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Prediction of tropical cyclonegenesis over the South China Sea using SSM/I satellite

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Abstract

We propose a method for predicting tropical cyclonegenesis over the South China Sea (SCS) based on the total latent heat release (TLHR) derived from the Special Sensor Microwave/Imager(SSM/I) satellite observations. A threshold value (3×10^{14} W) for distinguishing the non-developing and developing tropical disturbances is obtained based on the analysis for 25 developing and 43 non-developing tropical disturbances over the SCS during 2000 to 2005. One simple idealized model is further designed to verify that mean TLHR of 3×10^{14} W within 500 km of the center of tropical disturbance could maintain and develop the tropical disturbance, by heating the air at the upper level and dropping the sea level pressure by 3.2 hPa. A real time testing prediction of tropical cyclonegenesis over the SCS was conducted for the year of 2007 and 2008 using this threshold value of TLHR. We find that the method is successful in detecting the formation of tropical cyclones for 80% of all tropical disturbances over the SCS during 2007 and 2008.

1 Introduction

Tropical cyclone (TC) is one of the most destructive mesoscale weather systems. The early precursor of TC is tropical disturbance (Gray, 1968; Emanuel, 1989). A tropical disturbance is a discrete tropical weather system of apparently organized convection, generally 200 to 600 km in diameter, originating in the tropics or subtropics, having a non-frontal migratory character, and maintaining its identity for 24 h or more (Holweg, 2000). However, as real-time observations (https://listserv.illinois.edu/archives) show, not all tropical disturbances could develop to depressions, and most of them would become weaker gradually and disappear in the end. The average life time of a tropical disturbance is about two or three days.

Many researches have been done to find out the mechanisms of tropical cyclonegenesis associated with the large-scale circulation and climate background (Wang et al., 2007, 2008). Unfortunately, this background climatology often means little to the cyclone forecaster with day-to-day requirements to make formation predictions. Katsaros et al. (2001) assumed that the presence of closed circulation in the surface winds before depressions provide valuable guidance for cyclone forecasting. Sharp et al. (2002) found positive vorticity signals which exceed a certain threshold magnitude and horizontal extent within the swath of vector wind observations are useful for early detection of TC genesis. Venkatesh and Mathew (2004) supposed merger of mesoscale midlevel vortices to be a common precursor event, and used a vortex merger index to detect cyclonegenesis at an early stage. However, the threshold whether a disturbance is able to develop or not remains controversial.

The latent heat release through condensation and precipitation processes is essential to the development and maintenance of tropical disturbances. Wang et al. (2008) analyzed disturbances over the SCS in 2000 and 2001, indicating that 2×10^{14} W and 6×10^{14} W may be two important value of mean latent heat release within 500 km of the center of tropical disturbance to distinguish the developing and non-developing tropical disturbances. This paper is organized to extend the statistics to 2005, proposing a criterion of prediction based on satellite observations and testing the criterion in the prediction of disturbance over SCS in 2007 and 2008.

2 Data

The Special Sensor Microwave/Imager (SSM/I) data products including ocean wind speed (at 10 m), water vapor, cloud water, and rain rate are produced as a part of the Defense Meteorological Satellite Program (DMSP) (Hollinger et al., 1987) since 1987. The DMSP satellite which circles the earth 14 times a day is a polar-orbiting platform in a nearly sun-synchronous orbit. Remote Sensing Systems generates SSM/I data products using a unified, physically based algorithm. This algorithm is a product with 15 years of refinements, improvements, and verifications (Wentz, 1997; Wentz et al., 1998). The data used in this study is from three satellites (F13, F14 and F15), which could overlay all of the places we want to study, with a horizontal resolution of $0.25^{\circ} \times 0.25^{\circ}$.

The records of tropical disturbances over the SCS are derived from WX-TROPL Tropical Storm and Hurricane WX products issued by the National Hurricane Center in Miami. Satellites data is used in the products to confirm the position of tropical disturbances and tropical cyclones every day. In this paper, if a disturbance could develop and upgrade to a tropical depression, it is defined as a "developing disturbance". Otherwise, it is defined as a "non-developing disturbance". A disturbance day is defined as a day in which a disturbance is observed over SCS. A disturbance event is referred to the whole lifetime of a disturbance from its formation to its enhancement or dissipation.

3 The statistics of tropical disturbances

3.1 The total latent heat release

The SCS, the largest semi-enclosed marginal sea extending from the equator to 23° N and from 99° to 120° E in the Northwest Pacific, is an area with frequent occurrence of TC genesis.

The energy for disturbance comes from interaction of cumulus-scale convection and synoptic-scale dynamic field. The large-scale flow provides moisture convergence necessary for the convection (Xu and Emanuel, 1989; Williams, 1993), and the heating due to condensation and precipitation maintains the large disturbance (Adler and Rodgers, 1977). The dynamic conditions and thermodynamic conditions both influence the amount of The total Latent Heat Release (TLHR), which may be a good parameter to predict tropical cyclonegenesis. TLHR is calculated by the rain rate observed from SSM/I according to Eq. (1) given by Adler and Rodgers (1977).

$$\mathrm{TLHR} = L\rho \int_A R\,da \tag{1}$$

Where ρ is the density of rain (1.0×10^3 kg m^{-3}), and L is the latent heat of condensation (2.5×10^6 J kg^{-1}). A is the area of integration (a circle with the radius of 500 km) and R is the rain rate, which is from the measurements of SSM/I satellites of F13, F14 and F15 every day.

Mean TLHR within 500 km of the center of tropical disturbance for 25 developing ones and 43 non-developing ones over the SCS during 2000 to 2005 is shown in Fig. 1. For developing disturbance, mean TLHR of their generation day(the day when a tropical depression generates) is not always larger than that of the day before cyclonegenesis. If we only analyze the mean TLHR on the day before cyclogenesis or their disappearance, 2×10^{14} W and 6×10^{14} W are two clear criterions to differentiate them. The mean TLHR for developing disturbances one day before their cyclonegenesis is greater than 2×10^{14} W, while the mean TLHR is lower than 2×10^{14} W for 81.4% of non-developing disturbances one day before their dissipation. There are only 4 developing cases with mean TLHR larger than 6×10^{14} W one day before their genesis. However, 69.8% of the non-developing cases have their maximum daily mean TLHR greater than 2×10^{14} W. It is difficult to do prediction for the tropical disturbances with daily mean TLHR between 2×10^{14} W and 6×10^{14} W.

3.2 Accumulated latent heat release

Accumulated latent heat release (ALHR) is defined as the summation of daily TLHR during the lifetime of a tropical disturbance. The ALHR at the day n of the tropical disturbance can be calculated according to Eq. (2).

$$(\mathrm{ALHR})_n = \sum_{i=1}^{n} (\mathrm{TLHR})_i \tag{2}$$

Where, $(\mathrm{TLHR})_i$ is TLHR at the day i.

Figure 2 presents the variation of mean ALHR within 500 km of the center of tropical disturbance during their whole life over SCS during 2000 to 2005. The green line and pink line are criterions with the constant daily mean TLHR of 2×10^{14} W and 6×10^{14} W per day separately. The slopes of red lines which represent developing disturbance are nearly greater than that of blue lines which represent non-developing ones in Fig. 2. One dark line with the constant daily mean TLHR of 3×10^{14} W is used to separate developing disturbances and non-developing disturbances, which are better than using the pink or green line. 21 out of 25 developing disturbances and 34 out of 43 non-developing disturbances could be estimated according to this standard. Most tropical disturbances over SCS may need certain energy every day to maintain their intensity and to develop. The amount of energy determines whether a disturbance could develop to a tropical depression or not.

As shown in Fig. 1, The value of mean TLHR for nearly all of the developing disturbances is larger than 2×10^{14} W. For a developing disturbance with mean TLHR of 3×10^{14} W, the energy of 2×10^{14} W is assumed to maintain itself and 1×10^{14} W is to heat the upper level of cumulus. The decrease of surface pressure could be estimated by a simple calculation as follow.

3.3 Idealized model

We assumed an air column with radius of 500 km, the air in which only flow out on the top. In an isometric process, when TLHR is released, the air at upper level will expand and flow out of this air column and the surface pressure decrease at last. The decrease of surface pressure (p) is determined by air mass loss of the whole column.

$$dQ = C_p m dT \quad (3)$$

$$dH = \frac{R dT}{g} \ln\left(\frac{p_{500\ \mathrm{hPa}}}{p_{200\ \mathrm{hPa}}}\right) \quad (4)$$

$$dp = \rho g dH \quad (5)$$

Where dQ is the energy of 1×10^{14} W. C_p is specific heat content at constant pressure (1005 J kg^{-1} K^{-1}). m indicates the mass of air between 200 hPa and 500 hPa. dT

is the variation of temperature. dH means the height increase of air column. R is the molar gas constant (287 J kg^{-1} K^{-1}). g is the acceleration of gravity (10 m s^{-2}). ρ is the density of air at the upper level which is equal to 0.33 kg m^{-3} according to American Standard Atmosphere. The equations show that when the air column between 500 hPa and 200 hPa is heated by 1×10^{14} W, the surface pressure could decrease for 3.2 hPa, which matches the real TC genesis well. This simple model proves 10^{14} W is a reasonable magnitude in theory.

3.4 The two threshold to distinguish developing and non-developing disturbances

In conclusion, average daily mean TLHR of 3×10^{14} W within 500 km of the center of tropical disturbance during their life is a good threshold to distinguish developing disturbances from non-developing disturbances. As shown in Fig. 2, for some non-developing disturbances, the mean TLHR on the first day is so large that the average daily mean TLHR in the following days is greater than 3×10^{14} W, even though the mean TLHR may be less than 3×10^{14} W after the first day. To avoid this error, whether daily mean TLHR is more than 3×10^{14} W should be considered. Then the threshold for developing and non-developing disturbances can be concluded into two conditions: one is that its average daily mean TLHR is greater than 3×10^{14} W , and the other one is that the mean TLHR of the latest day is greater than 3×10^{14} W. If these conditions are satisfied, a disturbance will be more possible to upgrade in the future. Otherwise, it will tend to dissipate.

According to the two conditions above, all of the tropical disturbances during 2000 to 2005 are examined and the results are compared with the observation, both for disturbance days and disturbance events (Fig. 3). If the prediction of a day agrees with the observation next day, it is called as “correct day”. Otherwise, it is called as “incorrect day”. If a disturbance can be predicted according to the criterion one day earlier or more, it is called a “correct event”, and otherwise, it is called as “incorrect event”. There are 199 disturbance days and 68 disturbance events in SCS from 2000 to 2005. Among 199 disturbance days, 164 of them are correct days. The accurate rate of disturbance day is 82.4%. Of all the disturbance events, 61 are correct events, and the success rate is 89.7%. As shown in many former researches (Li et al., 2007; Wang et al., 2008), seasonal variation of disturbances is obvious in the SCS. The period from Jul to Oct is "peak TC season", in which the monthly average number of events is 8.75, while in the "neap TC season" from January to April, the monthly average number of events is 1.5. The months with the highest success rate are March and April, in which every day and event is correct. October has the lowest success rate of event (66.7%) and day (68%). In most cases correct day has a positive correlation with correct events.

Figure 4 presents the correct and incorrect days of each disturbance in its lifetime. For developing disturbances, the rate of correct day is 89.3%, while it is 68% for non-developing disturbances. 51.4% disturbances can be predicted correctly three days before, and 78.6% disturbances can be predicted correctly two days before, and 92.3% disturbances can be predicted one day before their upgrading or dissipation. Another important phenomenon is that for non-developing disturbancesonce the previous daily mean TLHR is less than 3×10^{14} W, they will never upgrade to depression any more even though some of them may last for a long time.

3.5 Real time predicting for 2007 and 2008

Based on the criterion above, a real time prediction system is set to predict the tropical cyclonegenesis in 2007 and 2008 over SCS (Fig. 5). There are 20 events (6 of them are developing ones and 14 are non-developing ones) and 55 disturbance days from 2007 to 2008. Among the 55 (20) disturbance days (events), 46 (16) are correct days (events). The rate of correct days is 83.6%, and the rate of correct events is 80%. The real time prediction results prove that it is an effective method to predict the disturbances using TLHR from SSM/I satellite. It should be noted that the four failed-predicted disturbances events all occurred in autumn, which also has low success rate during 2000 to 2005. It is implied that there should be some other external factors in determining the development of disturbance in autumn.

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4 Conclusions

On the basis of disturbance records from WX-TROPL Tropical Storm and Hurricane WX products and satellite data from SSM/I, TLHR of developing and non-developing disturbances during 2000 to 2005 over the SCS is analyzed, and an attempt is made in this study to assess and predict whether a disturbance could develop or not every day by calculating TLHR. Our analysis shows that if the mean TLHR within 500 km of the center of a disturbance on the latest day and its daily mean TLHR during previous life are both greater than 3×10^{14} W, the disturbance will be a developing one in the future. Otherwise it is a non-developing one. Among 199 disturbance days from 2000 to 2005, 164 of them can be predicted correctly one day before, and the success rate is 82.4%. In the 68 disturbance events from 2000 to 2005, 61 disturbances can be predicted one day before their upgrading or dissipation, and the success rate is 89.7%. According to the criterion, a real time prediction system is established. From the verification in 20 disturbance events and 55 disturbance days over the SCS from 2007 to 2008, the success rate of disturbance events is 80%, and the success rate of disturbance day is 83.6%. The result suggests that TLHR is an available factor in the prediction of tropical cyclogenesis. For non-developing disturbances, our statistics imply that once the average daily mean TLHR is less than 3×10^{14} W, they would never reach the level of depression.

In addition, some questions are still unresolved. For instance, some disturbances are not well predicted in autumn during statistic and real-time forecasting, which needs to be studied in more details.

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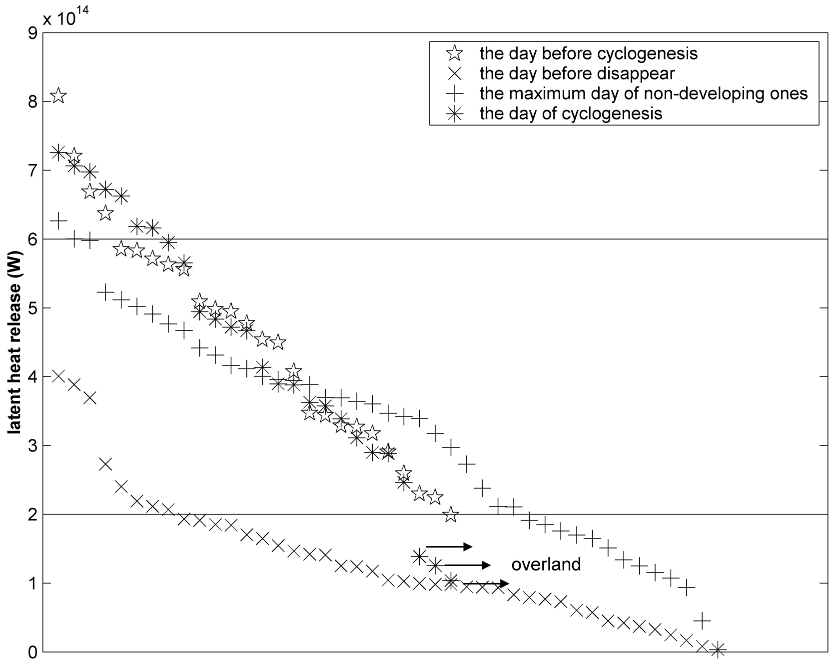

Fig. 1. The distribution of mean TLHR within 500 km of the center for 25 developing and 43 non-developing tropical disturbances over SCS during 2000 to 2005.

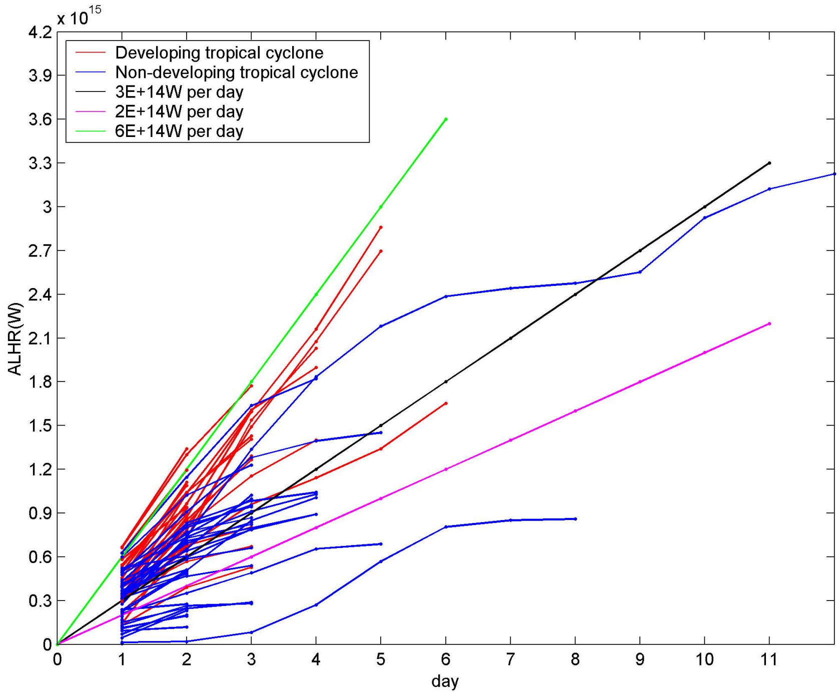

Fig. 2. The variation of daily mean ALHR within 500 km of the center of disturbances every day during 2000 to 2005. The red lines are processes of developing ones and the blue lines are processes of non-developing ones.

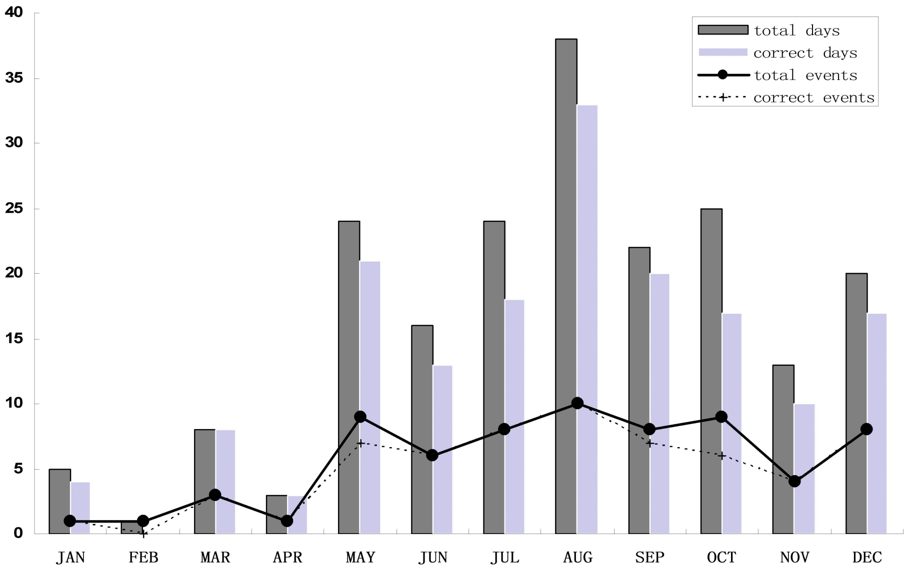

Fig. 3. The checkout of criterions in every month from 2000 to 2005.

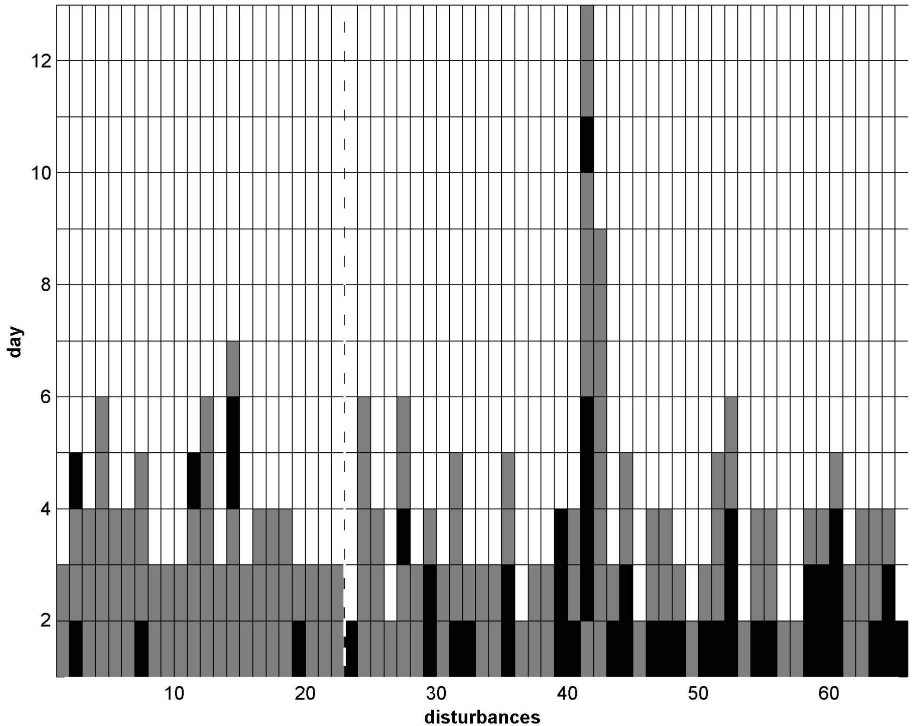

Fig. 4. Comparison of prediction and observation in each disturbance day. Developing disturbances are on the left of the dotted line, while non-developing disturbances are on the other side. The grey bar stands for correct day, and the black one stands for incorrect day.

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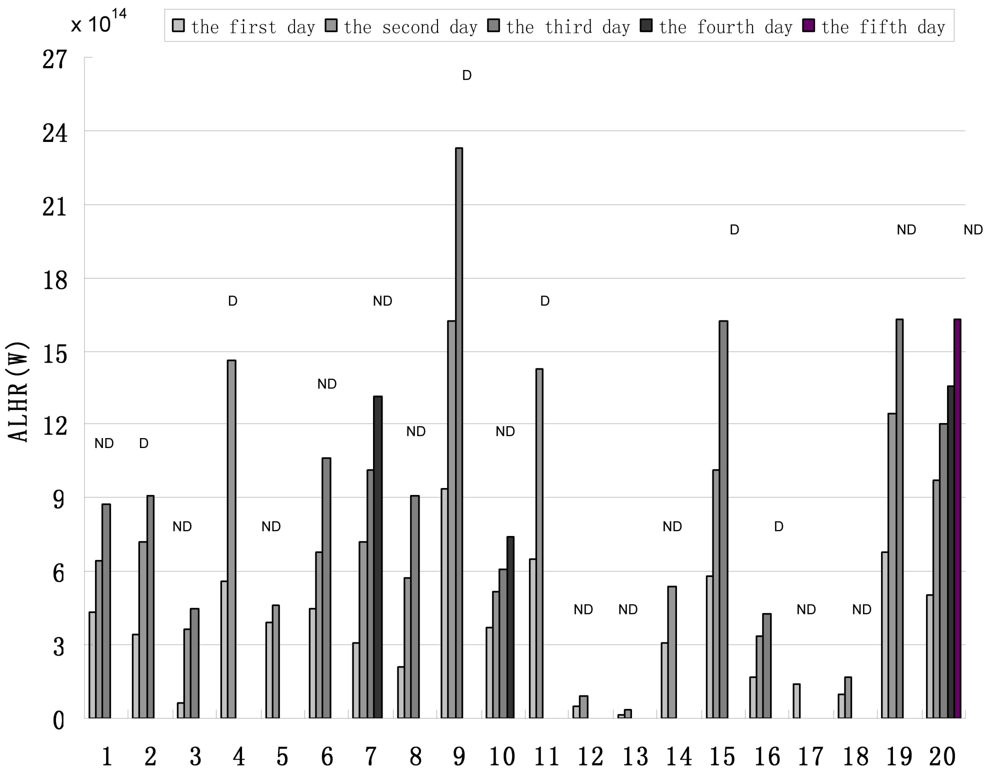

Fig. 5. Mean ALHR within 500 km of the center of 20 disturbances over the SCS during 2007 to 2008. The disturbances marked "D" are the developing ones, while the disturbances marked "ND" are the non-developing ones.