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Convective Cloud Systems over the Tibetan Plateau and Their Impact on Meso-Scale Disturbances in the Meiyu/Baiu Frontal Zone —A Case Study in 1998—

Tetsuzo YASUNARI and Takeshi MIWA[1]

Hydrospheric Atmospheric Research Center, Nagoya University, Nagoya, Japan

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Abstract

The relationship between convective activity over the Tibetan Plateau (TP) and meso-scale cloud systems in the Baiu/Meiyu frontal zone, are examined for the 1998 summer monsoon season by using GEWEX Asian Monsoon Experiment (GAME) reanalysis data and Geostationary Meteorological Satellite (GMS)-IR Tbb data.

Diurnal cycle of the plateau-scale heat low associated with convective clouds is dominated, forming a plateau-scale convergence line. Moisture transport from south of TP is essential for developing convective clouds, and the convergence line. Occasionally, the convergence line extends to the eastern edge of the TP, which triggers a meso-scale cyclonic vortex over the head of the Yangtze River basin through the plateau edge cyclogenesis (PEC). This vortex induces a strong low level jet with moisture inflow to the east of it, which facilitates further development of the vortex to a meso-α scale cloud system embedded in the Baiu/Meiyu front (BMF) over China. The occurrence of PEC is likely to be modulated by an interaction between mid-latitude westerly waves, with a quasi-biweekly time scale, passing over the TP, and a shorter-period oscillation of the monsoon trough over the Indian sub-continent, with around a 4–7 day period.

1. Introduction

The Baiu/Meiyu front (BMF) is one of the most remarkable subtropical fronts in the world, and produces a large amount of precipitation over East Asia covering China through Japan during early summer. Its strong (or weak) activity sometimes causes floods (or droughts) in this region. Therefore, it is important to understand genesis and evolution processes of the rainfall systems, embedded in BMF.

Many previous studies for the several decades related to the BMF activities have been made from various viewpoints summarized as follows;

(1) BMF corresponds to a quasi-stationary cloud zone located along the northern periphery of the warm and humid maritime tropical air mass, and is characterized by the large meridional moisture gradients (e.g., Ninomiya and Muraki 1986; Ninomiya and Murakami 1987).
(2) BMF is associated with a strong southwesterly at 700–900 hPa called the low level jet (LLJ), which transports a large amount of moisture to the BMF, and generates not only moisture gradients but also a thick, moist, neutral layer (e.g., Ninomiya and Akiyama 1974; Akiyama 1975).

Corresponding author: Tetsuzo Yasunari, Hydrospheric Atmospheric Research Center, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan.
E-mail: yasunari@hyarc.nagoya-u.ac.jp
1 Present affiliation: Japan Meteorological Agency
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(3) The structure of the BMF changes from region to region, as well as in the seasonal march, e.g., the BMF over China has little temperature gradient but large moist gradients, whereas over Japan, the temperature gradient is more dominate (Kato 1985).
(4) the BMF embeds many medium to meso-scale disturbances, which move eastward along the front as developing and cause heavy rains. The disturbances tend to develop near Japan, where the temperature gradient is large (e.g., Iwasaki and Takeda 1993; Ninomiya 2000; Shibagaki et al. 2000).

In understanding genesis and development of the BMF rainfall systems over China, we cannot ignore the orographic effects of the Tibetan Plateau (TP). Kato (1985) suggested that the rapid heating over the plateau in early summer results in weakening and disappearance of the upper westerly jet, flowing to the south of the plateau. This heating causes separation of the upper frontal zone from the lower frontal zone over East Asia and promotes the change of frontal characteristics. Through the numerical experiments, Sun and Lorenzo (1984) showed that the orography of the plateau played a key role to maintain the southwesterly LLJ in the southeastern side of the plateau. Ninomiya and Muraki (1986) suggested that the TP partially contributes to generate a moisture gradient in the BMF through restraining the southern humid air mass from moving north by an orographic effect. Murakami and Huang (1984) studied cyclogenesis and developing processes of disturbances over the area from the TP to East Asia during early summer in 1979. They indicated that some of the vortices over the TP, which are frequently generated in the boundary layer over the plateau, move eastward as developing, and cause rainfall over South China.

During the Baiu/Meiyu season in 1998, severely-heavy rain and flood events occurred in the Yangtze River basin in late June through July. Many studies indicated that heavy rains and floods in China during the Baiu/Meiyu season were closely associated with the meso-scale disturbances generated over the Sichuan basin, which is called the southwest (SW) vortex (Tao and Ding 1981; Ding 1992). The disturbances are thought to be generated, and develop by latent heating, through convective activities originating over the TP, and moving eastward toward the Plain area of China (Wang 1987; Kuo et al. 1986; Wang et al. 1993; Cheng et al. 1998). Some studies focused on the heavy floods over Yangtze River basin in 1998, pointing out that the convective activity over the TP might have some relationship to the heavy rain over the Yangtze River basin. For instance, Li and Chen (2001) showed a negative correlation between the convective activity over the BMF and that over the TP for rainy season in 1998. However, few studies have been devoted to understanding the full evolution processes, including the role of diurnal cycle of convective activity over the TP, development of the meso-scale systems, and their consequences in rain systems in the BMF.

Fortunately, the period from April to October in 1998 corresponded to the intensive observing period (IOP) of GAME (GEWEX Asia Monsoon Experiments). One of the objectives of GAME-IOP was to obtain better data for full understanding of energy and water cycle processes in the Asian monsoon system, including the diurnal cycle, water vapor transport, meso-scale disturbances and roles of land-atmosphere interactions. Enhanced radiosonde observations based on four times (00, 06, 12, 18Z) per day were made at more than 100 sites in the Asian monsoon region, including the TP, the Yangtze River basin, Thailand and so on. Based on these observations, the objectively analyzed GAME reanalysis data was produced with better quality and high time-space resolution. As part of GAME-IOP, coordinated intensive observations were made over the TP, under the cooperation between GAME-Tibet, and the second Chinese Tibetan Plateau scientific experiment (TIPEX). Some of the meteorological results during the GAME-IOP over the TP were already reported elsewhere (e.g., Uyeda and Yamada 2001; Xu et al. 2002; Wang et al. 2003; Fujinami et al. 2005; Yamada and Uyeda 2006).

The purpose of this study are to scrutinize the relationship between convective activity over the TP, and that over the BMF during the Baiu/Meiyu season in 1998, and solve how convective activity over the TP influenced the heavy floods over the Yangtze River Basin by using GAME reanalysis data, and GMS-IR Tbb data.

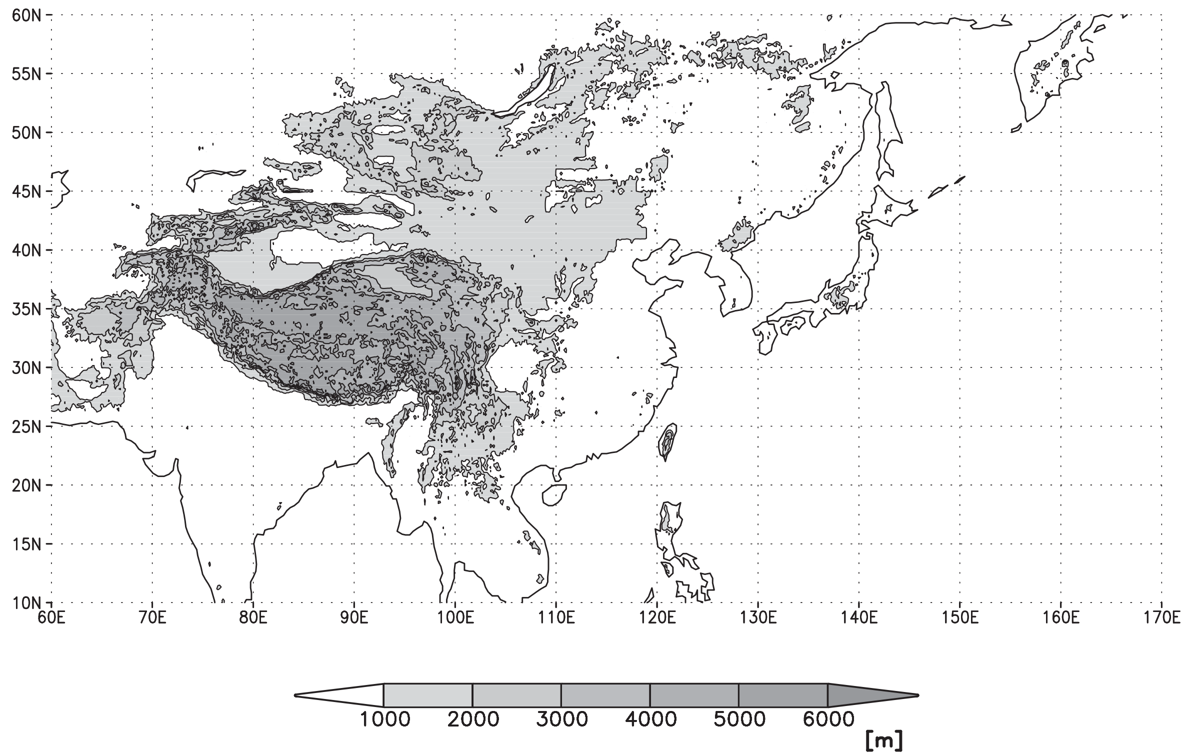

Fig. 1. Study area.

2. Data and method of analysis

We used GAME reanalysis data Version 1.1, to analyze the atmospheric field over the study area, with spatial resolution of 0.5° and temporal resolution of 6 hours for May to September in 1998, in the Asia area. The data assimilation was made by the Japan Meteorological Agency (JMA) global operational model, using the enhanced radiosonde observation data during the GAME-IOP, as well as global operational observation data. The details of this data are described in Yatagai et al. (2000), and Ueda et al. (2003). We also used the Geostationary Meteorological Satellite (GMS)-IR Tbb (Infrared black-body equivalent temperature) data, to analyze the convective activity over Asian monsoon region from June to July in 1998, in particular East Asia from the TP to Japan. The study area including the orography of the TP is shown in Fig. 1. Tbb represents cloud top temperature calculated from the intensity of the infrared radiation from earth, when an area is covered by clouds. Lower Tbb values correspond to higher cloud top height, and means intensive convective activity. GMS-IR Tbb data, with 1.0° horizontal resolution and with 3 hourly time resolution, are used in this study.

3. The convective activity over East Asia during the Baiu period in 1998

To understand the relation between the convective activity over the TP, and that over the BMF zone, the longitude-time section of Tbb along 30°N from June to July in 1998 is produced, as shown in Fig. 2. We find two major regions with active convection as indicated with low Tbb values in Fig. 2. One is over the TP to the west of 105°E, the other region is over the plain area in China through the East China Sea. The convective activity over the TP shows a prominent diurnal change, in particular since June 13, which corresponds to the onset of rainy season in the eastern part of the TP (Li and Chen 2001). The convectively active region with diurnal cycle first appeared over the eastern part of the TP at the beginning of June, expanded westward after June 13, and

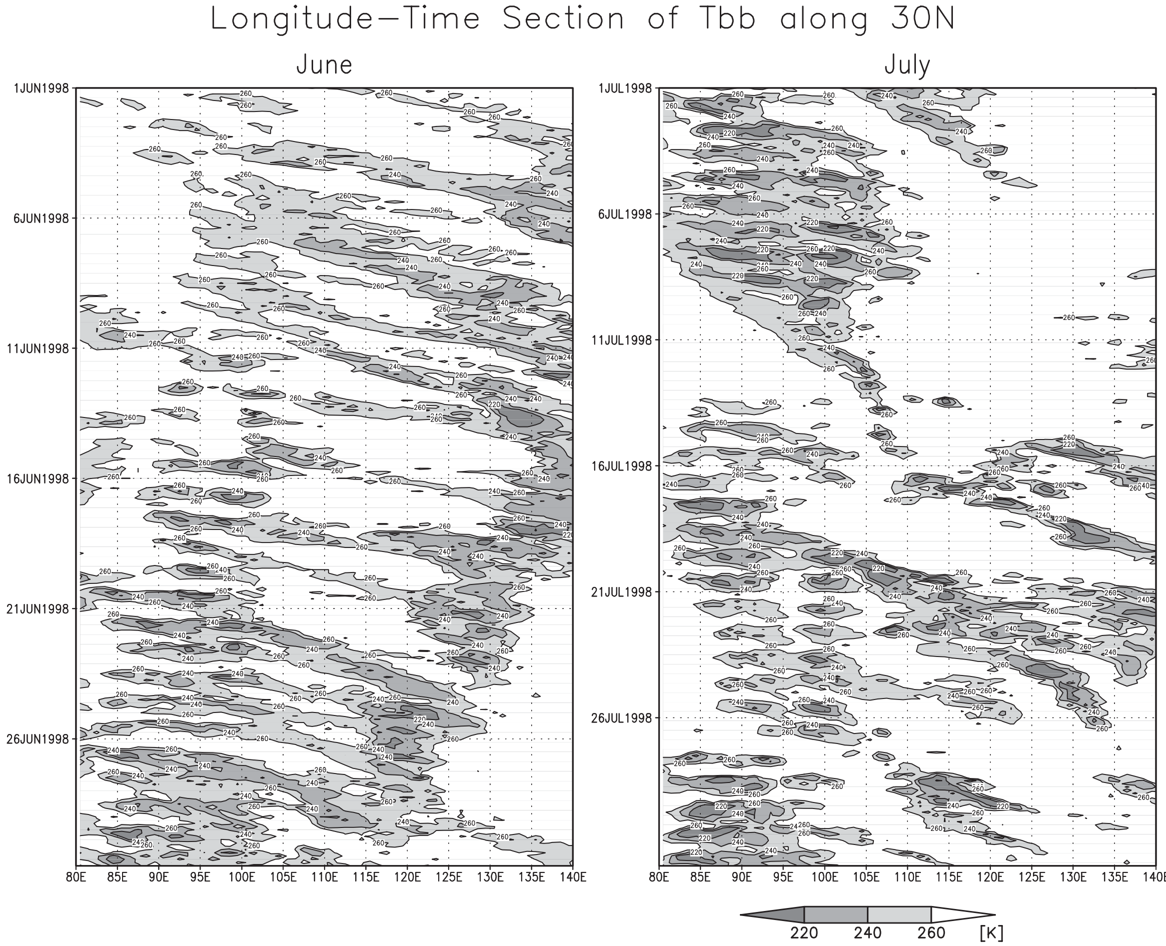

Fig. 2. Longitude-time section of Tbb along 30°N during June to July in 1998. The area lower than 260 K on Tbb is shaded to show the cloud activity. In this latitude, the area of 80–100°E corresponds to TP.

reached to the western part (80°E) by the end of the month. The westward expansion of active convection was closely related with the westward movement of summer monsoon onset over the TP, as shown by Li and Chen (2001). Another characteristic of the convective activity over the TP, was its quasi-periodic variations of about two weeks as is remarkably seen in the amplitude modulation of diurnal change of Tbb with maxima in 1–10, 16–20, and the end of July. This quasi periodic variation of convective activity was known as a sub-monthly-scale intraseasonal variation, notably seen in the Asia monsoon area (e.g., Nitta 1983; Fujinami and Yasunari 2001, 2004). On the other hand, the major region of convective activity over the plain area in China, and the East China Sea, moved westward toward the TP in the latter half of June. Afterward, it disappeared in the first half of July, but clearly appeared again July 20. This area of active convection corresponds to the mean position of the BMF. The convective activity over the BMF also showed weak diurnal change, though it is not so clear in comparison with that over the TP. This diurnal change is, though, likely to have a close relation with the generation of meso-α-scale cloud clusters, affected by the diurnal change of instability, closely associated with solar radiation (Kato et al. 1995).

These two regions of active convection over the TP and the MBF are separated clearly, one to the east, and the other to the west of around 105°E, where the eastern edge of the TP is located. However, the area of active convection over the TP occasionally moves eastward to the East China Sea through the plains in China for June 20–23, 26–28 and July 18–21. Interestingly, the convective cloud systems over the TP seem to propagate into the BMF zone, when the convective activities with diurnal cycles over the TP are enhanced. In this paper, we examine two notable cases, June 20–23 and July 18–21, to diagnose the atmospheric conditions related to development of the cloud systems in the MBF. The modulation mechanism of convective activities over the TP will also be discussed in section 7.

4. The atmospheric condition over the TP

Large diurnal cycle is one of the most remarkable features of the atmosphere over the TP (Yanai and Li 1994; Kuwagata et al. 2001; Fujinami et al. 2005). Before we examine the development of convective systems over the TP and BFZ, we need to understand the mean diurnal cycle over the TP, during the summer monsoon period. First, the diurnal changes of convective activity, temperature and moisture flux are examined for June to August in 1998. Two typical cases are also investigated as case studies.

4.1 The diurnal change over the TP during summer in 1998

Figure 3 shows mean Tbb, temperature and moisture transport fields at 500 hPa at each time (00, 06, 12, 18Z) of day averaged for the period from June through August. These Universal Time (UT) of the day roughly correspond to 6, 12, 18 and 24 local time (90 E) over the TP (90°E). The Tbb field shows the convective activity of a diurnal cycle is most active over the southern part of the TP around 30°N, with a maximum in the evening (12Z) and minimum around noon of local time (06Z). As shown in Fig. 2, the diurnal cycle of Tbb over the TP was intensified since the middle of June. In contrast, that to the south of the TP, centered in the Assam region (around 27°N, 90°E) showed nearly in the opposite phase to that over the TP, with a maximum in the morning, and a minimum in the evening. This feature of

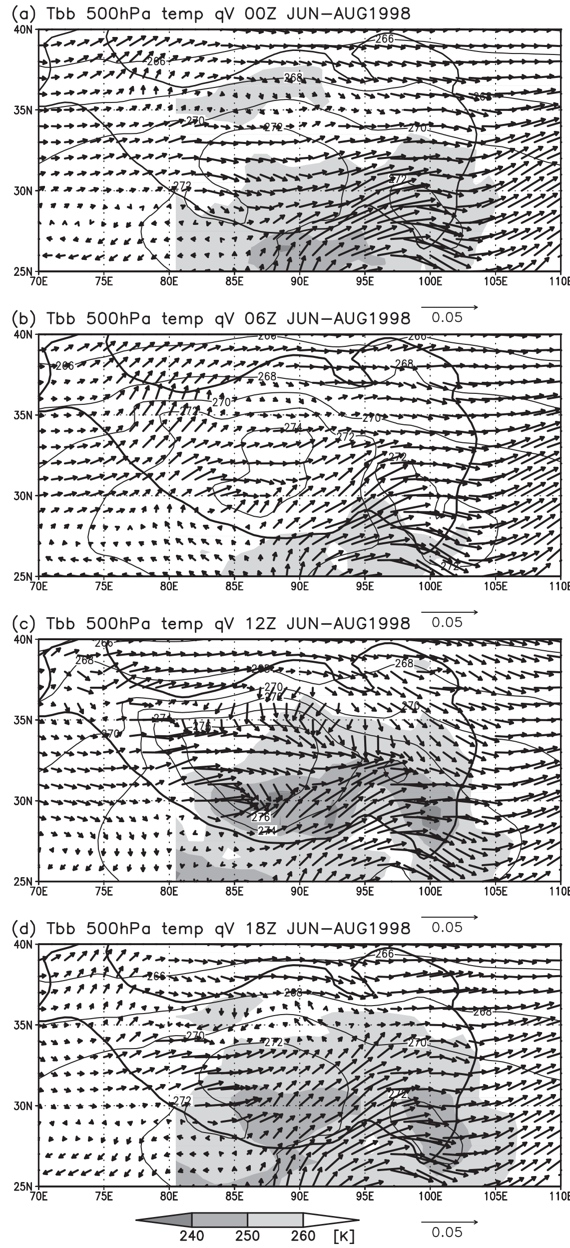

Fig. 3. The diurnal variation of Tbb, 500 hPa temperature and 500 hPa moisture flux around TP averaged from June to August in 1998. The shading area shows Tbb lower than 260 K. Contour interval for temperature is 2 K. Unit of moisture flux is g g^{-1}m s^{-1}. Topographic contour for 3,000 m is also shown (thick solid line).

convection, and rainfall in the Assam region, was also noticed by the previous studies (Prasad 1974; Murakami 1983).

The temperature field at 500 hPa also showed a prominent diurnal cycle over the central TP. The lowest temperature appeared at 00Z, with a minimum value of about 272 K, and the highest at 12Z with a maximum value of about 276 K. The temperature outside of the TP is nearly stable through the day. The large amplitude of the diurnal cycle over the TP is mostly due to sensible heating from the elevated surface, and latent heating through convection over the TP.

In the moisture transport field, a strong southwesterly inflow was remarkably seen from Assam/South China to the TP through the day, but the maximum tends to appear in the evening (12Z). A remarkable feature, is the appearance of two convergence zones over the southern (30°N), and northern (34°N) part of the TP at around 12Z. The southern one corresponds to the active convective zone, indicated by low Tbb. These two convergence zones are generated along the two mountain ranges (i.e., the Kunlung mountain range, and the great & trans-Himalaya mountain range) in the TP orography, which suggests that the convergence zones are associated with the mountain and valley wind circulation system. A moisture divergence area is also noted along the northern periphery of the TP, which may suggest a moisture source from the northern foothills (or the oasis zone) of the Kunglung mountain range. In addition, the two convergence zones seem to merge in the central eastern part of the TP (32°N/95°E) at 12Z. At 18Z, the two convergence zones are reformed to a plateau-scale cyclonic circulation over the TP. These processes are described in more detail in Fujinami et al. (2005). The diurnal change of the moisture flux field is similar to that of the wind field, shown by Yanai and Li (1994).

4.2 Convective activity and moisture transport over the TP for 20–23 June and 18–21 July

In reference to Fig. 2, we have chosen two remarkable cases, when convective clouds system generated over the TP moved eastward to the China plain; one case is June 20–23, and the other July 18–21. Figures 4 and 5 show Tbb, and 500 hPa moisture flux at 00z, 12z for June 20–23 and July 18–21, respectively. In June 20, the convective activity over the TP was active along the southern edge at 12Z, and two moisture convergence zones were generated over the TP at 12z, as shown in Fig. 3. On June 21, the moisture inflow from south of the TP was very active, and a cyclonic circulation was formed over the north TP (35°N/90°E). This moisture flux field was totally different from the average diurnal change shown in Fig. 3. At 12Z, two convergence zones developed and merged together, with more westward expansion than the mean case (Fig. 3). In addition, the eastern edge of the convergence zone reached to the eastern edge of the TP, with a length of 2000 km. The strong convergence zone was located along 33°N, which was about 3 degree to the north of the mean position in latitude. The area of strong convection expanded over most parts of the eastern TP. The active moisture transport area spread over the southern side of the convergence zone, and reached the eastern edge of the TP. At 00z on June 22, the convergence line stretching east to west disappeared, but a new convergence extending south to north, and a cyclonic circulation developed over the central TP. The moisture inflow from the south spread over the southeastern part of the cyclonic circulation. The active moisture transport area also spread eastward, and its edge reached around 110°E. The convective activity became active to the east of the new convergence zone. At 12z, the two convergence zones appeared to be similar to those indicated in Fig. 3. The active moisture transport spread eastward, and the convective area moved eastward, respectively. On June 23, the area of active convection, and strong moisture flux, showed an almost similar pattern to the mean diurnal change. It should be noted, however, that a cyclonic circulation was generated more southeastward over the TP (28°N/108°E).

Figure 5 shows the moisture flux and Tbb distribution during July 18 to 21. On July 18, the moisture inflow from the south was active over the eastern TP, and the convective activity was active over the central TP, even at 00z. At 12z, two convergence zones were formed in the diurnal change, and the convective activity was stronger over most parts of the TP. On July 19,

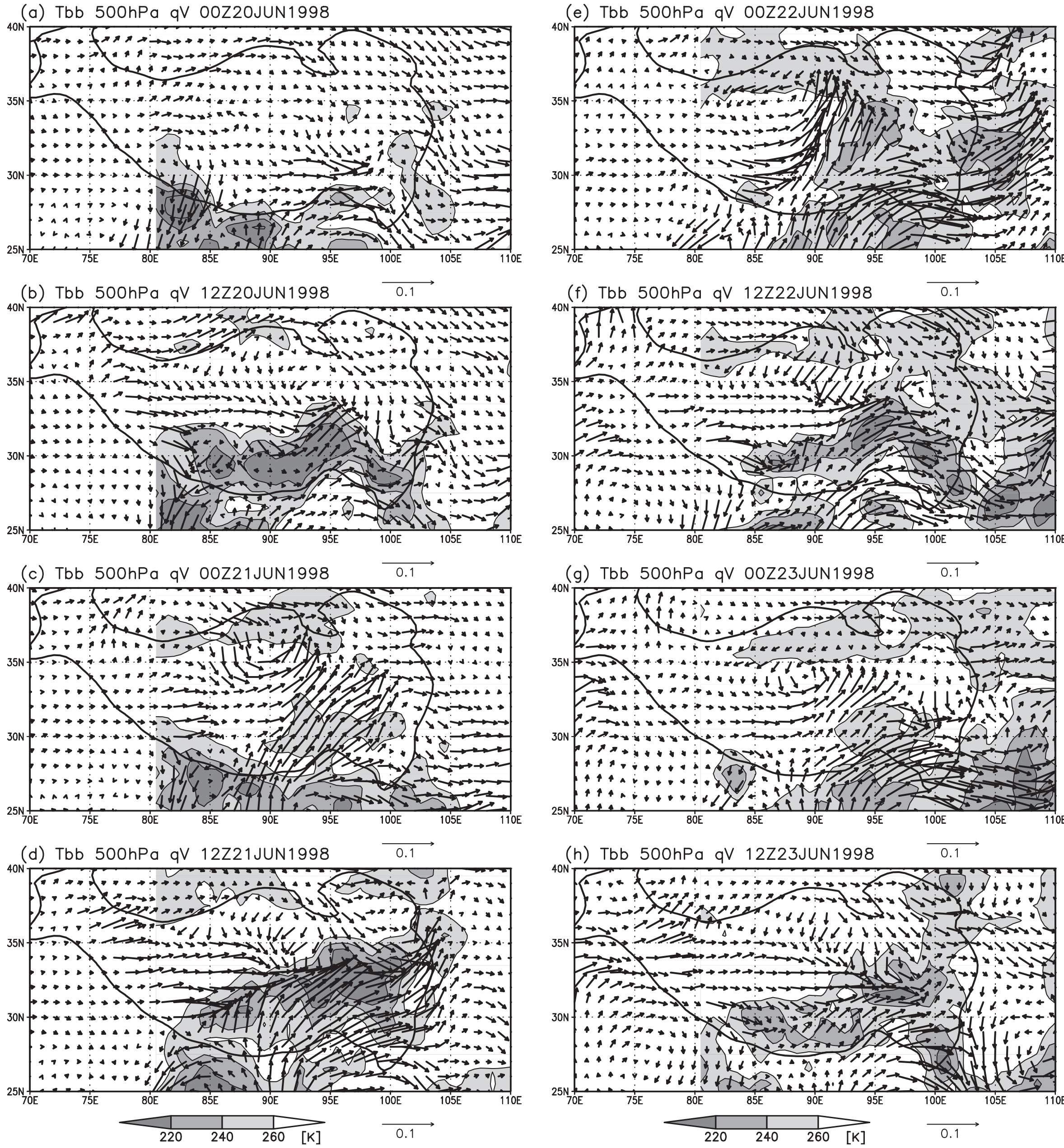

Fig. 4. Tbb and 500 hPa moisture flux over TP at 00Z and 12Z from 20 to 23 June. Shaded area shows Tbb less than 260 K same as Fig. 3. Unit of moisture flux is g g^{-1}m s^{-1}. Topographic contour for 3,000 m is shown (thick solid line).

the convergence zone extended eastward to the eastern edge of the TP, and the convective cloud system also moved eastward without decay at 00Z. At 12Z, two convergence zones were formed again, with the eastern edge extending more eastward. The convective area spread over the entire TP. On July 20, the moist strong westerly area, convergence zone and active convective area expanded to the east of the TP. At 12Z, a very long convergence zone, with meandering was formed, with a trough over central TP, and a ridge over the southeast TP, as

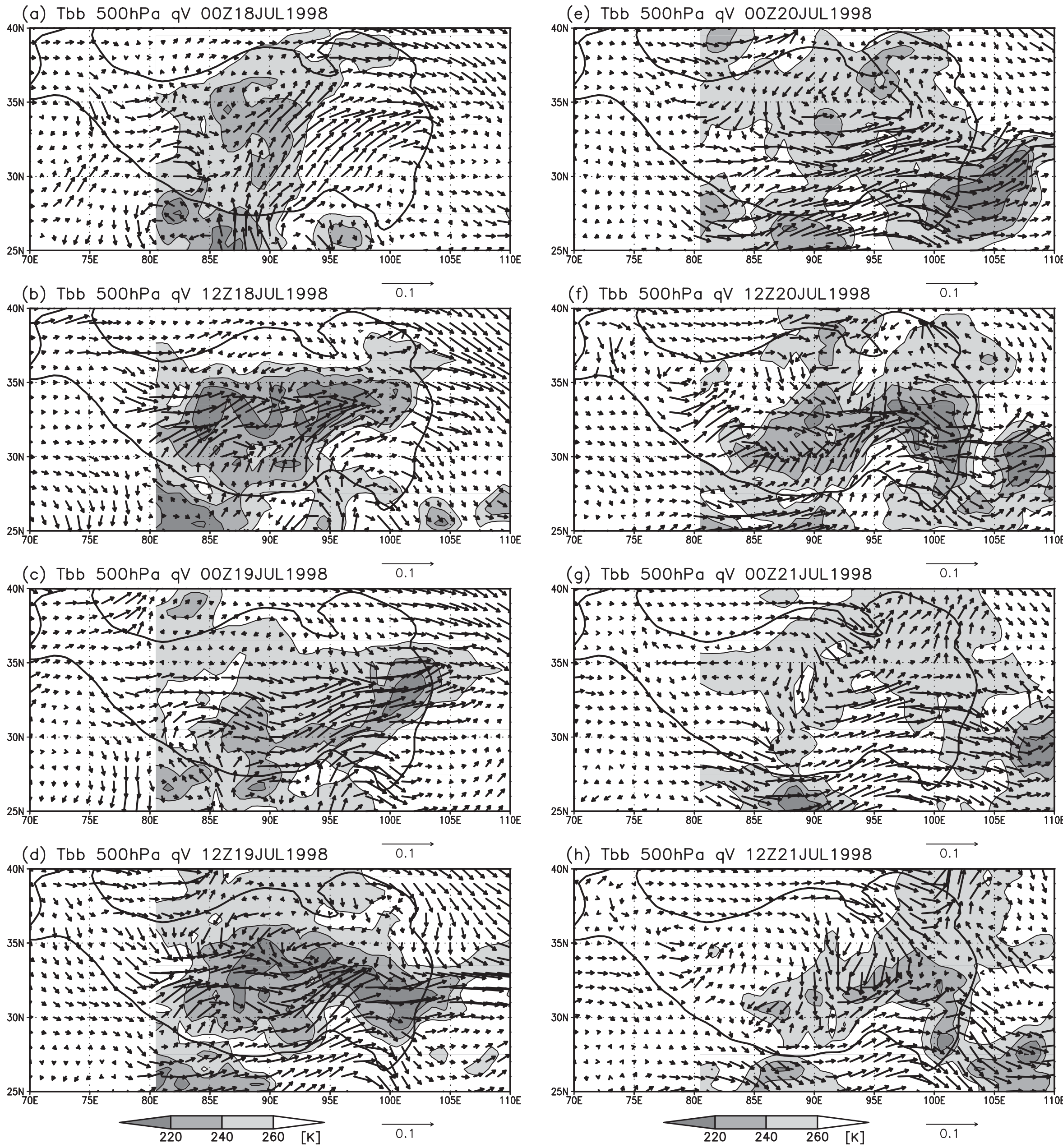

Fig. 5. Same as Fig. 4 but from 18 to 21 July.

shown in the moisture flux fields. On July 21, the trough developed and moved further eastward. Wang et al. (2003) also examined this case of July, suggesting the importance of moisture convergence in the boundary layer for the formation of meso-scale systems.

5. Cyclogenesis at the eastern edge of TP

In section 4, we have shown the two cases when convective cloud systems generated over the TP moved eastward to the China plain. In these cases, the convergence zone with convective clouds were formed over the TP, and reached to the eastern edge of the TP, where a meso-scale system, with cyclonic circulation in a moisture flux field was generated.

This section describes in more detail how the generation of the meso-scale convective system occurred. Figure 6 shows the longitude vertical section of relative vorticity, and meridional wind along 30°N for June 21–22, when the diurnal convective system moved from the TP, to the plain area of China. Since the convective system over the TP tends to move or expand eastward toward the eastern edge of the TP at late evening to mid-night to form relative vorticity tubes of 200–300 km scale over the plateau edge, we plot the diagrams for 18Z and 6Z, rather than 12Z and 0Z, to show more clearly the extreme phases of evolution. A vertically extended, positive vorticity was found in the lower to middle troposphere around 125°E, which corresponds to a meso (β to α scale) cyclonic disturbance in the MBF zone. Additionally, a positive vorticity tube in the lower troposphere was generated, and developed over the eastern edge of the plateau, around 100°E on June 21. At the same time, a LLJ, with a strong southerly core with more than 9m/s, appeared at 600 hPa around 105°E. On June 22, the vorticity tube moved eastward and reached around 105°E, and developed into another tall vorticity tube, extended from the surface to 300 hPa. In association with this vortex, the strong southerly also expanded in the lower troposphere. At 18z on June 22, the northerly wind area appeared in the mid troposphere to the west of the strong southerly. These features indicate that a cyclonic disturbance was generated to the east of the TP.

Figure 7 shows the longitude vertical section as Fig. 6, except for July 19–20 along 32°N. On July 19, we could see a positive vorticity tube, extended from 600 hPa to 400 hPa at the eastern edge of the TP at 06Z. The vorticity tube moved eastward and left from the TP, developing from the surface to 300 hPa through 18Z on July 20. Nearly simultaneously, a strong southerly core was generated at 600 hPa at the eastern side of the TP around 108°E, as is seen at 18Z on July 19 through 18Z on July 20. The southerly core developed from the surface to 300 hPa, coupled with the positive vorticity tube. The northerly wind was also found between the TP and the southerly core, which reached from the surface to 400 hPa, implying development of the cyclonic disturbance in the middle atmosphere. These characteristics of the cyclogenesis found near the eastern edge of the TP, were very similar to those found for the case on June 21–22.

6. Cyclone development over East Asia

In section 4 and 5, we described that the cyclogenesis occurred over the eastern foot of the TP (and the Sichuan basin), when the convergence zone with convective cloud systems over the TP developed, and expanded eastward across the eastern edge of the TP. In this section, we examine the processes; how these cyclonic disturbances formed over the Sichuan basin, and further developed as meso-α scale systems, in the BMF zone.

Figure 8 shows the daily mean Tbb, geopotential height and vorticity at 850 hPa, and moisture flux integrated from surface to 300 hPa, during June 20–27. In this period, the BMF in East Asia was located from south China northeastward to the Japan Islands, and the moist southwest monsoon flow was strong along the southern periphery of the BMF. The subtropical anticyclone (Pacific high) was also well established, supplying another moisture source from the Philippine Sea area toward the BMF. To the north of the BMF, a general decrease of height at 850 hPa towards the north, was recognized in a relatively dry air mass. It should be noted that a cyclonic circulation or disturbance with large-scale convection, was located over the Ganges Plain near the foothill of the Himalayas, which was responsible for enhancing a moist southerly flow toward the TP. This enhanced moist flow may have formed a thick moist layer at the near surface of the TP (Wang et al. 2003), and enhanced moist convective instability there. The eastward movement of the convective cloud system over the TP, and cyclogenesis at the eastern edge of the TP occurred on June 21–22.

Under this synoptic situation, a meso-α-scale circulation system was formed at the eastern edge of the TP on June 21–22, as described in section 4 and 5. This meso-system enhanced moist southwesterly flow to its southeast flank, and dry northern air to its northwest flank (as seen in Fig. 8(h)) on June 23. This enabled the

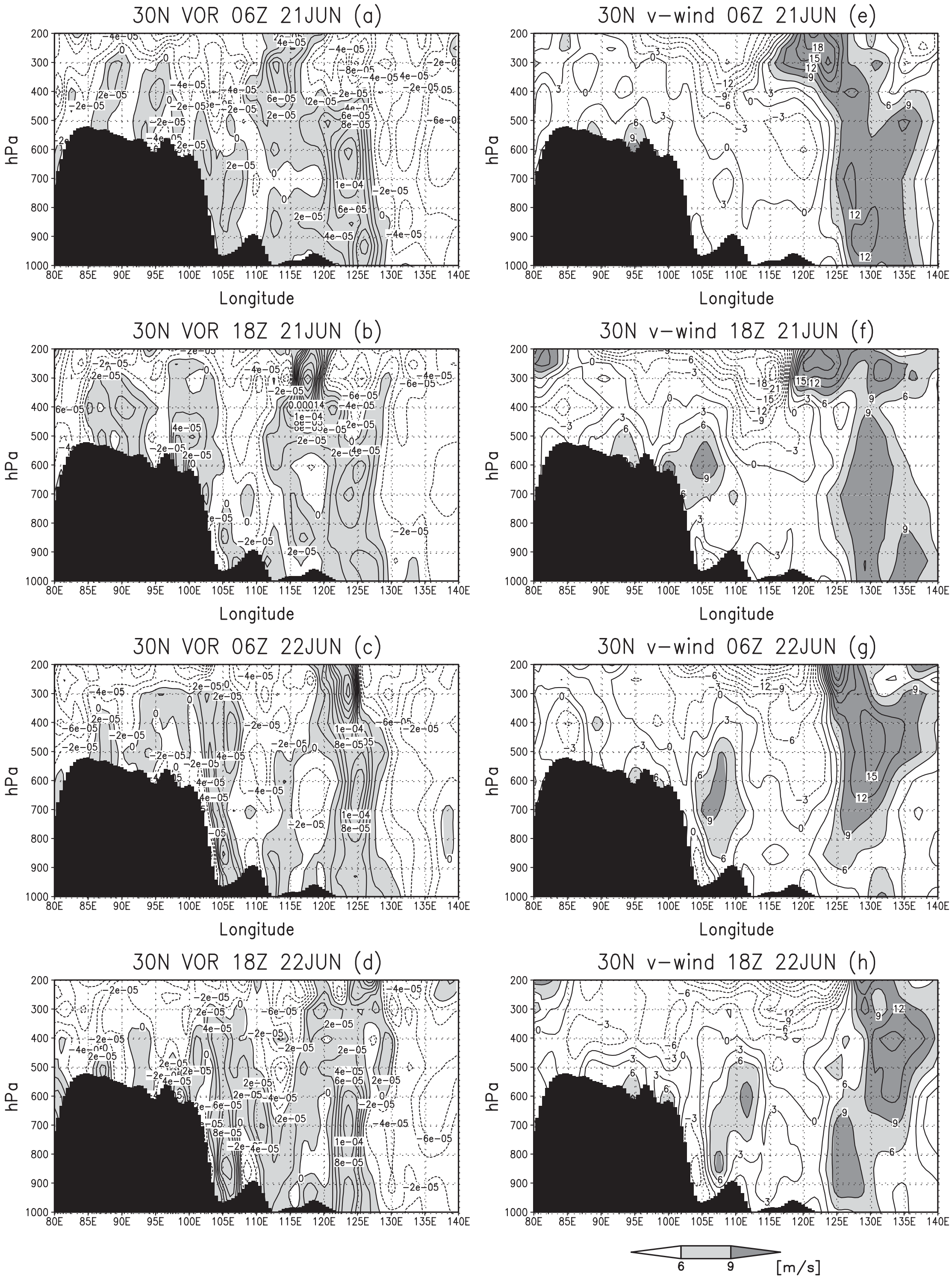

Fig. 6. Vertical cross section of vorticity (left) and meridional (right) wind along 30°N at 06Z and 18Z during 21 to 22 June. Shaded area of vorticity and meridional wind show positive value and southerly more than 6 m/s, respectively.

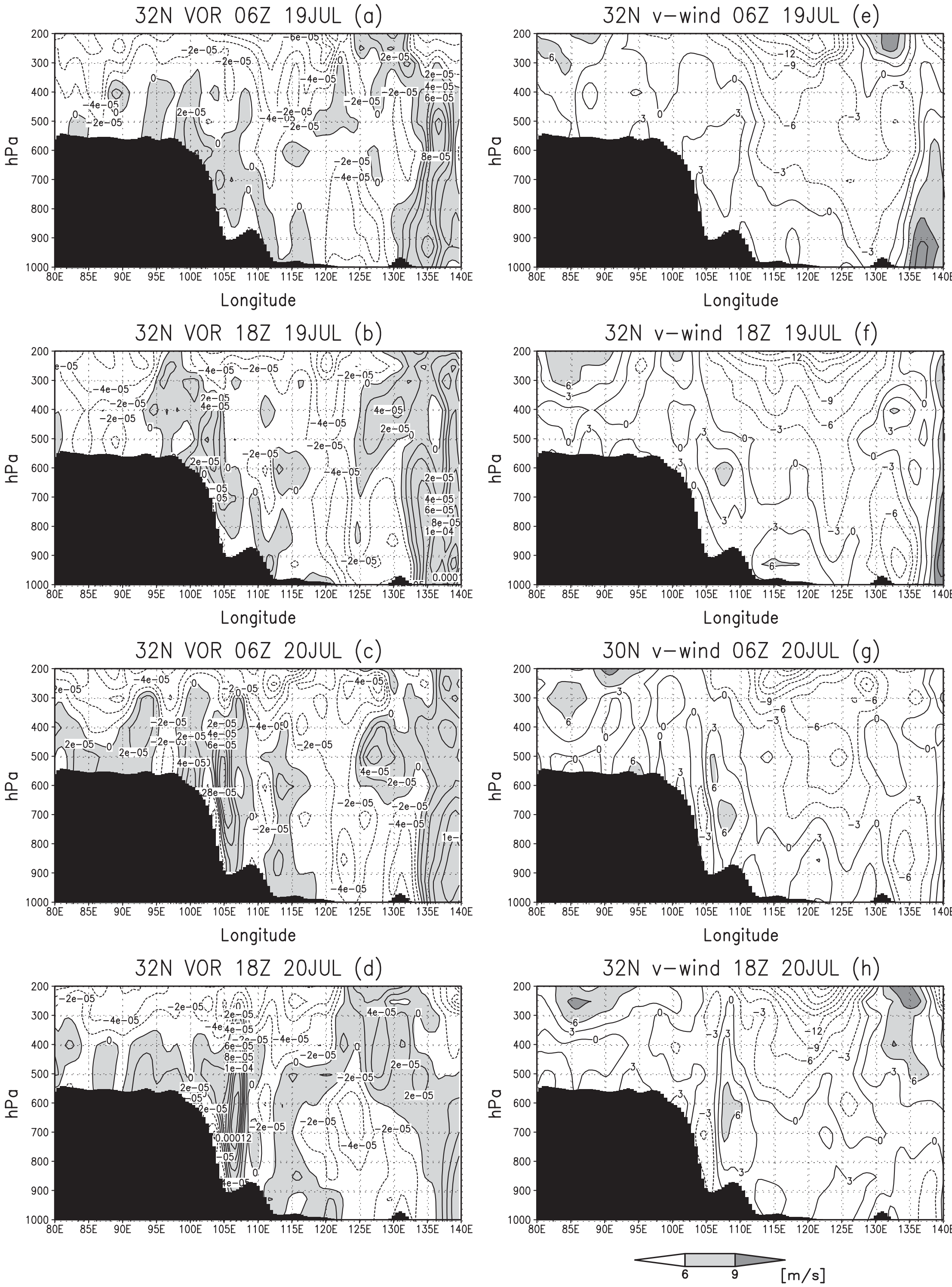

Fig. 7. Same as Fig. 5, expect that the latitude is 32°N and the period is from 19 to 20 July.

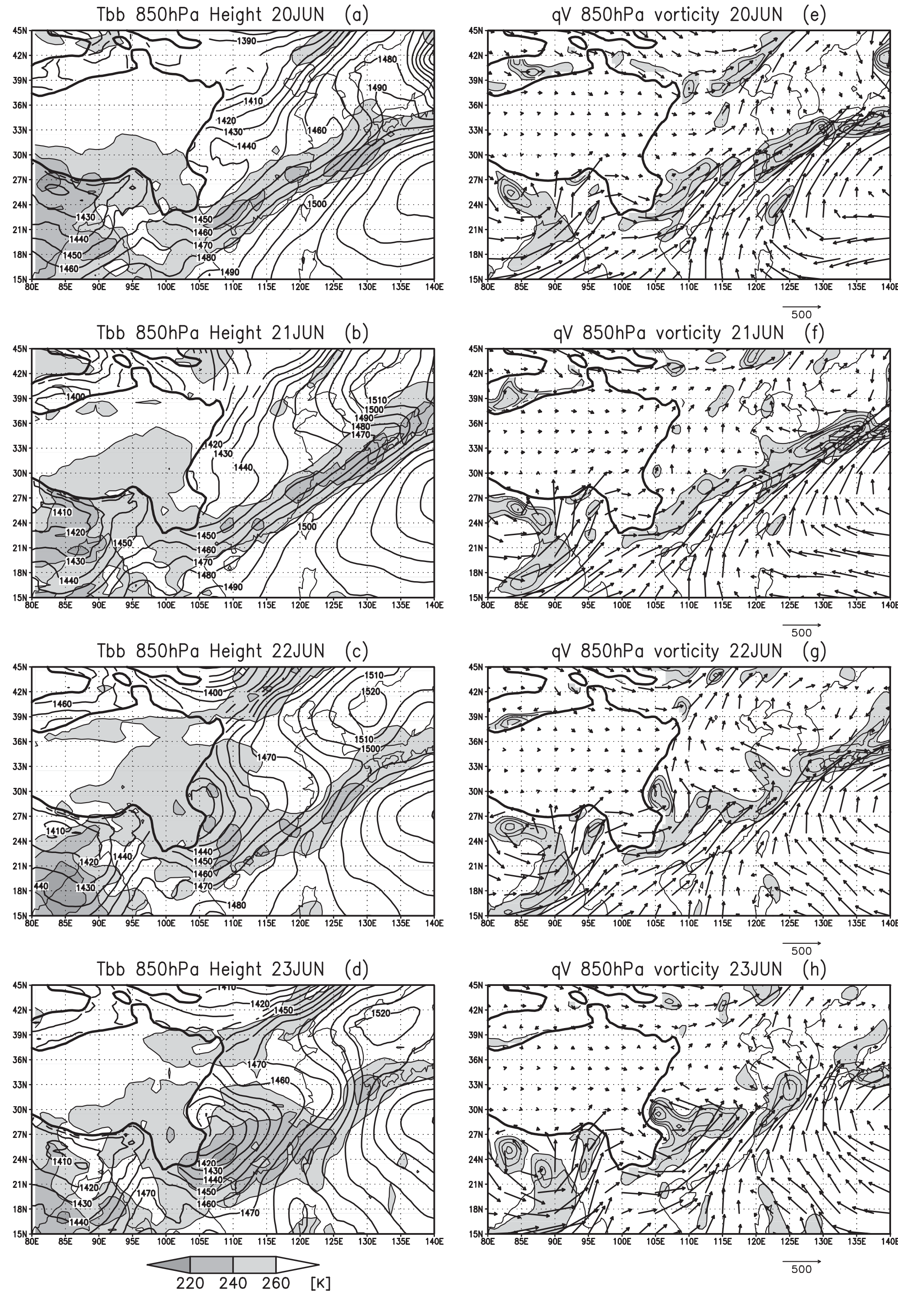

Fig. 8. Tbb, 850 hPa geopotential height (left), moisture transport and 850 hPa vorticity distribution (right) over Asia monsoon region during 20 to 27 June. Shading shows Tbb with lower than 260 K. Unit of moisture flux is g kg^{-1}m s^{-1}. Topographic contour for 1,500 m is shown (thick solid line).

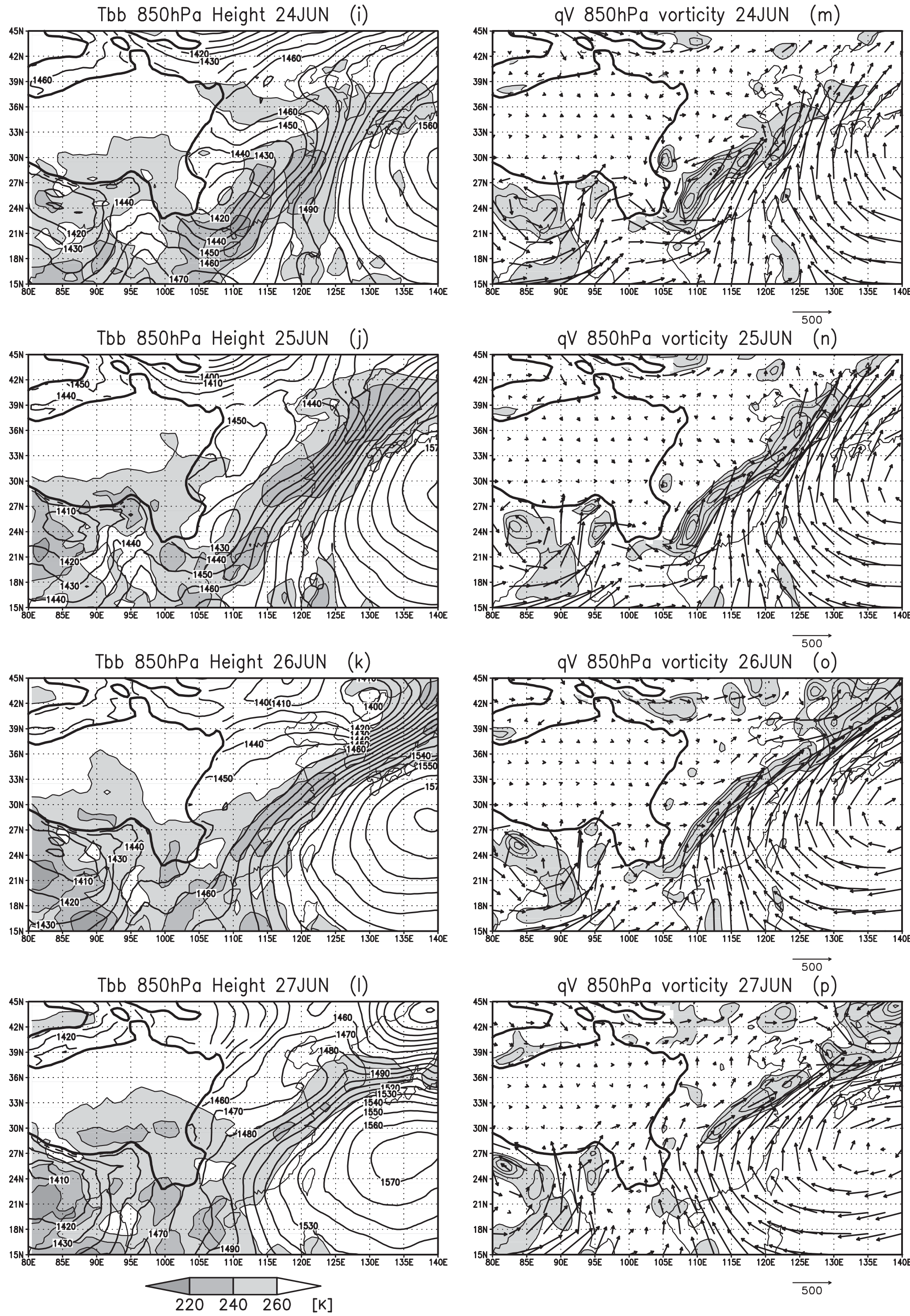
Tbb 850hPa Height 24JUN (i)
qV 850hPa vorticity 24JUN (m)
Tbb 850hPa Height 25JUN (j)
qV 850hPa vorticity 25JUN (n)
Tbb 850hPa Height 26JUN (k)
qV 850hPa vorticity 26JUN (o)
Tbb 850hPa Height 27JUN (l)
qV 850hPa vorticity 27JUN (p)
500
220 240 260 [K]

Fig. 8. (cont.)

system to have abruptly developed to a medium or near-synoptic scale system with more than 1000 km horizontal scale, presumably through intensified moist convective instability. On June 24–25, this system further developed, by merging with the other system, which had already been located over the Yangtze-river basin (at 125°E as shown in Fig. 6). These features on June 24–25 strongly suggest that the overall role of the cyclonic circulation genesis, at the eastern edge of the TP, is to activate the BMF itself by enhancing the moisture gradient across the BMF. On June 26–27 the developed system over the lower reach of the Yangtze-river basin, persisted as seen in Tbb and moisture flux fields, but a major cyclonic center (as seen in the vorticity field) moved eastward to Korea, and the Japan island area.

Figure 9 shows the same diagrams as Fig. 8, but for the case of July 19 to 27. A characteristic feature in this period was that there was no apparent BMF at the beginning stage (Jul 19) though the monsoon southwesterly was flowing into central China. Another distinct difference was the existence of a synoptic-scale cyclonic circulation system in northern China, and the moist flow was converging both from the southwest and the northwest, to the Yangtze river basin in central China. A meso-α scale system was located over the East China Sea, associated with the synoptic system to the north.

On July 19 to 20, a cyclonic vortex at the eastern edge of the TP appeared. Over Bangladesh, northern India and near the foothills of the Himalayas, a convective system was located, which seems to enhance moisture inflow to the TP, as was similar to the case in June. Simultaneously, another meso-α-scale vortex was formed to the east, presumably by the enhanced moist southwesterly flow, associated with the vortex genesis at the edge of the TP. On July 21 through 23, these vortices further developed to form a zonaly-elongated BMF, from the foot of the TP, to the East China Sea. It should be noted that the synoptic system to the north already passed through to further east, and no more apparent northwesterly intrusion was seen to the BMF zone in this stage. In other words, the BMF convergence with meso-scale systems were newly formed to the south of the convergence, as seen on July 19 to 20. On July 23–24, a new synoptic-scale disturbance was generated near the Yangtze River mouth, and further developed over the East China Sea on July 25–26.

7. Discussion

We have diagnosed the atmospheric circulation changes, for the two typical cases when the cloud systems originally generated over the TP developed at the eastern edge of the TP, and further developed to the meso-scale convective systems in the BMF zone in east Asia. Through the analyses, we have found some common characteristics as follows.

The convective activity with moisture flux convergence over the TP, showed clear diurnal cycles to form the convergence zone over central part of the plateau, basically caused by strong atmospheric diabatic heating (Li and Yanai 1996 etc.). Occasionally, the convective activity is enhanced and as a result, the convergence zone over the central plateau, developed to reach the eastern edge of the TP. When the convergence zone over the TP extends further eastward, to reach the eastern edge of TP, a meso-(β to α)scale vortex tube is generated with a vertical extension from the surface up to 300 hPa, as has clearly been shown in Fig. 4 and Fig. 5. We tentatively call this phenomenon the Plateau Edge Cyclogenesis (PEC). Though we need further study on the dynamics of the PEC, we can speculate that the vertical stretching of the cyclonic vortex, originally formed over the TP associated with the convergence zone, is a fundamental mechanism for the PEC, due to down-slope movement of the vortex at the edge of the Plateau. In addition, the intensified vorticity associated with this stretching of the vortex column is associated with the enhanced moist southern flow, to the east of the vortex, which in turn strengthens the cyclonic vortex, through enhanced latent heating to develop a meso-scale convective system. Thus, the PEC is an essential mechanism for the meso-scale cyclogenesis over the Sichuan basin area. These meso-scale systems, triggered by PEC, could be included to those named as Southwest (SW) vortices by Chinese meteorologists, which play an important role in causing heavy rainfall over the BMF zone in China. Some previous studies also suggested the importance of dynamical, as well as thermo-dynamical, effect of the eastern edge of

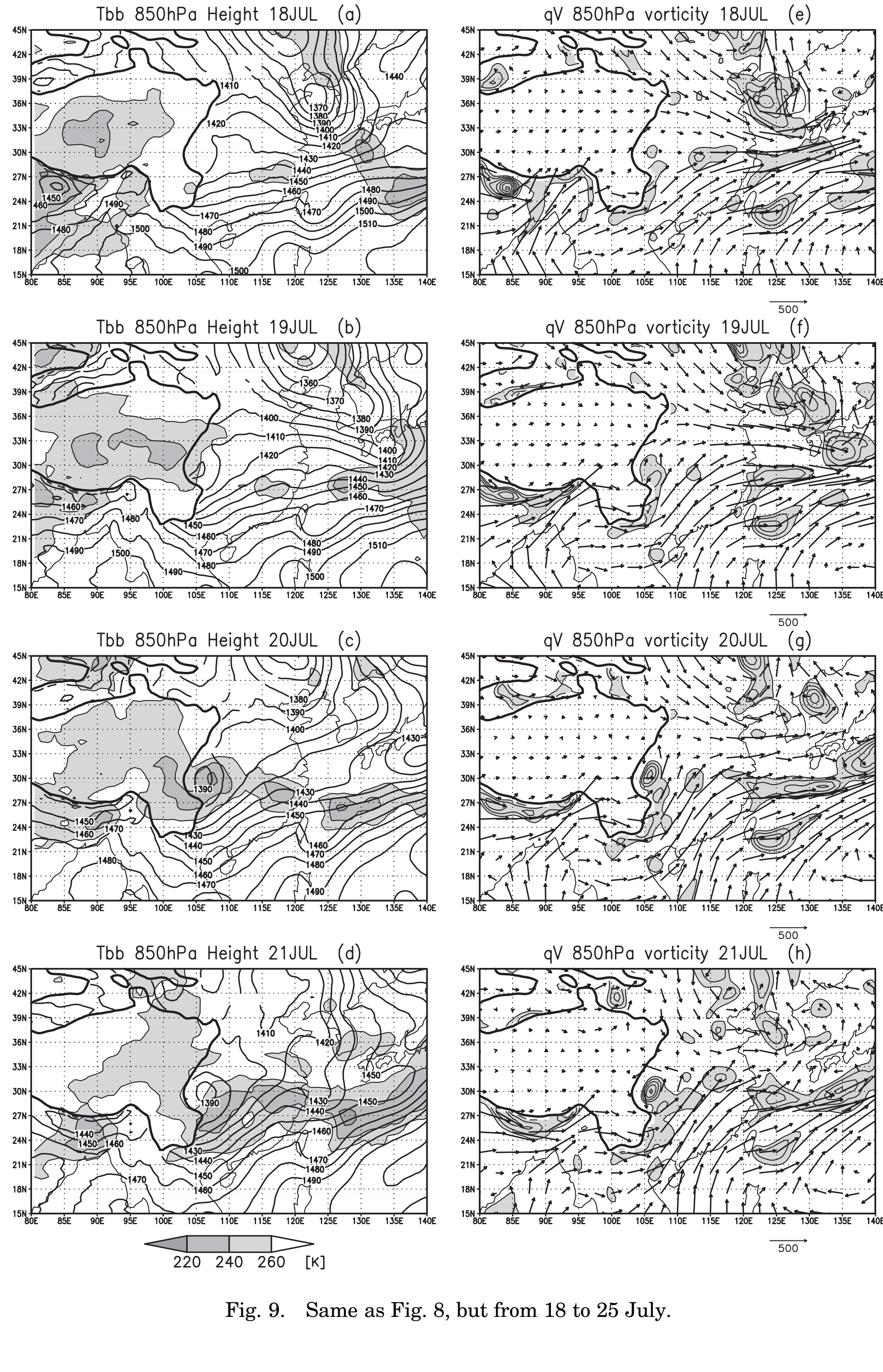

Fig. 9. Same as Fig. 8, but from 18 to 25 July.

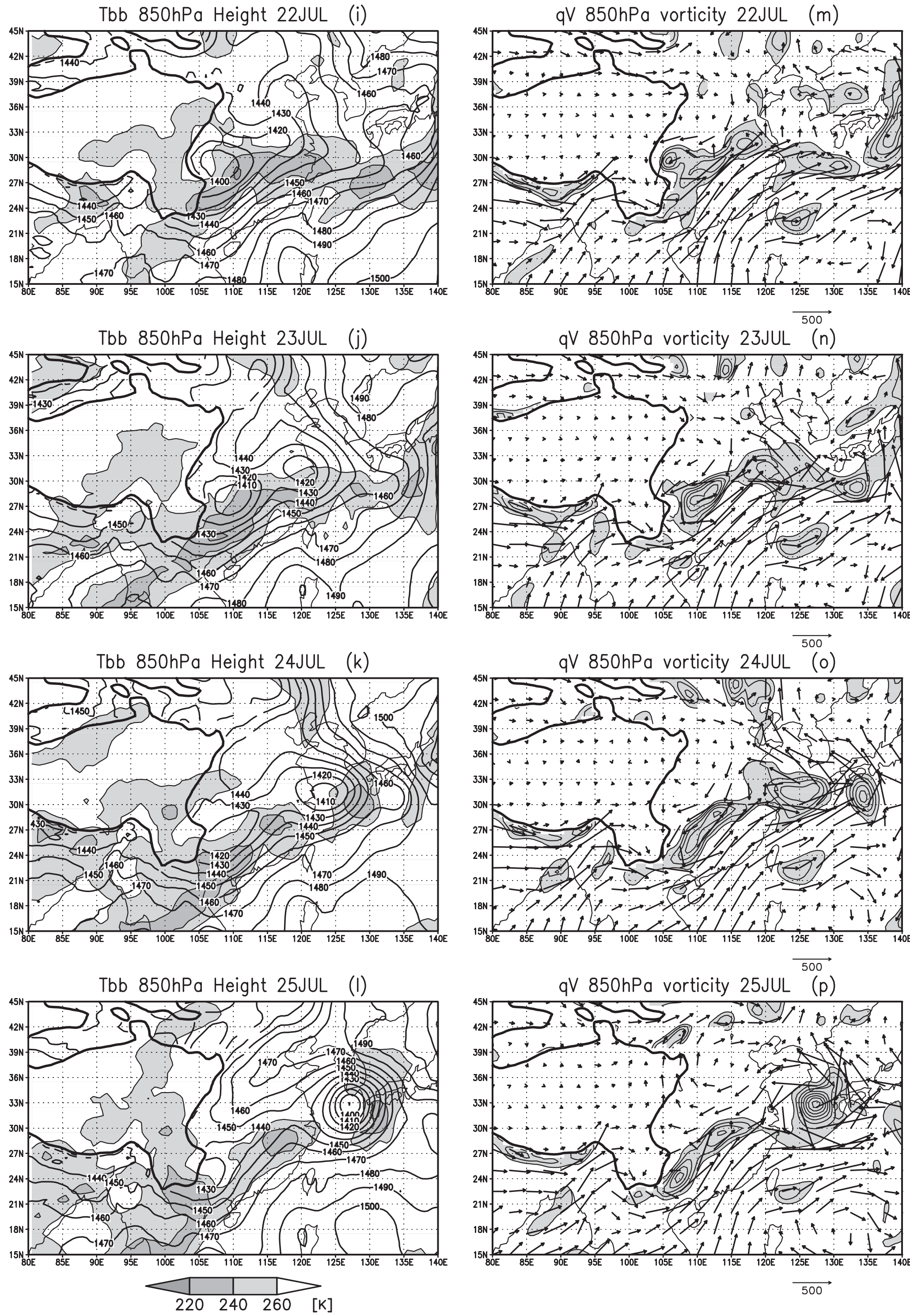
Tbb 850hPa Height 22JUL (i)
qV 850hPa vorticity 22JUL (m)
Tbb 850hPa Height 23JUL (j)
qV 850hPa vorticity 23JUL (n)
Tbb 850hPa Height 24JUL (k)
qV 850hPa vorticity 24JUL (o)
Tbb 850hPa Height 25JUL (l)
qV 850hPa vorticity 25JUL (p)
500
220 240 260 [K]

Fig. 9. (cont.)

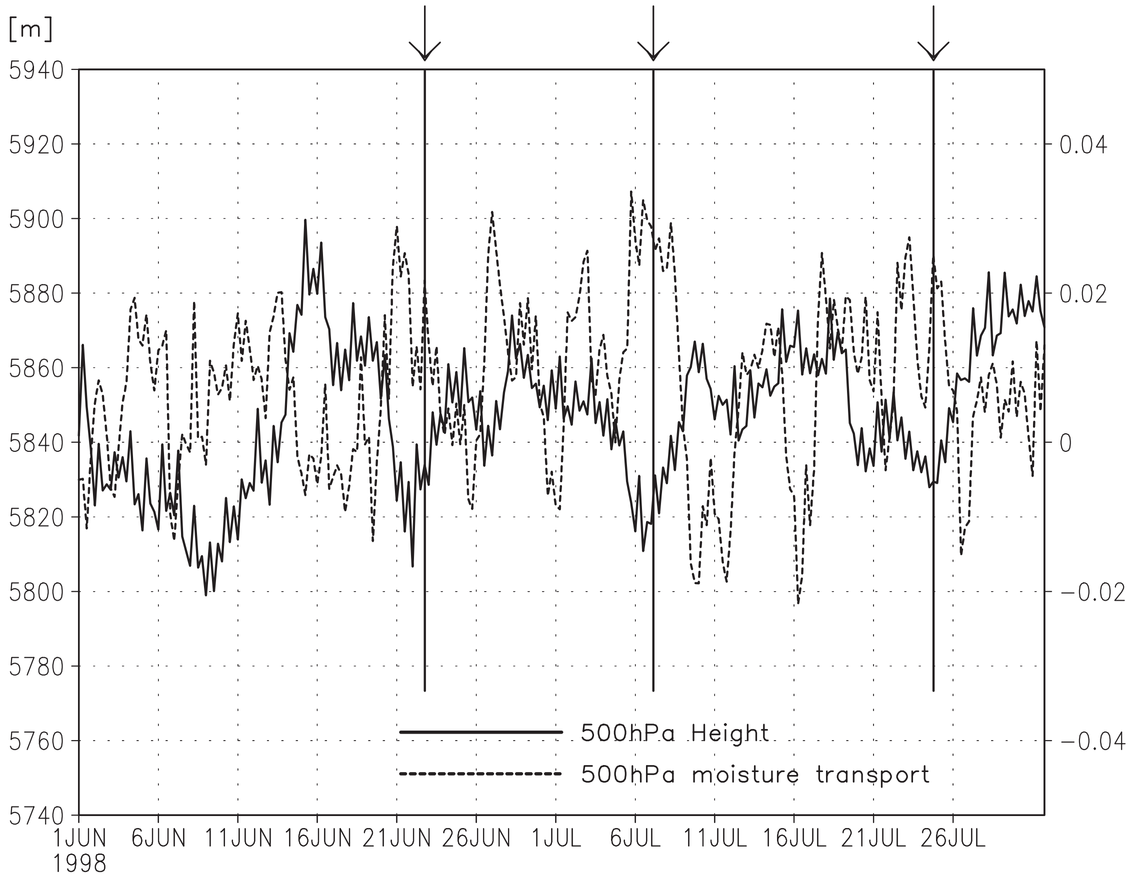

Fig. 10. Time series of the area averaged 500 hPa geopotential height over TP (30–35°N/80–100°E) and meridional moisture transport averaged 90–100°E along 30°N. The area with 90–100°E along 30°N corresponds to the southeastern part of TP. Three major events of PEC are shown with solid lines and arrows in the above. Unit of geopotential height (left axis) is geopotential meter. Unit of moisture flux (right axis) is g g^{-1}m s^{-1}.

the TP for the SW vortices (Wang and Orlanski 1987; Wang et al. 1993). In the concept of PEC, however, we have noted the enhancement of plateau-scale convective systems, and/or convergence zone over the TP, appearing in strong diurnal cycle and could interact dynamically with the Plateau edge slope orography, to abruptly form leeside meso-scale cyclogenesis. Enhanced moisture supply to the east of the TP, accompanied by this cyclogenesis is also an important process for further development to convective meso system in the BMF zone.

What triggers PEC to form meso-scale systems to the east of the TP? We have noticed that the PEC in cases of June–July 1998, occurred associated with enhanced southerly moisture inflow from the Indian plain. Then, what caused strong pulses of moisture inflow over the TP. To examine this, the time series of the meridional moisture transport, averaged 90–100°E along 30°N and 500 hPa geopotential height, averaged over the TP (30–35°N/80–100°E), are produced as shown in Fig. 10. Three major events of PEC are seen during the period (middle of June, early July and middle of July), though we described only two cases: middle of June and middle of July. In the case of early July, the meso-scale system developed through PEC moved further northward to Northern China (Shinoda et al. 2005), that could not appear in the longitude-time section in Fig. 2. From this figure, we can find that when the height over the TP is low, the southerly moisture inflow is active. The two cases analyzed circumstantially here, corresponded to the low geopotential height and active moisture inflow from the south. Furthermore, we can notice variations of two time-scales; one 4–6 days period, and another quasi-biweekly period, in the time series of geopotential height. The quasi-biweekly variation can be seen in the longitude time section of Tbb (Fig. 2). On the other hand, the 4–6 days variation can also be seen in the time series of moisture inflow (Fig. 10). So, the formation of the strong convergence zone over the TP, is thought to be associated closely with the 4–6 days variation in mid-latitude westerly, or monsoon low, formed over a monsoon trough along the Ganges River (Murakami 1976). The invasion of westerly disturbance into the TP, may be responsible for triggering the moisture inflow, the formation of enhanced, elongated convergence zones, with strong convective activity (Fujinami and Yasunari 2001, 2004).

To clarify the relationship among PEC, the intraseasonal westerly trough movement, and monsoon low with 4–6 days variation, we use a band-pass filter to pick up 4–6 days variation, and biweekly (10–20 days) variation on geopotential height. The predominance of the biweekly variation in convective activity, and geopotential field over the TP in the 1998 summer, is already reported by Fujinami and Yasunari (2004). Figure 11 shows the time series of (a) filtered geopotential height over the TP (30–35°N/80–100°E), and (b) Indian subcontinent (20–25°N/70–90°E), with 4–6 days filtered moisture inflow (30°N/90–100°E). From this figure, we notice that the major three PEC events (i.e., June 21–23, July 6–8, July 19–21), as shown with solid lines and arrows, occurred during the negative phases of 10–20 days, filtered geopotential height over the TP, overlapped with the negative phases of 4–7 days, filtered height fluctuation. These negative phases in 4–7 day filtered height, are well consistent with the positive phases of the 4–7 day filtered moisture transport over the TP. That is, the PEC is suggested to be closely associated with the interaction between the two different time-scale variations. Furthermore, negative phases of the 4–7 days geopotential height variation over the TP, and those over the monsoon trough region of the Indian subcontinent (Fig. 11[b]), appear nearly in the same timing. This may imply that the enhancement of southerly moisture inflow over the TP occurs when the mid-latitude westerly trough and the monsoon trough is synchronized under the larger-scale, intraseasonal variation of waves over the TP.

In this study, we have scrutinized the two cases in 1998, when the PEC triggered the development of meso-scale systems; one embedded in the BMF in June, and the other reforming the BMF in July. These cases, in addition to another case in the beginning of July, corresponded to the abnormally heavy rainfall, and flood events in the plain area in China. It is interesting to note that, in the two cases in middle June and middle July, another cyclogenesis occurred over the lower reach of the Yangtze river basin, through the East China Sea, which seemingly enhanced the heavy rainfall, and flood condition there.

8. Conclusion

In this study, we tried to solve the relation among convective activity over the TP, cyclogenesis at the edge of the TP, called the Plateau Edge Cyclogenesis (PEC), and the development of the meso-scale cloud systems over the BMF zone. These meso-scale systems caused the abnormally heavy rainfall and floods having in the Yangtze River basin, during the Baiu season in 1998.

The heavy floods occurred over the basin in the middle to late June and July. During these periods, we found two significant events, when the cloud systems generated over the TP moved eastward, and developed into meso-scale cloud systems over the BMF, and intensified the convective activity over south China.

The development of cloud systems and convergence zones over the TP, occurred by the enhanced southerly moisture inflow. Though the convergence zone is formed over the TP, every day in the summer monsoon period, it occasionally extended to the eastern edge of the TP, due to increase of moisture inflow. The cyclonic vortex, with convective cloud systems, were generated along the convergence zone, and expanded to the eastern edge of the TP.

When the cloud systems reached over the eastern edge of the TP, the PEC occurred by vertical stretching of the vortex, and latent heating due to convective activity. In generat-

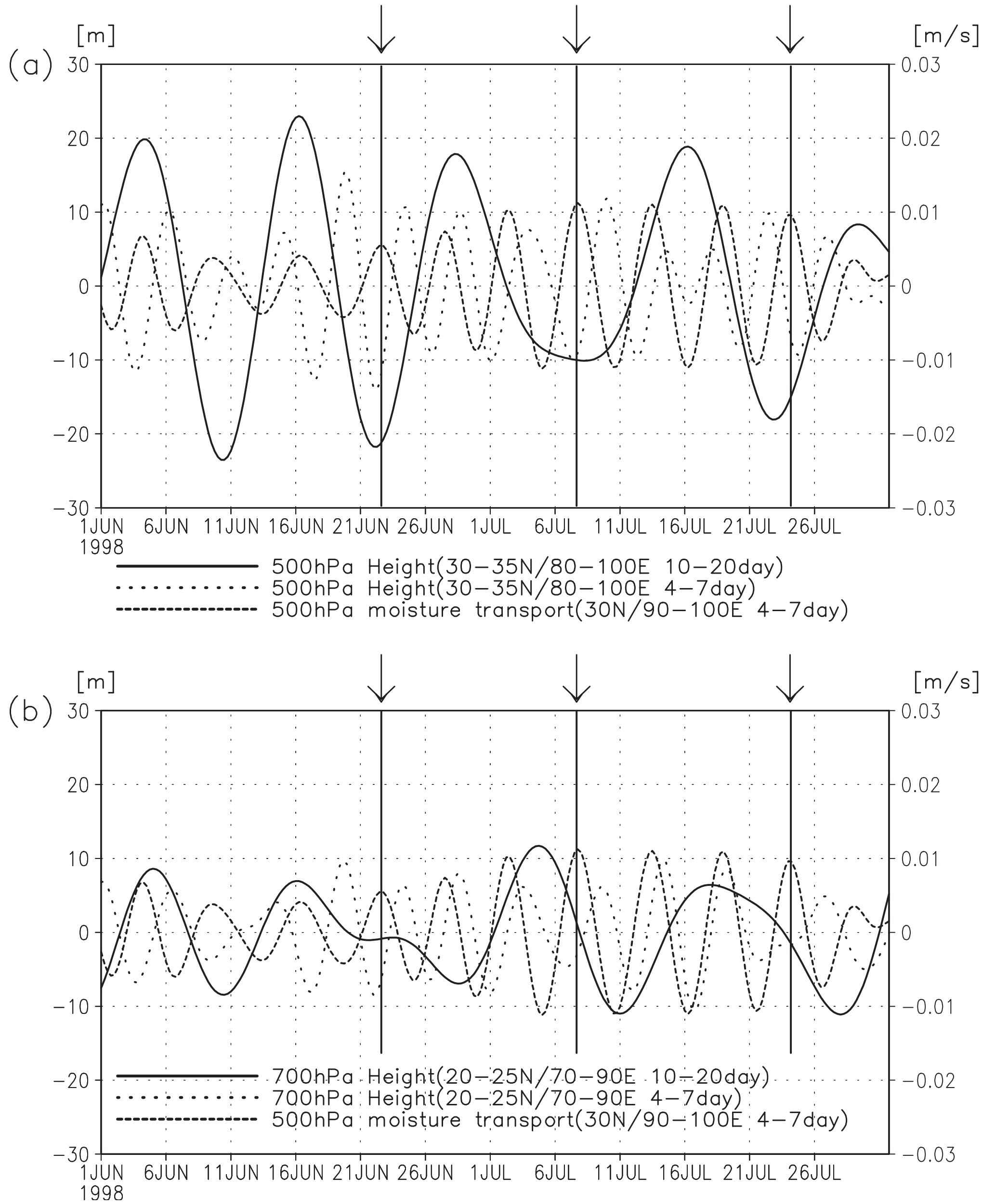

Fig. 11. Time series of 4–7 days (dot line) and 10–20 days (solid line) filtered area average geopotential height over (a) TP and (b) Indian subcontinent. The areas for averaging 500 hPa geopotential height and for 700 hPa geopotential height are 30–35°N/80–100°E and 20–25°N/70–90°E, respectively. Dashed lines show 4–7 day filtered meridional moisture transport averaged for 90–100°E along 30°N. Three major events of PEC are shown with solid lines and arrows in the above. Unit of geopotential height (left axis) is geopotential meter. Unit of moisture flux (right axis) is g g^{-1}m s^{-1}.

ing a disturbance, a strong southerly wind core is formed at the eastern edge of the TP, which is responsible to strong convection. At the same time, an area of northerly wind is formed along the eastern slope of the TP. These major PEC events are likely to be related to the movement of large-scale westerly troughs onto the TP with about a biweekly period, and its interaction with shorter-period monsoon activity with 4–7 day period.

From these analyses, it has been found that the convective activity over the TP is closely associated with the meso-scale systems, with heavy rainfall over the BMF in China, through PEC over the eastern edge of the TP, through the Sichuan basin. However, we also notice other cases of cyclogenesis over the Sichuan basin, and heavy rain cases in the Yangtze River basin, not directly related to PEC. These additional factors also need to be examined, to fully understand the dynamics of genesis and development of meso-scale cloud/precipitation systems, in the BMF zone. The detailed processes, and possible mechanisms, of these major cyclogeneses will be reported elsewhere.

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