STRUCTURAL FEATURES OF THE MEIYU FRONT SYSTEM*

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ABSTRACT

A new subtropical front near the periphery of the West Pacific subtropical anticyclone is found, which is never revealed in previous studies. The coupling of the subtropical front and Meiyu front forms a Meiyu front system (MFS) and is the most direct synoptic system for the Meiyu precipitation along the Mid-lower Reaches of Yangtze River (MRYR) in China. In this paper, The detailed structural features and cloud features of the MFS in 1998 and 1999 are analyzed, which manifests that the MFS is an objective phenomenon over the period of Meiyu along MRYR and the Southwest Japan. Generally, the subtropical front is mainly located between 850 hPa and 500 hPa. The moist southwest monsoon is transported in the passageway between the Meiyu front and the subtropical front. The vertical motion ascends in the passageway and descends on both sides of the MFS, forming the MFS's secondary circulation. A lower TBB band indicated that obvious convective activities are also located in the passageway of MFS. The horizontal wind of MFS is vertically asymmetric.

Key words: Meiyu front, subtropical front, Meiyu front system (MFS), structural features

I. INTRODUCTION

During June and July, from the Mid-lower Reaches of Yangtze River (MRYR) in China to the Southwest Japan, a precipitation zone appears and lasts for two to three weeks with high potential of torrential rain. This phenomenon is called as Meiyu in China and Baiu in Japan. In the period of Meiyu, the precipitation is excessively intensive, and serious floods often occur over the MRYR. The precipitation and floods cause tremendous damage to infrastructure, industry, agriculture, and people's lives. Chinese history recorded massive floods occurring in 1954, 1991, 1998 and 1999 over the MRYR. Therefore, the Meiyu has always been an important topic of meteorological research. Especially, meteorologists in China and Japan have particular interests in Meiyu. Previous researches showed that the Meiyu is mainly caused by the Meiyu front (or Baiu front in Japan) (Tao 1958; Matsumoto and Akiyama 1970) —a quasi-stationary front oriented in the northeast-southwest direction at lower levels. The Meiyu front is mainly characterized by the moisture contrast, and therefore, is expressed by a very dense gradient zone of θ_e isolines. A narrowly zonal precipitation band always exists near the Meiyu front and to its

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south, which makes meteorologists think that the Meiyu is caused by the Meiyu front. Therefore, Chinese and Japanese meteorologists have been attracted and studied various aspects of the Meiyu front (Tao 1958; Lin 1979; 1981; Zhang and Zhang 1990; Hu 1997; Hu and Peng 1995; Si 1989; Zhou 1996; Akiyama 1984a; 1984b; 1989; 1990; Gao et al. 1990; Iwasaki and Takeda 1993; Matsumoto et al. 1967; 1971; Ninomiya 1984; Ninomiya and Kurihara 1987; Ninomiya and Akiyama 1992).

The Meiyu front only reflects a convergence zone caused by the confluence of summer monsoon in East Asia and dry-warm air over Asia Continent, therefore, obvious convective activities and dense moisture gradient exist along the convergence zone, which causes apparent precipitation. This is only one aspect of the adjustment of the atmospheric circulation in East Asia. Another important aspect is the northward motion and westward extension of the West Pacific subtropical anticyclone (WPSA hereinafter). Although it has been proved that the intensity and location of the WPSA is a key factor to the Meiyu precipitation, the traditional method was to analyze the intensity of the WPSA by using 5880 gpm on 500 hPa, and the northward stretched position of the ridge-line of the WPSA on 500 hPa. The intensity of the WPSA on other levels was not examined. However, the WPSA on 500 hPa can not completely reflect three-dimensional structural features of the WPSA. It is obviously insufficient and unilateral to judge the enhancement of the WPSA by the 5880 gpm variation on 500 hPa, because the latter is unstable in the early summer. Even if the range covered by 5880 gpm is very wide on 500 hPa, it is only an intensive signal of the WPSA on 500 hPa. This signal does not imply whether the WPSA is strong or weak on other levels. Sometimes, it happens that the WPSA strengthens at the upper level and weakens at the lower level. Thus, the intensity of the WPSA on 500 hPa can not represent its intensity at lower levels. Meiyu precipitation is closely related to activities of the WPSA, but the stability features of the WPSA have never been well studied. The description of intensity and stability of the WPSA at lower levels is still unsatisfactory. Recently, the three-dimensional structures of the WPSA are analyzed, when the WPSA moves westward and becomes stable over the continent of China, the lower-level air temperature increases in the periphery of the WPSA because of air adiabatic sinking. It makes airflow in the sinking region drier than southwest monsoon flow. Therefore, as the moist southwest monsoon flow meets the relatively dry sinking airflow, a sharp moist transitional zone forms. This moist transitional zone just is a new subtropical front. The subtropical front is different from the Meiyu front (the Meiyu front is a quasi-stationary front), and the marked features of the subtropical front is that its location varied with the moving of the WPSA. When the WPSA moves westward and becomes stable, the subtropical front couples with the Meiyu front, then the two fronts force the southwest monsoon to transport moisture along the passageway between the two fronts, therefore, the moisture is continuously transported to MRYR in China and the Southwest Japan. It makes MRYR and Southwest Japan continuously increase moisture and warming. As a result, a potential unstable region of the moist potential energy forms in the passageway, and when it is disturbed, the instability easily occurs and will induce convective activities with inhomogeneous precipitation. It means that only when we consider the coupling of the Meiyu front and the subtropical front, can we really grasp the main features of the adjustment of atmospheric circulation in East Asia. Yang et al. (1998) paid attention to the existence of symmetric double fronts during the second period of Meiyu in 1998. The data they used were the conventional observational data, and they did not give out the whole coupling features between the subtropical front and the Meiyu front, and did not explain how the subtropical front forms. In this paper, the coupling structural features and cloud features between the Meiyu front and the subtropical front (hereafter, we call the coupling of the two fronts as Meiyu front system, abbreviated as MFS) are analyzed, a rather complete conceptual model of the MFS is given. Because the subtropical front also has obvious moisture contrast, it is also indicated by the large gradient zone of the equivalent potential temperature θ_e.

II. STRUCTURAL FEATURES OF THE MFS

By using the daily 1°×1° data of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), the three-dimensional structures of the WPSA are analyzed, and the new subtropical front near the periphery of the WPSA is found. This front is a phenomenon not yet reported in existing literatures. In Fig. 1a, there are two concentrative belts of θ_e isolines, one in the north (around 35°N) corresponds to the traditional Meiyu front, and the other in the south (around 25°N) corresponds to the subtropical front near the periphery of the WPSA. In the MFS, there is a passageway with a remarkably high value region of specific humidity, which extends from surface to 350 hPa indicated by the dashed line, and forms an obvious humidity ridge. From Fig. 1b, it is also seen that the concentrative belt of θ_e isolines near 30°N, corresponding to the traditional Meiyu front, and the concentrative belt of θ_e isolines near

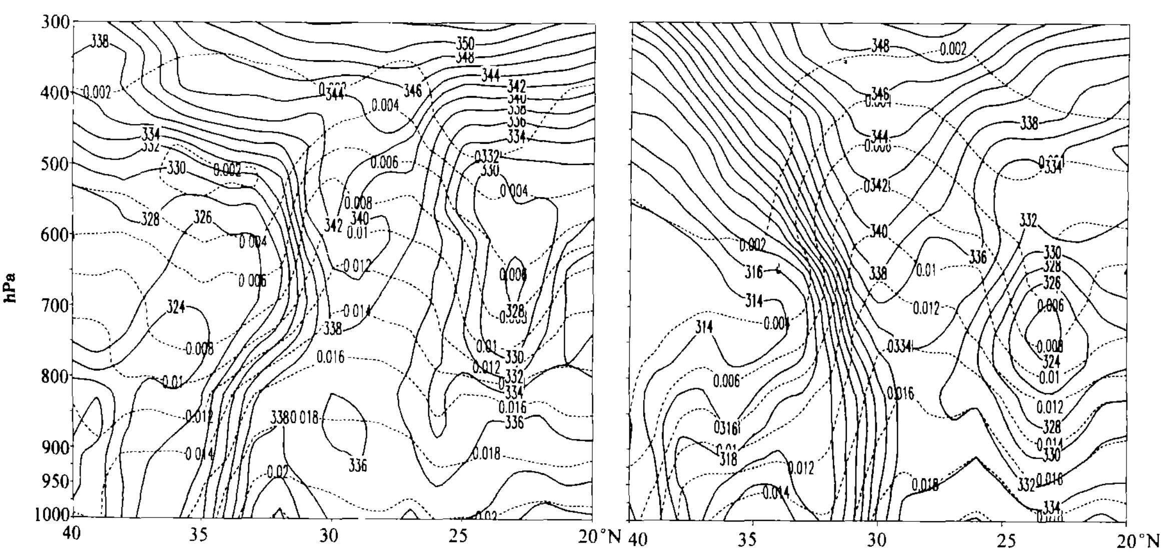


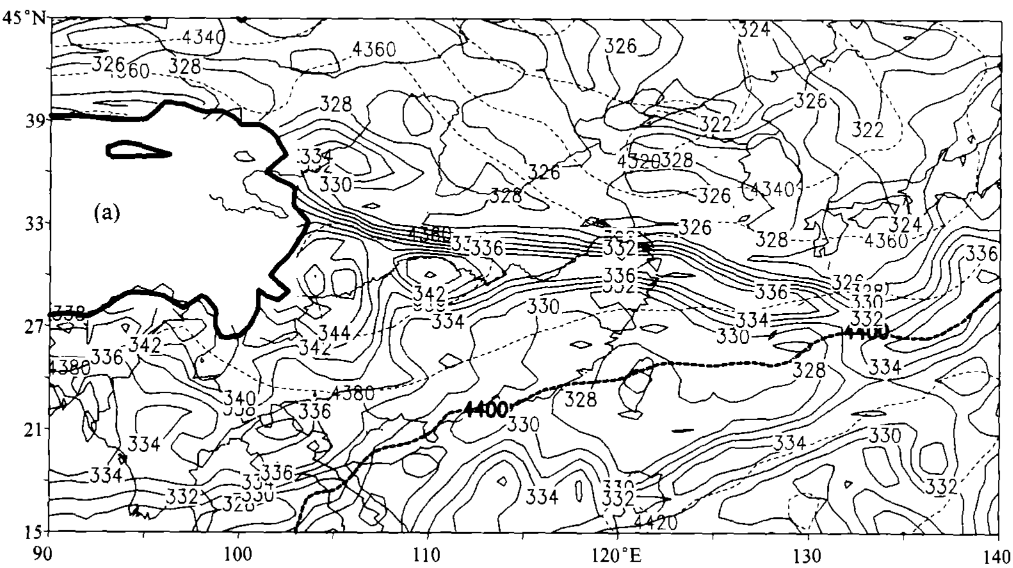
Fig. 1. Meridional cross-sections of θ_e and q: (a) along 117°E at 0000 UTC 23 July 1998; (b) along 118°E at 0000 UTC 24 June 1999. Solid line: θ_e (unit: K), and dashed line: q (unit: g g^{-1}).

25°N indicates the existence of the subtropical front. From the meridional cross sections, it is shown that the subtropical front is mainly located at the mid-lower levels in troposphere, and a high humidity region exists between the Meiyu front and the subtropical front.

Figures 2a and 2b are distributions of θ_e isoline on 600 hPa at 0000 UTC 22 July 1998 and on 500 hPa at 0000 UTC 24 June 1999, respectively. In Fig. 2a, there are two clusters of large gradient zones of θ_e isoline separately located to the north and south of 30°N, which is the MFS's embodiment on the constant pressure. The MFS elongates along MYRY in China to the Southwest Japan, therefore, a passageway form between the two fronts along MYRY in China and the Southwest Japan. With the MFS stretching to east, the subtropical front and the Meiyu front become closer and closer. The MFS over ocean is less obvious than over continent. The tendency of combining of the MFS can also be seen in Fig. 2b.

The MFS mainly appears in the period of Meiyu in 1998 and 1999. Before the period of Meiyu, the subtropical front is not obvious on constant pressure charts, but with enhancement of both the southwest monsoon flow and the adiabatic sinking flow in the periphery of the WPSA, the contrast of air moisture becomes distinct. As a result, the subtropical front forms near the periphery of the WPSA during the period of Meiyu, and elongates from 105°E to 135°E. Late in the period of Meiyu, the subtropical front becomes short and mainly exists over the continent of China. In the end of the period of Meiyu, the subtropical front disappears.

Analysis of the day-to-day distribution of rainfall zones during the period of Meiyu in 1998 and 1999 manifests that the rainfall zones are mainly situated in the MFS (figures omitted). It indicates that precipitation is strongly controlled by the MFS during the Meiyu period, because moisture from the Bay of Bengal and the South China Sea is mainly



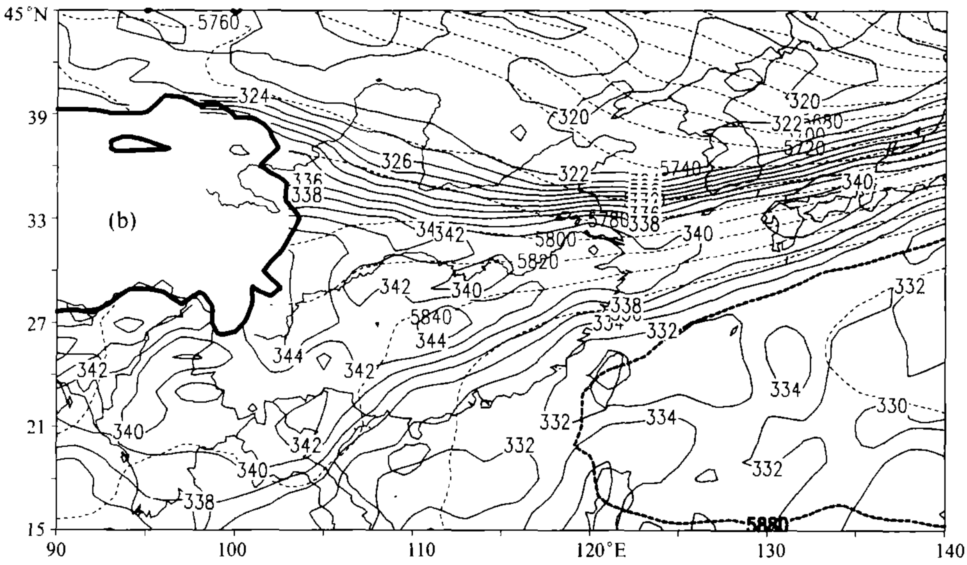


Fig. 2. Distribution of θ_e and geopotential height Φ: (a) on 600 hPa at 0000 UTC 22 July 1998; (b) on 500 hPa at 0000 UTC 25 June 1999. Solid line: θ_e (unit: K), dashed line: Φ (unit: gpm), thick-dashed line in (a): 4400 gpm, and thick solid line: 4000 m contour of the Tibetan Plateau. Thick-dashed line in (b): 5880 gpm.

transported by the southwest monsoon through the passageway of the MFS. This moisture transportation leads to a great amount of moisture convergence along the MRYR to the Southwest Japan. This provides a good condition for the strong convective activities and heavy precipitation. Figures 1a and 1b indicate that between 1000 hPa and 700 hPa in the MFS, there is a $\frac{\partial \theta_e}{\partial p}>0$ region that is propitious to convective developement. The zonal wind field (Figs. 3a and 3b) clearly shows that very strong west wind prevails at upper levels (above 300 hPa) over and to the north of the Meiyu front, and east wind exists below 600 hPa to the north of and against the Meiyu front. There is very strong vertical wind shear between 600 hPa and 650 hPa because of the interface of east and west winds. Over the subtropical front, the east wind prevails on 300 hPa, and the southwest wind exists at lower levels. The vertical asymmetric structure of the horizontal wind field is favorable to the shear instability and energy transportation caused by the turbulence exchange.

Above is the day-to-day analysis of the subtropical front and the MFS, we have also analyzed the temporal mean structure of the MFS during the whole period of Meiyu in 1998 and 1999. In Figs. 4 and 5, there are two dense zones of θ_e isolines identified, they correspond to the Meiyu front and the subtropical front, respectively, and constitute the MFS, in which a high humidity ridge appears. In Fig. 5, the strong descending motion is evident from 25°N to 27°N in the mid-lower troposphere. The maximum descending speed is up to 0.3 Pa s^{-1}. Such a descending motion promotes the formation of the subtropical front. Meanwhile, there is a very strong ascending motion in the MFS (between 30°N and 27°N). The maximum ascending speed is as high as 0.6 Pa s^{-1}, which is favorable to the

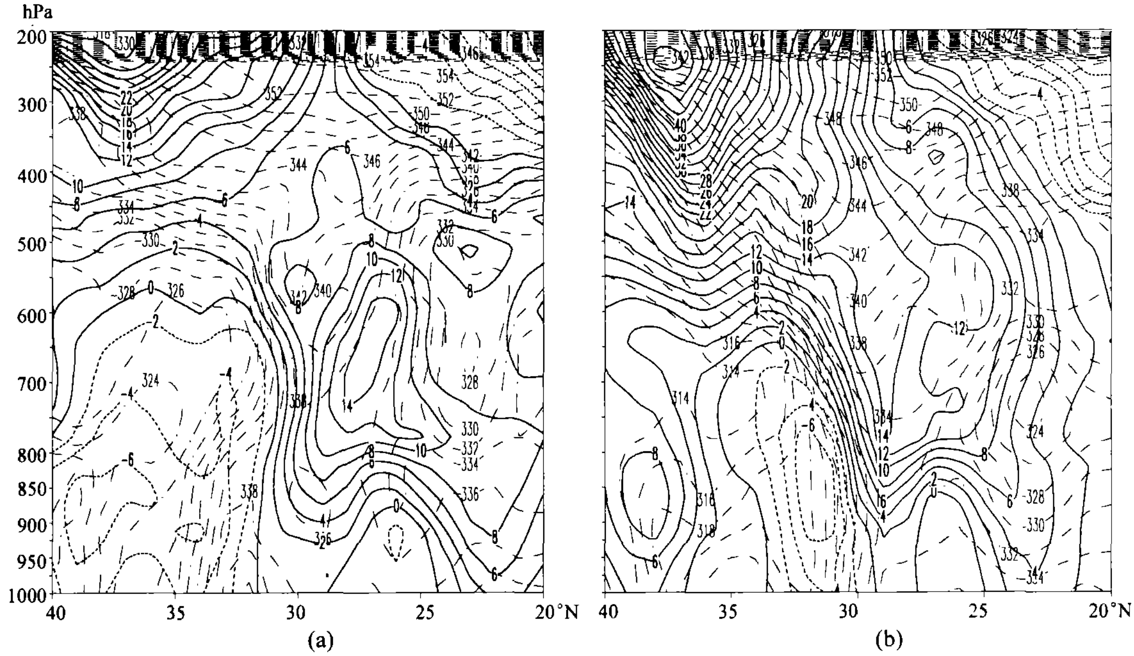
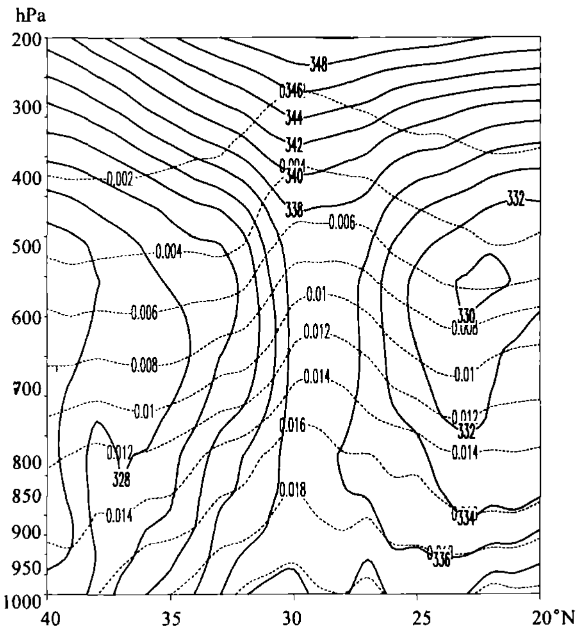


Fig. 3. Meridional cross-sections of the component of zonal wind u (unit: m s^{-1}) and equivalent potential temperature θ_e: (a) along 117°E at 0000 UTC 23 July 1998; (b) along 118°E at 0000 UTC 24 June 1999. Solid line: $u>0$ (west wind), dashed line: $u<0$ (east wind), and long-dashed line: θ_e (unit: K).

vertical transportation of moisture, and makes a high humidity ridge in the MFS. The ascending motion and its adjacent descending motion form the secondary circulation of the MFS. This is an important feature of the MFS.

Through analyzing the every 3-hour interval GMS cloud images during the period of Meiyu in 1999 (figures omitted), it can be found that clouds are mostly located in MFS and move eastward. Meso-micro scale cloud clusters are also situated in the passageway of MFS (Figs. 6a and 6b). Clouds of MFS always stretch from the Tibetan Plateau and along MRYR in China to the Southwest Japan, and are accompanied with obvious convective activities. Cloud bands located in the passageway of MFS correspond to precipitation bands. Especially, some sub-synoptical and meso-micro scale cloud clusters can be distinguished from the large-scale cloud system, it means that stronger convective activities occur in regions covered by meso-micro cloud clusters. Plotted in Fig. 7 is the averaged values of the daily 3-hour interval TBB data. This figure indicates that the region of lower TBB values elongates from the Tibetan Plateau and along the MRYR in China to the Southwest Japan, exactly along the passageway of MFS. It testified that the passageway of MFS is a region with strong convective activities during the period of Meiyu. Some lower value centers of TBB embedded in the low TBB band correspond to stronger convection in those regions. Therefore, both the large-scale cloud system and meso-micro cloud clusters mostly develop and move eastward in the passageway of MFS. It is obvious that the existence of MFS is an important background to the formation of cloud system and cloud cluster.



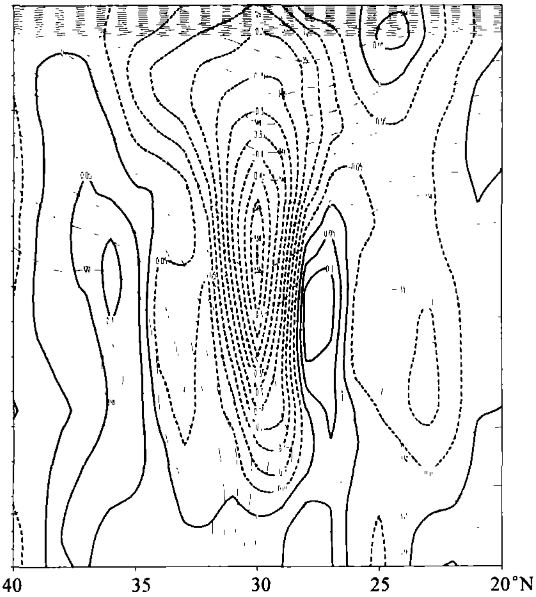


Fig. 4. Averaged meridional cross-section of θ_e and q along 117°E during the period of Meiyu (from 17 July to 2 August) in 1998. Solid line: θ_e (unit: K), and dashed line: q (unit: g g^{-1}).

Fig. 5. Averaged meridional cross-section of vertical motion ω (unit: Pa s^{-1}) and θ_e along 118°E at 0000 UTC during the period of Meiyu (from 22 June to 3 July) in 1999. Solid line: $\omega < 0$ (descending motion), dashed line: $\omega > 0$ (ascending motion), and long-dashed line: θ_e (unit: K).

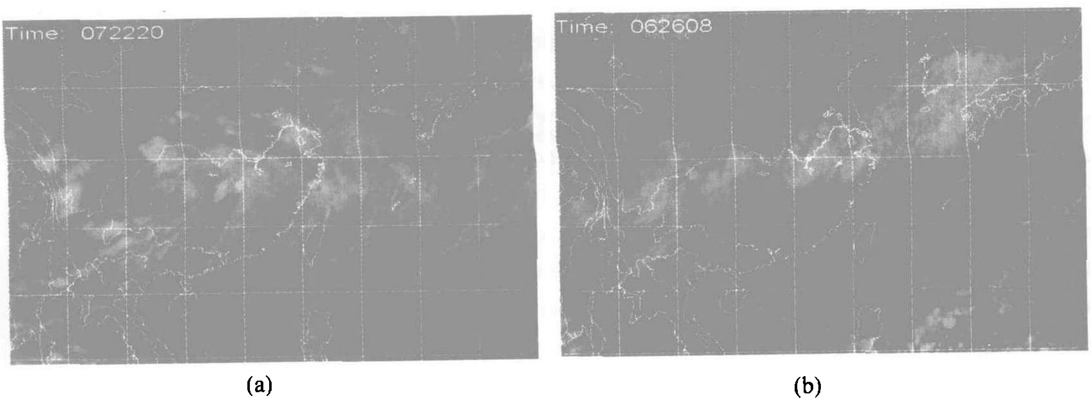


Fig. 6. Infrared cloud images at (a) 2000 UTC 22 July 1998, and (b) 0800 UTC 26 June 1999.

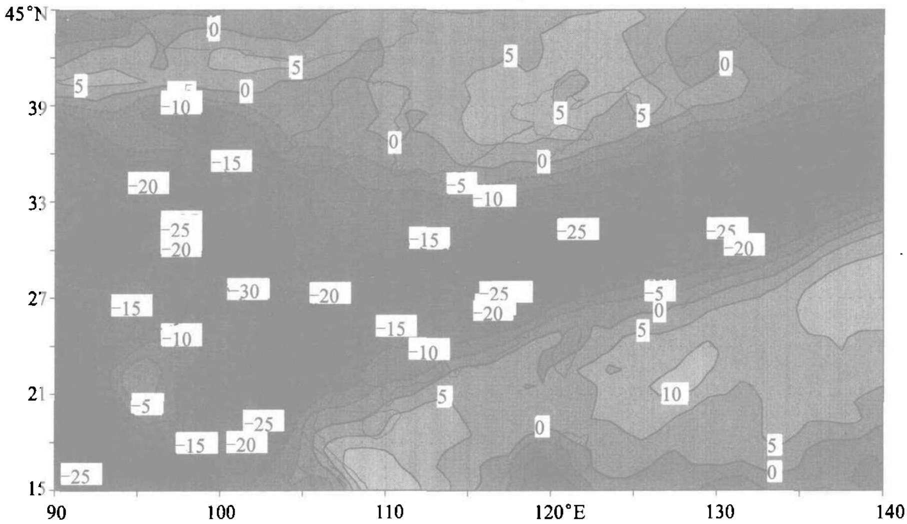


Fig. 7. Distribution of mean TBB in the whole Meiyu period from 0000 UTC 22 June to 2300 UTC 3 July 1999 (unit: °C).

The above analyses reveal the structural features and cloud features of MFS. The results manifest that the coupling of the Meiyu front and the subtropical front is an important characteristic and the MFS properly marks the adjustment features of circulation in East Asia during the period of Meiyu.

III. SUMMARY

The daily 1°×1° data of NCEP/NCAR, the black body temperature (TBB) data of cloud top, and cloud images of Geostationary Meteorological Satellite (GMS) are used to identify a subtropical front near the periphery of the West Pacific subtropical anticyclone. The importance of the subtropical front lies in that it can promote the transportation of the warm and moist southwest monsoon flow along the passageway of the MFS and the subtropical front blocks the warm and moist flow to penetrate southward widely. The flow is forced to lift to upper levels resulting in upward transportation of moist air and forms a narrow humidity ridge. As the moist air extends to upper levels in the passageway of the MFS, a region with deep potential instability forms along the MRYR, which is favorable to the development of strong convection and causes heavy rain. During summer in 2000 and 2001, it was dry over MRYR, the subtropical front was very weak (in 2000) and did not appear (in 2001), which maybe means that the existence of the subtropical front is a key factor to the occurrence of strong Meiyu. The strong Meiyu in 1998 is a typical example (Fig. 4). Analyses in this paper have clearly demonstrated the existence of the subtropical front, which has never revealed in previous studies. A conceptual model of MFS is given: the Meiyu front is a north branch of the MFS and located near 30—34°N, the subtropical front is a south branch of the MFS, situated at the range from 23°N to 28°N. The Meiyu front and the subtropical front both mainly take a southwest-northeast orientation. From analyses in this paper, the MFS mainly settles from 850 hPa to 500 hPa. The passageway formed by the coupling of the Meiyu front and the subtropical front is a necessary condition for the moisture transportation by southwest monsoon, and most clouds also occur in this passageway. The horizontal wind is asymmetric in MFS. The vertical motion ascends in the passageway and descends on both sides of the MFS, which forms the secondary circulation of MFS. The MFS can properly mark the adjustment features of circulation in East Asia during the period of Meiyu.

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