Environmental and External Factors in the Genesis of Tropical Cyclone Nargis in April 2008 over the Bay of Bengal

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Abstract

Tropical cyclone Nargis was generated over the Bay of Bengal (BoB) in late April 2008, and it devastated the coastal area of Myanmar. This study reveals the environmental and external factors in its genesis.

It is found that large-scale environmental conditions around the genesis point were generally favorable for cyclogenesis. Positive lower-tropospheric relative vorticity and the weak vertical shear of horizontal wind were observed, which were distinctive features of April 2008 that are not seen in April climatology. Sea surface temperature and atmospheric thermodynamic profile were also favorable for cyclogenesis, as in climatology. Mid-tropospheric humidity was significantly low and unfavorable until six days before the genesis; however, it increased abruptly to become favorable just before the genesis.

The atmospheric disturbance that seemed to trigger the genesis was lower-tropospheric easterly surge blowing into the genesis point. Horizontal convergence at the head of the surge associated with active convection was considered as an External Forced Convergence that triggered cyclogenesis. In addition, the active convection seemed to contribute to the preconditioning of mid-tropospheric humidity. The easterly surge was associated with a cold surge in the eastern coastal area of the Eurasian continent, which is a typical feature of cold surges in April.

1. Introduction

Over the Bay of Bengal (BoB), Tropical cyclones are generated mostly during pre-monsoon (April–June) and post-monsoon (October–December) seasons. After the genesis, they tend to move northward to reach South Asian countries and cause serious damage to local societies. One of the disastrous events happened in the 2008 pre-monsoon season, when cyclone Nargis devastated the coastal

area of Myanmar by storm surges (Webster 2008). While the North Indian Ocean cyclones had not been studied in detail until 2008, the severe damage aroused great interest of scientists in revealing the behavior of Nargis, including its cyclogenesis processes.

It is widely accepted that large-scale environmental conditions considerably influence the possibility of cyclogenesis. Favorable conditions for cyclogenesis include cyclonic circulation in the lower troposphere, that is, positive relative vorticity in the northern hemisphere, and weak vertical shear of horizontal wind between upper and lower troposphere. These factors are considered to be dynamic conditions (Gray 1975). As for thermodynamic

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conditions, high sea surface temperature (SST), unstable atmospheric profile, and high relative humidity in the mid-troposphere are also favorable for cyclogenesis (Gray 1975). The diagnosis of these environmental conditions is a powerful tool for understanding the seasonal variability of cyclogenesis (e.g., Gray 1975, 1977), interannual variability (Chan 2000; Goldenberg et al. 2001; Camargo et al. 2007), biases in model simulation (Yokoi et al. 2009), and future projection (Sugi et al. 2002; McDonald et al. 2005; Vecchi and Soden 2007; Yokoi and Takayabu 2009). We will reveal the peculiarities of the environmental conditions in a period before the genesis of Nargis and demonstrate that the conditions were favorable for cyclogenesis.

In addition to the establishment of appropriate environmental conditions, cyclogenesis necessitates an external forcing that plays a direct role in the triggering process. Some studies have stressed the contribution of enhanced lower-tropospheric wind surges (Lee et al. 1989; Briegel and Frank 1997; Gray 1998). These surges induce horizontal convergence, which is the so-called Externally Forced Convergence (EFC; Gray 1998), over an area where a concentration of positive relative vorticity has already established. This convergence tends to cause intense convection and spin-up of cyclonic circulation to trigger cyclogenesis. Gray (1998) listed a variety of wind surges that cause EFC: a trade-wind surge, a monsoon wind surge, a cross-equatorial wind surge, and a surge associated with an upper-tropospheric trough. We will reveal that the genesis of Nargis was associated with the EFC caused by an easterly surge.

Kikuchi et al. (2009) suggested that Nargis was initiated from a Rossby wave vortex emanated from equatorial intraseasonal variability (ISV). However, the northward migration of the vortex is a typical of the mature summer monsoon season, and strong easterly vertical shear plays a role in the migration (Jiang et al. 2004). Therefore, one may wonder whether the behavior of this vortex can be solely understood on the basis of the summer-type ISV, since vertical shear is westerly or only weak easterly during the pre-monsoon season. In this study, we will present that a cold surge propagating from the mid-latitudes was also related to the vortex and it played a role in the genesis of Nargis.

The rest of the paper is organized as follows. Section 2 explains reanalysis and satellite datasets analyzed in this study. Results and discussion are

presented in Section 3. At first, Subsection 3.1 outlines track and intensity of Nargis. Then, environmental conditions just before the genesis of Nargis are described in Subsection 3.2, and the characteristics of the cold surge and the EFC directly associated with the genesis are revealed through a case study and composite analysis in Subsection 3.3. Finally, Section 4 presents a brief summary and conclusion of this study.

2. Datasets

The atmospheric circulation dataset used in this study is the Japanese 25-Year Reanalysis (JRA-25) and Japan Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS) (Onogi et al. 2007) provided by JMA and Central Research Institute of Electric Power Industry (CRIEPI). Its horizontal resolution is 1.25° in longitude and latitude, and its temporal resolution is 6 h. There are 12 mandatory levels in the tropical troposphere (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 hPa).

This study also analyzes optimum interpolated SST (OISST; Reynolds et al. 2002) and outgoing longwave radiation (OLR; Liebmann and Smith 1996) datasets prepared by the National Oceanic and Atmospheric Administration (NOAA). The horizontal and temporal resolutions of the former dataset are 2.5° and 1 day, respectively, and those of the latter are 1° and 1 week, respectively. In addition, we use QuikSCAT sea surface wind dataset provided by National Aeronautics and Space Administration (NASA), which has the horizontal resolution of 0.5° . Information on the track and intensity of Nargis is taken from the best track data provided by the Joint Typhoon Warning Center (JTWC).

3. Results and discussion

3.1 Overview of the track and intensity

Firstly, the track and intensity of Nargis and pre-Nargis vortex are shown in Fig. 1. According to the best track data, Nargis attained a maximum sustained wind speed of 35 knots at 1200 UTC on April 27, 2008, at 12.2°N , 85.9°E , and thus was recognized as a tropical storm. We regard this time as the instance of the genesis of Nargis. The cyclonic vortex that was later to become Nargis had moved westward during 25–27 April to reach the genesis point. The JRA-25 dataset indicates that the vortex can be traced back to around the northern Sumatra

Fig. 1. (a) Track of Nargis. A thick line shows the center of Nargis and pre-Nargis vortex taken from the best track data, while a thin line represents the position of a maximum of 850-hPa relative vorticity of JRA-25. Circles and squares indicate positions at 0000 UTC each day. (b) Intensity of Nargis measured by the maximum sustained wind speed in knots (thick line), and the maximum value of 850-hPa relative vorticity (thin line). Note that the best track data started at 1200 UTC on 25 April.

Island on 23 April. This vortex is just the same as that Kikuchi et al. (2009) regarded as the Rossby wave vortex. It is worth noting that the intensity of the vortex measured by the wind speed and maximum relative vorticity did not vary significantly during the westward propagation.

After the genesis, Nargis stayed around the genesis point and intensified further for about one day, and then started to move northeastward toward Myanmar. Although the eastward movement and rapid intensification just before its landfall on 2 May are also of scientific interest, these topics are beyond the scope of this paper.

3.2 Large-scale environmental conditions

In order to examine the environmental conditions just before the genesis of Nargis, we compare the conditions averaged over the period of April 16–25, 2008, (Apr08 case) with those for climatology of the same period, the latter of which are calculated from the 26-year data of JRA-25/JCDAS and OISST from 1982 through 2007. Among the conditions that are considered to influence the possibility of cyclogenesis, here we examine 850-hPa relative vorticity, the vertical shear of horizontal wind between the 850- and 200-hPa levels, potential intensity (PI; Bister and Emanuel 1998, 2002), and 700-hPa relative humidity. The PI represents the maximum attainable cyclonic wind speed of cyclones under certain SST and atmospheric thermo-

dynamic stability conditions in units of $m s^{-1}$; higher PI means that these conditions are more favorable for cyclogenesis.

The climatological vorticity field (Fig. 2a) is characterized by a zonally-oriented positive band between the Equator and 10°N, which is recognized as a monsoon trough. To its north, a negative vorticity band associated with a subtropical ridge covers the Arabian Sea, BoB, and the Indochina Peninsula. As for the Apr08 case (Fig. 2b), while the monsoon trough was formed along nearly the same latitude band as in climatology, a secondary positive vorticity area elongated in a southwest–northeast direction to cover the western and northern parts of the BoB. As positive (negative) relative vorticity is favorable (unfavorable) for cyclogenesis, the Apr08 case was in more favorable vorticity condition than climatology over the BoB. Figure 3a shows that vorticity around the genesis point was positive almost throughout the 1–25 April period except for 6–7 and 14–15 April. The gradual increase since 15 April was considered to be associated with the arrival of active convection of the tropical ISV in eastern equatorial Indian Ocean (figure not shown), as studied by Kikuchi et al. (2009). The active convection could induce cyclonic circulation anomaly in the lower troposphere over the BoB through the Rossby wave response, contributing to the establishment of the favorable vorticity condition. Note that its abrupt increase after 25

Fig. 2. Large-scale environmental conditions (a, c, e, and g) in 16–25 April climatology, and (b, d, f, and h) in 16–25 April 2008. Shown are (a and b) 850-hPa relative vorticity with a contour interval of $6 \times 10^{-6} \text{ s}^{-1}$ with that larger than 0 s^{-1} shaded, (c and d) vertical shear of horizontal wind between 850- and 200-hPa levels with a contour interval of $3 \text{ m s}^{-1} (650 \text{ hPa})^{-1}$ with that smaller than 12 m s^{-1} shaded, (e and f) the potential intensity with a contour interval of 4 m s^{-1} with that larger than 40 m s^{-1} shaded, and (g and h) 700-hPa relative humidity with a contour interval of 10% with that larger than 40% shaded. The shaded areas are considered to be favorable for cyclogenesis. Solid circles indicate the genesis point of Nargis.

April reflected the genesis and further intensification of Nargis itself.

Figures 2c and 2d display vertical shear distribution. Climatological weak shear zone is located a

few degrees in the latitude north of the monsoon trough. In the Apr08 case, the weak shear zone was located roughly along 15°N , about 10° to the north of the climatological one. As a result, the

shear was weaker than $12 \text{ m s}^{-1} (650 \text{ hPa})^{-1}$ over the genesis point and along the track of Nargis, which probably contributed to the genesis and further intensification. Note that Zehr (1992) suggested that the shear of $12.5 \text{ m s}^{-1} (650 \text{ hPa})^{-1}$ was a threshold value for cyclogenesis over the western North Pacific, although it seems too strict when we apply this value to the reanalysis data (Elsberry and Jeffries 1996). The northward shift of the weak shear zone may also be attributable to the Rossby wave response to the ISV active convection.

The climatological PI over the BoB (Fig. 2e) reaches 84 m s^{-1} , which is the highest in the Tropics. Gray (1975) suggested a SST threshold of 26°C above which cyclogenesis can occur in the current climate condition. This threshold value corresponds to the PI of 40 m s^{-1} , under the condition of average atmospheric profile over the Tropics (20°S – 20°N). It can therefore be said that the climatological PI over the BoB is favorable for cyclogenesis. In addition, climatological SST is higher than 29.5°C and passes the SST threshold. In the Apr08 case (Fig. 2f), the PI was generally higher than climatology, and thus SST and atmospheric thermodynamic stability conditions were also favorable for cyclogenesis. It is interesting to note that the genesis point of Nargis was over a horizontal maximum of PI, although it is unclear whether this correspondence was inevitable or not.

As for mid-tropospheric humidity, Gray (1975) suggested that relative humidity lower than 40% was unfavorable for cyclogenesis, since convection under such condition tends to lose its buoyancy through the entrainment of ambient dry air and thus cannot grow into deep convection. The climatological 700-hPa relative humidity (Fig. 2g) is lower than this threshold over northern BoB. In the Apr08 case (Fig. 2h), the BoB was drier than climatology, and thus the humidity condition was apparently unfavorable for cyclogenesis. However, as shown in Fig. 3b, while relative humidity around the genesis point was considerably low until 21 April, it increased abruptly to exceed 60% by 24 April, implying that the mid-tropospheric humidity condition became favorable just before the genesis. Preconditioning by convection might play a role in this increase, as mentioned in the next subsection.

In summary, all of the four environmental conditions examined here were favorable for cyclogenesis for the Apr08 case. Remarkable peculiarities were found in the dynamic conditions. The relative vor-

Fig. 3. Time series of (a) 850-hPa relative vorticity in 10^{-6} s^{-1} and (b) 700-hPa relative humidity in % averaged over 10° – 12.5°N , 85° – 87.5°E (around the genesis point of Nargis). Values above thin horizontal lines are considered to be favorable for cyclogenesis.

ticity condition over the northern and western parts of the BoB was favorable in the Apr08 case but is unfavorable in climatology. The area of favorable vertical shear condition in the Apr08 case shifted northward compared with climatology, and covered the whole part of the BoB.

3.3 External forcing

In this section, we reveal an atmospheric disturbance that seemed to induce the EFC and directly contribute to the genesis of Nargis. At first, QuikSCAT sea surface wind on 25 April 2008 (two days before the genesis) is shown in Fig. 4. An easterly surface wind surge with speeds of more than 10 m s^{-1} was observed over eastern BoB. The surge was accompanied by a horizontal convergence at its head, where Nargis would be generated. The convergence was also associated with active convection, which will be shown later. Strong northeasterly and easterly winds were found over the South China Sea (SCS) and Thailand Bay, which seemed to link to the easterly surge.

We can capture the origin of the easterly surge by analyzing the JRA-25 dataset. Figures 5a, 5b, and 5c show 925-hPa horizontal wind and temperature anomaly from daily climatology on 21, 23, and 25 April 2008, respectively. To eliminate the diurnal

Fig. 4. QuikSCAT sea surface wind (vectors) and its zonal component (shadings) on April 25, 2008. The reference vector indicates 10 m s^{-1} .

cycle, a 1-2-2-2-1 temporal filter has been applied to the 6-hourly data. The surface northeasterly wind over the SCS and easterly wind over the BoB on 25 April were also found at the 925-hPa level (Fig. 5c). Associated with these winds was a negative maximum of 925-hPa temperature anomaly in the northeastern part of the Indochina Peninsula. These wind and temperature structures can be traced back to northeastern China. On 21 April (Fig. 5a), a negative temperature anomaly was centered at 37.5°N , 115°E , associated with northerly wind along 115°E . Two days later (Fig. 5b), the negative temperature anomaly and northerly wind expanded southward and eastward to reach the East China Sea and northern SCS. Such spatiotemporal structures resemble those of the cold surge (e.g., Compo et al. 1999).

In order to further demonstrate the propagation feature of the cold surge, Fig. 6 shows Hovmöller diagram along a path of the cold surge shown in the upper-left panel. The path starts at 35°N , 115°E in central China (the point A), runs southward toward the SCS, and circumvents the Indochina Peninsula to end over the BoB at 12.5°N , 80°E (the point F). Contours in Fig. 6a show an along-the-path component of 925-hPa horizontal wind with positive values representing winds from A toward F. In other words, positive values in the segments AB, BC, CD, DE, and EF mean northerly, northeasterly, easterly, southeasterly, and easterly wind, respectively. A positive maximum of the wind propagated from central China on 21 April to the BoB on 26 April, which indicated the passage of the surge. Note that large negative temperature anomalies accompanied the wind signal only over the continent (shadings in Fig. 6a). Over the ocean, the negative anomalies were weakened probably through air mass transformation due to high SST.

At the head of the wind surge signal, lower-tropospheric horizontal convergence (Fig. 6b) and mid-tropospheric ascent motion (figure not shown) were observed over the southern SCS, Thailand Bay, and BoB, which induced active convection and low OLR values (Fig. 6b). The convergence and active convection might interact with each other to intensify themselves. Around the genesis point of Nargis, the convergence appeared on 24 April, 3 days before the genesis. The horizontal convergence and ascent motion seemed to lead to the spin-up of cyclonic circulation over the area where environmental 850-hPa relative vorticity had been positive (Fig. 2b). The above description ar-

Fig. 5. The 925-hPa horizontal wind (vectors) and 925-hPa temperature anomaly from daily climatology (shadings) on (a) April 21, (b) 23, and (c) 25, 2008. The reference vectors indicate 10 m s^{-1} . The blacked-out areas are where the 925-hPa level is below the ground.

Fig. 6. Hovmoeller diagram along the path from point A through F shown in the upper-left panel. (a) Shadings indicate 925-hPa temperature anomaly, and contours indicate the along-the-path component of 925-hPa horizontal wind, with positive values representing winds blowing from point A toward F. The contour interval is 2.5 m s^{-1} . (b) Shadings indicate 925-hPa horizontal divergence anomaly, and contours indicate OLR with 40 W m^{-2} intervals. The genesis instance and point of Nargis are indicated by a solid circle.

gues that the easterly wind associated with the cold surge seemed to induce the EFC and trigger the genesis of Nargis. The convection might also contribute to the preconditioning of mid-tropospheric relative humidity (Fig. 3b). Note that the easterly wind signal over the BoB was accompanied to its south by the positive maximum of relative vorticity of which the position is indicated in Fig. 1a, which Kikuchi et al. (2009) regarded as the Rossby wave vortex.

It may be of concern that the easterly surge over the BoB is really associated with the cold surge, since a number of previous studies reported that the cold surges in midwinter, when most of the surges are found (Zhang et al. 1997), tend to propagate southward in the SCS toward and sometimes across the Equator (e.g., Love 1985). In contrast, Compo et al. (1999) briefly mentioned that significant easterly wind anomalies over the BoB were

associated with the cold surges but were not accompanied by convection signals. On the other hand, Yokoi and Matsumoto (2008) reported that cold surges occurring in different months exhibited different characteristics. Therefore, we should describe the mean behavior of cold surges found in April to confirm that the easterly surge over the eastern BoB is associated with the cold surge.

Using examples from Yokoi and Matsumoto (2008), we identify 20 cold surge events in April of the 29 years from 1979 through 2007 that meet the following three conditions:

- (1) A 3-day mean 925-hPa meridional wind anomaly from daily climatology averaged over 110° – 120° E along 20° N is negatively larger than -2.7 m s^{-1} ($-1 \times$ standard deviation) and is a temporal minimum. The day of the temporal minimum is referred to as lag 0 day.

- (2) A maximum of the meridional wind anomaly in the 8-day period from lag -8 through -1 day is larger than $+2.7 \text{ m s}^{-1}$ ($+1 \times$ standard deviation).
- (3) A 3-day mean 850-hPa temperature anomaly from daily climatology averaged over 105° – 115°E along 25°N records a temporal minimum in the 5-day period from lag -2 through $+2$ days.

Note that the cold surge event before the genesis of Nargis also met these conditions, and is hereafter referred to as the Apr08 surge.

Figure 7 shows the composite of 925-hPa horizontal wind and temperature anomalies from daily

Fig. 7. Composite of 925-hPa horizontal wind (vectors) and temperature (contours and shadings) anomalies for the April cold surges at (a) lag -2 days and (b) lag 0 days. Vectors are only plotted where its zonal or meridional component is statistically significant at the 99% confidence level. Reference vectors indicate 6 m s^{-1} . The contour interval is 2 K, and contours with positive values are omitted. Shadings indicate that the temperature anomaly is negative and statistically significant.

climatology. At lag -2 days (Fig. 7a), a negative maximum of temperature anomaly is found over south China, accompanied by large meridional gradients of temperature anomaly and northeasterly wind anomalies observed to the south of the negative maximum. Two days later (Fig. 7b), the negative temperature anomalies propagate southward and eastward to cover northern SCS and East China Sea. Strong northeasterly anomalies are found over the northern SCS, part of which blows into the inland areas of the Indochina Peninsula while the other part of which circumvents the peninsula to blow into southern SCS. Such composite behavior closely resembles that of the midwinter surges. On the other hand, weak but significant easterly wind anomaly can be found in the eastern BoB, which has not been discussed in detail in previous studies.

The composite behavior of the April cold surges is further examined by a Hovmöller diagram along the cold surge path. The along-the-path component of 925-hPa horizontal wind anomaly (Fig. 8a) shows that the surge signal propagates southward from central China to the central SCS (segment AB) with a relatively slow speed, and then expands westward rapidly. Over the BoB (segment EF), significant positive wind anomalies, which correspond to easterly anomalies, with speeds more than 2 m s^{-1} can be found. This confirms that the easterly surge over the BoB is not unique to the Apr08 surge, but is typical of the April cold surges.

The linkage between the cold surge and easterly wind surge can further be discussed from the viewpoint of wave dynamics. Nakamura and Murakami (1983), and Murakami and Nakamura (1983) suggested that the cold surge can be regarded as a Kelvin wave trapped by a mountain boundary of the Tibetan Plateau. According to the Kelvin wave dynamics, the wave propagated clockwise around the Plateau in the Northern Hemisphere. The cold surge, therefore, is able to change the direction of its propagation from southward to westward, leading to the easterly wind surge.

As for OLR anomaly (Fig. 8b), negative and significant anomalies are found over the SCS and the Thailand Bay after the arrival of wind signals, implying active convection caused by the surges. On the other hand, over the BoB, the OLR anomaly is weaker than that over the SCS and only partially significant at lag $+1$ and $+2$ days. Therefore, the active convection associated with the arrival of the easterly surge over the BoB is not common among the April cold surges. In fact, the examination

Fig. 8. Hovmoeller diagrams of composite of the April cold surges along the path shown in Fig. 6. Shown are (a) the along-the-path component of 925-hPa horizontal wind anomaly with a contour interval of 2 m s^{-1} , and (b) OLR anomaly with a contour interval of 20 W m^{-2} . Light and dark shadings indicate that the anomaly is statistically significant at the 95% and 99% confidence levels, respectively.

of OLR anomalies over western BoB (10° – 15°N , 82.5° – 87.5°E) over lags +1 and +2 days for each of the 20 cold surge events reveals that 5 events exhibit negative anomalies greater than -50 W m^{-2} , while 7 events exhibit positive anomalies. Note that the OLR anomaly in the Apr08 surge was about -60 W m^{-2} .

In addition to the Apr08 surge, another cold surge event that occurred in April 1991 seems to be associated with cyclogenesis. After the arrival of an easterly surge, a tropical depression was developed into a tropical storm in central BoB at 1800 UTC on April 24, 1991. This surge was also accompanied by active convection around the genesis location; the OLR anomaly in the western BoB over lags +3 and +4 days for this case was -74 W m^{-2} , which was the largest anomaly in the 20 cold surge events. This storm then moved northward to cause severe damage in Bangladesh with more than 138 thousand fatalities. On the other hand, the other 19 cold surge events were not associated with cyclogenesis.

Why only two cases out of 21 cold surges (including the Apr08 surge) were associated with cyclogenesis is of scientific interest. The establishment of background conditions favorable for cyclogenesis is a key to answer this question. In section 3.2, we showed that the dynamic conditions over the BoB were favorable in the Apr08 case while they are unfavorable in the April climatology. The favor-

able conditions were considered to result from the Rossby wave response to the active convection in the eastern equatorial Indian Ocean associated with the ISV. Note that similar ISV situation can be found in the cyclogenesis case in April 1991. Since this ISV convection is not always associated with the arrival of the cold surge, and since the ISV is not always found with large amplitudes, the dynamic conditions are not always favorable for cyclogenesis when the easterly wind surges associated with the cold surges arrive over the BoB. Further analyses are necessary for understanding what aspects of large-scale environmental conditions and low-frequency variability determine whether a cold surge triggers cyclogenesis, which is beyond the scope of this paper. On the other hand, the ISV active convection over the eastern equatorial Indian Ocean in April does not always accompany cyclogenesis (for example, the cases in 1983, 1985, 1992, and 2000), which suggests the importance of the triggering disturbance other than the ISV.

4. Conclusion

Tropical cyclone Nargis was generated at 1200 UTC on April 27, 2008, over the BoB, and it caused hazardous damage to Myanmar. This study describes large-scale environmental conditions before its genesis and the external forcing that triggered the genesis.

All of the large-scale environmental conditions

examined here were favorable for cyclogenesis in the genesis point of Nargis just before its genesis. While lower-tropospheric relative vorticity and vertical shear of horizontal wind are favorable for cyclogenesis only south of 10°N for late April climatology, the area of favorable conditions expanded northward to cover the northern and western parts of the BoB in 16–25 April 2008. The SST and atmospheric thermodynamic profile were also favorable for cyclogenesis as in climatology. While mid-tropospheric relative humidity around the genesis point had been low and unfavorable until 21 April, it increased abruptly to become favorable on 24 April, just before the genesis. The establishment of the favorable dynamic conditions prior to the genesis of Nargis may be induced by convection over the eastern part of equatorial Indian Ocean associated with tropical ISV through the Rossby wave response.

The atmospheric disturbance that seemed to trigger the genesis was lower-tropospheric easterly wind surge blowing into the genesis point. The horizontal convergence at the head of the surge was associated with active convection and led to the spin-up of cyclonic circulation over the area where the environmental 850-hPa relative vorticity had been positive. This convergence was therefore considered as the EFC that triggered the genesis of Nargis. The easterly surge was associated with the cold surge in the eastern coastal area of the Eurasia Continent. The composite analysis confirms that the easterly surge is a typical feature of the cold surges in April.

Kikuchi et al. (2009) concluded that Nargis was initiated from the Rossby wave vortex emanated from the equatorial ISV that had active convection over western part of the maritime continent. The present study does not deny their explanation, but provides farther description of the genesis event from another viewpoint. We stress that the cold surge induced the intensification of the vortex and triggered the genesis of Nargis; in addition, it seemed to contribute to the formation of the vortex over the northern Sumatra in cooperation with the equatorial ISV.

In this study, we point out the possible influence of the cold surge on convective activity over the BoB. Although a number of studies have revealed that the cold surges affect convective activity over the SCS, the eastern coast of the Indochina Peninsula, and Indonesia (e.g., Chang et al. 1979, 2005; Yokoi and Matsumoto 2008), their impact on the

BoB has not been studied in detail. It seems interesting to investigate the climatology and seasonality of the influence of the surges on BoB convection in our future study.

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