauve, dark blue, and light blue colors indicate a tropical depression, strom, and typhoon, respectively. This figure is adapted from the archive available through the UNISYS website.

Figure 3. The time series of a) all tropical cyclones, and b) tropical cyclones of local origin occurring within the SSCS region from 1960 – 2006. In a) the dashed line is the linear regression line.

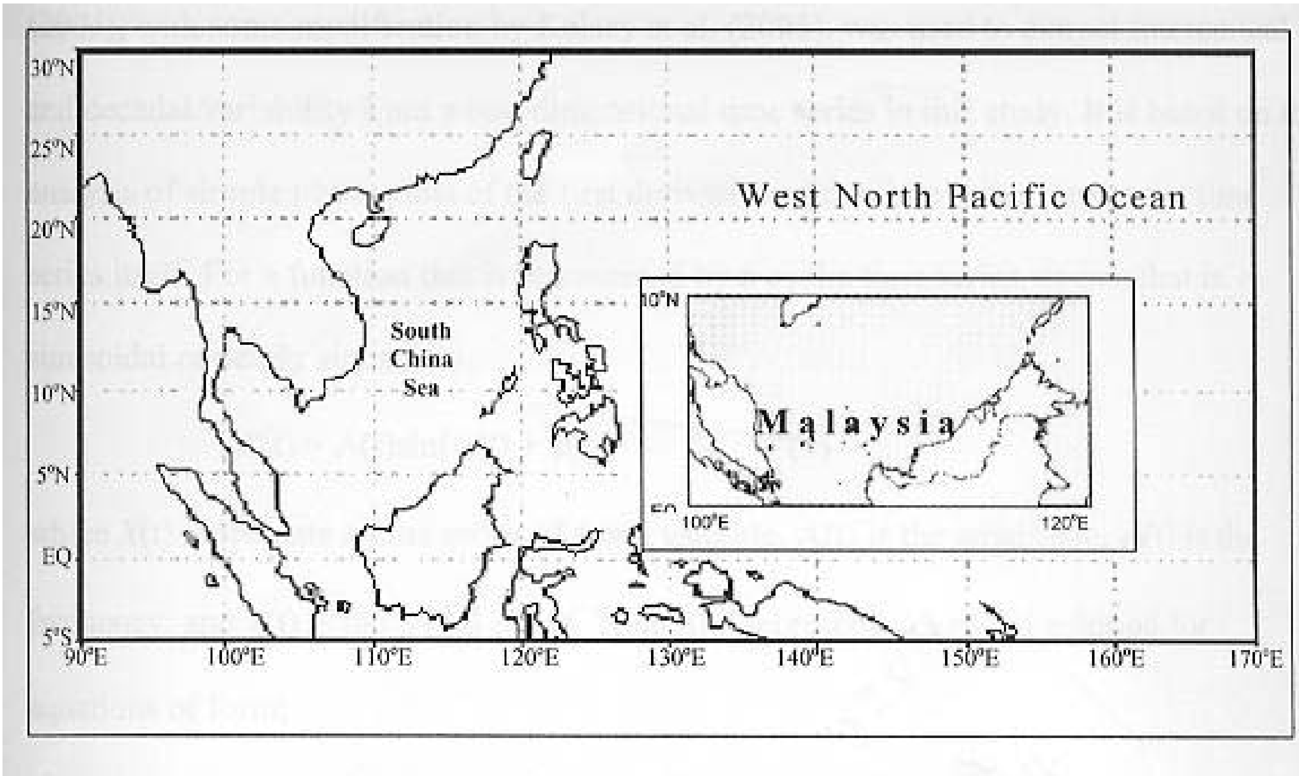
Figure 4. The raw mean monthly SSTs (^{o}C) for the SSCS region from 1963 – 2002.

Figure 5. The power spectra for the filtered mean SSTs in the SSCS region. The filter was set in order to remove the signal for time periods smaller than two years. The abscissa is cycles per decade, thus 10 is 10 cycles per decade or the annual cycle. The dashed line represents the 99% confidence interval for accepting the red noise spectrum null hypothesis.

Figure 6. The mean a) sea level pressure (hPa, interval 0.1 hPa), b) 500 hPa heights (m, interval 0.5 m), c) precipitable water (kg m^{-2}, interval 0.5 kg m^{-2}), and d) sea level pressure anomaly (hPa, interval 0.05 hPa) for November and December for the years shown in Table 7 in the SSCS region.

Figure 7. As in Fig. 6, except for the years in Table 8.

Figure 8. As in Fig. 7, except for the years in Table 9.



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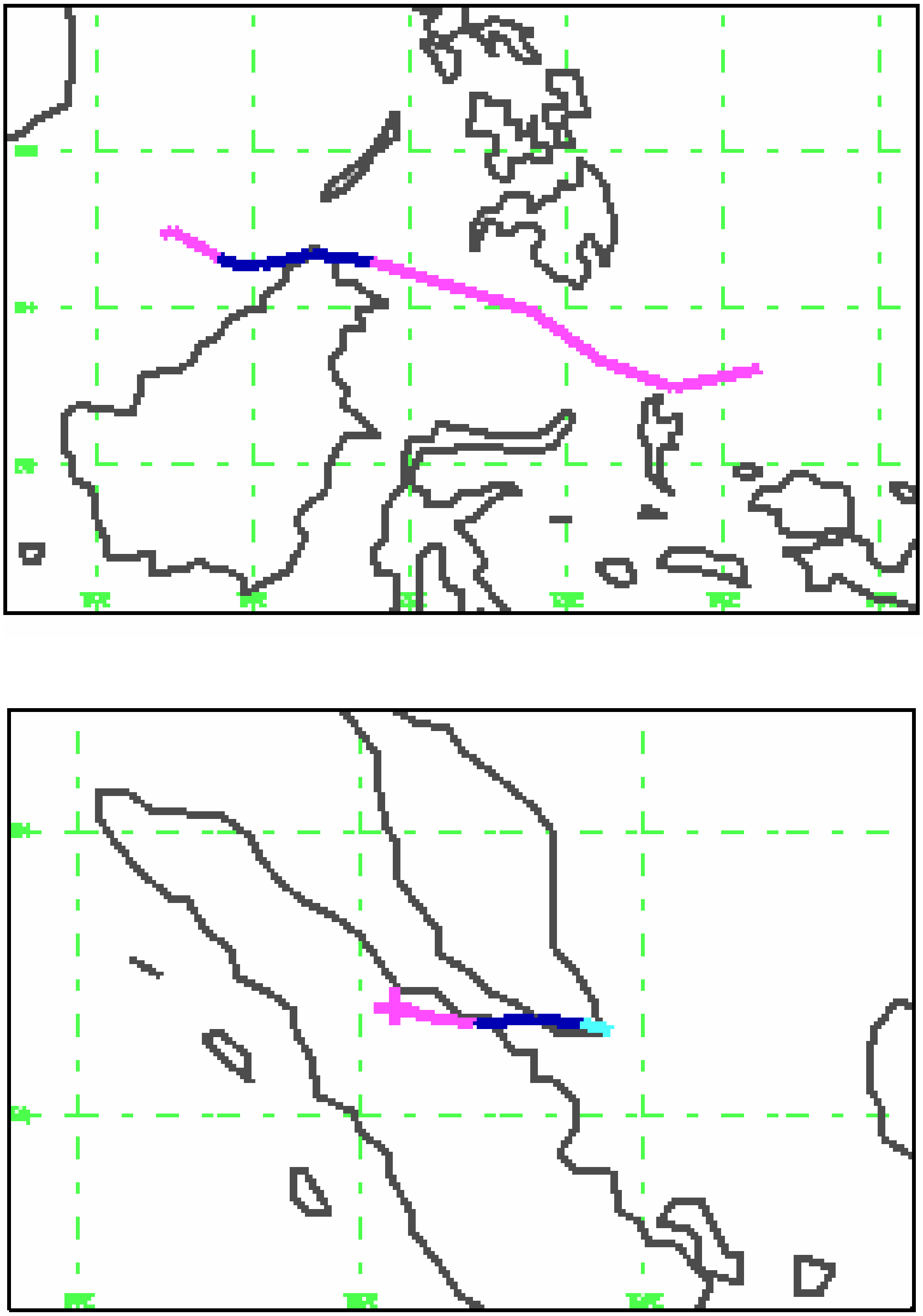

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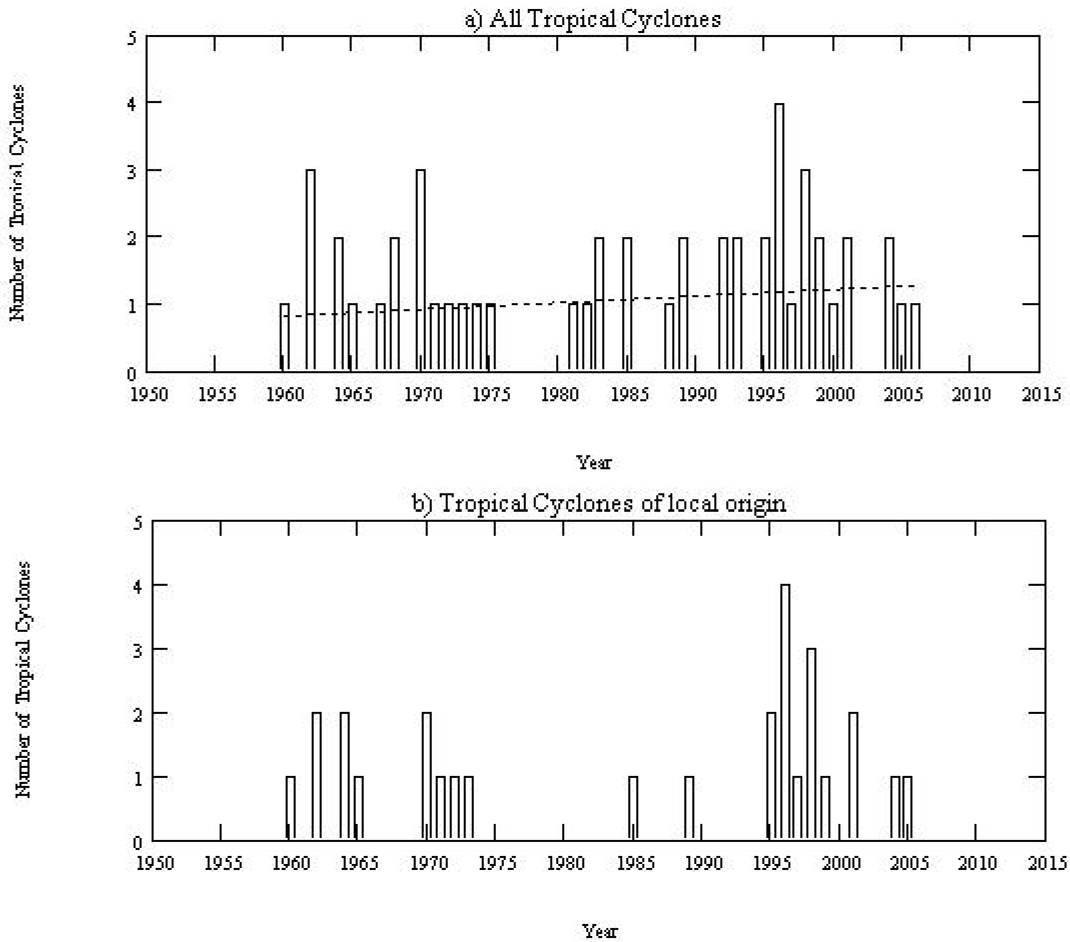

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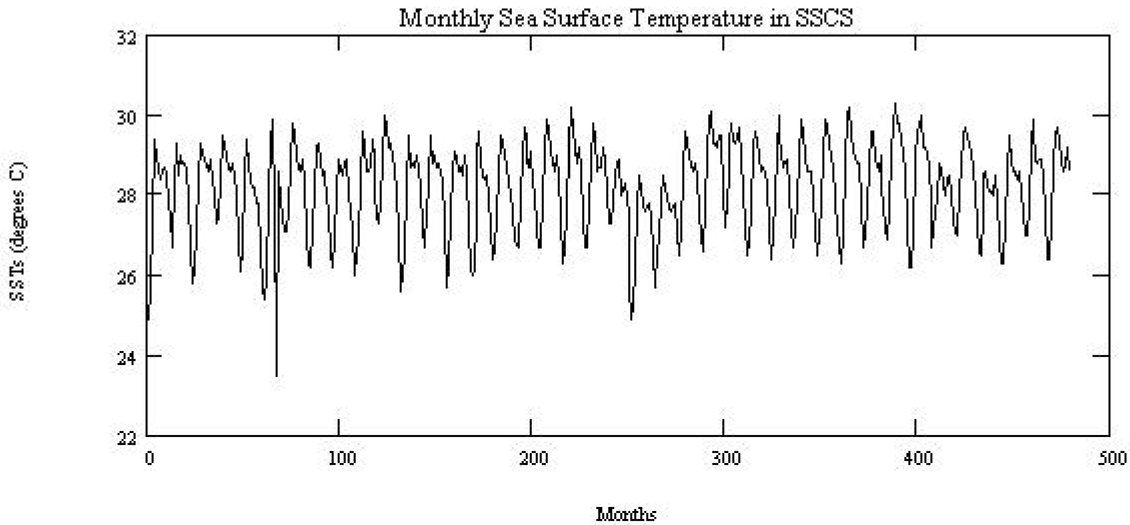

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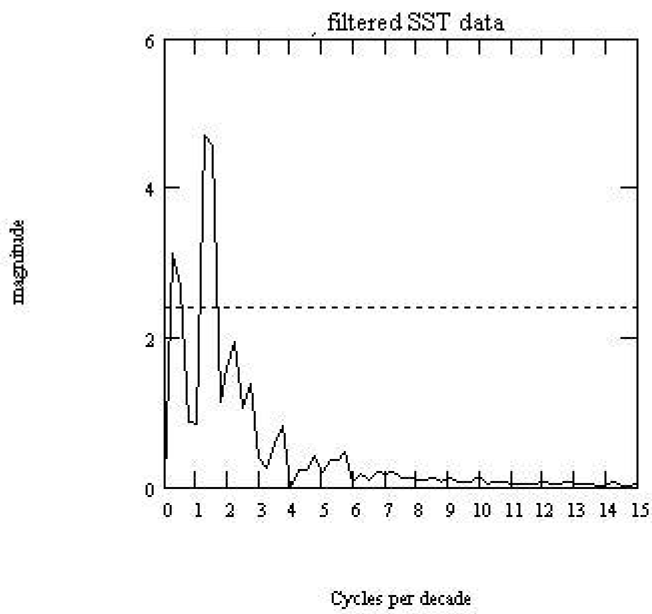

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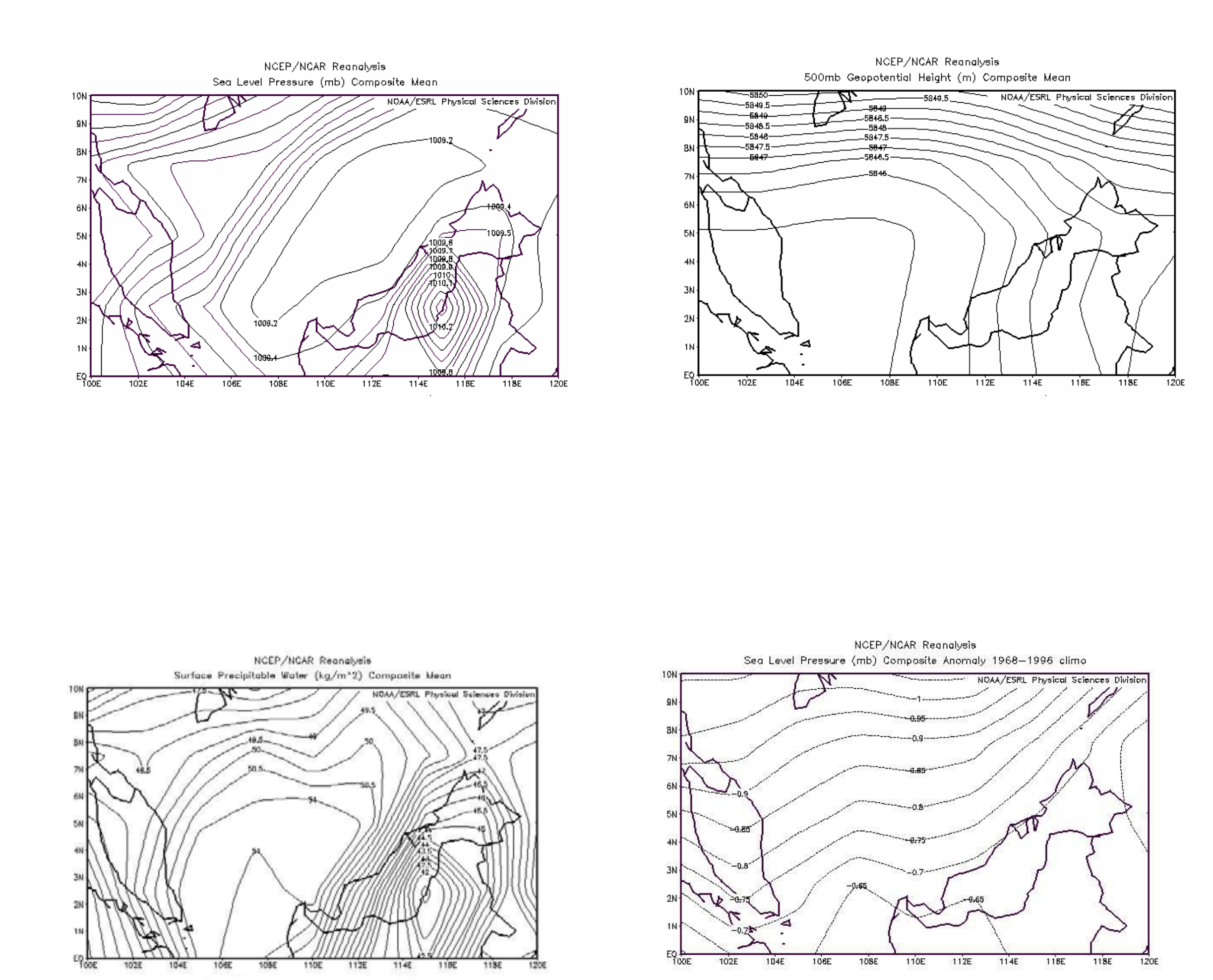

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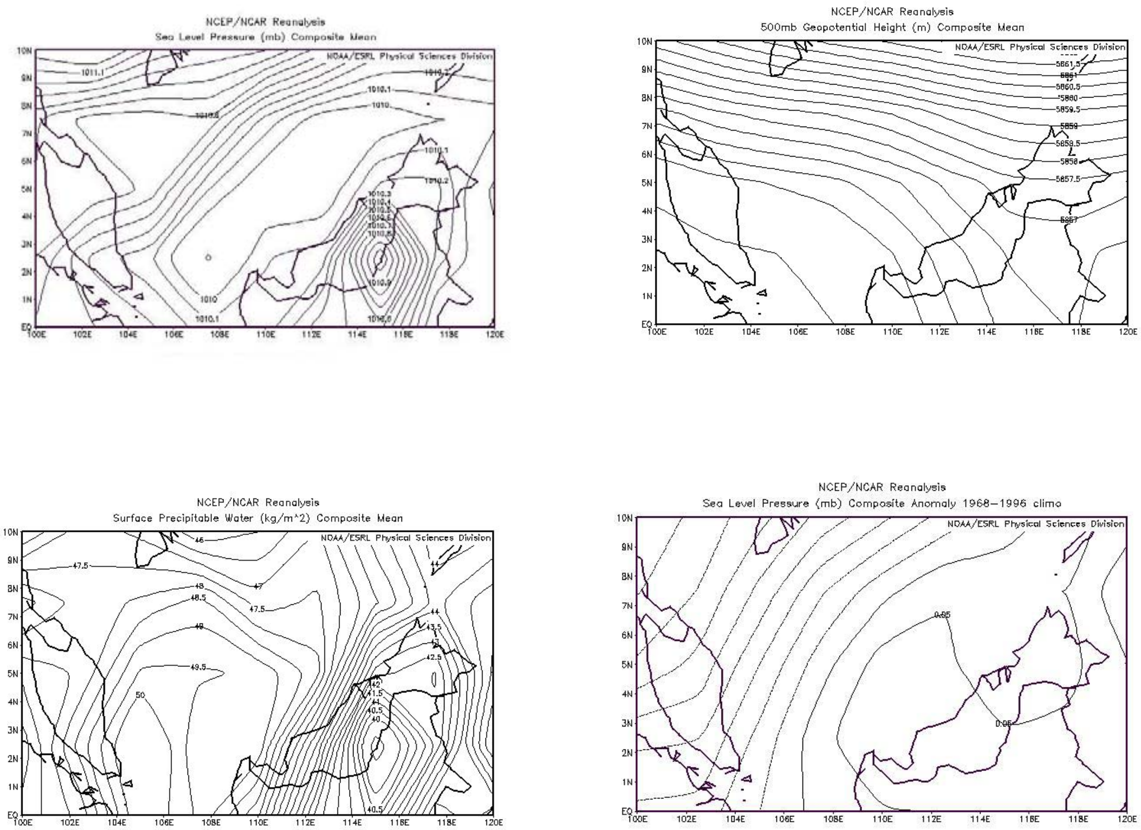

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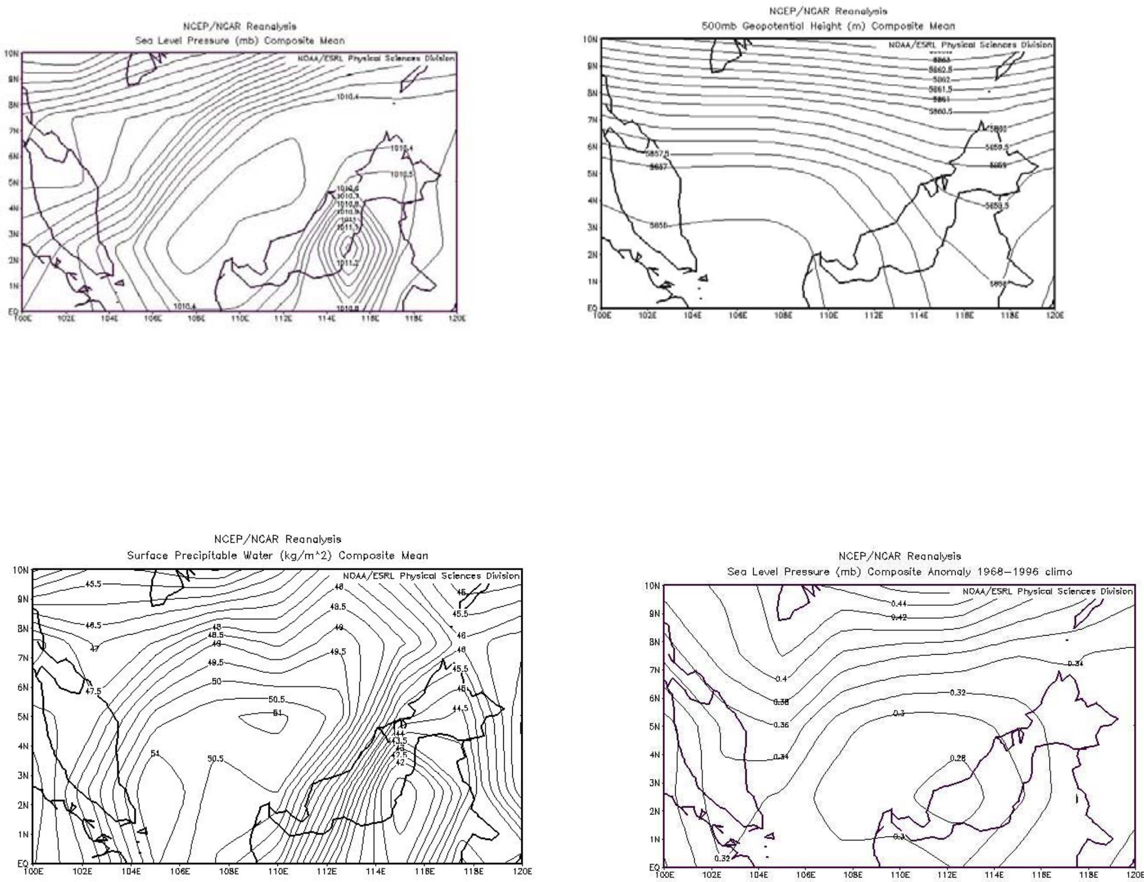

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