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Study on the Dynamic Characteristics of an Eastward-offshore Mesoscale Vortex along the Meiyu-Baiu Front

YU Fei[1, 2], FU Shen-Ming[1], ZHAO Si-Xiong[1], and SUN Jian-Hua[1]

[1] *International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*
[2] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

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Abstract The eastward-moving Meiyu-Baiu frontal mesoscale vortices (MBFMVs) appear frequently and often cause heavy rainfall events along their tracks. A move-off-shore MBFMV was selected to enhance our understanding of this type of vortex. Synoptic analyses indicate that the MBFMV is a type of meso-α vortex and mainly occurs in the lower troposphere. A short wave trough near the coastline is highly favorable for the formation, sustainment, and displacement of the MBFMV. Vorticity budgets indicate that at lower levels of the MBFMV, convergence is the dominant factor for the increase of positive vorticity, and at high levels of the MBFMV, the vertical transportation associated with convective activities is the most important factor. The horizontal transportation was the main factor decreasing the positive vorticity. The land and sea environments are crucial to the evolution of the MBFMV. The characteristics of the Meiyu-Baiu Front (MBF) are also vital to the variation of the vortex.

Keywords: Meiyu-Baiu Front, mesoscale vortex, vorticity budget

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1 Introduction

The mesoscale vortices over the Meiyu-Baiu Front (MBF) often induce heavy rainfall events that influence wide areas, including the Yangtze valley, the East China Sea, the Yellow Sea, the Korean Peninsula and the Japanese islands. Recognizing the important effect of Meiyu-Baiu frontal mesoscale vortices(MBFMVs) on extreme precipitation events, a fair number of related studies have studied this phenomenon. Some studies (Ninomiya and Akiyama, 1971, 1992; Akiyama, 1990a, b) have revealed that in certain cases, a weak positive vorticity area associated with cloud systems could develop into a frontal depression under the influence of an upper-level short-wave trough. Dong and Zhao (2004) noted that the coupling of the upper level jet (ULJ) and lower level jet (LLJ) is crucial to the development of MBFMVs. Some studies (Zhao et al., 1982, Zhao, 1988; Zhou et al., 1984) show that when the mesoscale vortices are in the developing stage, the energy conversion processes are significant. Therefore, the dynamic effects of the wind field cannot be ignored. Moreover, the release of latent heat is important during the developing and mature stages. Sun et al. (2010) analyzed an MBFMV during the Meiyu period of 2003 and found that convergence, tilting and vertical advection were the dominant factors in its formation.

During the Meiyu period, compared with the quasi-stationary mesoscale vortices, the eastward-moving vortices could influence a larger area. Some of these eastward-moving vortices could move offshore and influence Korea and even Japan. It should be noted that the severe weather events (such as strong wind and heavy rainfall) induced by these vortices in the East China Sea and Yellow Sea have become a significant problem for the shipping, fishing, and energy exploration industries of Northeast Asian countries, especially China. Although there are a certain number of studies focused on eastward-moving vortices (e.g., Yamada et al., 2003; Sun et al., 2010), the details of the move-off-shore vortices are still unclear due to the lack of observations at sea and the short lifespans of the vortices in general cases (Geng, 2008). Therefore, the purpose of this study is to investigate the evolution of the move-off-shore MBFMV and compare the maintenance mechanisms of the vortex under different environmental conditions. To minimize the uncertainties caused by the surface, the MBFMV is identified from the closed center over the stream field.

2 Data and methodology

Routine observations from the China Meteorological Administration (CMA) and 3-h precipitation from CMORPH (Climate-Prediction-Center MORPHing technique) (Joyce et al., 2004) with a resolution of 0.25 degrees are used to investigate the evolution of the MBFMV and the associated precipitation and convective activities.

The Weather and Research Forecast model (WRF, Skamarock et al., 2001) was employed in this study, and the configuration of the simulation is as follows: the horizontal grid spacing of the outer and inner domains is 36 km and 12 km, respectively. There are 27 sigma levels, with the top at 50 hPa in both the outer and inner domains. The numerical integration starts at 0000 UTC 10 July 2010 and runs 36 hours to include the whole life span of the vortex. Final analysis data from the National Centers for Environmental Prediction (NCEP) were used as initial

Corresponding author: ZHAO Si-Xiong, zhaosx@mail.iap.ac.cn

and boundary conditions in the simulation. Moreover, the 12-h soundings and 3-h surface observations from CMA are used to improve the first guess by using the objective analysis method. The RRTM (Rapid Radiative Transfer Model) radiation scheme, Kain-Fritsch cumulus parameterization scheme (only for the outer domain), Morrison cloud microphysics parameterization scheme, and Medium Range Forecast (MRF) planetary boundary layer scheme are used in this simulation.

Because the vertical vorticity is an effective measurement of vortices, we use the vertical vorticity budget equation from Kirk (2007) as Eq. (1) to analyze the evolution of the vortices.

$$\frac{\partial \zeta}{\partial t} = \underbrace{-\boldsymbol{V}_{\mathrm{h}} \cdot \nabla_{\mathrm{h}} \zeta_{\mathrm{h}}}_{\mathrm{V1}} \underbrace{- \omega \frac{\partial \zeta}{\partial p}}_{\mathrm{V2}} + \underbrace{\boldsymbol{k} \cdot \left(\frac{\partial \boldsymbol{V}_{\mathrm{h}}}{\partial p} \times \nabla_{\mathrm{h}} \omega\right)}_{\mathrm{V3}} \underbrace{- \beta v}_{\mathrm{V4}} \underbrace{- (\zeta + f) \nabla_{\mathrm{h}} \cdot \boldsymbol{V}}_{\mathrm{V5}} + \underbrace{D(\zeta)}_{\mathrm{RES}} , \tag{1}$$

where ζ is the vertical vorticity; $\boldsymbol{V}_{\mathrm{h}}=u\boldsymbol{i}+v\boldsymbol{j}$ is the horizontal velocity vector; $\boldsymbol{i}$, $\boldsymbol{j}$, and $\boldsymbol{k}$ stand for the unit vector points to the east, north, and zenith, respectively; $\nabla_{\mathrm{h}} = \frac{\partial}{\partial x}\boldsymbol{i} + \frac{\partial}{\partial y}\boldsymbol{j}$ is the horizontal gradient operator; $f = 2\Omega\sin\varphi$ is the Coriolis parameter; Ω is the rotational angular velocity of the earth; φ is the latitude; p is the pressure; ω is the vertical velocity in p coordinates; and $\omega = \mathrm{d}p/\mathrm{d}t$ and $\beta = \partial f/\partial y$.

Term V1 stands for the horizontal advection of vertical vorticity; term V2 is the vertical advection of vertical vorticity; term V3 reflects the influence of tilting, namely the conversion between the horizontal and vertical vorticity; term V4 represents the "β effect", which is closely related to the geographical position; term V5 reflects the influences associated with the divergence; and term RES is the dissipation of vorticity due to friction and subgrid processes.

3 The simulation validation and the overview of MBFMV

3.1 The simulation validation

As Fig. 1 depicted, during the life span of the MBFMV, intense rainfall events occur along the MBF, with a maximum 3-h precipitation amount above 35 mm. Our simulation successfully captured the intensity and main trend of the observed rain belt, although the simulated rain belt is approximately 100 km to the north of the observed. The geopotential height field at 500 hPa is also successfully reproduced by the simulation (Fig. 2), especially the leading trough near the eastern coastline. There are differences between the observed and simulated temperature fields; however, the simulation still captures the main characteristics of the observation (Fig. 2). As mentioned above, our simulation is successful and can be used for further studies.

3.2 The overview of MBFMV

As Fig. 2 shows, during the life span of the MBFMV, the amplitudes of the short wave troughs in the middle and high latitudes were large, which indicates the warm and cold air were active. The West Pacific Subtropical High (WPSH) was intense, with its western boundary line at approximately 115°E. There was a short wave trough near the eastern coastline that moved slowly eastward. The trough was important because it provided favorable

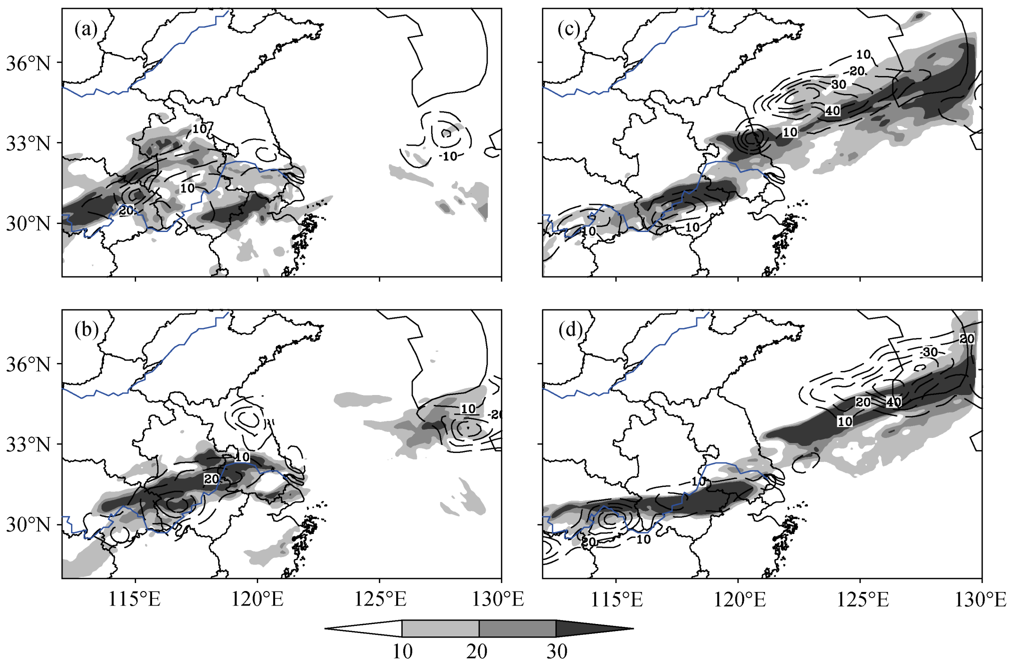

Figure 1 The 3-h precipitation from CMORPH (solid, units: mm) and from the simulation (shaded, units: mm): (a) 0600 UTC 10 July 2010, (b) 1200 UTC 10 July 2010, (c) 1800 UTC 10 July 2010, and (d) 0000 UTC 11 July 2010.

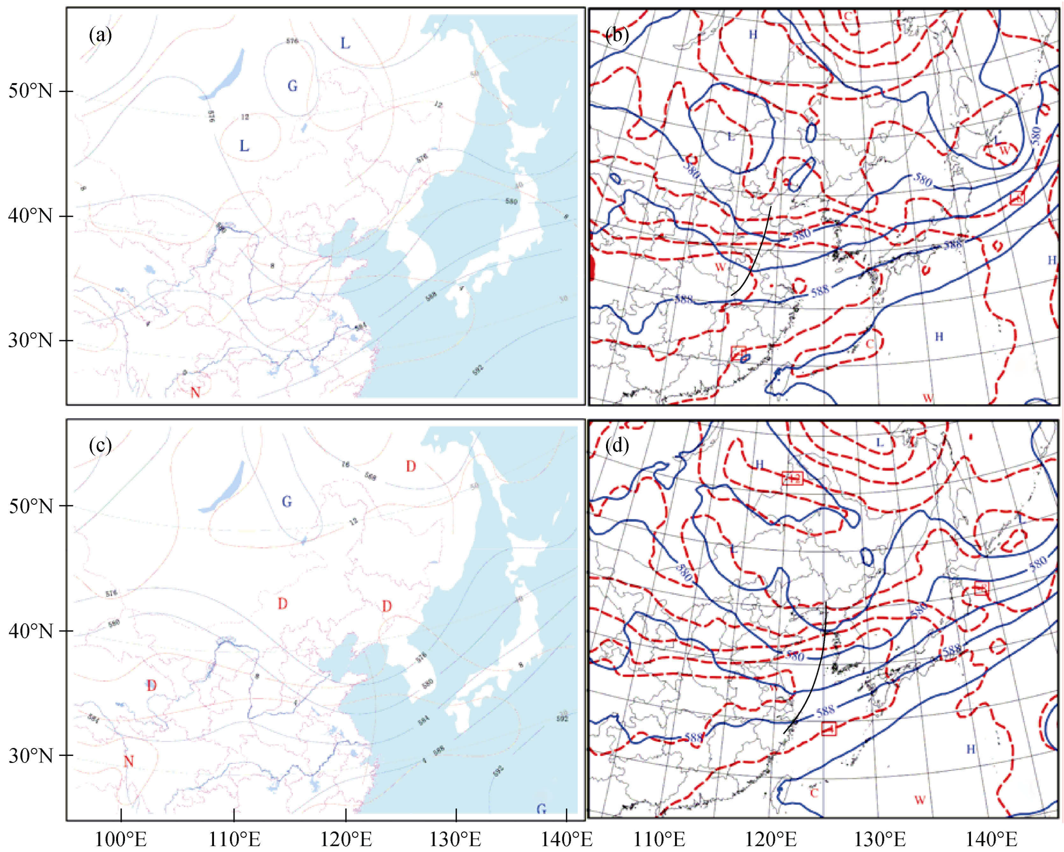

Figure 2 The left column shows 500 hPa weather charts of from CMA, where the blue solid lines represent the geopotential height (units: dagpm, D for low, G for high, L for cold center, and N for warm center) and the red solid lines represent the temperature (units: °C). The right column is the simulation at 500 hPa, where the blue solid lines are the geopotential height (units: dagpm, L for low, H for high, C for cold center, and W for warm center) and the red dashed lines are the temperature (units: °C). (a) 1200 UTC 10 July 2010; (b) 1200 UTC 10 July 2010; (c) 0000 UTC 11 July 2010; (d) 0000 UTC 11 July 2010.

conditions for the formation, development, and sustainment of the MBFMV, moreover, the southwest wind ahead of the trough was vital to the displacement of the vortex. The ULJ at 200 hPa was mainly located at approximately 40°N and stretched from the west to east, whereas the LLJ at 700 hPa was mainly located along the northwestern periphery of the WPSH and stretched from the southwest to northeast (figure not shown). It should be noted that the LLJ was conducive to the precipitations along the MBF, and the coupling of the ULJ and LLJ were important to the convective activities associated with the MBFMV.

The MBFMV formed at 0000 UTC 10 July 2010 (Fig. 3a), then the vortex moved northeastward along the MBF with an enlarging area, increasing vorticity and enhanced ascent until 1800 UTC 10 July, when the MBFMV moved offshore and matured. From 0000 UTC 11 July, the MBFMV began to weaken, and the area of the vortex shrank with time, while the ascents also weakened. The MBFMV dissipated at 1800 UTC 11 July, having lasted for approximately 36 hours. As noted above, the MBFMV is identified from the closed center over the stream field in this study. When the vertical stretch of the vortex is examined form bottom to top, the first level with a closed center over the stream field is defined as the bottom of the vortex, and the last level is defined as the top. Figure 4 shows that the vortex developed from the bottom up and was mainly located in the lower levels of the troposphere with a maximum vertical stretching of 750 hPa (Fig. 4). There were obvious closed low surface centers corresponding to the MBFMV during its lifespan (not shown). To perform a simple but representative analysis, the typical stages of the MBFMV were selected for detailed study: the formation stage (0000 UTC 10 July), the developing stage (0600 UTC 10 July), the maintaining stage (1200 UTC 10 July, 1800 UTC 10 July, and 0000 UTC 11 July), and the decaying stage (1200 UTC 11 July). It should be noted that because the MBFMV moved offshore during the maintaining stage, three typical stages were selected, including the maintaining stage on land, the maintaining stage at transition (as Fig. 3d shows, half of the vortex was on land and half was over the sea), and the maintaining stage at sea to investigate the variation of the maintenance mechanisms.

4 Vorticity budget results

The vorticity budgets are calculated according to Eq. (1), and the terms V1, V2, V3, V4, and V5 as well as the term total are all averaged within the key areas of the

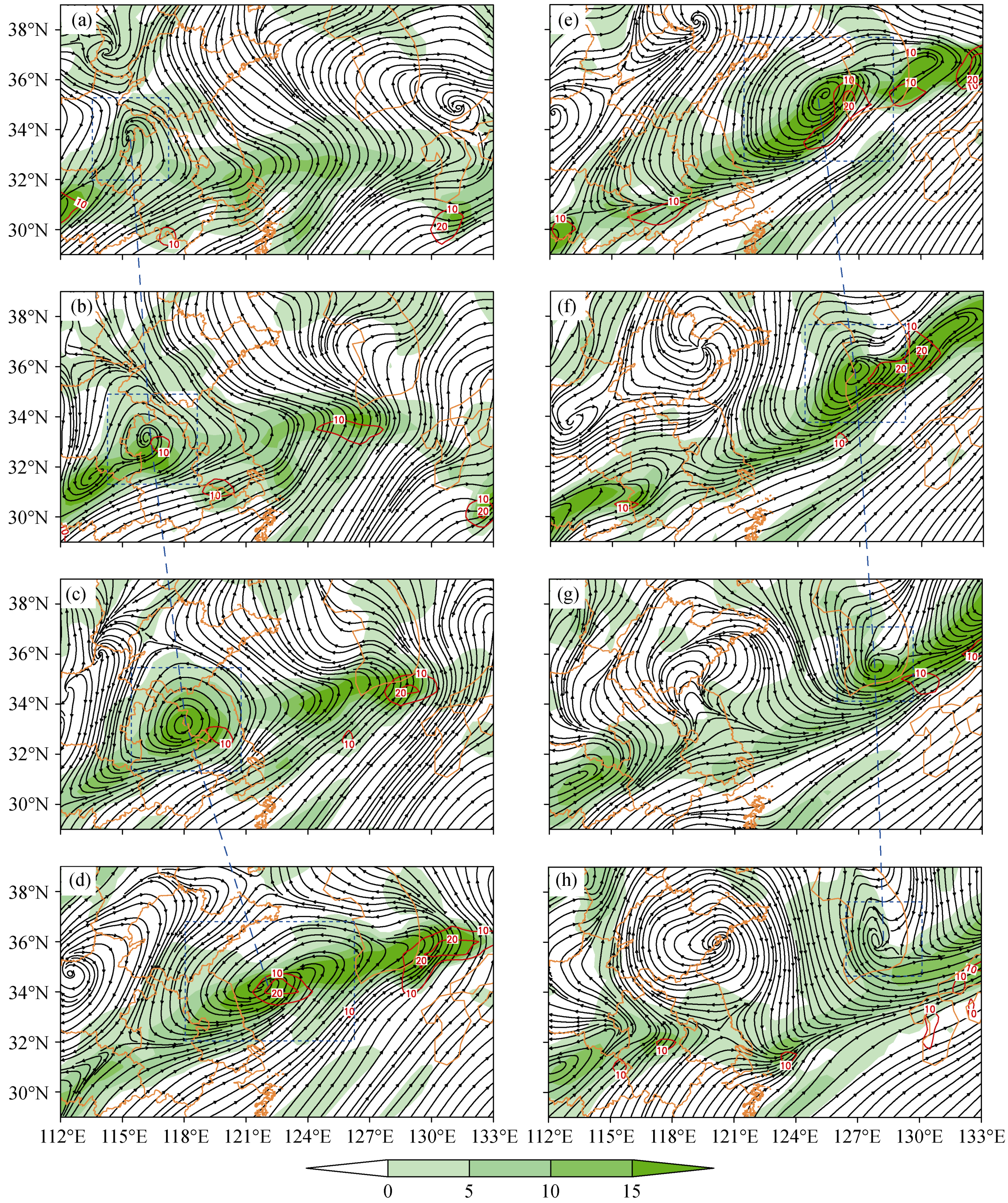

Figure 3 The stream field, vorticity (shaded, units: 10^{-5} s^{-1}) and vertical velocity (dashed, units: 10^{-2} m s^{-1}) at 850 hPa, where the dotted box stands for the key areas of the MBFMV. (a) 0000 UTC 10 July 2010; (b) 0600 UTC 10 July 2010; (c) 1200 UTC 10 July 2010; (d) 1800 UTC 10 July 2010; (e) 0000 UTC 11 July 2010; (f) 0600 UTC 11 July 2010; (g) 1200 UTC 11 July 2010; (h) 1800 UTC 11 July 2010.

MBFMV (the dashed rectangles shown in Fig. 3). The key-area-averaged vorticity budget terms shown in Fig. 5 are used to analyze the variation mechanisms of the MBFMV. During the formation stage, the term total is positive below 750 hPa, which was highly favorable for the formation of the MBFMV (Fig. 5a): below 900 hPa, the convergence was the most important factor for the enhancement of positive vorticity within the key area, while among the levels of 900–800 hPa, the vertical transportation, which was closely related to the convective activities, was the dominant factor. The horizontal advection and the tilting are mainly detrimental to the formation of the vortex. During the developing stage, the term total was obviously enhanced, which was conducive to the development of the MBFMV (Fig. 5b). The convergence dominated the development of the vortex, and the tilting accelerated the development, while the horizontal and vertical advections were unfavorable to the enhancement of the vortex. During the maintaining stage over land, the total effects were favorable for the maintaining of the MBFMV (Fig. 5c). The convergence was the dominant factor in the maintenance of the vortex, whereas the horizontal transportation was the main factor detrimental to its maintenance. During the maintaining stage at the transition, the vortex was moving from land to sea (Fig. 3), and the convergence decreased significantly (Fig. 5d) because the friction at sea is much lower than that over land (fiction at the surface was favorable for the convergence at lower levels). Therefore, term V5 weakened significantly, as did the term total. Convergence and vertical transport were the main factors favoring the sustainment of the MBFMV, whereas the horizontal advection was the main factor detrimental to the maintenance of the vortex. During the maintaining stage at sea, the convergence clearly enhanced (Fig. 5e) because the MBFMV moved eastward and merged with an intense convergence zone to its east (Fig. 3). Meanwhile, the horizontal advection became intensely negative, which canceled out the effects of convergence, leaving moderate positive areas of the term total below 900 hPa. Moreover, the vertical advection was detrimental to the sustainment of the vortex, while the tilting acted conversely. During the decaying stage, the total effects of terms V1, V2, V3, V4, and V5 became negative among the levels of the MBFMV (Fig. 5f), which implies that the vortex weakened quickly. The horizontal transportation of positive vorticity out of the key area dominated the attenuation of the MBFMV, whereas the convergence and tilting slowed the dissipating process of the vortex.

5 Summary and conclusions

In this study, a northeastward moving MBFMV that lasted approximately 36 hours and caused several heavy rainfall events along the MBF was successfully reproduced by the WRF model. Based on the simulation, the MBFMV was investigated in detail, and the main results are as follows. Synoptic analyses indicate that the MBFMV is a type of meso-α vortex with an obvious closed low center at its surface. In this case, the MBFMV developed from the bottom up and was mainly located in the lower troposphere (below 750 hPa). During its lifespan, the WPSH was intense and stable, with its western boundary line at approximately 115°E, and the LLJ along the north border of the WPSH was favorable for the precipitation along the MYF. The amplitudes of the westerly waves in the middle and high latitudes were large, which was conducive to the intersection of warm and cold air and favorable for convective activity. The short wave trough near the coastline was closely related to the MBFMV, and it was highly favorable to the formation, sustainment and displacement of the MBFMV. The vorticity budgets indicate that at lower levels of the MBFMV, the convergence was the dominant factor for the increase of positive vorticity, whereas at high levels of the MBFMV, the vertical transportation associated with convective activities was highly important to the vortex. Because the MBFMV was a positive vorticity source, the horizontal transportation was the main factor decreasing the positive vorticity, and during the decaying stage, the MBFMV dissipated quickly due to the intense horizontal advection. By comparing the typical maintaining stages on land, at transition and at sea, it can be found that when the environment changed, the maintenance mechanisms also changed. When the MBFMV was on land, the convergence associated with the surface friction dominated the sustainment of the vortex; when the vortex was at the transition stage, the surface friction decreased significantly, as did the convergence (Fig. 5d); when the vortex moved offshore and merged with a convergence zone within the MYF, the convergence intensified remarkably (Fig. 5e) and again became the dominant factor of the sustainment. Therefore, it can be concluded that the land and sea environment are crucial to the evolution of the MBFMV. Moreover, the characteristics of the MYF are also vital to the variation of the vortex. However, the influence of the latent heat and sea surface fraction on the evolution of the vortex is not discussed. This influence could be important, and this issue needs to be studied and clarified in the future.

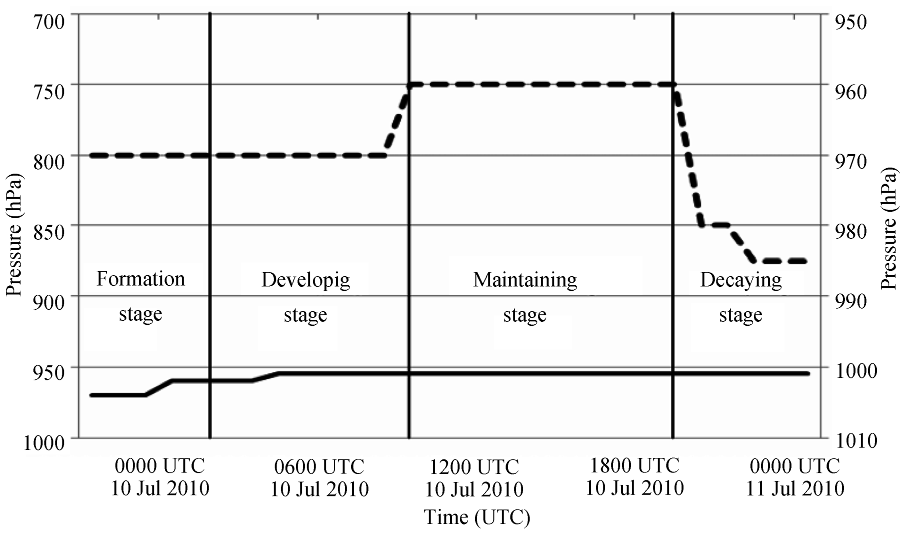

Figure 4 The top level of the MBFMV (dashed line) and the sea level pressure (solid line, units: hPa) averaged in key areas of the MBFMV.

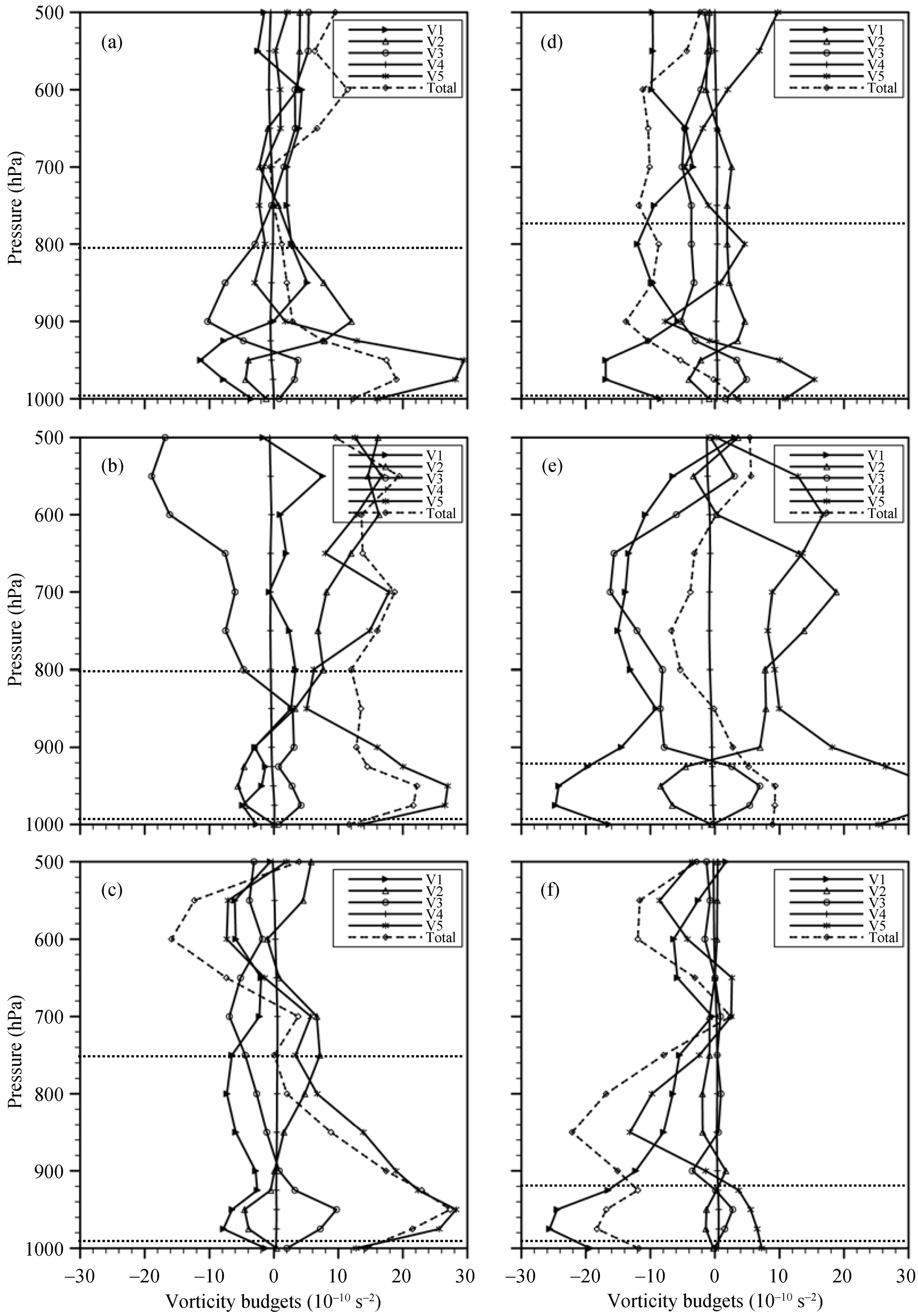

Figure 5 The vorticity budgets (units: 10^{-10} s^{-2}), where terms V1, V2, V3, V4, and V5 are the same as in Eq. (1), and the term Total stands for the total effects of terms V1, V2, V3, V4, and V5. (a) Formation stage (0000 UTC 10 July 2010); (b) developing stage (0600 UTC 10 July 2010); (c) maintaining stage on Land (1200 UTC 10 July 2010); (d) maintaining stage while moving (1800 UTC 10 July 2010); (e) maintaining stage at Sea (0000 UTC 11 July 2010); and (f) decaying stage (0600 UTC 11 July 2010).

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