Chapter 5

Comparison of non-developing versus developing tropical disturbances over the SCS

As *Gray* [*1998*] once commented, “It seems unlikely that the formation of tropical cyclones will be adequately understood until we more thoroughly document the physical differences between those systems which develop into tropical cyclones from those prominent tropical disturbances which have a favorable climatological and synoptic environment, look very much like they will develop but still do not develop.” Our understanding of the detailed physical processes associated with the early stages of tropical cyclone formation is still inadequate and operational forcast skill is not very high. The study in this chapter will follow this comment from Gray to examine why some tropical disturbances could develop, while other tropical disturbances never developed. These studies will improve the understandings of the physical processes associated with the early stages of tropical cyclogenesis and the ability to do operational daily forecast for tropical cyclone formation.

5.1 Introduction

A tropical disturbance is a discrete tropical weather system with apparently organized convection (generally 200 to 600 km in diameter) originating in the tropics or subtropics, having a non-frontal migrating character and maintaining its identity for 24 hours or more [*Holweg, 2000*]. Tropical disturbances are often the precursors of tropical cyclones. The different stages of development typically follow one another as tropical disturbance to tropical depression to tropical storm to typhoon/hurricane. Compared to the number of tropical disturbances, the number of formed tropical cyclones is much less due to the high percentage of the non-developing tropical disturbances. The relative rareness of tropical cyclone formation has not been easily explained by existing theories and has not been well understood. Therefore, a primary concern related to tropical disturbances is determining their potential for developing into tropical cyclones [*Simpson et al., 1968*].

Tropical disturbances and tropical cyclones always form over the warm tropical oceans where traditional data sources are sparse. The sparseness of conventional in-situ data (from aircraft, ships and buoys) in the regions typical of tropical cyclogenesis has limited observational studies of tropical cyclogenesis. Observational analysis of tropical cyclone formation was done by comparing non-developing versus developing systems in the study of *McBride and Zehr* [*1981*] and *Lee* [*1989*]. Due to the limitation of traditional observations, composite data sets were used in these studies, in which large amounts of rawinsonde data at different time periods around many weather systems are averaged together to yield a composite weather system.

Remote sensing from satellites can provide information in ocean regions where traditional surface-based observations are not available [e.g., *Chelton et al., 2004; Santer et al., 2007*]. Observations from remote sensing make it possible to obtain enough data around any individual storm or cloud cluster at one time period to permit quantitative analyses for each individual weather system, rather than the composite weather system from composite data sets. Satellite observations have been useful tools for the study of tropical cyclogenesis [e.g., *Liu et al., 1995; Katsaros et al., 2001; Sharp et al., 2002; Li et al., 2003; Wang et al., 2008b*]. In this study, 13 developing tropical disturbances and 30 non-developing tropical disturbances in the SCS are compared using satellite observations and reanalysis data sets, in order to understand why some tropical disturbances formed tropical cyclones while others did not.

5.2 Statistical analyses of tropical disturbances over the SCS

The record of tropical disturbances over the SCS used in this study are from topical disturbance alert messages forwarded by the University of Illinois at Urbana-Champaign (UIUC) weather server as Tropical Storm and Hurricane WX (WX-TROPL) products (http://listserv.uiuc.edu/archives/wx-tropl.html). The originator of these alert messages includes the various national weather services, including the Joint Typhoon Warning Center (JTWC), the Japan Meteorological Agency (JMA), the Hong Kong Observatory

(HKO), and the National Hurricane Center (NHC). The information for global tropical disturbances and tropical cyclones are included in these products. For tropical disturbances, information about the positions, intensity estimates and potential for the development to tropical cyclones are provided. If a tropical disturbance intensifies and develops into a tropical depression later, this tropical disturbance is called developing tropical disturbance in this study. Tropical depressions are defined as weak tropical cyclones having maximum sustained surface winds of less than 18 m s^{-1}, characteristically having one or more closed isobars. Tropical depressions must have a closed surface circulation in order to be classified in this category, while tropical disturbances may or may not be associated with detectable perturbations of wind fields. If a tropical disturbance does not intensify and later dissipates, this tropical disturbance is called non-developing tropical disturbance.

All tropical disturbances formed over the SCS from 1997 to 2006 are statistically analyzed. Totally, there are 158 tropical disturbances formed over the SCS in these ten years. 54 of these 158 tropical disturbances are developing tropical disturbances, which developed into tropical depressions later; while other 104 tropical disturbances are non-developing tropical disturbances, which never developed into tropical depressions.

5.2.1 Formation locations of tropical disturbances

Formation location of a tropical disturbance is defined as the first position in record for this tropical disturbance in WX-TROPL products. Formation locations of tropical cyclones from 1997 to 2006 for every month in the SCS are presented in Fig.5.1, in which the non-developing and developing tropical disturbances are represented by asterisks and christcrosses separately. *Wang et al.* [*2007d*] found that genesis locations of tropical cyclones in the SCS are located in the northern SCS during the summer monsoon months (from May to September) and in the southern SCS during the winter monsoon months (from October to December), which could be explained by the relative vorticity of ocean surface winds. Similar with the distributions of genesis locations of tropical cyclones, the formation locations of tropical disturbances mainly concentrated in the northern SCS during the summer monsoon and in the southern SCS during the winter monsoon. The relative vorticity may also affect the formation of tropical disturbances.

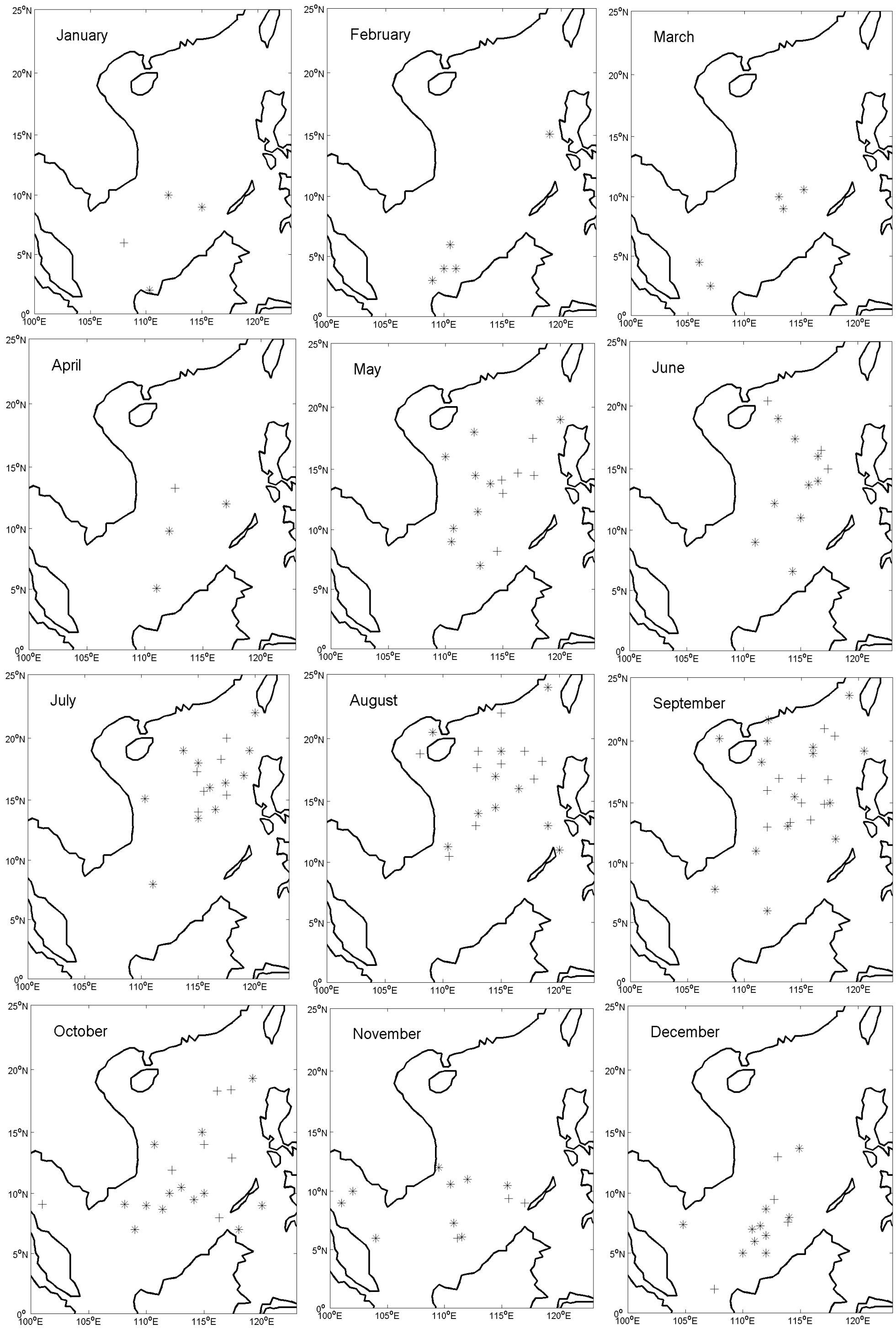

Figure 5.1: Formation locations of tropical disturbances (from 1997 to 2006) for every month over the SCS. The asterisks are for non-developing tropical disturbances and the christcrosses are for developing tropical disturbances.

The positive relative vorticity due to the monsoon trough and coastal mountains in the northern SCS during the summer monsoon and in the southern SCS during the winter monsoon is favorable for the occurrence of tropical disturbances. The negative relative vorticity induced by coastal mountains in the southern SCS during the summer monsoon and in the northern SCS during the winter monsoon is unfavorable for the occurrence of tropical disturbances.

The monthly mean formation positions (MFPs) of all tropical disturbances (including non-developing and developing tropical disturbances) are listed in table 5.1. From February to August, the monthly MFP traveled northward gradually, reaching the northernmost position in August. From September to December, the monthly MFP traveled southward gradually. The monthly MFPs of non-developing tropical disturbances and for developing tropical disturbances are listed in table 5.2 and table 5.3 separately. There are no information for February and March in table 5.3, since no developing tropical disturbances occurred in these two months from 1997 to 2006 over the SCS. Comparing table 5.2 and table 5.3, the MFPs of developing tropical disturbances tend to be located more northward than the ones of non-developing tropical disturbances from April to October.

Table 5.1**:** The monthly mean and the standard deviations of formation positions of all tropical disturbances (including non-developing and developing tropical disturbances) from 1997 to 2006 over the SCS.

Month	Latitude (^{o}N)	Longitude (^{o}E)	Standard deviation of latitude (^{o})	Standard deviation of longitude (^{o})
Jan	6.75	111.33	3.11	2.55
Feb	6.42	111.90	4.45	3.61
Mar	7.32	110.92	3.22	3.70
Apr	10.05	113.18	3.12	2.28
May	14.02	114.60	3.75	2.90
Jun	14.23	114.63	3.88	1.97
Jul	16.38	115.38	2.97	2.50
Aug	16.67	114.65	3.61	3.34
Sep	16.16	114.43	4.15	3.21
Oct	11.41	113.84	3.66	4.47
Nov	8.91	110.00	2.00	5.01
Dec	7.62	111.44	2.93	2.56

Table 5.2**:** The monthly mean and the standard deviations of formation positions of non-developing tropical disturbances from 1997 to 2006 over the SCS.

Month	Latitude (^{o} N)	Longitude (^{o} E)	Standard deviation of latitude (^{o})	Standard deviation of longitude (^{o})
Jan	7.00	112.43	3.56	1.94
Feb	6.42	111.90	4.45	3.61
Mar	7.32	110.92	3.22	3.70
Apr	8.97	113.37	2.88	2.61
May	13.94	113.42	4.28	3.10
Jun	13.21	114.36	3.76	1.74
Jul	16.20	115.76	3.48	3.07
Aug	16.03	115.10	3.96	3.46
Sep	16.13	113.95	5.02	3.78
Oct	10.51	113.95	3.25	3.92
Nov	9.17	108.48	2.08	4.70
Dec	7.46	111.30	2.37	2.57

Table 5.3**:** The monthly mean and the standard deviations of formation positions of developing tropical disturbances from 1997 to 2006 over the SCS.

Month	Latitude (^{o} N)	Longitude (^{o} E)	Standard deviation of latitude (^{o})	Standard deviation of longitude (^{o})
Jan	6.00	108.00	0.00	0.00
Apr	13.30	112.60	0.00	0.00
May	14.14	116.28	2.84	1.39
Jun	17.30	115.43	2.28	2.37
Jul	16.67	116.20	1.86	1.05
Aug	17.30	114.19	4.16	3.58
Sep	16.20	115.09	2.53	2.03
Oct	13.23	113.61	3.77	5.40
Nov	8.13	114.57	1.52	2.52
Dec	8.03	111.78	1.52	3.76

5.2.2 Lifetimes of tropical disturbances

The lifetime of a non-developing tropical disturbance is defined as the duration from the occurrence of tropical disturbance to the dissipation of this tropical disturbance. The lifetime of a developing tropical disturbance is defined as the duration from the occurrence of tropical disturbance to the development of this tropical disturbance into tropical depression. The mean lifetime of 104 non-developing tropical disturbances formed in the SCS during 1997-2006 was 47.2 h, with a standard deviation of 31.27 h. For 54 developing tropical disturbances, the mean lifetime was 48.77 h, with a standard deviation of 28.05 h. The mean lifetime of non-developing tropical disturbances and developing tropical disturbances were both about 2 days.

5.2.3 Development rate of tropical disturbances

The development rate of tropical disturbances (DRTD) is defined as the ratio of the number of developing tropical disturbances to the total number of all tropical disturbances (including developing tropical disturbances and non-developing tropical disturbances). The DRTD can represent how many percentages of tropical disturbances can be intensified and develop into tropical depressions. For all 158 tropical disturbances formed in the SCS from 1997-2006, 54 of these 158 tropical disturbances developed into tropical depressions, so the DRTD over the SCS during 1997-2006 was 34.18%.

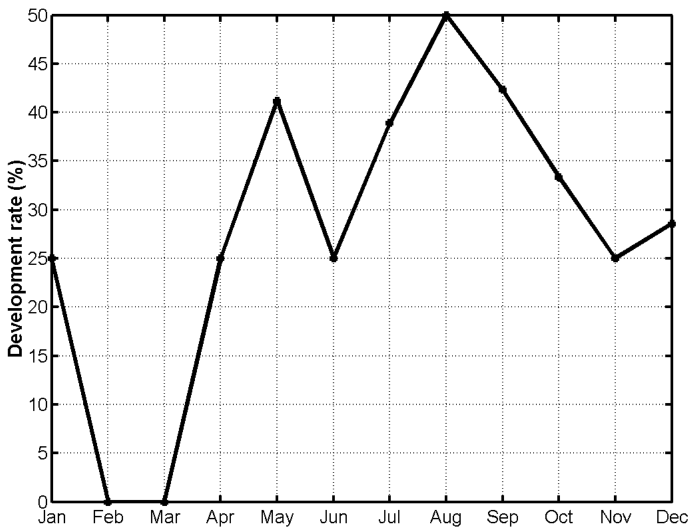

Figure 5.2: The development rate of tropical disturbances over the SCS in every month.

The DRTD in the SCS in every month is shown in Fig.5.2. The DRTD was maximum in August, with the magnitude of 50%. The DRTDs were minimum and equal to zero in February and March, since no tropical disturbances developed during these two months.

The number of tropical disturbances formed in the SCS from 1997 to 2006 in every month is presented in Fig.5.3. These are two significant peaks in Fig. 5.3. One peak occurred in September, with the maximum number of total tropical disturbances and developing tropical disturbances among all months. There was a bias between the highest peak occurred in August in Fig.5.2 and the highest peak in September in Fig.5.3. The other weak peak in Fig.5.3 occurred in May, which was consistent with the weak peak in May in Fig.5.2. Tropical cyclogenesis in May and June in the SCS is related with the Mei-yu front [*Lee et al., 2006*]. The peak occurring in May in Fig. 5.2 and Fig.5.3 may also have some relationships with the Mei-yu front.

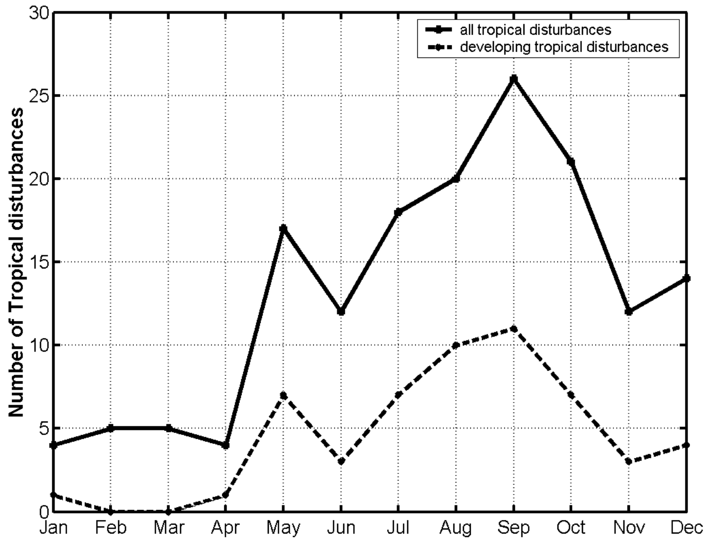

Figure 5.3: The number of tropical disturbances formed in the SCS from 1997 to 2006 in every month. The solid line is for all tropical disturbances including developing and non-developing ones, and the dashed line is for the developing tropical disturbances.

Wang et al. [*2007c*] gave the total number of tropical cyclones formed in the SCS from 1945 to 2005 in every month (shown in Fig. 5.4). Only one peak occurring in August for the total number of tropical cyclones formed in the SCS from 1945 to 2005 according to Fig. 5.4. It is suggested that more tropical cyclones tend to occur in September and May during the recent ten years (1997-2006), comparing Fig.5.3 and Fig.5.4.

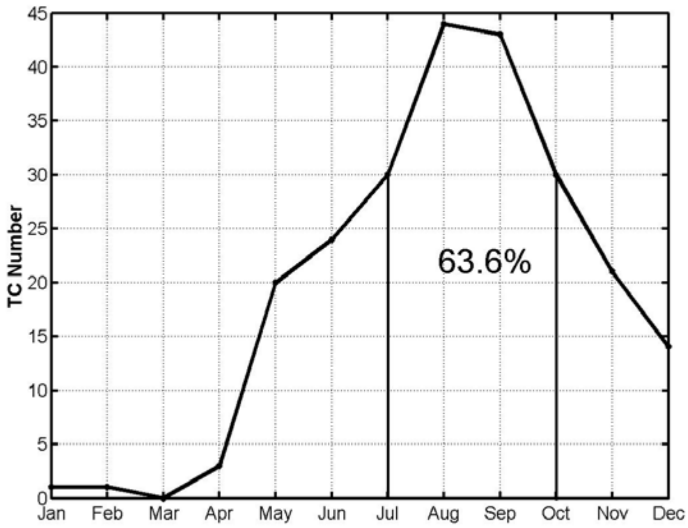

Figure 5.4: The total number of tropical cyclones formed in the SCS from 1945 to 2005 in every month. The July-October season accounts for 63.6% of the total. [From *Wang et al. 2007c*]

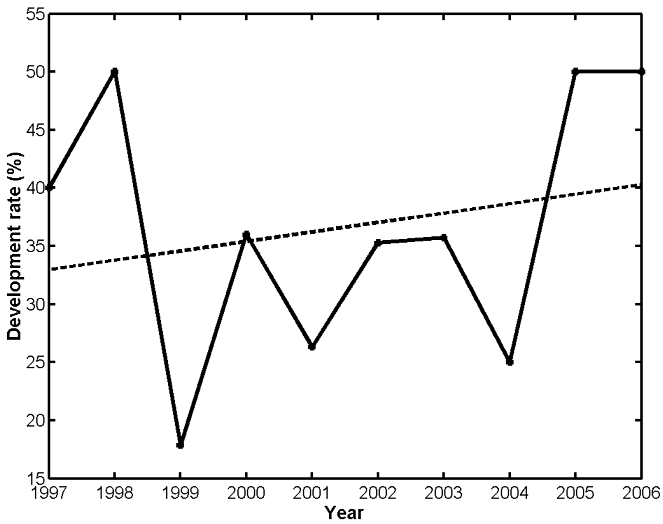

Figure 5.5: The development rate of tropical disturbances occurred over the SCS from 1997 to 2006. The dashed line is for the linear trend line.

The long-term change of DRTDs during the ten years from 1997 to 2006 is shown in Fig. 5.5. The minimum DRTD occurred in 1999, with a value of 17.86%. The maximum DRTD occurred in 1998, 2005 and 2006, with a value of 50%. The whole linear trend line in Fig. 5.5 shows a weak trend of increase. The long-term changes of total tropical disturbances and developing tropical disturbances occurred over the SCS from 1997 to 2006 are shown in Fig. 5.6 and Fig. 5.7, which show trends of decline for the numbers of total tropical disturbances and developing tropical disturbances over the SCS in recent ten years. Although more less tropical disturbances occurred over the SCS, the percentages of the tropical disturbances which can develop into tropical depressions tend to increase in recent ten years.

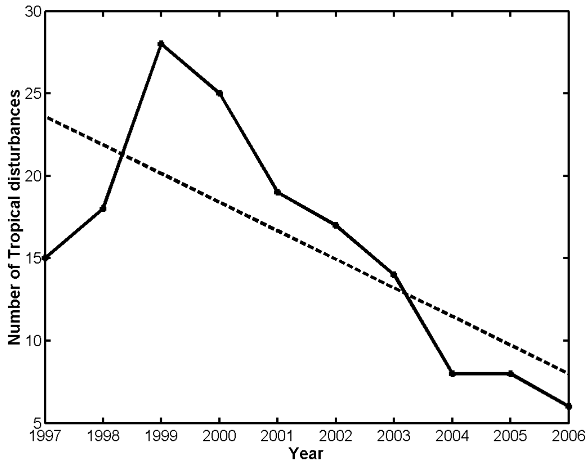

Figure 5.6: The number of total tropical disturbances (including developing and non-developing tropical disturbances) occurred over the SCS from 1997 to 2006. The dashed line is for the linear trend line.

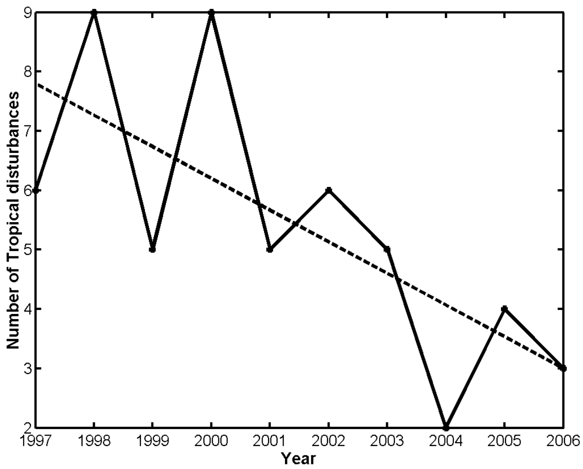

Figure 5.7: The number of developing tropical disturbances occurred over the SCS from 1997 to 2006. The dashed line is for the linear trend line.

5.2.4 Summary

Formation locations, lifetime and development rates of tropical disturbances over the SCS during 1997-2006 are analyzed using the WX-TROPL products. The results of the analysis are as follows:

(1) The formation locations of tropical disturbances over the SCS were mainly located in the northern SCS during the summer monsoon and in the southern SCS during the winter monsoon. The MFPs of developing tropical disturbances tend to be located more northward than those of non-developing tropical disturbances from April to October.

(2) The mean lifetime of non-developing tropical disturbances and developing tropical disturbances formed the SCS were both about 2 days.

(3) The DRTD over the SCS during 1997-2006 was 34.18%. Among all months, the DRTD was maximum in August (50%) and minimum (0%) in February and March.

(4) Although the numbers of total tropical disturbances and developing tropical disturbances over the SCS had a trend of decline in recent ten years, the percentages of the tropical disturbances which can develop into tropical depressions tended to increase in recent ten years (1997-2006).

5.3 Observation of non-developing and developing tropical disturbances using SSM/I satellite

5.3.1 Data

Since 1987, a series of SSM/I instruments were launched. The SSM/I is a passive radiometer measuring the thermal emission of the earth and atmosphere at four frequencies (19, 22, 37, and 85 GHz). The propagation of the microwave radiation through the atmosphere is influenced by the integrated amounts of water vapor and liquid water in the atmospheric column [*Wentz 1992 and 1997*]. Therefore, the brightness temperatures carry signals from all these geophysical parameters and can then be converted into geophysical parameters (e.g., columnar water vapor (CWV), columnar liquid water (CLW) and rain rate) using retrieval algorithms [*Wentz, 1997; Wentz and Spencer, 1998*]. The SSM/I data from three satellites (F13, F14 and F15) are used in this analysis. With a swath width of about 1400 km for each of the satellites, high-resolution coverage is now available almost globally on a daily basis. The SSM/I observations have been used in operational marine analysis [*Gemmill and Krasnopolsky, 1999*], indicating rapidly deepening midlatitude cyclones [*Mcmurdie and Katsaros, 1996*] and the study of tropical cyclones [*Alliss et al., 1992; Liu et al., 1994; Rodgers and Pierce, 1995*].

5.3.2 Typical cases of non-developing and developing tropical disturbances

The SCS, a large marginal sea extending from the equator to 23°N and from 99° to 120°E, is one region where tropical cyclones occur frequently. Totally, there were 43 tropical disturbances formed in the SCS in the two years of 2000 and 2001. Among these 43 tropical disturbances, 13 tropical disturbances were developing tropical disturbances, which later developed into tropical depressions; while the other 30 tropical disturbances were non-developing tropical disturbances, which never developed into tropical depressions. The rate of development for tropical disturbances over the SCS during these two years was 30.2%.

The CWV, CLW and the total latent heat release (TLHR) derived from the SSM/I will be examined for non-developing and developing tropical disturbances in the SCS. The CWV and CLW values are vertically integrated through the entire atmosphere. The CWV, which is also known as total precipitable water, is the depth of water that would fall on the ocean if all the water vapor were condensed and precipitated. The liquid water resides in clouds and is more directly related to regions of precipitation and to active weather systems such as storms and fronts [*McMurdie and Katsaros, 1996*]. Large liquid water amounts are generally associated with strong convective activity (cumulus clouds) and unstable surface weather conditions, while small amounts of liquid water conditions are associated with neutral or stable regions (stratiform clouds). When water vapor condenses into liquid water, it releases latent heat into the surrounding atmosphere, and then the atmosphere around this condensation warms. The TLHR can be calculated using the rain rate observed from SSM/I according to equation (5.1) given by [*Rodgers and Adler, 1981*].

$$TLHR = L\rho \int_A R da \qquad (5.1)$$

Where ρ is the density of rain water assumed to be 1.0×10^3 kg m^{-3}, L is the latent heat of condensation (2.5×10^6 J kg^{-1}). A is the area of integration and R is the rain rate at each grid point observed from SSM/I.

5.3.2.1 Typical case of non-developing tropical disturbance

An area of convection developed near (113.4ºE, 9.0ºN) over the SCS on 6 March 2000. This tropical disturbance lasted over the SCS for about 5 days and dissipated on 10 March. This is one non-developing tropical disturbance which did not develop into tropical depression during its lifetime.

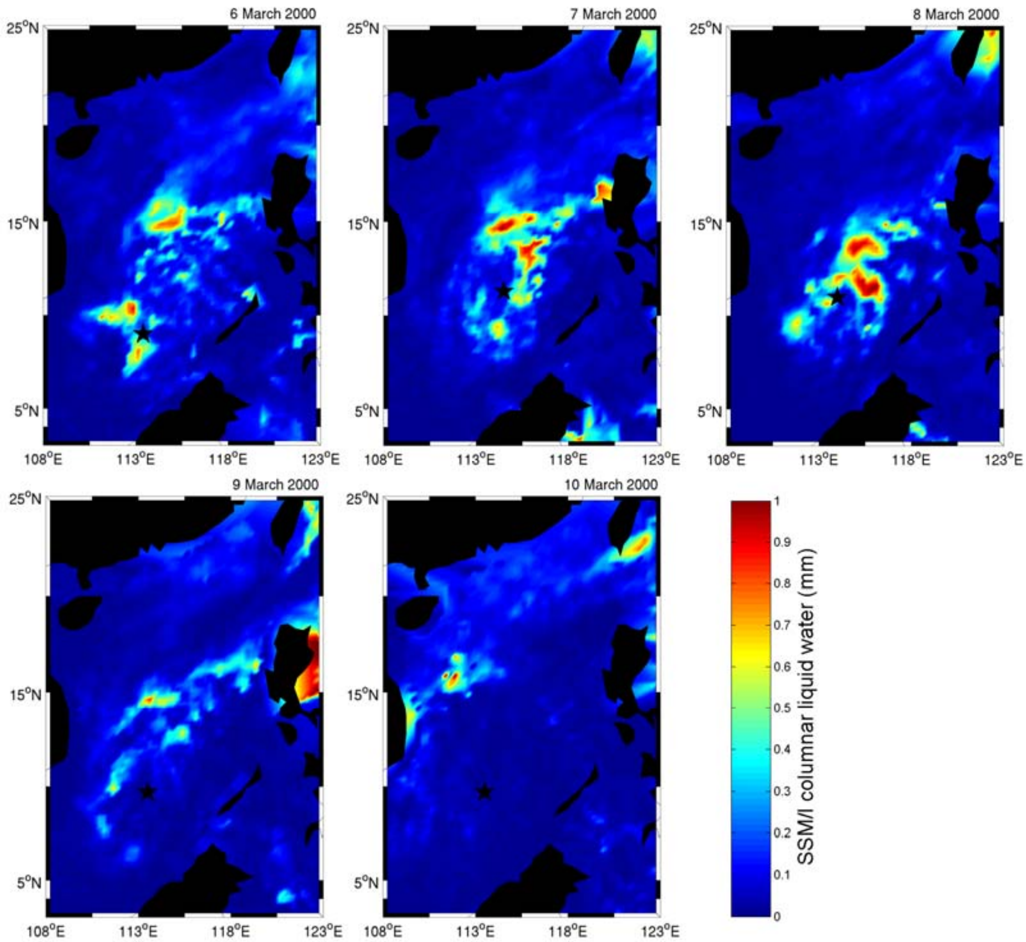

Figure 5.8: SSM/I observed daily-mean CLW during the lifetime of the non-developing tropical disturbance from 6 to 10 March 2000. The center of the tropical disturbance is

marked by the pentagram. The maximum daily mean CLW and TLHR within 500 km from the center of the tropical disturbance during the lifetime both occurred on 8 March, with the value of 0.159 mm and 1.910 $\times 10^{14}$ W. After 8 March, the mean CLW and TLHR both decreased significantly with the dissipation of this tropical disturbance.

Fig. 5.8 presents the SSM/I observed daily-mean CLW during the lifetime of the non-developing tropical disturbance from 6 to 10 March 2000. Large liquid water amounts associated with convective activities can be observed. Along with the dissipation of this tropical disturbance on 10 March, the pattern of large liquid water amounts disappeared. The maximum daily mean CWV within 500 km from the center of the tropical disturbance during the lifetime occurred on 7 March, with the value of 55.716 mm. The maximum daily mean CLW and TLHR within 500 km from the center of the tropical disturbance during the lifetime both occurred on 8 March, with the value of 0.159 mm and 1.910 $\times 10^{14}$ W. After 8 March, the mean CWV, CLW and TLHR all decreased significantly with the dissipation of this tropical disturbance.

5.3.2.2 Typical case of developing tropical disturbance

An area of convection developed near (115.0ºE, 8.0ºN) over the SCS on 5 October 2000. This tropical disturbance is one developing tropical disturbance and developed into one tropical depression near (113.5ºE, 9.0ºN) on 6 October 2000.

Fig. 5.9 shows the SSM/I observed daily-mean CLW on 5 and 6 October. Large liquid water amounts in the region around this tropical disturbance can be observed. On 5 October one-day prior to cyclogenesis, the mean CWV, CLW and TLHR within 500 km from the center of the tropical disturbance are 56.992 mm, 0.408 mm and 5.750×10^{14} W respectively. On 6 October when the cyclogenesis occurred, the mean CWV, CLW and TLHR within 500 km from the center of the tropical disturbance are 57.417 mm, 0.461 mm and 7.968×10^{14} W respectively. The cyclogenesis occurred under the conditions with large amount of water vapor and latent heat release, which provide the energy necessary for the occurrence of tropical cyclogenesis.

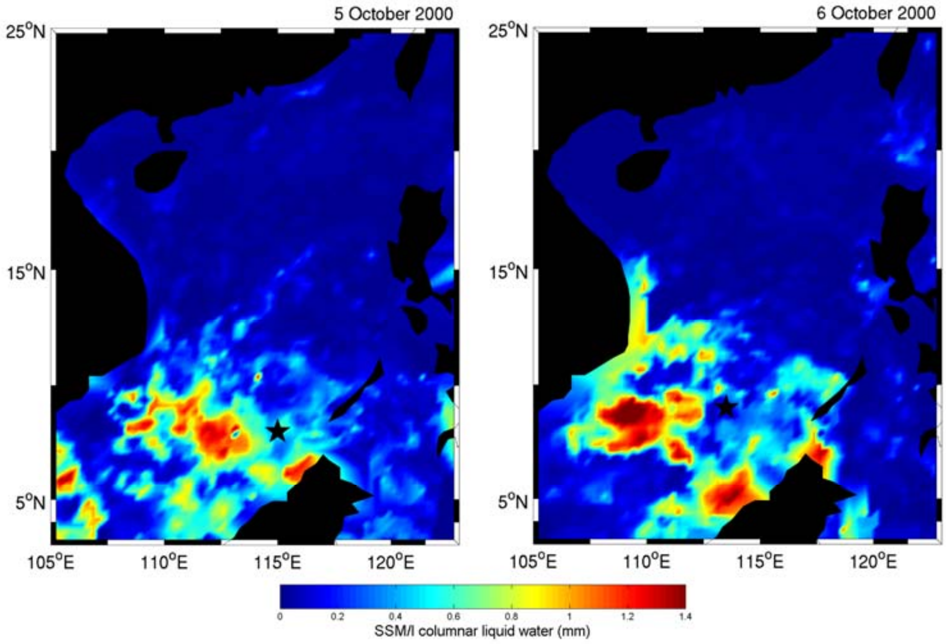

Figure 5.9: SSM/I observed CLW in the day prior to cyclogenesis (5 October 2000) and in the day of cyclogenesis (6 October 2000). The center of this developing tropical disturbance is marked by the pentagram.

5.3.3 Statistics for 30 non-developing and 13 developing tropical disturbances

In the following, the CWV, CLW and TLHR derived from SSM/I will be statistically analyzed and compared for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. These 30 non-developing tropical disturbances and 13 developing tropical disturbances are all tropical disturbances over the SCS occurring in the two years of 2000 and 2001.

Table 5.1 lists the comparison of parameters derived from SSM/I observations for these 30 non-developing and 13 developing tropical disturbances. For non-developing tropical disturbances, parameters including the climatological CWV and CLW, the maximum daily mean CWV, CLW and TLHR during the lifetime within 500 km from the center of tropical disturbance are statistically analyzed. For developing tropical disturbances, parameters including the climatological CWV and CLW, the mean CWV, CLW and TLHR in the day prior to cyclogenesis 500 km around the center of tropical disturbance are statistically analyzed. The climatological values of CWV and CLW are derived from the two-year monthly mean observational values of SSM/I during 2000-2001. The TLHR is calculated according to the rain rate observed from SSM/I according to equation 5.1. The mean values and standard deviations of each parameter are given in table 5.1.

Table 5.1**:** Comparison of parameters derived from SSM/I observations for 30 non-developing and 13 developing tropical disturbances over the SCS in 2000 and 2001[a]

Parameters	Non-developing tropical disturbances		Developing tropical disturbances		Significant difference or not?
	Mean	Standard deviation	Mean	Standard deviation	
Climatological CWV (mm)	52.839	3.991	55.767	1.816	Yes
Daily CWV (mm)	57.754	2.594	58.381	2.202	No
Climatological CLW (mm)	0.119	0.029	0.149	0.027	Yes
Daily CLW (mm)	0.237	0.080	0.353	0.067	Yes
TLHR ($\times 10^{14}$ W)	2.760	1.327	4.671	1.469	Yes

[a]Climatological CWV and CLW is derived from the two-year monthly mean observational values of SSM/I during 2000-2001. Daily CWV and CLW, refer to the maximum daily mean value during the lifetime within 500 km of the center for non-developing tropical disturbances and the mean value on the day prior to cyclogenesis 500 km around the center for developing tropical disturbances. TLHR refers to the maximum daily TLHR during the lifetime for non-developing tropical disturbances and the daily TLHR on the day prior to cyclogenesis for developing tropical disturbances. The last column shows whether the differences in the means of parameters for non-developing and developing tropical disturbances are statistically significant based on the *t*-test with 95% confidence level.

For 13 developing tropical disturbances, the mean daily CWV and CLW within 500 km of the center of tropical disturbances on the day immediately prior to tropical cyclogenesis are 58.381 mm and 0.353 mm, which are 1.04 and 2.37 times the mean climatological values of CWV (55.767 mm) and CLW (0.149 mm) in the same region. For 30 non-developing tropical disturbances, the maximum daily-mean CWV and CLW within 500 km of the center of tropical disturbances during the lifetime of tropical disturbances are 57.754 mm and 0.237 mm, which are 1.09 and 1.99 times the mean climatological values of CWV (52.839 mm) and CLW (0.119 mm) in the same region. The mean TLHR within 500 km of the center of tropical disturbances on the day immediately prior to tropical cyclogenesis for 13 developing tropical disturbances is 4.671×10^{14} W, while the maximum daily-mean TLHR within 500 km of the center of tropical disturbances during the lifetime for 30 non-developing tropical disturbances is 2.760×10^{14} W. On average, the mean TLHR of developing tropical disturbances one-day prior to cyclogenesis is 1.7 times the mean maximum daily TLHR of non-developing tropical disturbances during their lifetime. The differences in the means of all parameters excluding the daily CWV between non-developing and developing tropical disturbances are statistically significant with 95% confidence level.

Fig. 5.10 presents the distribution of values of the TLHR for 30 non-developing tropical disturbances and 13 developing tropical disturbances. In the day of cyclogenesis for 13 developing tropical disturbances, the mean TLHR within 500 km of the center of tropical disturbances is 6.373×10^{14} W with a standard deviation of 1.411×10^{14} W. According to Fig. 5.10, the values of TLHR on the day prior to cyclogenesis and on the day of cyclogenesis are greater than 2.0×10^{14} W for 13 developing tropical disturbances. For 13 of 30 non-developing tropical disturbances, the values of maximum TLHR during the lifetime are less than 2.0×10^{14} W. If we use the value of 2.0×10^{14} W as the first critical value for determining the potential of development of tropical disturbances, about 43.3% (13 of 30) of non-developing tropical disturbances can be judged correctly due to the low value of TLHR less than 2.0×10^{14} W. For 30 non-developing tropical disturbances, the values of the maximum daily TLHR are less than 6.0×10^{14} W. If we use the value of 6.0×10^{14} W as the second critical value, about 23.1% (3 of 13) of developing tropical disturbances can be judged correctly one-day prior to cyclogenesis due to the high value of TLHR greater than 6.0×10^{14} W. When the value of TLHR is between 2.0×10^{14} W and 6.0×10^{14} W, the tendency of TLHR needs to be monitored. If the value of TLHR has an increasing trend, the potential of the development for this tropical disturbance is good; on the contrary, the potential will be poor if the value of TLHR has a decreasing trend.

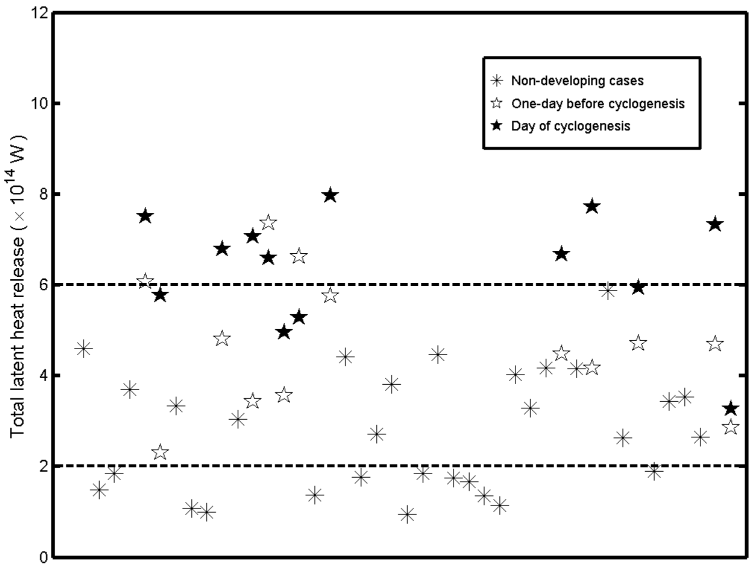

Figure 5.10: The distribution of values of the TLHR for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the TLHR refers to the maximum daily TLHR within 500 km of the center during the lifetime. For developing tropical disturbances, the values of TLHR 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

5.3.4 Summary and discussion

In this study, SSM/I satellite observations are used to investigate non-developing and developing tropical disturbances over the SCS. The CWV, CLW and TLHR derived from the SSM/I are compared for 13 developing tropical disturbances and 30 non-developing tropical disturbances over the SCS in 2000 and 2001. The differences in the means of parameters including climatological CWV and CLW, daily CLW and TLHR between non-developing and developing tropical disturbances are statistically significant. These results suggest that observations from SSM/I are helpful in determining the potential of development for tropical disturbances. On average, the mean TLHR of developing tropical disturbances one-day prior to cyclogenesis is 1.7 times the mean maximum daily TLHR of non-developing tropical disturbances during their lifetime. The differences in the climatological values of CWV and CLW between non-developing and developing cases may be one reason for the differences in the daily TLHR between non-developing and developing tropical disturbances. Background conditions with higher values of CWV and CLW provide more favorable conditions for the development of tropical disturbances.

Direct satellite observations from SSM/I reveal that a persistent high value of TLHR is necessary for the occurrence of tropical cyclogenesis. Although about 56.7% (17 out of 30) non-developing tropical disturbances once obtained a relatively high TLHR during the lifetime, they never developed due to the lack of persistence of high TLHR.

5.4 Comparison of environmental conditions for 30 non-developing and 13 developing tropical disturbances over the SCS

5.4.1 Introduction

Each year there are approximately 80 tropical cyclones over the globe. Nearly two-thirds of these cyclones eventually reach hurricane or typhoon intensity with maximum sustained surface winds greater than 33 m s^{-1}. However, only a small percentage of tropical disturbances (cloud clusters) develop into tropical cyclones. The physical processes that lead to the formation of a tropical cyclone from a tropical disturbance or cloud cluster are still not well understood. Complications arise because cyclone formation occurs under somewhat differing large-scale circulation patterns in different ocean basins and because that the processes that control cyclone development appear to differ from those that control formation of the cloud cluster. Moreover, the question of why some cloud clusters develop into tropical cyclones includes the question of why many prominent cloud clusters do not form tropical cyclones. Investigation of systems that fail to complete the genesis process will also result in a better understanding and prediction of tropical disturbances in general so that distinction can be better made between developing and non-developing tropical disturbances. Comparisons between non-developing and developing tropical disturbances have been made in different ocean basins using different datasets in previous studies. *McBride and Zehr* [*1981*] examined the differences between non-developing and developing tropical weather systems in the northwest Pacific and northwest Atlantic using the composite data sets. The results show that the low-level vorticity in the vicinity of a developing cloud cluster is approximately twice as large as that observed with non-developing cloud clusters. *Foster and Lyons* [*1988*] constructed case studies of developing and non-developing tropical systems in the north-west Australian region using conventional and the GMS-1 geosynchronous satellite observations. Results show that enhanced low-level winds can occur during the lifetime of non-developing disturbances and are not exclusively associated with cyclogenesis. At upper levels, development was associated with the subtropical ridge being situated over the surface position of the disturbance. In contrast, the ridge tended to be located southward of non-developers. However, non-development could still occur under the ridge axis if not all the essential conditions for cyclogenesis were met. *Lee* [*1989*] examined the evolution of both genesis and non-genesis cloud clusters in the western North Pacific using the rawinsonde composite techniques. Results show that genesis cloud clusters have much stronger middle to low-level cyclonic circulation extending over a radius 2^o-8^o outward from the center, which is associated with varying combinations of a stronger than normal monsoon trough and low-level tradewind and/or monsoon wind surges. *Zehr* [*1992*] revealed that small vertical wind shear, sufficient low-level convergence, and sufficient low-level relative vorticity are shown to be necessary conditions for tropical cyclogenesis by comparing individual non-developing and developing disturbances in the western North Pacific. One or more of these three conditions can usually be identified as being deficient for non-developing tropical disturbances. *Gray* [*1998*] found that the magnitude of low-level radial winds near the disturbance's center was the primary observational factor which differentiated between developing and non-developing tropical disturbances using composite data sets from 53 developing cases and 49 non-developing cases. These differences are believed to be due to differences in center penetrating wind surge action.

Wang et al. [*2008a*] compared 30 non-developing and 13 developing tropical disturbances over the SCS in 2000 and 2001 using the SSM/I satellite, and found that the amount of latent heat release for developing tropical disturbances is 1.7 times the amount for non-developing tropical disturbances. In the next, other environmental conditions will continue to be compared for these 30 non-developing and 13 developing tropical disturbances over the SCS in 2000 and 2001.

5.4.2 Data

The SST observations are from the TRMM microwave imager (TMI) satellite with the resolution of 25 km. In November 1997, the Tropical Rainfall Measuring Mission (TRMM) spacecraft was launched [*Kummerow et al., 1998*]. The TMI has a full suite of channels ranging from 10.7 to 85 GHz and represents the first satellite sensor that is capable of accurately measuring SST through clouds [*Wentz et al., 2000*]. The TMI data used in this study are produced by Remote Sensing Systems (Data are available at http://www.remss.com).

The relative humidity and vertical velocity at 500 hpa, the divergence at 200 hPa and the vertical wind shear are from the National Center for the Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set [*Kalnay et al., 1996*; *Kistler et al., 2001*]. The horizontal resolution of the reanalysis data is 2.5º latitude × 2.5º longitude. The NCEP/NCAR Reanalysis project uses a state-of-the-art analysis/forecast system to perform data assimilation using past data. Six-hourly, daily, and monthly averages of the NCEP/NCAR reanalysis are available from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (CDC) in Boulder, Colorado (http://www.cdc.noaa.gov/cdc/reanalysis/).

The outgoing longwave radiation (OLR) is from the NOAA interpolated OLR data set with 2.5º latitude × 2.5º longitude resolution which is provided by CDC (http://www.cdc.noaa.gov/cdc/data.interp_OLR.html). The temporal coverage of the data set is from 1974 to present. For details of OLR data, see *Liebmann and Smith* [1996].

5.4.3 SST

For non-developing tropical disturbances, the daily mean SST 500 km around the center of tropical disturbances is calculated for each day during the lifetime of tropical disturbances. The mean SST during the lifetime is then obtained by doing average for daily mean SSTs in each day. For developing tropical disturbances, the daily mean SST 500 km around the center of tropical disturbances is calculated on the day prior to cyclogenesis and on the day of cyclogenesis. Fig. 5.11 presents the distributions of SST values for 30 non-developing and 13 developing tropical disturbances. The mean SST during the lifetime of 30 non-developing tropical disturbances is 28.47 ℃, with a standard deviation of 1.26 ℃. The mean SST was lower than 26 ℃ in two cases among these 30 non-developing tropical disturbances. For 13 developing tropical disturbances, the mean SST on the day prior to cyclogenesis is 29.24 ℃, with a standard deviation of 1.13 ℃; the mean SST on the day of cyclogenesis is 29.14 ℃, with a standard deviation of 0.68 ℃. Warmer mean SSTs during the developing tropical disturbances provide more favorable conditions for the occurrence of cyclogenesis.

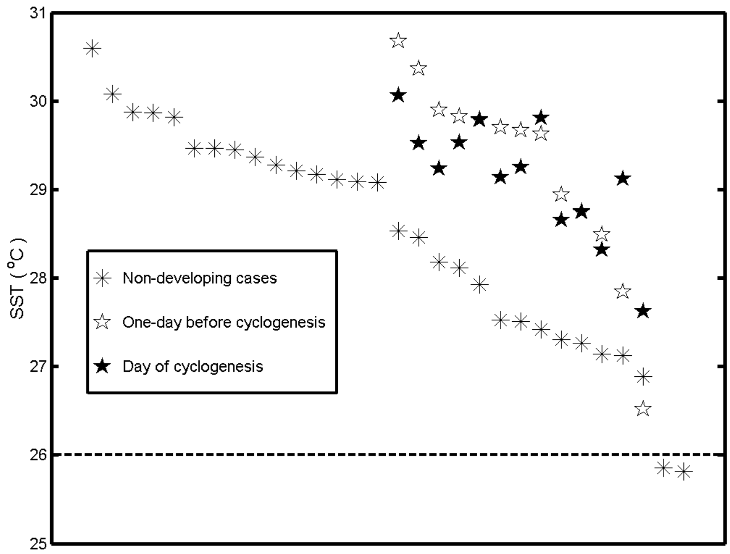

Figure 5.11: The distribution of values of the SST for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the SST refers to the mean SST within 500 km of the center during the lifetime. For developing tropical disturbances, the values of SST 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

5.4.4 Vertical wind shear

The mean vertical wind shear (VWS) is derived from the NCEP/NCAR reanalysis data set. In operational situation, the VWS is often calculated between the 850 hPa and 200 hPa levels, because these are the levels with the best data coverage of cumulus and cirrus cloud-drift winds from geostationary satellite imagery. In this study, the VWS is defined as the magnitude of the difference between the zonal and meridional wind at the 200 and 850 hPa and is given by the equation (5.2).

$$\mathrm{VWS} = \left[(u_{200hPa} - u_{850hPa})^2 + (v_{200hpa} - v_{850hPa})^2\right]^{1/2}, \tag{5.2}$$

Where, u_{200hPa} and u_{850hPa} are zonal winds at the 200 and 850 hPa; v_{200hPa} and v_{850hPa} are meridional winds at the 200 and 850 hPa. The VWS is calculated according to equation (5.2) by using zonal and meridional winds at the 200 and 850 hPa from the NCEP/NCAR reanalysis data set.

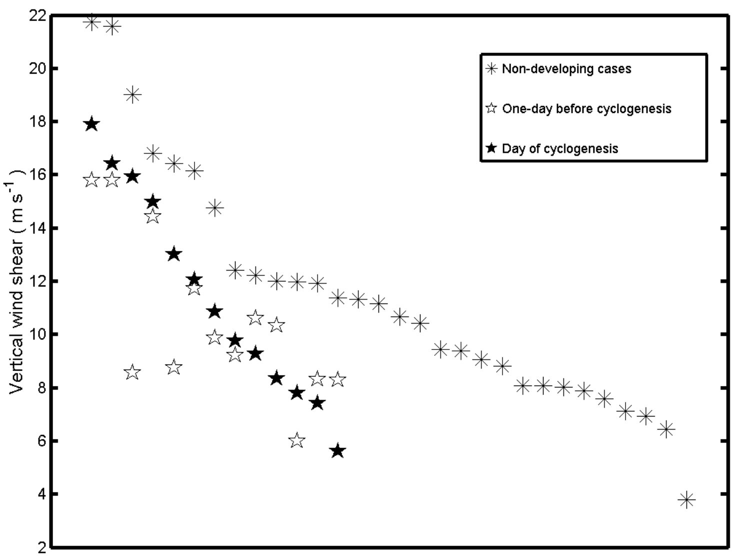

Figure 5.12: The distribution of values of the VWS for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the VWS refers to the mean VWS within 300 km of the center during the lifetime. For developing tropical disturbances, the values of VWS 300 km around the center in the day prior to cyclogenesis and in the day of cyclogenesis are presented.

For non-developing tropical disturbances, the daily mean VWS 300 km around the center of tropical disturbances is calculated for each day during the lifetime of tropical disturbances. The mean VWS during the lifetime is then obtained by doing average for daily mean VWSs in each day. For developing tropical disturbances, the daily mean VWS 300 km around the center of tropical disturbances is calculated on the day prior to cyclogenesis and on the day of cyclogenesis. Fig. 5.12 presents the distributions of VWS values for 30 non-developing and 13 developing tropical disturbances. The mean VWS during the lifetime of 30 non-developing tropical disturbances is 11.415 m s^{-1}, with a standard deviation of 4.405 m s^{-1}. For 13 developing tropical disturbances, the mean VWS on the day prior to cyclogenesis is 10.591 m s^{-1}, with a standard deviation of 3.051 m s^{-1}; the mean VWS on the day of cyclogenesis is 11.488 m s^{-1}, with a standard deviation of 3.900 m s^{-1}.

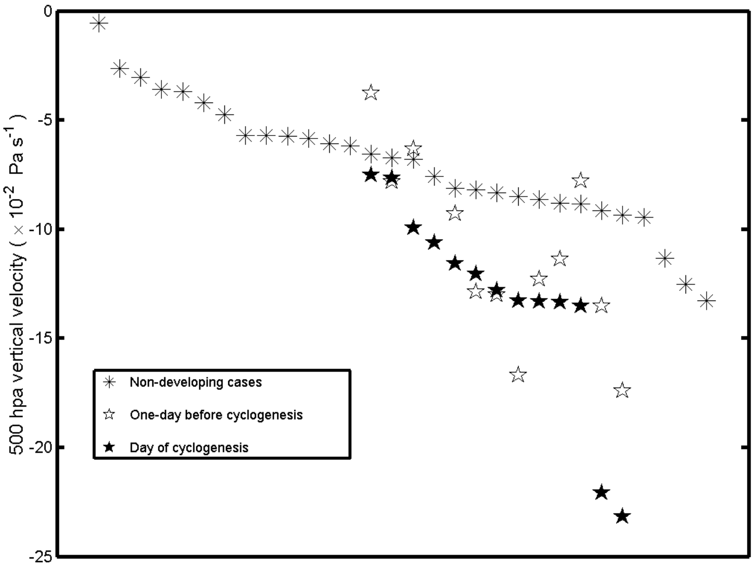

Figure 5.13: The distribution of values of the 500 hPa vertical velocity for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the vertical velocity refers to the mean vertical velocity within 500 km of the center during the lifetime. For developing tropical disturbances, the values of vertical velocity 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

5.4.5 500 hPa vertical velocity

For non-developing tropical disturbances, the daily mean 500 hPa vertical velocity 500 km around the center of tropical disturbances is calculated for each day during the lifetime of tropical disturbances. The mean 500 hPa vertical velocity during the lifetime is then obtained by doing average for daily mean vertical velocity in each day. For developing tropical disturbances, the daily mean vertical velocity 500 km around the center of tropical disturbances is calculated on the day prior to cyclogenesis and on the day of cyclogenesis. Fig. 5.13 presents the distributions of 500 hPa vertical velocity values for 30 non-developing and 13 developing tropical disturbances. The mean 500 hPa vertical velocity during the lifetime of 30 non-developing tropical disturbances is -7.007 $\times 10^{-2}$ Pa s^{-1}, with a standard deviation of 2.884×10^{-2} Pa s^{-1}. For 13 developing tropical disturbances, the mean 500 hPa vertical velocity on the day prior to cyclogenesis is -10.981×10^{-2} Pa s^{-1}, with a standard deviation of 3.949×10^{-2} Pa s^{-1}; the mean 500 hPa vertical velocity on the day of cyclogenesis is -13.153×10^{-2} Pa s^{-1}, with a standard deviation of 4.685×10^{-2} Pa s^{-1}.

5.4.6 500 hPa relative humidity

For non-developing tropical disturbances, the daily mean 500 hPa relative humidity 500 km around the center of tropical disturbances is calculated for each day during the lifetime of tropical disturbances. The mean 500 hPa relative humidity during the lifetime is then obtained by doing average for daily mean relative humidity in each day. For developing tropical disturbances, the daily mean relative humidity 500 km around the center of tropical disturbances is calculated oin the day prior to cyclogenesis and on the day of cyclogenesis. Fig. 5.14 presents the distributions of 500 hPa relative humidity for 30 non-developing and 13 developing tropical disturbances. The mean 500 hPa relative humidity during the lifetime of 30 non-developing tropical disturbances is 60.304%, with a standard deviation of 9.256%. For 13 developing tropical disturbances, the mean 500 hPa relative humidity on the day prior to cyclogenesis is 63.544%, with a standard deviation of 11.117%; the mean 500 hPa relative humidity on the day of cyclogenesis is 66.129%, with a standard deviation of 9.537%. For all these 30 non-developing and 13 developing tropical disturbances, the values of the mean relative humidity at 500 hPa are higher than 40%.

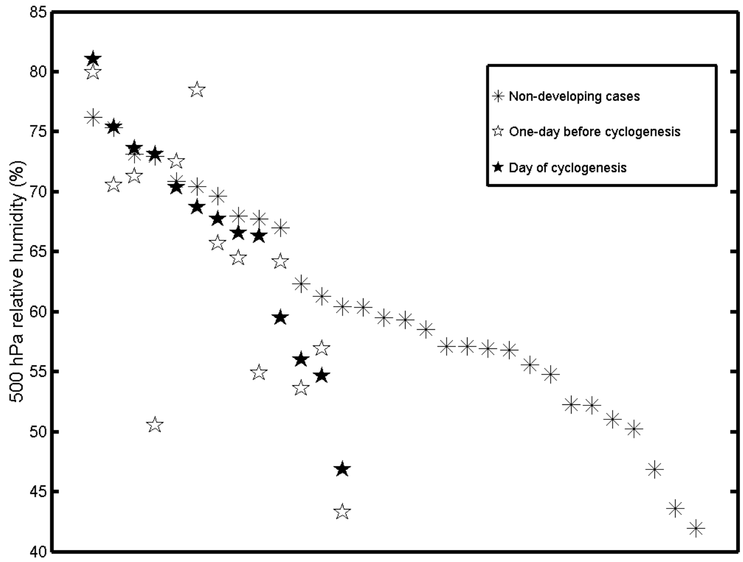

Figure 5.14: The distribution of values of the 500 hPa relative humidity for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the relative humidity refers to the mean relative humidity within 500 km of the center during the lifetime. For developing tropical disturbances, the values of relative humidity 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

5.4.7 Relative vorticity of horizontal winds at 850 hPa and 200 hPa

For non-developing tropical disturbances, the daily mean 850 hPa relative vorticity 500 km around the center of tropical disturbances is calculated for each day during the lifetime of the tropical disturbance. The mean 850 hPa relative vorticity during the lifetime is then obtained by doing average for daily mean relative vorticity in each day. For developing tropical disturbances, the daily mean relative vorticity 500 km around the center of tropical disturbances is calculated on the day prior to cyclogenesis and on the day of cyclogenesis. Figure 5.15 presents the distributions of 850 hPa relative vorticity for 30 non-developing and 13 developing tropical disturbances. The mean 850 hPa relative vorticity during the lifetime of 30 non-developing tropical disturbances is 1.813×10^{-5} s^{-1}, with a standard deviation of 0.866×10^{-5} s^{-1}. For 13 developing tropical disturbances, the mean 850 hPa relative vorticity on the day prior to cyclogenesis is 1.953×10^{-5} s^{-1}, with a standard deviation of 0.893×10^{-5} s^{-1}; the mean 850 hPa relative vorticity on the day of cyclogenesis is 2.962×10^{-5} s^{-1}, with a standard deviation of 0.735×10^{-5} s^{-1}.

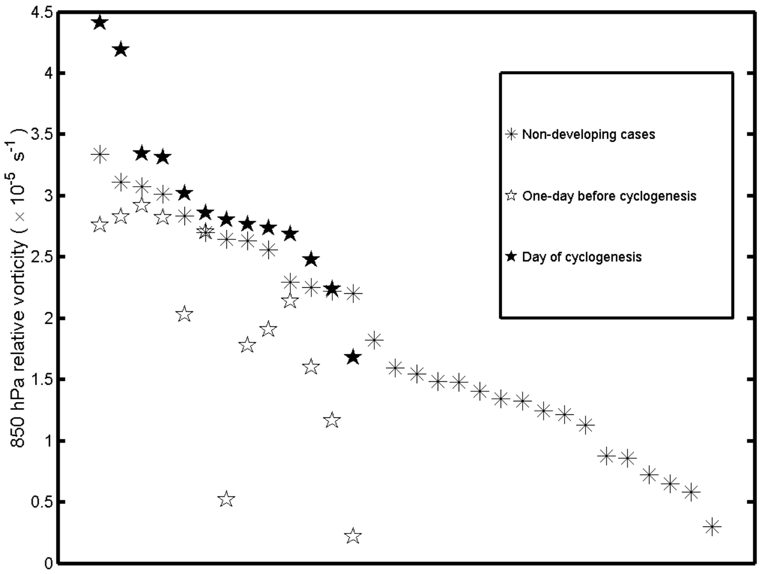

Figure 5.15: The distribution of values of the 850 hPa relative vorticity for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the relative vorticity refers to the mean relative vorticity within 500 km of the center during the lifetime. For developing tropical disturbances, the values of relative vorticity 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

Fig. 5.16 presents the distributions of 200 hPa relative vorticity for 30 non-developing and 13 developing tropical disturbances. The mean 200 hPa relative vorticity during the lifetime of 30 non-developing tropical disturbances is -1.198×10^{-5} s^{-1}, with a standard deviation of 1.098×10^{-5} s^{-1}. For 13 developing tropical disturbances, the mean 200 hPa relative vorticity on the day prior to cyclogenesis is -0.958×10^{-5} s^{-1}, with a standard deviation of 1.018×10^{-5} s^{-1}; the mean 200 hPa relative vorticity on the day of cyclogenesis is -0.937×10^{-5} s^{-1}, with a standard deviation of 1.003×10^{-5} s^{-1}.

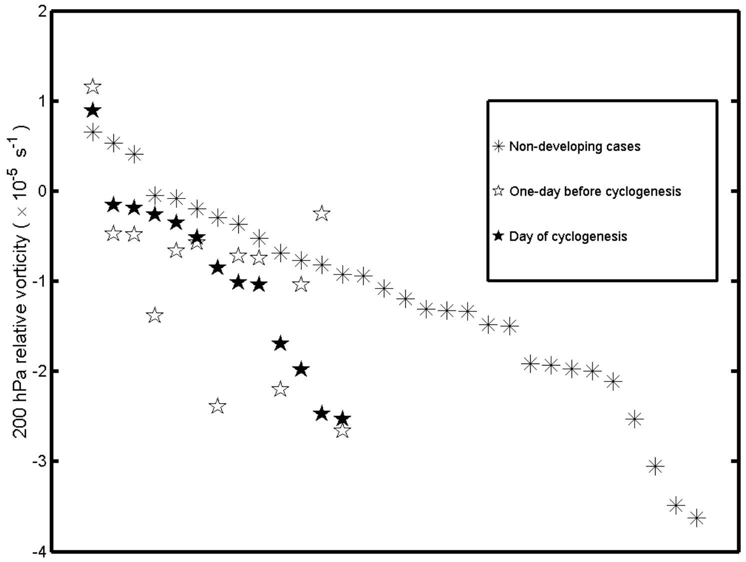

Figure 5.16: The distribution of values of the 200 hPa relative vorticity for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the relative vorticity refers to the mean relative vorticity within 500 km of the center during the lifetime. For developing tropical disturbances, the values of relative vorticity 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

McBride and Zehr [*1981*] defined a genesis potential for developing tropical disturbance based on mean relative vorticity differences between 900 and 200 mb:

$$\text{Daily Genesis Potential (DGP)} = \zeta_{900mb} - \zeta_{200mb}, \quad (5.3)$$

Where ζ_{900mb} and ζ_{200mb} are mean relative vorticities at 900 and 200 mb. Similar with this DGP, the difference of mean relative vorticity between 850 hPa and 200 hPa ($\Delta\zeta = \zeta_{850hPa} - \zeta_{200hPa}$) is examined for these 30 non-developing and 13 developing tropical disturbances. Fig. 5.17 presents the distributions of $\Delta\zeta$ for 30 non-developing and 13 developing tropical disturbances. The mean $\Delta\zeta$ during the lifetime of 30 non-developing tropical disturbances is 3.016×10^{-5} s^{-1}, with a standard deviation of 1.281×10^{-5} s^{-1}. For 13 developing tropical disturbances, the mean $\Delta\zeta$ on the day prior to cyclogenesis is 2.911×10^{-5} s^{-1}, with a standard deviation of 1.260×10^{-5} s^{-1}; the mean $\Delta\zeta$ on the day of cyclogenesis is 3.899×10^{-5} s^{-1}, with a standard deviation of

1.339×10^{-5} s^{-1}. These results suggest that it is not doable to determine the potential of tropical disturbances using $\Delta\zeta$ for tropical disturbances examined here.

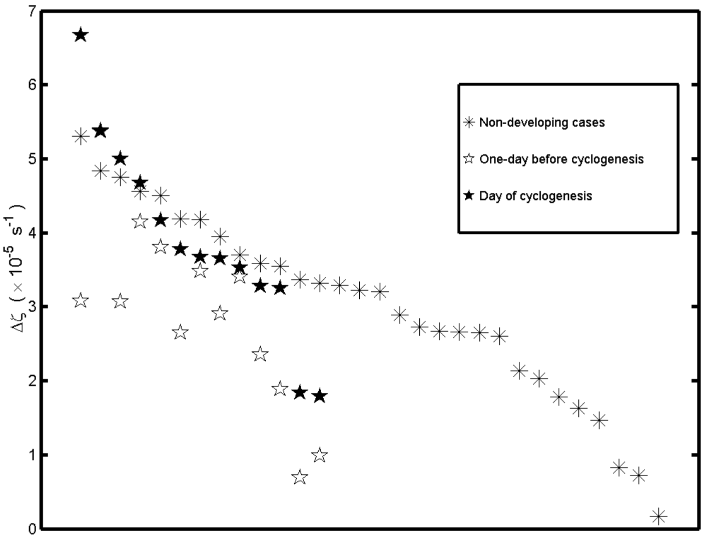

Figure 5.17: The distribution of values of mean relative vorticity differences between 850 hPa and 200 hPa ($\Delta\zeta = \zeta_{850hPa} - \zeta_{200hPa}$) for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the $\Delta\zeta$ refers to the mean relative vorticity difference within 500 km of the center during the lifetime. For developing tropical disturbances, the values of $\Delta\zeta$ 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

5.4.8 Divergence of horizontal winds at 850 hPa and 200 hPa

For non-developing tropical disturbances, the daily mean 850 hPa divergence 500 km around the center of tropical disturbances is calculated for each day during the lifetime of tropical disturbances. The mean 850 hPa divergence during the lifetime is then obtained by doing average for daily mean divergence in each day. For developing tropical disturbances, the daily mean divergence 500 km around the center of tropical disturbances is calculated on the day prior to cyclogenesis and on the day of cyclogenesis. Fig. 5.18 presents the distributions of 850 hPa divergence for 30 non-developing and 13 developing tropical disturbances. The mean 850 hPa divergence during the lifetime of 30 non-developing tropical disturbances is -0.723×10^{-6} s^{-1}, with a standard deviation of 0.985×10^{-6} s^{-1}. For 13 developing tropical disturbances, the mean 850 hPa divergence on the day prior to cyclogenesis is -1.785×10^{-6} s^{-1}, with a standard deviation of 1.3356×10^{-6} s^{-1}; the mean 850 hPa divergence on the day of cyclogenesis is -2.339×10^{-6} s^{-1}, with a standard deviation of 1.291×10^{-6} s^{-1}.

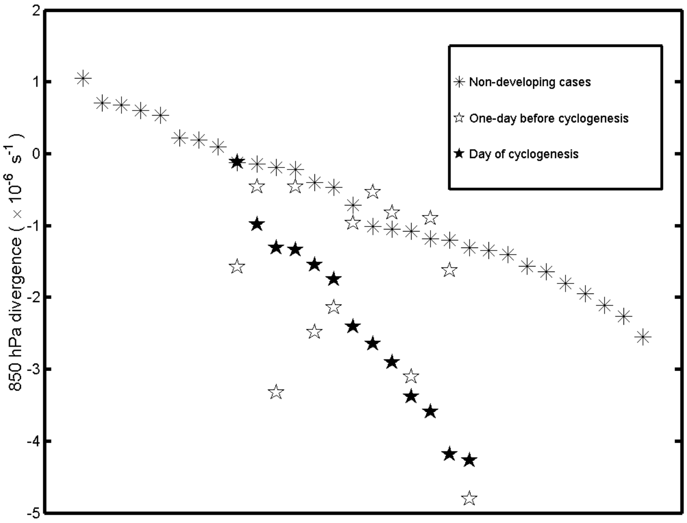

Figure 5.18: The distribution of values of the 850 hPa divergence for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the divergence refers to the mean divergence within 500 km of the center during the lifetime. For developing tropical disturbances, the values of divergence 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

Fig. 5.19 presents the distributions of 250 hPa divergence for 30 non-developing and 13 developing tropical disturbances. The mean 200 hPa divergence during the lifetime of 30 non-developing tropical disturbances is 5.459×10^{-6} s^{-1}, with a standard deviation of 2.953×10^{-6} s^{-1}. For 13 developing tropical disturbances, the mean 200 hPa divergence on the day prior to cyclogenesis is 7.189×10^{-6} s^{-1}, with a standard deviation of 2.607×10^{-6} s^{-1}; the mean 200 hPa divergence on the day of cyclogenesis is 7.307×10^{-6} s^{-1}, with a standard deviation of 2.566×10^{-6} s^{-1}.

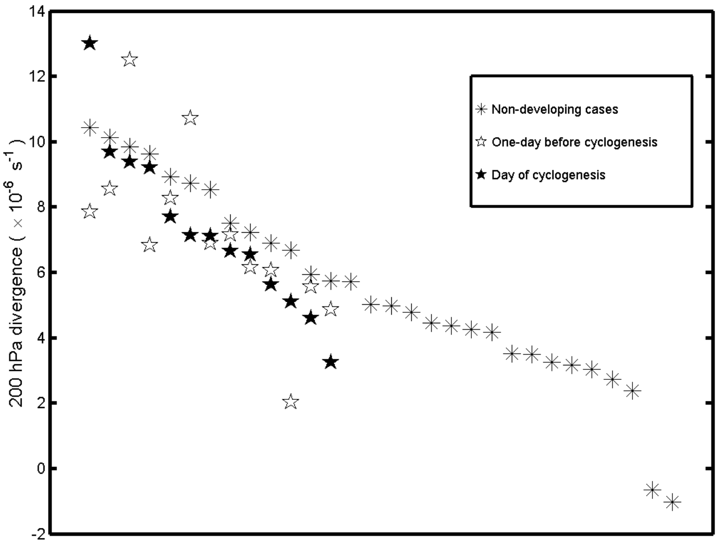

Figure 5.19: The distribution of values of the 200 hPa divergence for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the divergence refers to the mean divergence within 500 km of the center during the lifetime. For developing tropical disturbances, the values of divergence 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

To combine the effects of the divergence at 850 hPa and 200 hPa together, the difference of mean divergence between 200 hPa and 850 hPa ($\Delta D = D_{200hPa} - D_{850hPa}$) is examined for these 30 non-developing and 13 developing tropical disturbances. Fig. 5.20 presents the distributions of ΔD for 30 non-developing and 13 developing tropical disturbances. The mean ΔD during the lifetime of 30 non-developing tropical disturbances is 6.170×10^{-6} s^{-1}, with a standard deviation of 3.027×10^{-6} s^{-1}. For 13 developing tropical disturbances, the mean ΔD on the day prior to cyclogenesis is 8.974×10^{-6} s^{-1}, with a standard deviation of 2.975×10^{-6} s^{-1}; the mean ΔD on the day of cyclogenesis is 9.646×10^{-6} s^{-1}, with a standard deviation of 3.195×10^{-6} s^{-1}. These results suggest that it is helpful to determine the potential of tropical disturbances using ΔD for tropical disturbances examined here.

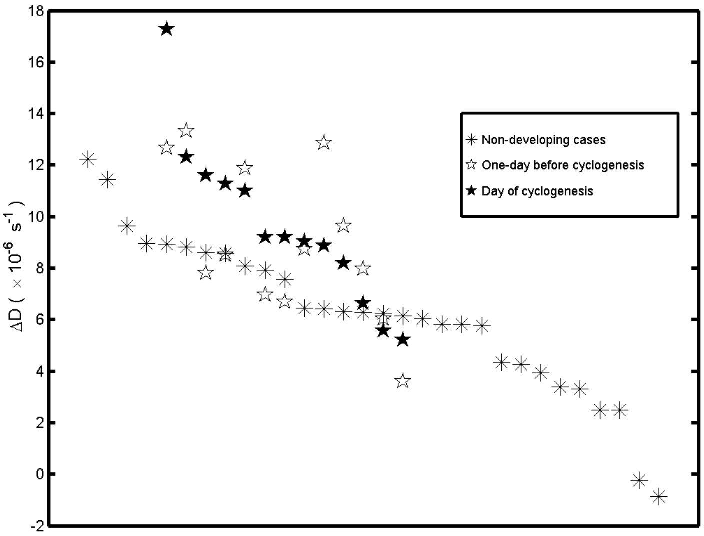

Figure 5.20: The distribution of values of mean divergence differences between 850 hPa and 200 hPa ($\Delta D = D_{200hpa} - D_{850hPa}$) for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the ΔD refers to the mean divergence difference within 500 km of the center during the lifetime. For developing tropical disturbances, the values of ΔD 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

5.4.9 Outgoing longwave radiation

Outgoing longwave radiation (OLR) is a proxy for convective activity in the tropics. Lower OLR indicates deeper convection. For non-developing tropical disturbances, the daily mean OLR 500 km around the center of tropical disturbances is calculated for each day during the lifetime of tropical disturbances. The mean OLR during the lifetime is then obtained by doing average for daily mean OLR in each day. For developing tropical disturbances, the daily mean OLR 500 km around the center of tropical disturbances is calculated on the day prior to cyclogenesis and on the day of cyclogenesis. Fig. 5.21 presents the distributions of OLR for 30 non-developing and 13 developing tropical disturbances. The mean OLR during the lifetime of 30 non-developing tropical disturbances is 198.714 W m^{-2}, with a standard deviation of 19.241 W m^{-2}. For 13 developing tropical disturbances, the mean OLR on the day prior to cyclogenesis is

164.740 W m^{-2}, with a standard deviation of 9.645 W m^{-2}; the mean OLR on the day of cyclogenesis is 166.615 W m^{-2}, with a standard deviation of 21.147 W m^{-2}.

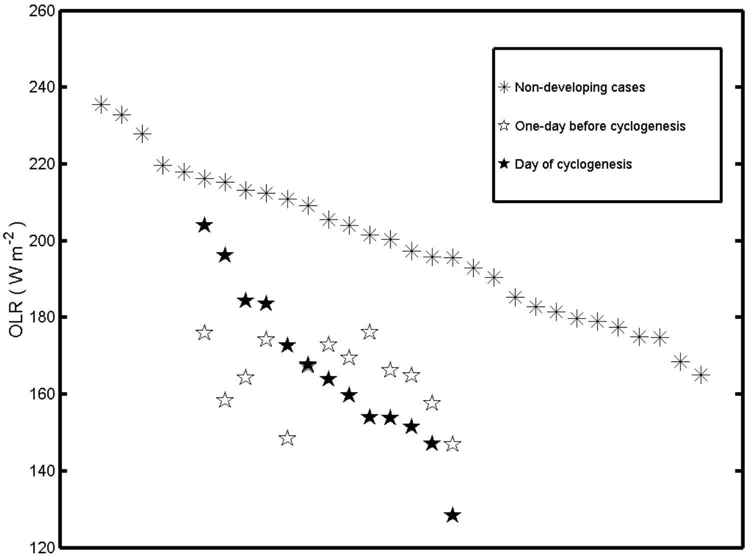

Figure 5.21: The distribution of values of the OLR for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the OLR refers to the mean OLR within 500 km of the center during the lifetime. For developing tropical disturbances, the values of OLR 500 km around the center on the day prior to cyclogenesis and on the day of cyclogenesis are presented.

5.4.10 Summary

Table 5.2 summarizes the comparison of environmental conditions for 30 non-developing and 13 developing tropical disturbances over the SCS in 2000 and 2001. The environmental conditions which are significant different in the means of parameters for non-developing and developing tropical disturbances with 95% confidence level include 500 hPa vertical velocity, 850 hPa divergence, $D_{200hPa} - D_{850hPa}$ and OLR. SST and 200 hPa divergence are significant different with 90% confidence level. The reasons inhibiting the development of non-developing tropical disturbances include insufficient 500 hPa ascending motions, insufficient convergent flow at 850 hPa and divergent flow at 200 hPa, higher OLR, and colder SST.

Table 5.2: Comparison of environmental conditions for 30 non-developing and 13 developing tropical disturbances over the SCS in 2000 and 2001

Parameters	Non-developing tropical disturbances		Developing tropical disturbances		Significant difference or not?[a]	
	Mean	Standard deviation	Mean	Standard deviation	95%	90%
SST (℃)	28.47	1.26	29.24	1.13	No	Yes
VWS (m s^{-1})	11.415	4.405	10.591	3.051	No	No
500 hPa relative humidity (%)	60.304	9.256	63.544	11.117	No	No
500 hPa vertical velocity ($\times 10^{-2}$ hPa s^{-1})	-7.007	2.884	-10.981	3.949	Yes	Yes
850 hPa relative vorticity ($\times 10^{-5}$ s^{-1})	1.813	0.866	1.953	0.893	No	No
200 hPa relative vorticity ($\times 10^{-5}$ s^{-1})	-1.198	1.098	-0.958	1.018	No	No
$\zeta_{850hPa} - \zeta_{200hPa}$ ($\times 10^{-5}$ s^{-1})	3.016	1.281	2.911	1.260	No	No
850 hPa divergence ($\times 10^{-6}$ s^{-1})	-0.723	0.985	-1.785	1.336	Yes	Yes
200 hPa divergence ($\times 10^{-6}$ s^{-1})	5.459	2.953	7.189	2.607	No	Yes
$D_{200hPa} - D_{850hPa}$ ($\times 10^{-6}$ s^{-1})	6.170	3.027	8.974	2.975	Yes	Yes
OLR (W m^{-2})	198.714	19.241	164.740	9.645	Yes	Yes

[a]The last two columns show whether the differences in the means of parameters for non-developing tropical disturbances and developing tropical disturbances are statistically significant based on the *t*-test with 95% and 90% confidence levels.

5.5 The relationship between the latent heat release and environmental conditions

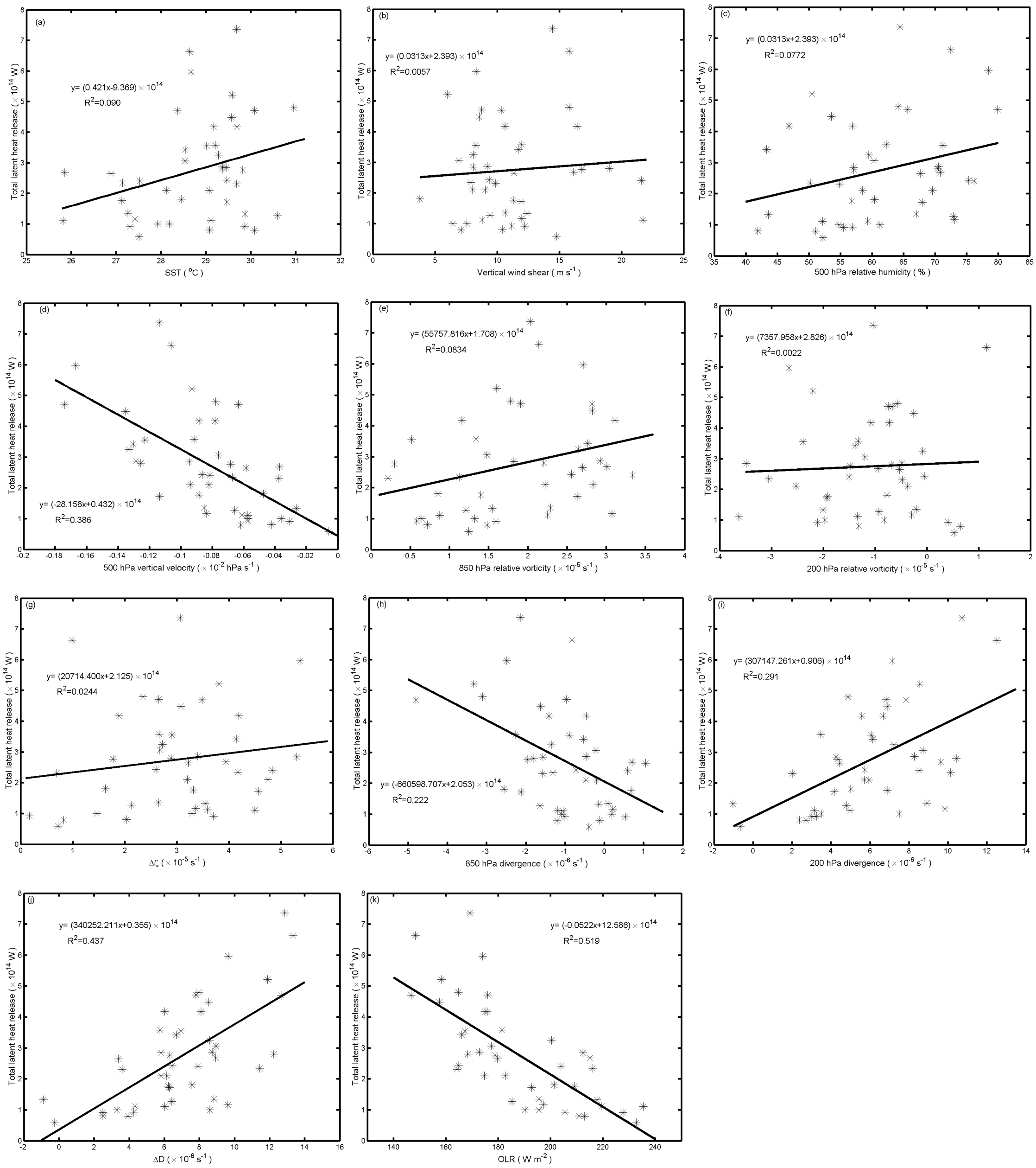

Figure 5.22: The relationship between total latent heat release and environmental factors for 30 non-developing and 13 developing tropical disturbances. The linear least-squares regression lines are statistically significant for SST, 500 hPa relative humidity, 500 hPa relative vorticity, 850 hPa and 200 hPa divergence, ΔD, and OLR.

Direct observations from SSM/I satellite reveal that the amount of total latent heat release is one critical factor to determine one tropical disturbance to develop or not. What determine the amount of latent heat release during cyclogenesis? The relationships between the latent heat release and environmental conditions will be examined in the next.

Table 5.3: Correlation coefficients between total latent heat release and environmental conditions for 30 non-developing and 13 developing tropical disturbances.

Parameters	Correlation coefficient with TLHR	Significant or not?[a]
SST	0.300	Yes
VWS	0.075	No
500 hPa relative humidity	0.278	Yes
500 hPa vertical velocity	-0.621	Yes
850 hPa relative vorticity	0.289	Yes
200 hPa relative vorticity	0.047	No
$\zeta_{850hPa} - \zeta_{200hPa}$	0.156	No
850 hPa divergence	-0.471	Yes
200 hPa divergence	0.539	Yes
$D_{200hpa} - D_{850hPa}$	0.661	Yes
OLR	-0.720	Yes

[a]The last column shows whether the correlation coefficients are statistically significant with 95% confidence levels.

The correlation coefficients between the total latent heat release and different environmental factors are calculated. For 30 non-developing tropical disturbances, the mean total latent heat release 500 km around the center of tropical disturbance and the mean values of environmental factors during the lifetime of tropical disturbances are counted. For 13 developing tropical disturbances, the mean total latent heat release 500 km around the center of tropical disturbance and the mean values of environmental factors on the day immediately prior to cyclogenesis are counted. Fig. 5.22 presents scatter plots of the total latent heat release and environmental factors for these 30 non-developing and 13 developing tropical disturbances. Table 5.3 presents correlation coefficients between total latent heat release and environmental conditions. Among these environmental conditions examined in the table, environmental conditions which are closely related with the latent heat release include: SST, 500 hPa relative humidity, 500 hPa vertical velocity, 850 hPa relative vorticity, 850 hPa and 200 hPa divergence, ΔD and OLR.

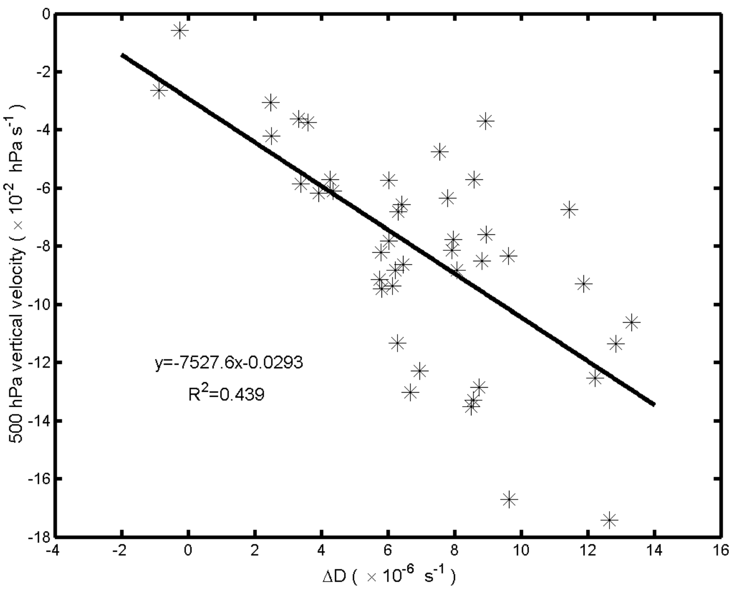

Figure 5.23: The relationship between 500 hPa vertical velocity and ΔD (the difference between the divergence at 200 hPa and 850 hPa). The linear least-squares regression line is statistically significant.

Fig. 5.23 shows the scatter plot of 500 hPa vertical velocity and the difference between the divergence at 200 hPa and 850 hPa for these 30 non-developing and 13 developing tropical disturbances. The correlation coefficient between 500 hPa vertical velocity and ΔD is -0.663**,** which is statistically significant with 95% confidence level.

Stronger convergent flow at 850 hPa and divergent flow at 200 hPa can generate stronger ascending motion. The positive divergence at 200 hPa and negative divergence at 850 hPa provide favorable conditions for strong ascending motion.

To combine the effects of different environmental conditions, one index for total latent heat release (ITLHR) is defined as follows using related environmental factors:

$$ITLHR = \sum_{i=1}^{4} |R_i| \frac{M_i - M_i^*}{\Delta M_i^*} + |R_5| \frac{M_5^* - M_5}{\Delta M_5^*}, \qquad (5.4)$$

where M_i refers to five related environmental factors ($M_1 = SST$, $M_2 = \Delta D$, M_3 = 500 hPa relative humidity , M_4 = 850 hPa relative vorticity and $M_5 = OLR$). Because the effects of upward motion can be expressed by ΔD, 500 hPa vertical velocity is not used in defining this index. One reason for choosing ΔD rather than 500 hPa vertical velocity is due to the difficulty in observing the vertical velocity directly. $|R_i|$ is the absolute value of correlation coefficient between M_i and total latent heat release ($|R_1| = 0.300$, $|R_2| = 0.661$, $|R_3| = 0.278$, $|R_4| = 0.289$ and $|R_5| = 0.720$). M_i^* is the average of the mean M_i for 30 non-developing tropical disturbances and the mean M_i for 13 developing tropical disturbances ($M_1^* = 28.855$ ℃ , $M_2^* = 7.572$ $\times 10^{-6}$ s^{-1}, M_3^* = 61.924 % , M_4^* = 1.883 $\times 10^{-5}$ s^{-1} and $M_5^* = 181.727$ W m^{-2}). ΔM_i^* is the average of the standard deviation of M_i for 30 non-developing tropical disturbances and the standard deviation of M_i for 13 developing tropical disturbances ($\Delta M_1^* = 1.195$ ℃ , $\Delta M_2^* = 3.001$ $\times 10^{-6}$ s^{-1}, ΔM_3^* = 10.187 % , ΔM_4^* = 0.880 $\times 10^{-5}$ s^{-1} and $\Delta M_5^* = 14.443$ W m^{-2}).

Fig. 5.24 presents the scatter plot of ITLHR based on five environmental factors and total latent heat release from SSM/I satellite for these 30 non-developing and 13 developing tropical disturbances. The correlation coefficient between ITLHR and total latent heat release is 0.780**,** which is statistically significant with 95% confidence level. The defined index ITLHR combing five environmental factors can represent the trend of the amount of the total latent heat release. Fig. 5.25 presents the distribution of the ITLHR for these 30 non-developing tropical disturbances and 13 developing tropical disturbances. If we use ITLHR=0.3 as the critical value to determine the potential of development for tropical disturbances, 90% (27 of 30) of non-developing tropical disturbances can be judged correctly due to the value of ITLHR lower than 0.3. For developing tropical disturbances, 84.6% (11 of 13) of developing tropical disturbances can be judged correctly one-day prior to cyclogenesis due to the high value of ITLHR greater than 0.3.

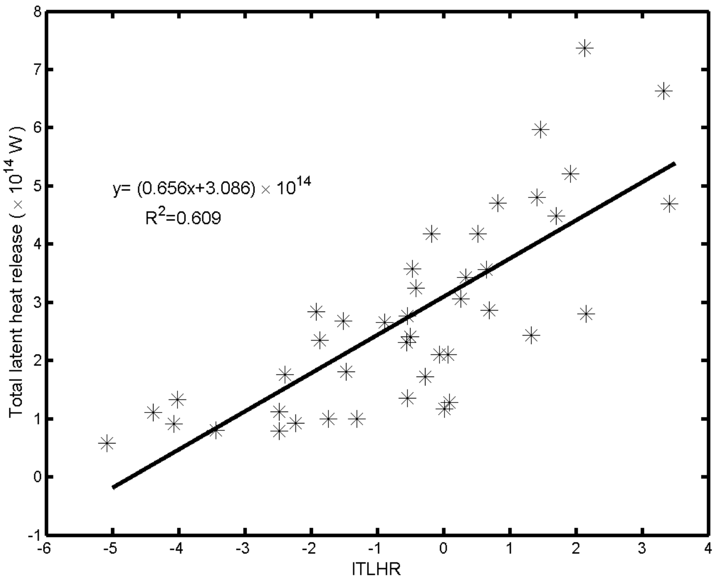

Figure 5.24: The relationship between ITLHR based on five environmental factors and Total latent heat release from SSM/I satellite. The linear least-squares regression line is statistically significant.

5.6 Summary and Conclusion

In this chapter, 30 non-developing and 13 developing tropical disturbances over the SCS in 2000 and 2001 are compared using satellite and reanalysis data sets, in order to understand why some tropical disturbances developed into tropical cyclones, while others did not. Direct satellite observation from SSM/I reveal that persistent large amount of latent heat release is necessary for cyclogenesis, and the amount of latent heat release is one critical factor to determine one tropical disturbance to develop or not. The amount of latent heat release is determined by five following factors: (1) SST; (2) ΔD, which determines the strength of ascending motion; (3) 500 hPa relative humidity; (4) 850 hPa relative vorticity; and (5) OLR. One index for latent heat release combining these five factors is defined, and this index can represent the trend of the amount of total latent heat release. Among environmental factors examined, factors which are significant different in the means of parameters for non-developing and developing tropical disturbances with 95% confidence level include 500 hPa vertical velocity, 850 hPa divergence, $D_{200hPa} - D_{850hPa}$ and OLR. SST and 200 hPa divergence are significant different with 90% confidence level. These results suggest that the reasons why the amount of total latent heat release is low for non-developing tropical disturbances include: (1) insufficient convergent flow at 850 hPa and divergent flow at 200 hPa, under which conditions the upward motion is insufficient; (2) high OLR, which indicates higher cloud-top temperature; (3) cold SST. These three factors are main factors inhibiting the latent heat release and the development of non-developing tropical disturbances over the SCS.

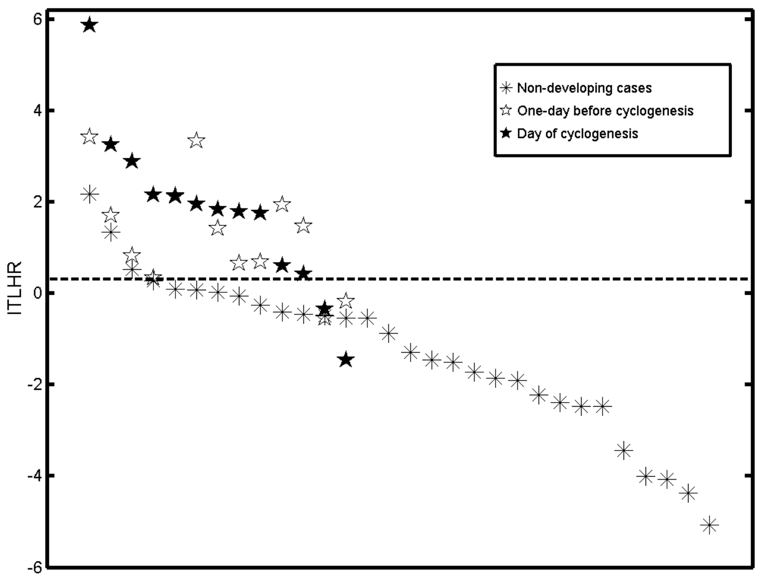

Figure 5.25: The distribution of values of the ITLHR for 30 non-developing tropical disturbances and 13 developing tropical disturbances over the SCS in 2000 and 2001. For non-developing tropical disturbances, the ITLHR is calculated using mean environmental factors during the lifetime. For developing tropical disturbances, the values of ITLHR on the day prior to cyclogenesis and on the day of cyclogenesis are presented.