Mechanisms of westward and northward movement of sub-monthly scale disturbances over Asian monsoon regions.

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Abstract

Sub-monthly scale disturbances, which have time scales between 10 and 25 days, are found frequently over the Bay of Bengal during the boreal summer. They have strong cyclonic circulation anomaly in the lower troposphere and move north-westward with its speed of about a few meters per second. We discuss the mechanisms for westward and northward components of the movement in the complex environmental condition.

The westward component mainly results from balance between advection of the planetary and relative vorticity. The advection of the planetary vorticity (the beta effect) contributes to the westward movement, like the Rossby wave dynamics. On the other hand, advection of the disturbance by the environmental flow tends to move the disturbance eastward, and especially counterbalances the beta effect when the center of the disturbance is around 10°N where low-level westerly jet axis exists. In this case, advection of the environmental relative vorticity by the disturbance is second contributor to the westward movement.

For the northward component, both advection of the disturbance by the environmental low-level southerly wind and tilting effect of the environmental horizontal vorticity vector by the disturbance are main contributors. The former works mainly in the lower troposphere, while the latter works in the middle and upper troposphere.

keyword: sub-monthly scale disturbance, vorticity budget, the beta term, advection effect, tilting effect

1 Introduction

During the boreal summer, sub-monthly scale disturbances are frequently observed over the Bay of Bengal and cause precipitation over the South and Southeast Asia (Chen and Chen, 1993; Yokoi and Satomura, 2004). They have typical time scales between 10 and 25 days, typical horizontal scales of a few thousand kilometers, and accompany cyclonic circulation in the lower troposphere.

They tend to move westward and slightly northward with time. Because of their time and horizontal scales, the disturbances seem to obey Rossby wave dynamics to some extent. However, in the South and Southeast Asia during the boreal summer, environmental condition is complicated, which influences strongly the disturbances' movement. For example, strong low-level westerly jet tends to move the disturbances eastward.

In the present study, we discuss qualitatively the mechanisms for westward and northward movement of the disturbances with use of vorticity budget analysis.

2 Data and Method

ECMWF 40 Years Re-Analysis (ERA40) data was used. The used variables for the vorticity budget analysis are three dimensional wind (u,v,ω), vertical relative vorticity ζ, and horizontal divergence $\nabla_h \cdot \mathbf{u}$. The analyzed period is from May to September in 1979-1999 (total 3213 days). We used a Lanczos band-pass filter with cutoff period of 10 and 25 days to retrieve 10-25-day component, and a low-pass filter with cutoff period of 25 days to retrieve environmental component. The 10-25-day and environmental components are referred to as $(\cdot)'$ and $\bar{(\cdot)}$, respectively.

To clarify effects of the complicated environmental condition on the disturbances' movement, we investigate statistical characteristics and mechanisms from a number of disturbances existed over the Bay of Bengal. We focus on two regions; one is (7.5°N-12.5°N, 80°E-100°E) rectangular region and referred to as SBB, while the other is (17.5°N-22.5°N, 80°E-100°E) and referred to as NBB (Fig. 1). From the analyzed period, we picked up 158 and 182 days when centers of the disturbances exist in SBB and NBB regions, respectively (The center of a disturbance was defined as a maximum of ζ' at the 850-hPa level). For each region, the picked days were averaged with respect to the position of the center.

3 Structure of the disturbances

Composite horizontal and vertical structures of NBB and SBB are quite similar to each other. They have zonal and meridional scales of a few thousand kilometers and about one thousand kilometers, respectively. Anomalous northerly (southerly) wind, whose magnitude is about 1 m s $^{-1}$, exists to the west (east) of the center of ζ'. They move northwestward with their speed of about 2 to 3 degrees per day in longitude (Figs. 2 a and b) and 1 to 1.5 degrees per day in latitude (Figs. 2 c and d).

Figure 3 shows latitude-height cross sections of ζ' and ω' averaged over 10 degrees in longitude around the disturbances' center. Below the 200-hPa level, ζ' is nearly standing. Negative ω' is found around the center (or a few degree to the south) with its maximum in the middle troposphere (the 600- and 400-hPa levels for NBB and SBB composites, respectively). This negative ω' will be turned out to be important for the northward movement.

4 Vorticity budget

In this section, we discuss the mechanisms for westward and northward movement through vorticity budget analysis.

The vorticity budget equation used in the present study is

$$\begin{aligned}\underbrace{\zeta'_t}_{A} = & \underbrace{-(\bar{\mathbf{u}}\cdot\nabla)\zeta'}_{B}\underbrace{-(\mathbf{u}'\cdot\nabla)(f+\bar{\zeta})}_{C} \\ & \underbrace{-(f\nabla_h\cdot\mathbf{u}'+\bar{\zeta}\nabla_h\cdot\mathbf{u}'+\zeta'\nabla_h\cdot\bar{\mathbf{u}})}_{D} \\ & \underbrace{+(\omega'_y\bar{u}_p-\omega'_x\bar{v}_p)}_{E}\underbrace{+(\bar{\omega}_y u'_p-\bar{\omega}_x v'_p)}_{F}+[Res.].\end{aligned}$$

Subscripts t, x, y and p indicate partial differential of time, zonal, meridional and pressure directions, respectively. The capital letters below the equation are symbols of the terms. Nonlinear terms, such as $-(\mathbf{u}'\cdot\nabla)\zeta'$, are neglected in the present analysis because they are small compared to the linear terms.

Figure 4 shows horizontal distribution of these terms of the SBB composite integrated from the sur-

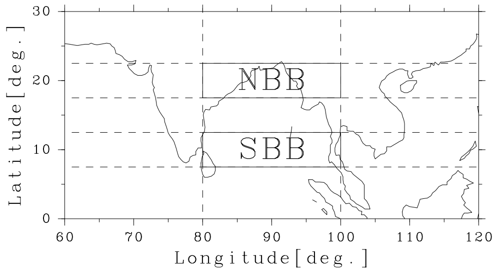

Fig. 1: Location of NBB and SBB regions.

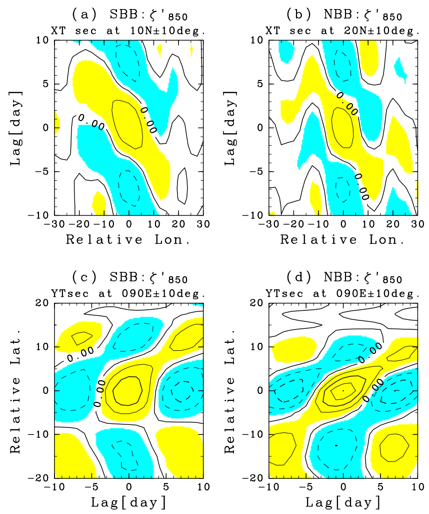

Fig. 2: (a and b) Longitude-time cross sections of ζ' at the 850-hPa level averaged over 20 degrees in latitude around the center: of (a) SBB and (b) NBB. Contour interval is 2×10^{-6} [s^{-1}]. (c and d) Latitude-time cross sections of ζ' at the same level averaged over 20 degrees in longitude around the center of (c) SBB and (d) NBB. Contour interval is the same as (a) and (b).

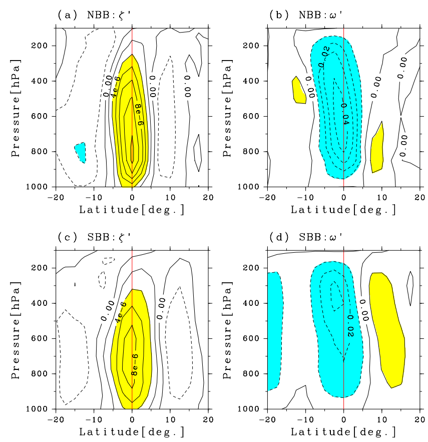

Fig. 3: Latitude-height cross sections of ζ' and ω' averaged over 10 degrees in longitude around the centers' longitude: (a) ζ' of NBB, (b) ω' of NBB, (c) ζ' of SBB, and (d) ω' of SBB. Contour intervals are 2×10^{-6} [s^{-1}] for (a) and (c), and 0.01 [Pa s^{-1}] for (b) and (d).

face to the 100-hPa level. In Fig. 4A, which represents tendency of ζ', positive and negative maxima exist north-western and south-eastern side of the center, respectively, which are consistent with the northwestward movement.

Looking into positive and negative maxima in Figs. 4B-4F, we can identify which term is a contributor to the westward and northward components of the movement. The term B, which represents advection of the disturbances by the environmental flow, tends to move the disturbances north-eastward because positive and negative maxima exist north-eastern and south-western side of the center, respectively. On the other hand, the term C, which represents advection of the environmental absolute vorticity by the disturbances, tends to move the disturbances south-westward. The term E, which represents tilting effect of the environmental horizontal vorticity vector by the disturbances, tends to move the disturbances northward. The terms D and F seem to hardly contribute to the movement, though the term D tends to maintain the disturbances because a positive maximum is around the center.

As documented above, different terms contribute the disturbances' movement for different directions. To discuss the relative importance of each term, horizontal gradient vectors of the terms at the center were calculated. Figure 5 shows zonal and meridional components of the vectors divided by vertically integrated ζ'_{xx} and ζ'_{yy} at the center, respectively. Although the disturbances analyzed in the present study are not recognized as sinusoidal waves, these normalization will helpful for us to compare results of SBB with those of NBB. The terms B and C are divided as

$$\underbrace{-(\bar{\mathbf{u}}\cdot\nabla)\zeta'}_{B} = \underbrace{-\bar{u}\zeta'_x}_{B1}\underbrace{-\bar{v}\zeta'_y}_{B2}$$

$$\underbrace{-(\mathbf{u}'\cdot\nabla)(f+\bar{\zeta})}_{C} = \underbrace{-(\mathbf{u}'\cdot\nabla)\bar{\zeta}}_{C1}\underbrace{-f_y v'}_{C2}$$

where the vertical advection term in the term B is not displayed because it turns out to be small.

The zonal components of the gradient of SBB composite are shown in Fig. 5c. As recognized in Fig. 4C, the term C contributes to the westward movement. The zonal component of the term C2 is about three times larger than that of the term C1. The term B hinders the westward movement, and nearly

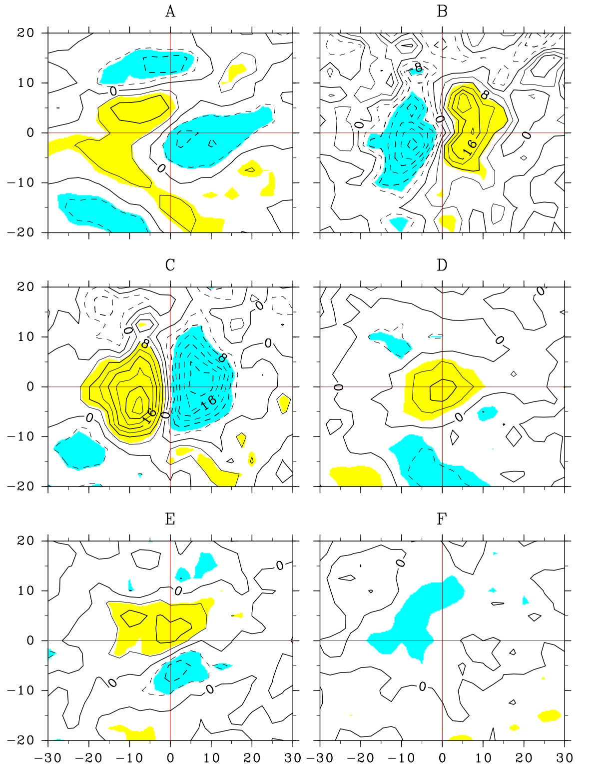

Fig. 4: Spatial distributions of each term of the vorticity budget equation of SBB. The term symbols are explained in the text. Abscissas and ordinates indicate relative longitude and latitude to the center, respectively. The contour interval is 4×10^{-7} [Pa s^{-2}]. Color tone marks significance greater than 99%.

balances with the term C2. This fact means that though the beta term is the best contributor to the westward movement, the disturbances can not move westward by the beta term alone because the advection by the environmental flow counterbalances the beta term. We can not neglect the contribution of the term C1 which represents the advection of the environmental relative vorticity by the disturbances.

The relationship between the terms B and C is different for the case NBB (Fig. 5a). While the term C2 of NBB is about 1.3 m s^{-1} smaller than that of SBB, the term B of NBB is about 2.4 m s^{-1} smaller than that of SBB. On the other hand, the term C1 of NBB is positive and tends to make the disturbances move eastward.

This difference of relation between the term B and C is due to the latitude where the disturbances exist. The centers of the SBB disturbances are in 7.5°N-12.5°N band where the low-level westerly jet axis exists, while that of NBB disturbances are at 17.5°N-22.5°N, where the environmental westerly is weaker.

Figures 5b and 5d show the meridional components of the gradient vectors of NBB and SBB, respectively. They show quite similar characteristics to each other. The term A is positive, which means the northward movement. The contributors to the northward movement are the terms B2 and E. The term B2 is due to the environmental southerly wind in the lower troposphere over the Bay of Bengal, thus it contributes to the northward movement mainly in the lower troposphere (Fig. 6a). On the other hand, Fig. 6b shows that the term E contributes to the northward movement mainly in the middle and upper troposphere. The terms B2 and E work at different height, though their integrated magnitudes are similar to each other. The physical explanation of the effect of the term E is as follows. As shown in Fig. 3, negative ω' exists at the same latitude of positive ζ' and positive meridional gradient of ω' is found at the northern side of the positive ζ'. This meridional gradient of ω' twists the environmental horizontal vorticity vector which points toward south because of vertical easterly shear, produces positive ζ' tendency, and thus move the disturbance northward.

5 Conclusion

Sub-monthly scale disturbances over the Bay of Bengal during the boreal summer tend to move north-westward with their speed of a few meters per second. The vorticity budget analysis revealed the contributors to the westward and northward components of the movement. The main contributor to the westward movement is the beta term, while strong low-level westerly jet tends to move the disturbances eastward. When the centers of the disturbances are around 10°N where the axis of the westerly jet locates, the eastward advection nearly counterbalances the beta term, and advection of the environmental relative vorticity by the disturbances is the second contributor to the westward movement. For the disturbances which have their centers at 20°N, the advection effect by the westerly jet is weaker than the beta effect.

For the northward movement, the main contributors are advection by the low-level southerly wind

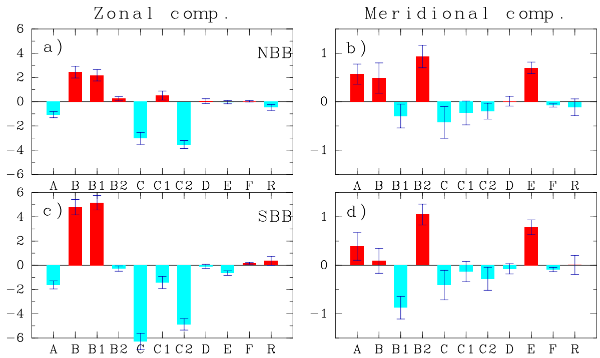

Fig. 5: Zonal and meridional components of gradient vectors of the terms: (a) zonal component of NBB, (b) meridional component of NBB, (c) zonal component of SBB, and (d) meridional component of SBB. Symbols on the abscissas are explained in the text. The dimension of ordinates is [m s^{-1}]. Positive value of zonal and meridional components indicate that the term tends to move the disturbances eastward and northward, respectively.

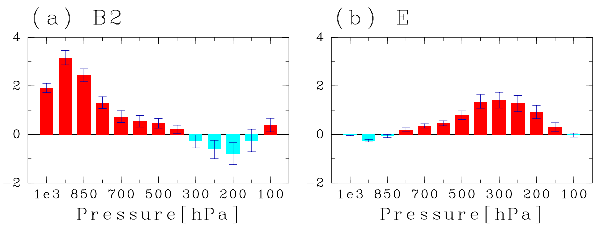

Fig. 6: Vertical distribution of meridional components of the gradient vectors of the terms (a) B2 and (b) E of SBB. The abscissas indicate pressure, and the dimension of the ordinates is [m s^{-1}]. Each component is divided by ζ'_{yy} at the 850-hPa level at the center for normalization.

over the Bay of Bengal and tilting effect of the environmental horizontal vorticity vector. The former effect mainly works at lower troposphere, while the latter at middle and upper troposphere. The magnitudes of northward forcing is similar to each other.

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