Tropical cyclogenesis associated with four types of winter monsoon circulation over the South China Sea

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Abstract

In boreal winter during the period 1958–2013, more than two third of tropical cyclone (TC) genesis over the South China Sea (SCS) is found to occur in specific atmospheric environmental fields associated with four types of East Asian winter monsoon circulation which are named the monsoon gyre (MG), the easterly, the reverse-oriented monsoon trough (RMT), and the monsoon confluence (MC), respectively. The first two types account for about 80% of TC genuses. Before TC formation over the SCS, lower-level positive relative vorticity and humidity anomalies are accompanied by mid-troposphere ascent and upper-level divergence anomalies, which are favorable for TC genesis. These anomalies are the most significant in the MG type. Moreover, the eddy kinetic energy (EKE) growth from the barotropic energy conversion contributes beneficially to the evolving of incipient disturbances to a TC over the SCS. In all four types, the meridional wind convergence and the zonal wind shear play an important role in the EKE growth.

Keywords: tropical cyclogenesis; East Asian winter monsoon; circulation type

1. Introduction

Tropical cyclone (TC) genesis over the western North Pacific (WNP) is a hot topic. TC formation is closely related to environmental fields, such as low-level relative vorticity, mid-level relative humidity, and so on (Emanuel, 2003; Richard and Zhou, 2012). Besides, TC genesis often occurs in the east part of the monsoon gyre (Lander, 1994). A subsequent study (Ritchie and Holland, 1999) indicates that there are four low-level circulation types favorable for TC genesis and 70% of tropical cyclogenesis occurs along the monsoon shear line and the monsoon convergence zone. A recent study (Feng et al., 2014) investigated large-scale circulation patterns favorable for TC genesis over the WNP. Moreover, the dynamic effect of the large-scale circulation on TC genesis from the perspective of the energy conversion is increasingly concerned. The barotropic energy transformation in the basic flow of the lower troposphere can provide synoptic-scale disturbances for TC genesis (Maloney and Hartmann, 2001). TC frequency is modulated by synoptic-scale disturbances related to the barotropic energy conversion in the monsoon trough over the WNP (Wu et al., 2012). The variation in the location and intensity of the monsoon trough lead to the conversion from mean kinetic energy to eddy kinetic energy, which can influence TC genesis (Wu et al., 2014a).

Although TCs generated over the South China Sea (SCS) are not much, they have an important influence on countries near the SCS (Wang et al., 2013). In contrast with the WNP, the large-scale circulation feature over the SCS is more complicated. The SCS is located in the WNP warm pool where the atmosphere–ocean interaction is active (Huang et al., 2003; He and Wu, 2010; Wu et al., 2014b) and the large-scale atmospheric circulation not only provides appropriate low-level relative vorticity and vertical shear of the horizontal wind for tropical cyclogenesis (Lander, 1994; Briegel and Frank, 1997; Ritchie and Holland, 1999) but also favors the rapid intensification of a TC (Chen et al., 2015). Besides, the SCS is a conjunction region of atmospheric circulations from East Asia, the Indian Ocean, and the Pacific Ocean and is directly influenced by the East Asian monsoon in the lower troposphere. The East Asian monsoon plays a key role in TC genesis over the SCS (Wang et al., 2007).

It is worth noting that the large-scale circulation of the East Asian winter monsoon (EAWM) favorable for TC genesis over the SCS during boreal winter is seldom concerned. The EAWM is established in East Asia after the abrupt change in East Asian atmospheric circulation in October (Yeh et al., 1959). Along the coast of East Asia, the EAWM flow is channeled down into the SCS (Krishnamurti et al., 1973; Lau and Chang, 1987; Chen et al., 2005). The convective activity over the SCS is closely related to the EAWM (Chang et al., 1979, 2003; Compo et al., 1999; Wang and Chen, 2010). In the winter of the El Niño year, there is an anomalous anticyclone near Philippines (Wang et al., 2000) with the southerly anomaly over the offshore region of the East Asia (Zhang et al., 1996). Tropical cyclogenesis over the SCS often occurs during October through December when the EAWM flow occupies gradually the low-level...
over the SCS (Wang et al., 2007). The present study classifies the EAWM circulation into four types and investigates their dynamic effect on TC genesis over the SCS, respectively.

2. Data and methodology

The Japanese 55-year Reanalysis (JRA-55) data (6 hourly and 1.25° latitude/longitude grid) from the Japan Meteorological Agency is used to analyze dynamic characteristics of EAWM circulation types favorable for tropical cyclogenesis over the SCS (100–120°E, 0–30°N). Besides, the TC best track data (including 6 hourly TC position and intensity) from the International Best Tracks Archive for Climate Stewardship (IBTrACS) project is used to identify the location and time of TC genuses over the SCS.

The TC genesis location and time are derived from the first record of its track in the IBTrACS data. A composite analysis is exerted to reveal EAWM circulation types favorable for TC formation and explore the associated environmental fields. In addition, the band-pass filter is applied to extract synoptic-scale disturbances in order to investigate the role of the barotropic energy transformation in TC genesis.

3. Winter monsoon circulation types associated with tropical cyclogenesis

TC genesis over the SCS is considered to be influenced by the EAWM if the 72-h mean meridional wind before TC genesis in both area 1 (105–120°E, 10–25°N) and area 2 (115–130°E, 25–40°N) shows northerly. About 95 TCs were generated over the SCS from October to December during 1958–2013.

Table 1. The number and percentage of tropical cyclogenesis in four East Asian winter monsoon circulation types over the SCS (0°–30°N, 100–120°E) from October to December during 1958–2013.

|        | MG | Easterly | RMT | MC |
|--------|----|----------|-----|----|
| Number | 32 | 22       | 8   | 5  |
| Percentage | 47.8% | 32.8% | 11.9% | 7.5% |

Figure 1. Composites of 850 hPa streamline at −72 h from tropical cyclogenesis in (a) MG, (b) easterly, (c) RMT, and (d) MC type from October to December during 1958–2013. Typhoon symbols show TC genesis locations. Stippling denotes regions where the difference between four circulation types and the climatic mean from October to December during 1958–2013 is significant above the 90% confidence level according to the Student’s t test.
December during 1958–2013, of which 67 were influenced by the EAWM, accounting for about 70.5% of the total. The winter monsoon circulation type may be identified by the feature of the large-scale (the $10^\circ \times 10^\circ$ region around the TC) streamline field at $-72$ h from TC genesis. Because the TC generated over the SCS can quickly land ashore after its genesis (Wang et al., 2013), this identification method provides support for the in situ TC forecast. As shown in Figure 1, the winter monsoon circulation favorable for TC genesis includes four types: the monsoon gyre (MG), the easterly, the reverse-oriented monsoon trough (RMT), and the monsoon confluence (MC). The number of TCs from the MG, easterly, RMT, and MC types accounts for about 47.8, 32.8, 11.9, and 7.5%, respectively, of the total from all winter monsoon circulation types (Table 1).

The monsoon gyre is a kind of special monsoon circulation (Lander, 1994). Both the monsoon gyre and the disturbance at its east part can develop into TC. Previous studies provide different definitions for the monsoon gyre (Lander, 1994; Wu et al., 2013). These differences mainly lie in the life cycle of a monsoon gyre. In view of the complex circulation and short TC life cycle over the SCS, the TC is defined as the one generated in the MG type if the streamline field around it shows an obvious closed vortex at $-72$ h from its genesis. As shown in Figure 1(a), the circulation of the MG type is modulated by the EAWM flow, the easterly from the central-eastern Pacific and the eastward cross-equatorial flow influenced by the Coriolis force, which makes strong shear flow existing over the SCS so that the monsoon gyre forms in the lower troposphere. Near this monsoon gyre, there are a lot of TC geneses, which account for about half of all in winter monsoon circulation types.

From October to December, the low-level easterly from the central-eastern Pacific is an important part of the low-level circulation over the SCS. This easterly contains multiple time scale perturbations which provide initial perturbation kinetic energy for TC genesis. If the streamline field around a TC shows an obvious easterly at $-72$ h from its genesis, this one is defined as the TC generated in the easterly type. The circulation of the easterly type near the equator is often accompanied by small and medium scale disturbances, which is favorable for tropical cyclogenesis (Figure 1(b)).

In boreal winter, the trough line of the monsoon trough over the SCS generally shows northwest-southeast direction. However, it is sometimes along
Figure 3. Composites of 500 hPa omega anomalies (the 72-h mean before tropical cyclogenesis minus the climatic mean from October to December during 1958–2013; $10^{-2}$ Pa s$^{-1}$; shaded) in (a) MG, (b) easterly, (c) RMT, and (d) MC type. Typhoon symbols show TC genesis locations. Stippling denotes regions where the anomalies are significant above the 90% confidence level according to the Student’s $t$ test.

northeast-southwest direction and is favorable for TC genesis. Thus, the TC generated in the monsoon trough with northeast-southwest direction is defined as the one of RMT type. As shown in Figure 1(c), the EAWM flow goes southwestward via Vietnam, then eastward via the Kalimantan Island, which leads to a monsoon trough with the northeast-southwest direction forming over the SCS. This RMT type provides the horizontal wind shear and vertical vorticity for tropical cyclogenesis.

When the EAWM flow prevails over the SCS, the low-level circulation over the SCS is dominated by northeasterly, easterly and cross-equatorial flow. These airflows converge over the SCS. Thus, the TC generated in this kind of monsoon circulation is defined as the one of MC type. As shown in Figure 1(d), compared with the RMT type, the cross-equatorial flow is stronger and extends to the southern-central SCS. It converges with the EAWM flow and the easterly over the southern-central SCS, which provides plenty of perturbation kinetic energy for tropical cyclogenesis.

4. Environmental fields in winter monsoon circulation types

The low-level flow provides dynamical and thermodynamic conditions for tropical cyclogenesis (Gray, 1979). From October to December, the EAWM has an important influence on environmental fields, such as low-level vorticity, mid-troposphere relative humidity, and so on (Wang et al., 2007). These key environmental fields play a crucial role in tropical cyclogenesis over the SCS.

In the MG type, tropical cyclogenesis mainly occurs over the southern-central SCS where there are suitable environmental fields. There is an apparently positive vorticity anomaly in the lower troposphere over the SCS, especially in the central SCS (Figure 2(a)). Corresponding to the location of the vorticity anomaly, a mid-tropospheric ascent anomaly and an upper-level positive divergence anomaly are also obvious (Figures 3(a) and 4(a)). These dynamic conditions are accompanied by a positive relative
humidity anomaly in the lower troposphere over the SCS (Figure 5(a)), which is favorable for TC formation. In the easterly type, the lower-level positive vorticity anomaly, mid-tropospheric ascent anomaly, upper-level positive divergence anomaly, and positive relative humidity anomaly in the lower troposphere are weaker compared with the MG type, especially in the central SCS (Figures 2(b), 3(b), 4(b) and 5(b)). However, these environmental fields are still favorable for tropical cyclogenesis. TCs in the easterly type are mainly generated in the eastern-central SCS (Figure 2(b)). In the RMT type, the strong positive vorticity anomaly, mid-tropospheric ascent anomaly, positive divergence anomaly, and positive relative humidity anomaly occur over the southern SCS where all of TC genases in this type are observed (Figures 2(c), 3(c), 4(c) and 5(c)). In contrast with the RMT type, four environmental field anomalies favorable for tropical cyclogenesis in the MC type mainly exist in the northern-central SCS where TC genases in this type mainly occur (Figures 2(d), 3(d), 4(d) and 5(d)). In addition, low-level convergence also shows apparent positive anomalies in these types over the SCS (figure not shown). Although vertical wind shear in these types seems to be a little strong (figure not shown), other environmental fields mentioned above basically determine dynamic and thermodynamic conditions favorable for TC genesis over the SCS. This feature shows that vertical wind shear is not a key factor influencing TC genesis in EAWM types over the SCS.

5. The synoptic-scale disturbance in winter monsoon circulation types

The barotropic energy transformation in the basic flow of the lower troposphere can increase the eddy kinetic energy (EKE), which provides the synoptic-scale disturbance for TC genesis (Maloney and Hartmann, 2001). The EKE can be computed from the eddy winds ($u', v'$):

$$EKE = \frac{(u'^2 + v'^2)}{2}$$

where the overbar denotes a 72-h mean of before tropical cyclogenesis and prime indicates a time-mean perturbation which is obtained by exerting a 3- to 8-day bandpass filter.
Recent studies show that the growth of the EKE comes mainly from the transformation from the mean kinetic energy to the EKE (Chen and Sui, 2010; Hsu et al., 2011). As shown in the following equation (Maloney and Hartmann, 2001):

$$\frac{\partial K'_b}{\partial t} = \frac{-u'v'}{\partial y} - \frac{u'v'}{\partial x} - \frac{u'^2}{\partial x} - \frac{v'^2}{\partial y}$$

where $u$, $v$ and $K$ indicate the zonal wind, the meridional wind and the EKE, respectively, overbar denotes a 72-h mean before tropical cyclogenesis, and prime a perturbation which is obtained by a 3- to 8-day band-pass filter, the tendency of barotropic energy conversion term ($\partial K'_b/\partial t$) is calculated with 850-hPa wind data and contributed from the zonal wind shear term, the meridional wind shear term, the zonal wind convergence term, and the meridional wind convergence term.

As shown in Figure 6, the EKE growth over the SCS occurs in all of winter monsoon circulation types to different extent. Meanwhile, TCs are generated basically in the region where the EKE growth is obvious. Figure 6(a) shows that anomalous northerly converges with anomalous southwesterly over the central SCS in the MG type. The EKE from the barotropic energy conversion of the basic flow is obvious over the SCS. TC geneses are focused in the region where the EKE growth is fast. In the easterly type, anomalous easterly dominates most parts of the SCS and the region of the EKE growth in the easterly type is smaller than that of the MG type and is mainly located in the southern-central SCS where TC formation often occurs (Figure 6(b)). In the RMT type, the EKE increases obviously over the southern SCS where there is a reverse-oriented monsoon trough and TC geneses are observed (Figure 6(c)). As shown in Figure 6(d), the central SCS is a convergent region of anomalous northerly, westerly, and cross-equatorial flow. In this convergent region, there are TC geneses near the area of the EKE growth. In addition, most of TC geneses occur in region 1 (100–110°E, 5–10°N) and region 2 (110–120°E, 5–20°N), where the meridional wind convergence term and the zonal wind shear term make a key contribution to the EKE growth. Therefore, the convergence and shear related to the EAWM play an important role in the EKE growth favorable for TC geneses.
6. Summary

Four types of EAWM circulation favorable for tropical cyclogenesis over the SCS are defined from October to December during 1958–2013, namely the MG, easterly, RMT and MC. The number of TC genuses in these circulation types accounts for about 70.5% of all in the same period over the SCS. Compared with the climatic mean from October to December during 1958–2013, four types of EAWM circulation provide more beneficial environmental fields for TC formation. An apparent positive vorticity anomaly is located in the lower troposphere over the SCS. This vorticity anomaly is accompanied by a mid-tropospheric ascent anomaly and an upper-level positive divergence anomaly. Meanwhile, a positive relative humidity anomaly is obvious in the lower troposphere over the SCS. Moreover, these circulation types over the SCS play an important role in the EKE growth which is beneficial to evolving of incipient disturbances to TCs. From the perspective of the barotropic energy conversion, the meridional wind convergence term and the zonal wind shear term make a key contribution to the EKE growth in the tropical cyclogenesis region. These types of EAWM circulation provide a support for the important influence of the EAWM on TC genesis over the SCS in boreal winter.

It is a remarkable fact that the vertical wind shear is not a key factor for tropical cyclogenesis in four types of EAWM circulation over the SCS in boreal winter. In view of few TC genuses occurring in the MC type while its distinct circulation feature from other circulation types, this type is classified but not emphatically analyzed. In addition, anomalies of the mid-tropospheric omega and the lower troposphere relative humidity documented above are strongly significant, while anomalies of the EKE time change rate due to the barotropic energy conversion in basic flow are less significant. This feature may be due to the limited quantities of tropical cyclogenesis over the SCS in boreal winter or the influence of other factors which need to be further investigated.

Acknowledgements

This study is supported by the National Natural Science Foundation of China (Grant No. 41375065), the Open Fund of the Key Laboratory of Global Change and Marine-Atmospheric
Chemistry (Grant No. GCAMC1304), and the National Natural Science Foundation of China (Grant No. 41461164005). The authors are grateful for the two anonymous reviewers for their constructive comments.

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