

Tropical Circulations Associated with Southwest Monsoon Onset and Westerly Surges over the South China Sea

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ABSTRACT

The earliest onset of the Asian summer monsoon occurs in early to middle May over the South China Sea. This onset is signified by the development of low-level westerlies and leads to heavy convective rainfall over southern China (pre-Mei-Yu). In June, low-level westerly surges over the northern South China Sea are associated with the Mei-Yu rainfall system in the Yangtze region and southern Japan. In this work, the ECMWF data for 1981–86 are used to study the tropical circulations associated with the development of low-level westerlies during both events.

Composites of horizontal wind, geopotential height, moisture, and vertical velocity during six May onsets and nine June surges, respectively, indicate that both events occur with the approach of a midlatitude trough–front system. The possible triggering of the South China Sea summer monsoon onset by the midlatitude system may explain why the South China Sea onset occurs prior to other regions of the Asian monsoon. During boreal spring, this is the only Asian monsoon region where midlatitude fronts can move into the Tropics without having to overcome significant terrain barriers.

Following the two events, opposite teleconnection-like patterns develop in the Tropics in both hemispheres. During the May onsets, the arrival of the midlatitude trough/front appears to lead to a southwestward extension of a cyclogenesis zone into the equatorial Indian Ocean. Along this zone, cyclonic vortices develop over the Andaman Sea, the Bay of Bengal, and perhaps the southern equatorial Indian Ocean, and increased deep convection is indicated by the OLR composites. During the June surges, a pair of anticyclones develop straddling the equator at the longitudes of Indochina. This anticyclonic couplet is associated with decreased deep convection and propagates westward to dominate the flow changes over the Bay of Bengal and the southern Indian Ocean. The steady $4\text{--}5\text{ m s}^{-1}$ westward speed and near-perfect symmetry with respect to the equator indicate the possibility of an equatorial Rossby wave generation in conjunction with the June westerly surges in the northern South China Sea.

1. Introduction

Chinese literature (e.g., Tao and Chen 1987) has suggested that the East Asia summer monsoon onset, usually in early-to-middle May, almost always occurs before the South Asian monsoon development over the Bay of Bengal during late May and over the western coast of the Indian subcontinent in early June. The composite by Tao and Chen (1987) of mean onset dates of the Asian monsoon from different regional climatological studies is shown in Fig. 1. The earliest onset line is in the northern South China Sea and extends to the western Pacific east of Taiwan and south of Ja-

pan. The onset dates progress systematically northward and northwestward to signify the development of the East Asian and the South Asian monsoons, respectively. Over land, the onset of the former clearly leads the latter, with the May dates over southeastern China and the June dates over India.

Immediately after the onset over the northern South China Sea, heavy convective rainfall develops along an almost zonally oriented belt from the southern coast of mainland China and Taiwan and extending into western Pacific south of Japan (Johnson et al. 1993). This is often referred to as the southern China presummer rainy season, or pre-Mei-Yu, which is the first quasi-stationary stage of the East Asian monsoon trough/front that develops north of the western Pacific subtropical ridge. During this period, the East Asian monsoon trough exhibits mixed midlatitude frontal and tropical ITCZ-like properties (Chen and Chang 1980; Chou et al. 1990), even though the ITCZ itself is over

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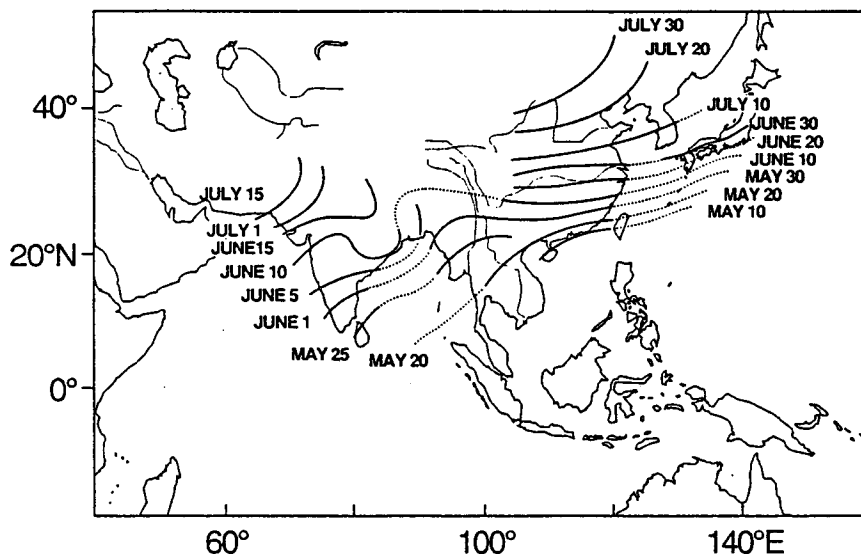


FIG. 1. Mean onset date of the summer monsoon (adapted from Tao and Chen 1987).

the equatorial South China Sea/western Pacific south of the subtropical ridge. This period is followed by the northward jump of the elongated rain belt to the Yangtze River valley in June, which is referred to as Mei-Yu in China and Baiu in Japan. The next stage occurs in July when the rain belt jumps northward to cover the Yellow River basin of northern China, the Yellow Sea, and the southern Japan Sea. In August, the monsoon begins to withdraw southward (Tao and Chen 1987; Ding 1992, 1994).

The onset of the summer monsoon over the South China Sea is essentially the beginning of the entire Asian summer monsoon regime. Understanding of this process and the subsequent northward jumps of the heavy rain belt may be important to the understanding of the development and evolution of the complete monsoon system. In this paper, we focus on the following two questions that are related to the monsoon onset:

- 1) Why does the summer monsoon appear over the South China Sea first, and what is the mechanism of the onset?
- 2) What are the origins of the low-level southwesterly wind accelerations that accompany the onset and the subsequent Mei-Yu development? Are there related broadscale tropical circulation changes during these East Asian monsoon developments?

Several hypotheses have been proposed to explain the South China Sea summer monsoon onset. A possible direct local mechanism is the seasonal increase of conditional instability due to the increase in sea surface temperature. He et al. (1992) showed that the monthly mean sea temperature averaged from 0 to 100 m in the southern part of the South China Sea increases rapidly from a maximum of 23°C in March and April to 27°C

in May. They proposed that the first occurrence of the high temperature in May may be related to the onset of the East Asian summer monsoon. However, the upper-ocean temperature increases during late spring in other tropical oceans as well. For instance, the sea surface temperatures continue to rise above 28°C over the Indian Ocean, but convection and monsoon rainfall do not start until well into June (e.g., Webster 1994).

Murakami et al. (1986) suggested that of all the monsoon regions, the South China Sea is the most sensitive region of the large-scale seasonal (winter to summer) transformation of the pressure gradient due to differential heating between Asia and Australia. When the proper (wet) phase of a low-frequency oscillation, such as the Madden-Julian oscillation (Krishnamurti et al. 1985) or the 10–20-day oscillation (Krishnamurti and Ardanuy 1980; Li and Zhou 1994), propagates into this region, the summer monsoon is activated. Others have proposed that synoptic tropical systems external to the region provide the impetus to trigger the onset. Orgill (1967) reported that about half of the onsets in the Southeast Asia occurred in conjunction with a tropical storm in the Bay of Bengal that drifted poleward and brought southwesterly flow along the southern flank into the Indochina Peninsula. Forecasters at the Malaysian Meteorological Service (B. K. Cheang 1993, personal communication) have associated onset with a tropical synoptic disturbance propagating into the equatorial South China Sea from the western Pacific. This “easterly wave” type of disturbances often turns northward after crossing into the Indochina Peninsula and spreads heavy rain over a large area.

The development and enhancement of the Mei-Yu rainfall in southern China near the Yangtze River valley in June (Fig. 1) is also associated with an increase

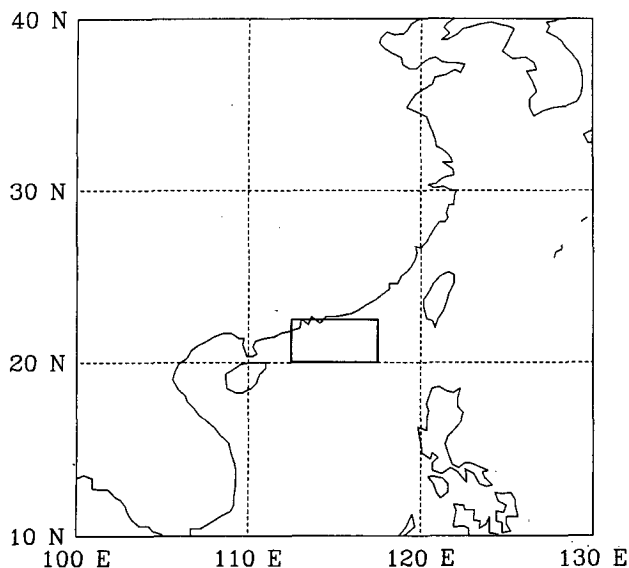


FIG. 2. The domain of the study. Six grid points within the rectangular 20° – 22.5° N, 112.5° – 117.5° E are used to produce the westerly wind index for the composites.

in low-level southwesterly winds over the South China Sea (Tao and Chen 1987). During this period, the southwest monsoon is already established over South Asia from the Indian Ocean to the western Pacific. Freshening southwesterly winds import large amounts of moisture from the northern South China Sea, which is usually required to sustain the Mei-Yu rainfall. Thus, the mechanism and origin of the low-level southwesterly acceleration in June are also interesting questions.

Chinese scientists identified three main upstream branches of the monsoon southwesterlies:

- 1) the equatorial westerly wind from the Bay of Bengal;
- 2) the easterly wind south of the western Pacific subtropical high; and
- 3) the southeast trade wind that crosses the equator from northern Australia.

The relative contributions of these three possible sources for the South China Sea summer monsoon vary greatly among different studies. For example, Liang et al. (1983) indicated that the freshening of the South

China Sea monsoon wind originates mainly from the Bay of Bengal during the early summer monsoon, and from the cross-equatorial airflow near 105° E during midsummer. However, Tao et al. (1983) found that the early season monsoon wind comes from the recurved flow south of the subtropical high and the cross-equatorial flow near 105° E, while during midsummer the main flow originates in the Bay of Bengal.

The purpose of this study is to conduct a diagnosis of the freshening of low-level southwesterlies over the South China Sea, both during the monsoon onset in May over the northern South China Sea and the southern China coast, and during June when the Mei-Yu develops near the Yangtze River. Our purpose is to document the tropical circulations during the freshening of the southwesterlies during the South China Sea onset and the development in June. It is hoped that the onset and the Mei-Yu development processes, and the relative roles of the upstream branches of the freshening of the South China Sea southwesterlies, may be elucidated by comparing the two structures.

2. Data

The main data used are the twice-daily, uninitialized European Centre for Medium-Range Weather Forecasts (ECMWF) analyses on a 2.5° latitude by 2.5° longitude grid during May–June 1981–86. A westerly wind index is defined by the time series of area-averaged 850-hPa zonal wind (u) components over the six grid points between 20° and 22.5° N and 112.5° and 117.5° E in the northern South China Sea (Fig. 2). Monsoon onset is defined as the first event in May of each year in which the westerly index accelerates by at least 3 m s^{-1} over 24 h and the strengthened westerly wind is sustained for at least 48 h. Westerly surges are defined as events occurring in June in which westerly index increase satisfies the same criteria. By definition, one onset is defined for each of the six seasons. Either one or two surges occurred each June for a total of nine surge cases (Table 1). Here, the reference time point (00 h) is the first observation after the westerly index exceeds the May–June mean. Usually, within each season, there is another westerly acceleration occurring in May after the onset, but it is not included in this study because the timing is not associated with the development or enhancement of the Mei-Yu rainfall in the Yangtze River valley.

TABLE 1. Reference time (00 h) of monsoon onsets and June surges used in the composites.

Onsets	Surges	
1200 UTC 6 May 1981	1200 UTC 24 June 1981	
1200 UTC 4 May 1982	1200 UTC 6 June 1982	0000 UTC 13 June 1982
1200 UTC 8 May 1983	1200 UTC 11 June 1983	
0000 UTC 12 May 1984	1200 UTC 12 June 1984	
0000 UTC 3 May 1985	0000 UTC 5 June 1985	1200 UTC 23 June 1985
1200 UTC 5 May 1986	1200 UTC 14 June 1986	1200 UTC 25 June 1986

Composites of the westerly index for the onsets and the surges are shown in Fig. 3, respectively. The average duration of the steady westerly acceleration during onsets is from -36 h to $+24$ h. Although the two acceleration profiles are quite similar, the average June surge acceleration starts before -48 h and lasts through $+36$ h.

As an independent check of the results obtained by the ECMWF analysis over data-sparse tropical oceans, the outgoing longwave radiation (OLR) data at $2.5^\circ \times 2.5^\circ$ grids are also used.

3. Results and discussion

The data are composited into two types of diagrams: time–height or time–latitude cross sections, and time sequences of 850-hPa maps. The former are used to focus on the time changes over the northern South China Sea, and the latter are used to depict the large-scale circulation changes in the upstream region of the southwesterly wind accelerations.

Time–height sections of horizontal wind averaged over the base area of 20° – 22.5° N, 112.5° – 117.5° E during the onsets and surges are shown in Fig. 4. Throughout the onset (Fig. 4a), the domain is dominated by westerlies with a 200-hPa jet maximum of 24 m s^{-1} at -36 h. This upper westerly jet decelerates gradually, even as the lower troposphere undergoes westerly acceleration starting from around -24 h. Examination of the low-level maps confirms that the westerly acceleration is associated with the approach of a midlatitude front. During the June surges (Fig. 4b), the levels at and above 300-hPa are occupied by easterlies, because the upper-level tropical easterly jet with a maximum over India has developed. The lower-troposphere westerly acceleration has a quite different structure from the monsoon onsets, with a low-level jet developing in the 700–850-hPa layer. Such a low-level jet is typically

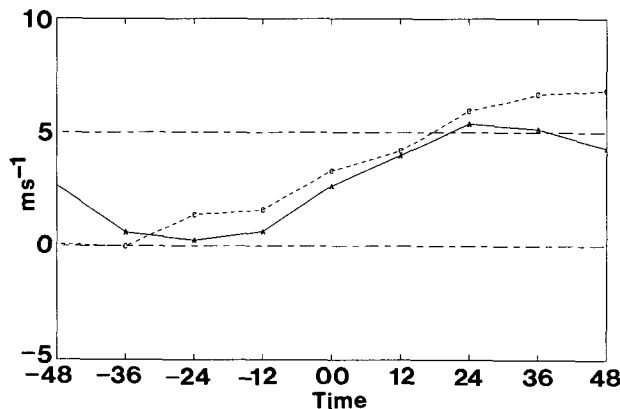


FIG. 3. Averages of the westerly wind index during the monsoon onsets (solid) and the June surges (dashed) as a function of time (h). See text for definition of the 00 h reference time.

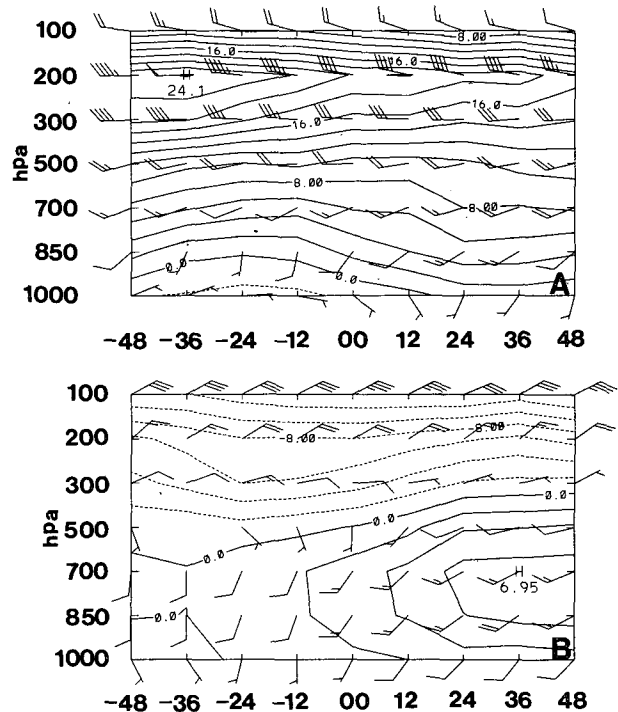


FIG. 4. Time–height sections of the composite horizontal wind averaged over the area 20° – 22.5° N, 110° – 112.5° E for (a) the monsoon onsets and (b) the June surges. The westerly (solid) and easterly (dashed) zonal wind isotachs are also plotted.

associated with the Mei-Yu front (e.g., Chou et al. 1990).

Time–latitude sections of the composite low-level geopotential height anomalies, averaged between 112.5° and 117.5° E, for the monsoon onsets and surges are shown in Fig. 5. Here the low-level anomaly is the departure from the respective monthly mean and is averaged over 1000, 850, and 700 hPa. Notice a couplet of positive and negative height anomalies in the lower troposphere propagates equatorward from the midlatitudes into the northern South China Sea during monsoon onsets (Fig. 5a) and that this propagation can be traced back to at least -48 h. For the June surges (Fig. 5b), an equatorward propagation of positive and negative height anomalies occurs, but the negative anomalies reach only 25° N at 36 h. The meridional gradient of height anomaly is also weaker during surges. Although both the onset and the surges follow the arrival of midlatitude trough–front systems, the midlatitude influence appears to be stronger for the onset.

Similar time–latitude sections along the 115° E longitudinal belt for the composite low-level mixing ratio during the monsoon onset (Fig. 6a) indicate that the maximum mixing ratio remains at 17.5° N with a near constant value of about 13.5 g kg^{-1} . However, a widespread increase of mixing ratio occurs at and north of 20° N from -24 to 12 h. The increase is apparently a

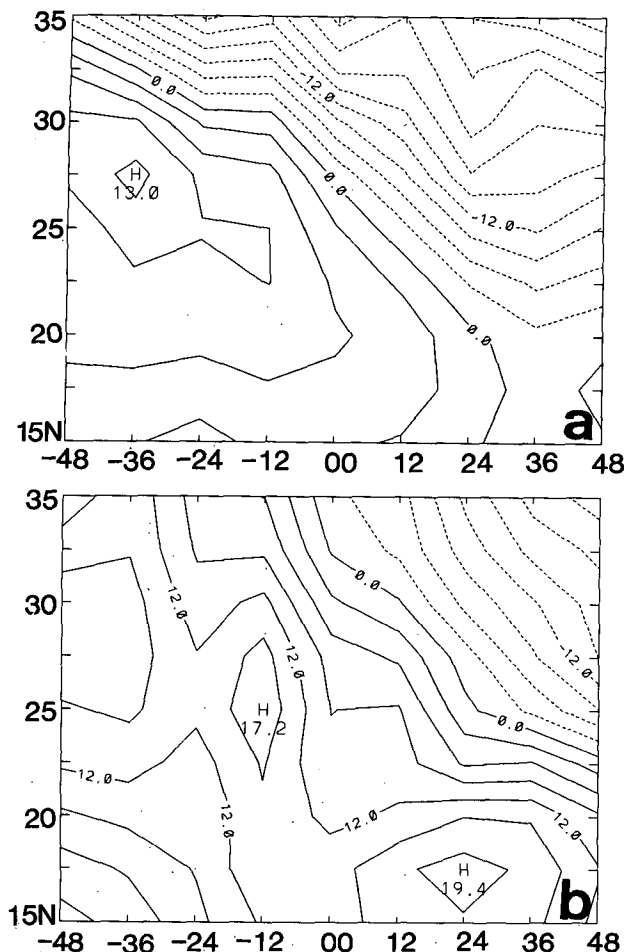


FIG. 5. Time-latitude sections of the composite geopotential height anomaly (departure from the monthly mean) averaged over 1000-, 850-, and 700-hPa and between 112.5° and 117.5°E for (a) the monsoon onsets and (b) the June surges. The unit is geopotential meter (gpm), and negative contours are indicated by dashed lines.

result of the freshening of the southwesterlies as a mid-latitude trough/front approaches the South China Sea. The increase in the mixing ratio occurs first in the north (about 2.5 g kg^{-1} over southern and central China), and appears to propagate equatorward, with an increase of about 1 g kg^{-1} in the northern South China Sea. For the June surge composite (Fig. 6b), the maximum mixing ratio belt of about 15 g kg^{-1} remains stationary near 25°N. Only a small increase in moisture is observed in this zone as the surge develops. Although some moisture increase is indicated north of this zone between -36 and 0 h, the increase is smaller and much more gradual compared to the monsoon onsets.

Time-latitude sections along the 115°E longitudinal belt of the composite low-level vertical motion for the May onsets and June surges are given in Fig. 7. Similar to the mixing ratio, there is a stronger increase in pressure velocity for the onsets. The maximum rising mo-

tion during the onsets (Fig. 7a) moves poleward from 20° to 26°N, and its magnitude increases from about $-0.3 \times 10^{-3} \text{ hPa s}^{-1}$ at 48 h to $-0.7 \times 10^{-3} \text{ hPa s}^{-1}$ at 00 h. The Yangtze River region around 30°N has sinking motion of about $0.3 \times 10^{-3} \text{ hPa s}^{-1}$ until -12 h when rising motion of about $-0.2 \times 10^{-3} \text{ hPa s}^{-1}$ develops. For the June surges (Fig. 7b), the maximum rising motion stays near 30°N in the Yangtze River valley, which is climatologically the Mei-Yu region during middle and late June. Although the maximum ascent of around $-0.8 \times 10^{-3} \text{ hPa s}^{-1}$ occurs around -24 to -12 h, no consistent increasing trend is noted.

A daily sequence of composite 850-hPa maps of horizontal wind and geopotential height during the monsoon onset from -24 to 96 h is given in Fig. 8. During this period, the South China Sea is under the influence of the western Pacific subtropical ridge, which extends southwestward into the central South China Sea. To the north of the South China Sea, a northeast-southwest-oriented midlatitude trough near 105°E moves slowly from central China southeastward. The freshening of

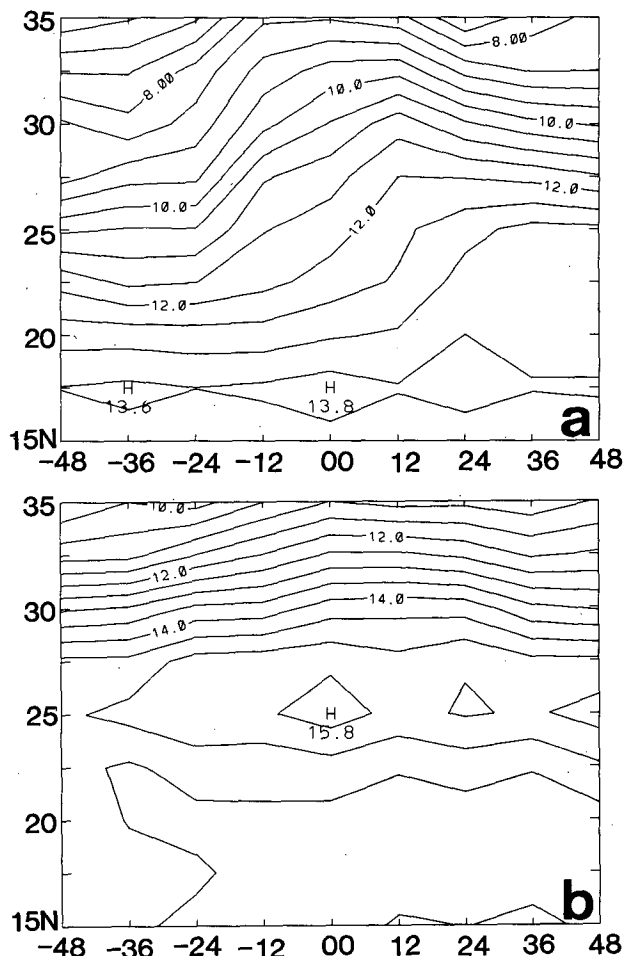


FIG. 6. As in Fig. 5 except for mixing ratio (g kg^{-1}).

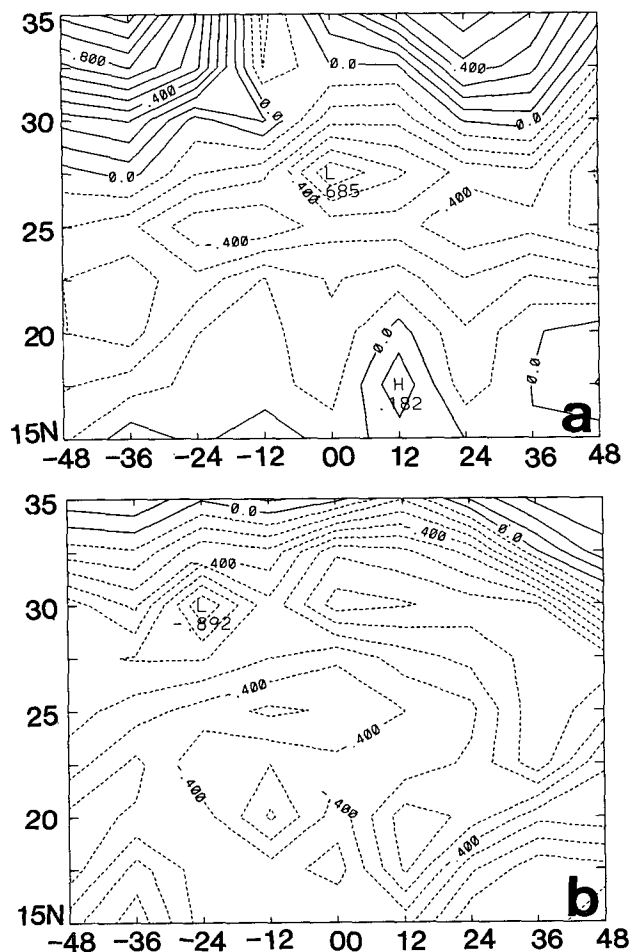


FIG. 7. As in Fig. 5 except for pressure velocity (10^{-3} hPa s^{-1}).

southwesterlies over the northern South China Sea occurs to the southeast of the trough throughout the period. The southwesterly flow over the Bay of Bengal (10° – 20° N, 80° – 100° E) does not appear to be directly connected with the northern South China Sea southwesterly acceleration during the onset period, because the southwesterly flow is blocked by a ridge over the eastern Bay of Bengal. The ridge forms between a thermal trough over Indochina and another east of the India subcontinent near 85° E. In addition, the monsoon low north of India has not fully developed, so that the westerly winds over the Arabian Sea are still light and tend to be deflected around the southern tip of India, which contributes to the formation of the trough near the east coast of India.

Similar to the monsoon onset, a midlatitude trough (although somewhat weaker) also moves in from central China during June surges (Fig. 9). However, the wind structure over most of the domain is quite different. The western Pacific subtropical ridge has retreated eastward of the Philippines and a monsoon low is es-

tablished in northeastern India. The ridge over the eastern Bay of Bengal during the monsoon onset (Fig. 8) is replaced by a broad trough. As a result, strong southwesterly winds over the Bay of Bengal appear to flow downstream without much obstruction and connect with the southwesterlies over the South China Sea.

Overall, the southwesterlies over the northern South China Sea during the monsoon onset (Fig. 8) may be traced to the three upstream branches reported by the previous studies: flow from the west that crosses the Indochina Peninsula; anticyclonic flow around the western edge of the western Pacific subtropical ridge that penetrates into the South China Sea; and a cross-equatorial flow near 105° E that appears to originate from Java and southern Sumatra. On the other hand, in June surges (Fig. 9) the western Pacific subtropical ridge has retreated to the east and no cross-equatorial flow appears in the longitudes of the South China Sea. The entire field is dominated by southwesterlies from the Bay of Bengal.

To examine the southwesterly wind acceleration, the time changes of the composite 850-hPa maps during the monsoon onset are shown in Figs. 10a–e. Here the different panels show the differences between the indicated time and -24 h. Starting at 00 h, a continuous trend of falling geopotential heights over southern China indicates the intrusion of the midlatitude trough. A height increase to the southeast occurs at the same time. This anticyclogenesis is centered near the Philippines and contributes to the increase of pressure gradient associated with the onset. At the same time, cyclonic development covers the entire Bay of Bengal. Starting from 24 h, the development evolves into two centers that are separated by the ridging over the eastern Bay of Bengal: a stronger development over the Andaman Sea northwest of the Malay Peninsula, and another over southwestern Bay of Bengal. The cyclogenesis over the Andaman Sea may be related to Orgill's (1967) observation that there is tropical storm activity in the Bay of Bengal or vicinity prior to the southwesterly onset.

The split of the vortex development over the Bay of Bengal leads to an obstruction of the cross-Indochina southwesterlies and an enhancement of the southerlies from the northern equatorial zone near 105° E. However, no acceleration of the cross-equatorial flow from the Southern Hemisphere at this longitude, as reported by some investigators (e.g., Tao et al. 1983), is observed. The southerly acceleration is part of the spinup of the Andaman Sea vortex and is connected with the westerly acceleration along the northern equatorial Indian Ocean.

From 48 to 96 h, the negative height tendency over southern China appears to extend southwestward to connect with these Bay of Bengal developments. In the meantime, there is a strong cyclonic development south of the equator in the Indian Ocean. By 96 h, the southwest extension of the northern troughing axis that con-

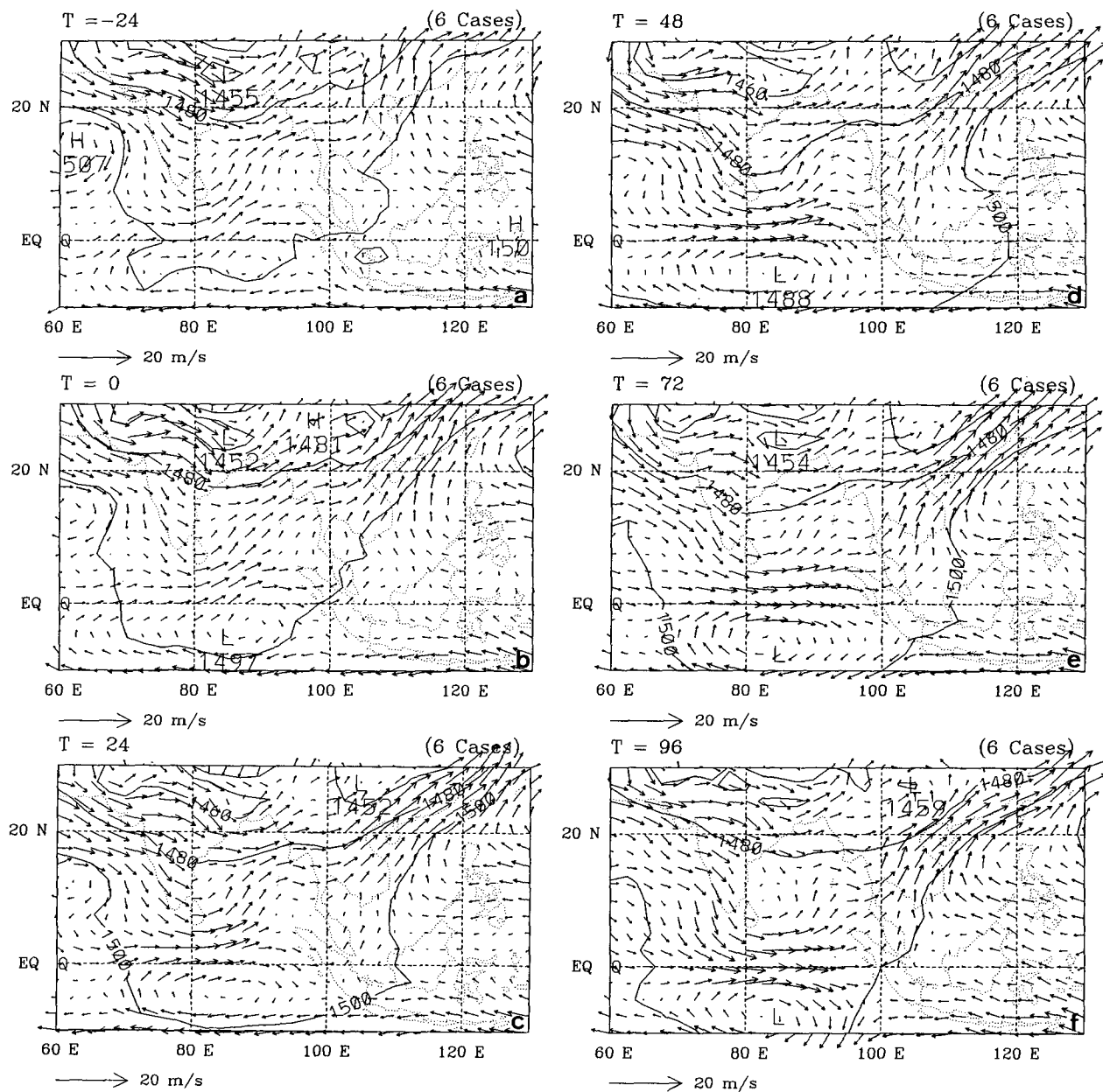


FIG. 8. Composites of the 850-hPa horizontal wind and geopotential height (interval: 20 gpm) for (a) -24 h, (b) 00 h, (c) 24 h, (d) 48 h, (e) 72 h, and (f) 96 h for the monsoon onsets.

nects the southern China geopotential height fall region and the Bay of Bengal cyclonic developments appears to link with this southern equatorial cyclonic development to form a large-scale teleconnection pattern. This pattern is not in the usual sense of a "wave train" as the pattern consists of a series of cyclogenesis cells, and the development in the southern equatorial Indian Ocean is near concurrent with the southwestward intrusion of the northern cyclogenesis system.

Since the radiosonde coverage over the equatorial oceanic region is very sparse, a question may be raised

as to whether the ECMWF analysis, which is the basis of the composite wind and height fields, represents the atmosphere. We therefore compared the time changes of the composite OLR for the monsoon onset (Fig. 11) with the time changes of the composite wind and height fields shown in Fig. 10. Superimposed on the OLR diagrams are the main cyclogenesis axes (axes of lowering heights and/or increasing cyclonic vorticity) determined from the height and wind change fields in Figs. 10. It is readily seen that these axes correspond closely to negative OLR changes. Since lower OLR is

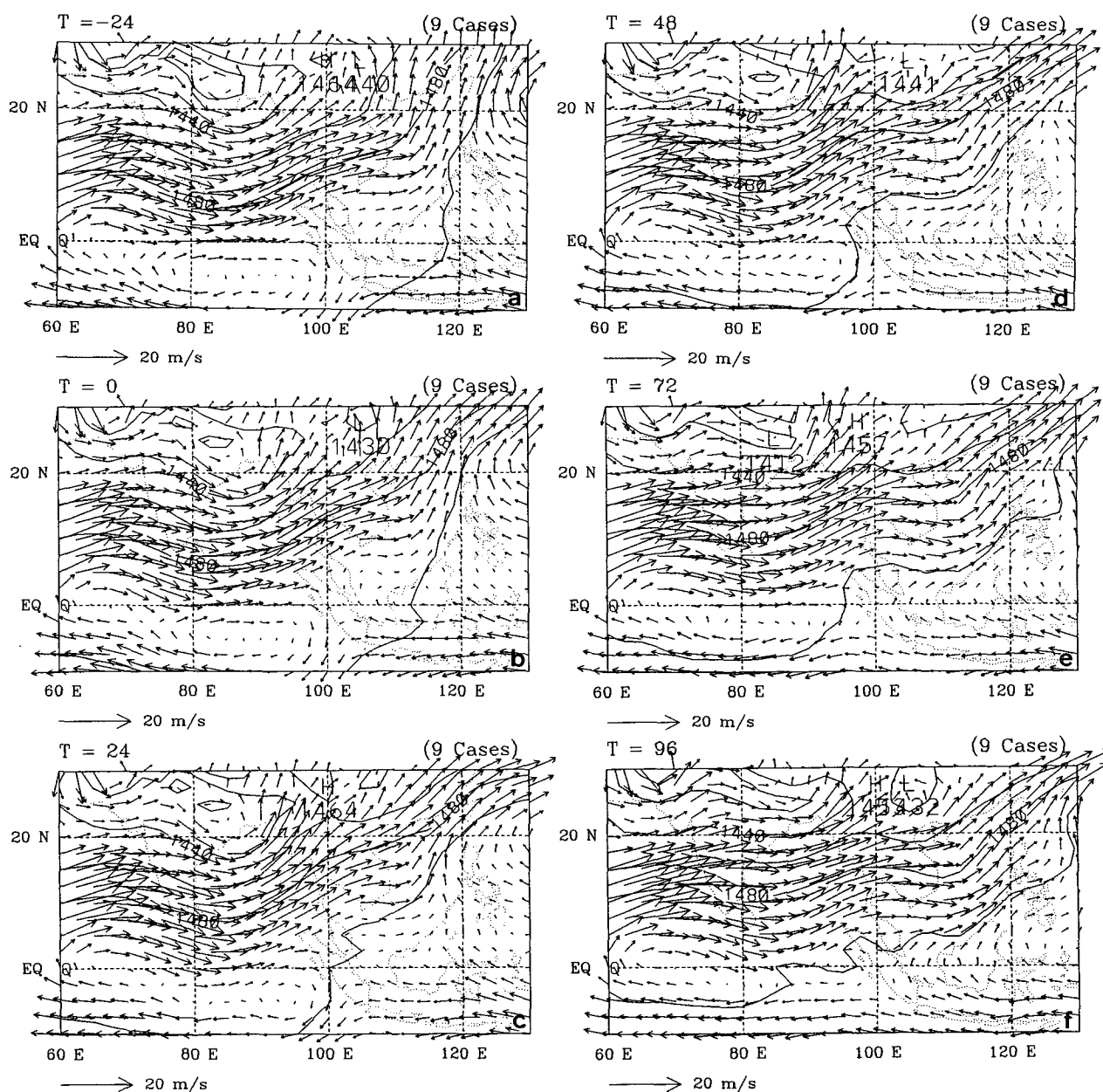


FIG. 9. As in Fig. 8 except for the June surges.

correlated to increased deep convection, which is expected along cyclogenesis axes, the satellite data confirm the tropical development indicated by the composite wind and height fields during the monsoon onset.

The time changes of the composite 850-hPa maps for the June surges are shown in Fig. 12. The intrusion of a midlatitude trough from central China is again indicated by the continuous geopotential height falls over southern China. A region of height increase to the southeast (centered between Taiwan and the Philippines) is again noted. The most striking difference from

the May onset is over the Indochina Peninsula, where height rises and an anticyclonogenesis cell appears at 00 h. Afterward, this cell moves slowly to the west-southwest with its axis extending farther southwestward. It also connects with the ridging center to the east at 24 h to make the latter appear to be an eastward extension of the main cell. The result is a ridging zone over the northern South China Sea, with significant westerly wind acceleration between this ridging zone and the cyclonic development zone to the north. This acceleration has a southerly component from -24 to

trough-front system appears to trigger both the monsoon onsets and the June surges, large-scale flow changes during the two events are quite different. Dur-

phase, resulting in opposite flow accelerations and development or decay of deep convection in the maritime continent and the eastern equatorial Indian Ocean.

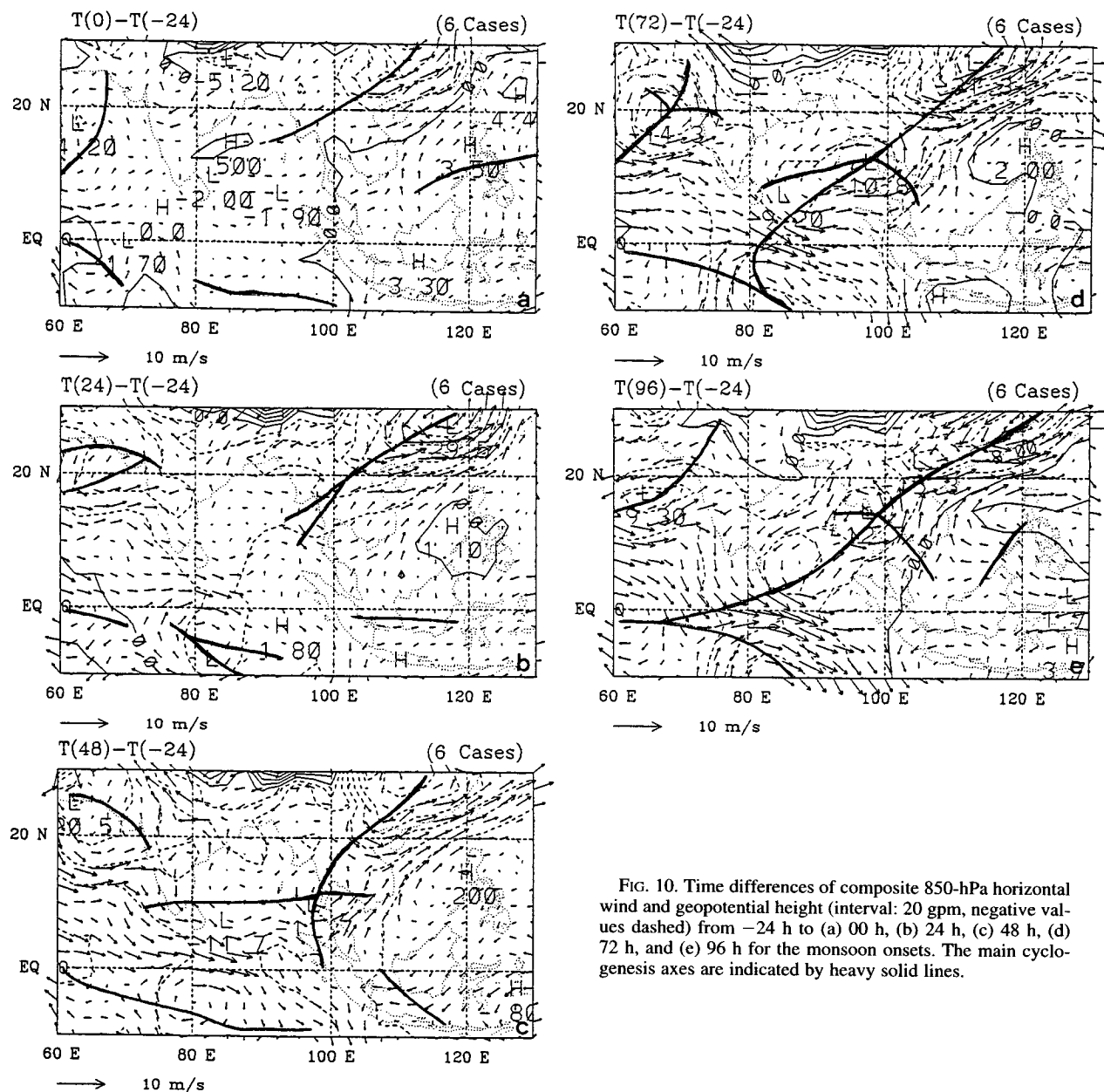


FIG. 10. Time differences of composite 850-hPa horizontal wind and geopotential height (interval: 20 gpm, negative values dashed) from -24 h to (a) 00 h, (b) 24 h, (c) 48 h, (d) 72 h, and (e) 96 h for the monsoon onsets. The main cyclogenesis axes are indicated by heavy solid lines.

24 h, indicating that there is enhanced moisture transport (not shown) toward the Mei-Yu rainfall system in the Yangtze region and southern Japan.

By 96 h, the center of the westward-propagating anticyclonic development cell reaches 12.5°N , 87.5°E , which gives a propagation speed of about $4\text{--}5\text{ m s}^{-1}$. The area of this anticyclonic development continues to expand so that by 96 h it is the dominant feature covering the entire Bay of Bengal and most of India, with the southwestward extension of its axis reaching the northern equatorial Indian Ocean southwest of India. South of the equator another anticyclonic development

cell appears at the same longitude as the northern cell, and it also continues to develop so that a symmetric pattern is maintained with the two anticyclogenesis cells saddling the equator. At 96 h, the two cells cover the entire eastern tropical Indian Ocean, with a jetlike easterly acceleration of about 5 m s^{-1} over 5 days between them. This easterly acceleration turns west-southwestward across the equator near 80°E and slows down the equatorial westerlies (Fig. 9).

Figure 12 is also compared to the time changes of the composite OLR for the June surges (Fig. 13). Here the main anticyclogenesis axes determined from the

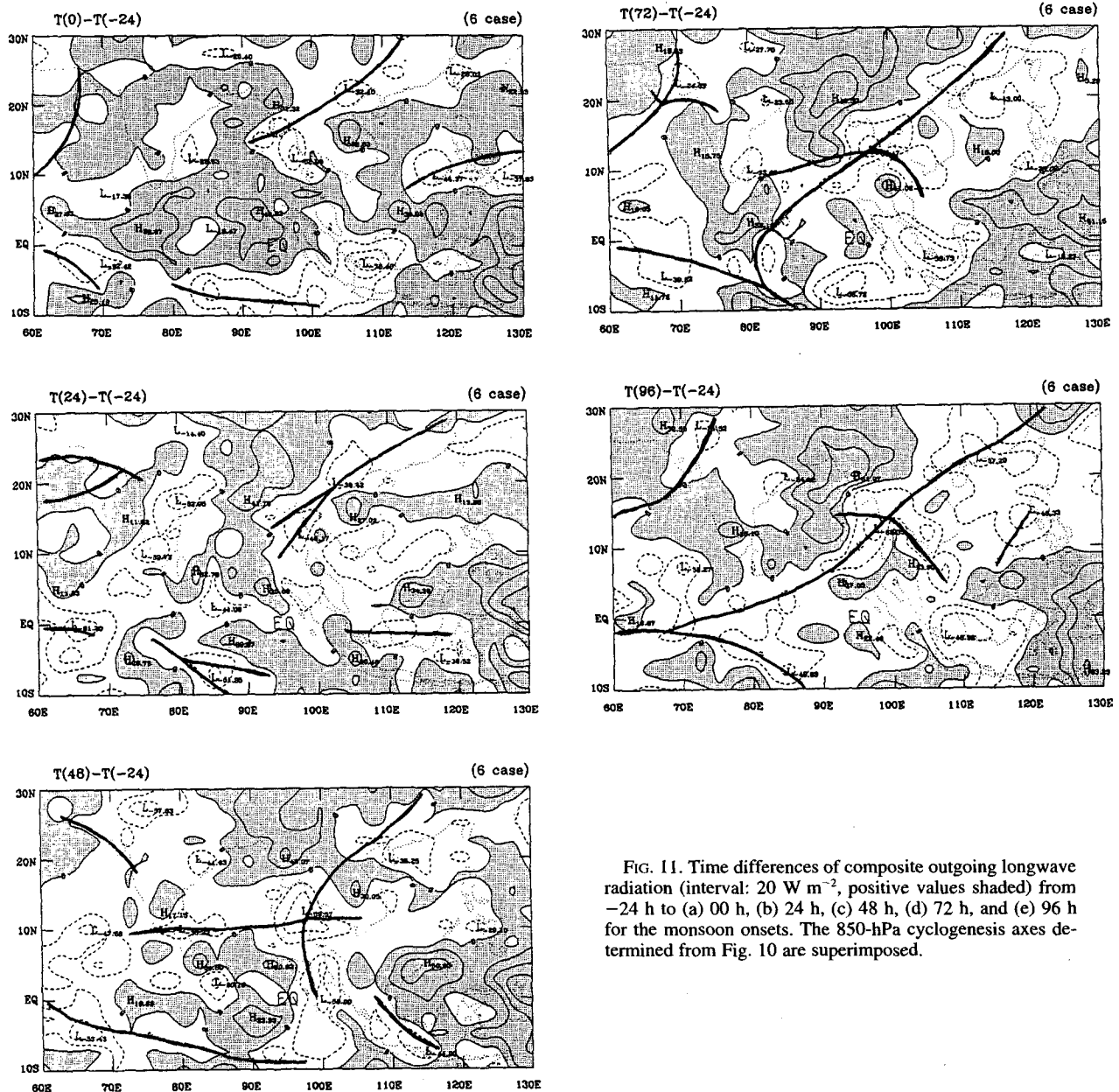


FIG. 11. Time differences of composite outgoing longwave radiation (interval: 20 W m^{-2} , positive values shaded) from -24 h to (a) 00 h , (b) 24 h , (c) 48 h , (d) 72 h , and (e) 96 h for the monsoon onsets. The 850-hPa cyclogenesis axes determined from Fig. 10 are superimposed.

height and wind change fields in Figs. 12 are superimposed on the OLR diagrams, along with cyclogenesis axes near 20°N . Again, the anticyclogenesis axes correspond closely to positive OLR changes, and the cyclogenesis axes correspond closely to negative OLR changes. Thus, the tropical development indicated by the composite wind and height fields during the June surges is also confirmed by the satellite data.

In summary, while the arrival of a midlatitude trough–front system appears to trigger both the monsoon onsets and the June surges, large-scale flow changes during the two events are quite different. Dur-

ing the onsets, the freshening of southwesterlies occurs along an extended southwest–northeast belt that spans from the equatorial Indian Ocean near 90°E across the Malay and Indochina Peninsulas, the northern South China Sea to the East China Sea. During the June surges the acceleration is confined to the vicinity of the southern China coast. In the equatorial region south of 20°N the distribution of height change during the monsoon onsets and the June surges is almost 180° out of phase, resulting in opposite flow accelerations and development or decay of deep convection in the maritime continent and the eastern equatorial Indian Ocean.

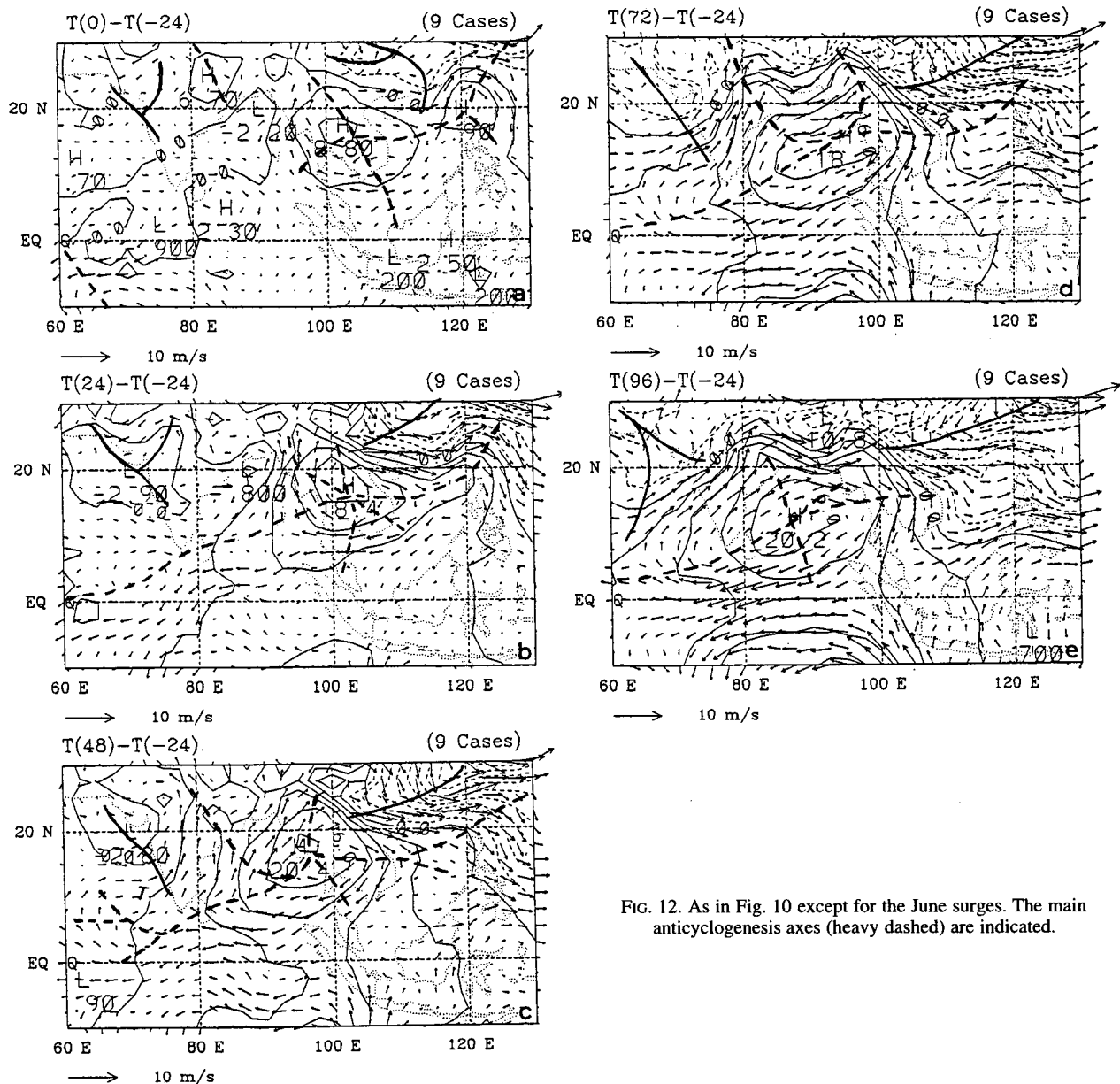


FIG. 12. As in Fig. 10 except for the June surges. The main anticyclogenesis axes (heavy dashed) are indicated.

4. Concluding remarks

These composites of ECMWF analyses depict an evolution of events for the East Asian monsoon onsets that are associated with an equatorward movement of a midlatitude trough–front system into southern China and the northern South China Sea and increased southwesterlies, moisture, and rising motion that move poleward from the Tropics to meet with the midlatitude trough/front. The June surges, which supply moisture to the Mei-Yu rainbelt, are also associated with the approach of a midlatitude system (the Mei-Yu front), but

the latter's influence appears more limited to the northern latitudes.

Previous studies have suggested that the monsoon onset over the South China Sea may be triggered by tropical forcing, including sea surface temperature increases (e.g., He et al. 1992), intraseasonal oscillations (e.g., Murakami et al. 1986; Lau et al. 1988; Li and Zhou 1992), and tropical storms (e.g., Orgill 1967). Without excluding any of these as possible contributory causes, these composites illustrate the importance of the midlatitude trough–front system in the onset process. The front establishes a quasi-stationary position

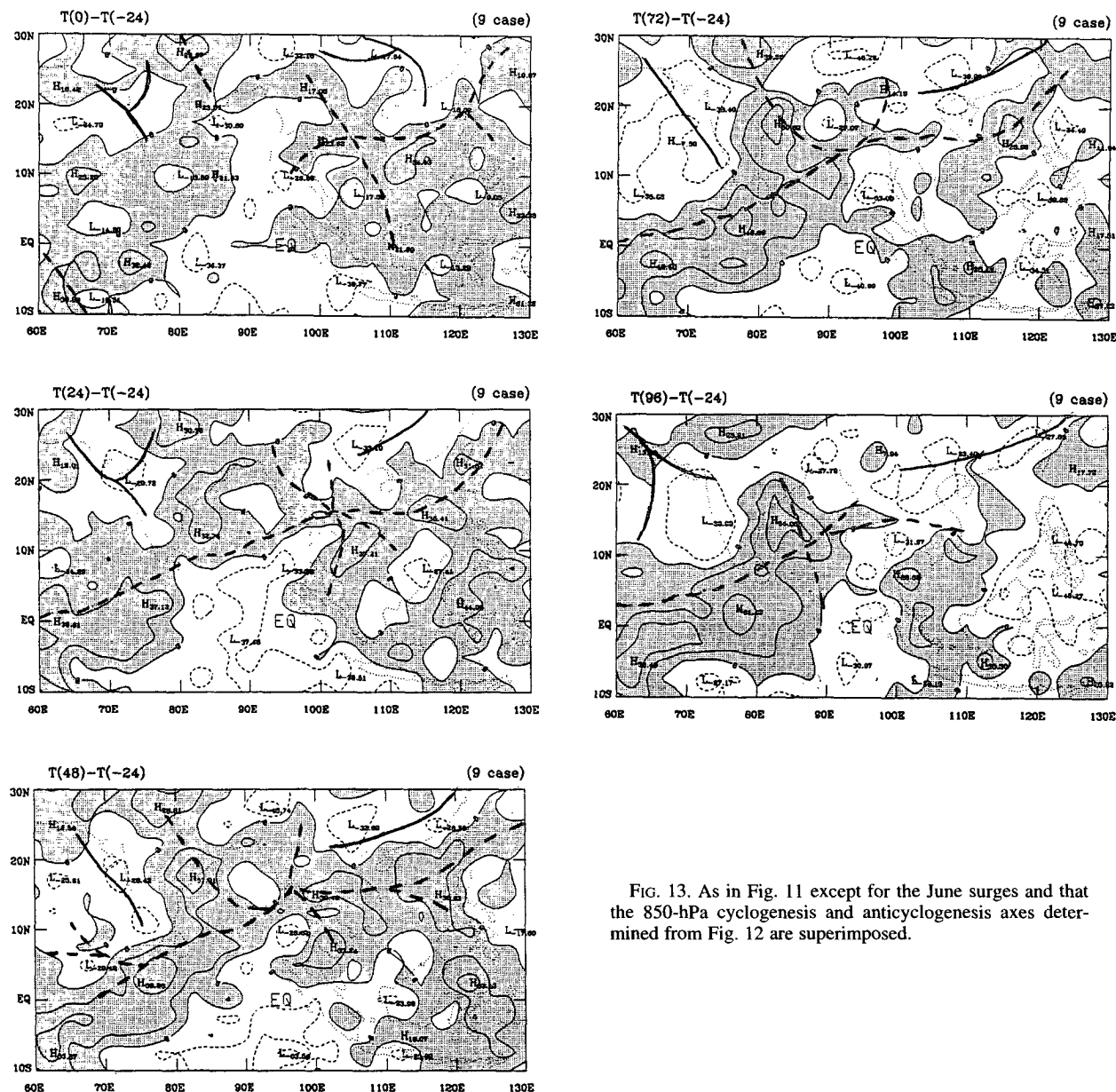


FIG. 13. As in Fig. 11 except for the June surges and that the 850-hPa cyclogenesis and anticyclonogenesis axes determined from Fig. 12 are superimposed.

near the southern China coast and allows an acceleration of southwesterlies to its south and a sustained transport of moisture from the Indochina Peninsula and the warm sea surface of the South China Sea. These westerly surges occur about two times during May, and the first one may correspond to the onset of the summer monsoon. In this point of view, the midlatitude front that is associated with the presummer rainy period is the triggering mechanism of the South China Sea summer monsoon onset.

The triggering by a midlatitude system may provide an explanation for why the onset over the South China Sea is the earliest in the entire Asian monsoon

system. The Tibetan Plateau and the adjacent high mountains from southwestern China to west Asia form a barrier that prevents midlatitude systems from moving into the Arabian Sea, India, and the Bay of Bengal during boreal spring. For the entire longitudinal span of Asia, the South China Sea is the westernmost tropical region where the baroclinic disturbances in the lower troposphere can penetrate into the subtropics. Meanwhile, the rising sea surface temperature makes the tropical atmosphere increasingly favorable for monsoon development. Thus, onset may occur earliest over the South China Sea with the invading midlatitude fronts as an impetus. Over

the South Asian monsoon regions (Arabian Sea, India, and Bay of Bengal), the onset has to wait for more matured local conditions, as enhancement of winds from midlatitude systems in the lower troposphere is not available.

These composites indicate that the southerly flow near 105°E just north of the equator is enhanced following the monsoon onset over the South China Sea. However, this acceleration comes from the west as a result of a vortex development in the Andaman Sea/eastern Bay of Bengal, rather than an enhancement of the cross-equatorial flow. Thus, during the May onset the significance of the cross-equatorial flow near 105°E, and the implied Southern Hemisphere forcing, is not clear. For the June surge composite, the equatorial South China Sea is dominated by westerlies driven by the Indian monsoon trough, and the cross-equatorial flow is shifted eastward with the retreating subtropical ridge and the establishment of the monsoon trough over the central Philippine Sea.

Time change fields during the monsoon onsets and the June surges reveal interesting teleconnections in the Tropics. During the onsets, there is cyclogenesis over the Andaman Sea and Bay of Bengal, as well as the southern Indian Ocean. The midlatitude trough that arrives at the southern China coast during onset connects with these cyclogenesis systems and results in a south-westward teleconnection pattern in the time change field that extends into the southern tropical Indian Ocean. The acceleration of southwesterlies thus spreads southwestward from southern China and the East China Sea to the southern tropical Indian Ocean, resulting in an extensive northeast-southwest-oriented belt of midlatitude-tropical interaction. During the June surges, the southwesterly wind acceleration is limited to southern China, the northern South China Sea, and the East China Sea. Height and vorticity changes south of 20°N are opposite those during the monsoon onsets, with large-scale anticyclonic vortices appearing in the time-change field over the Bay of Bengal and southern Indian Ocean. These anticyclonic developments also propagate westward as a couplet that is symmetric with respect to the equator. With this pair of anticyclonic developments, the intervening zone of equatorial westerly winds decelerates. The OLR data indicate a close correspondence between the cyclonic development and increased deep convection and between the anticyclonic development and decreased deep convection.

Although the tropical development is different between monsoon onsets and June surges, they both suggest a possible forcing of tropical motions by the midlatitude system and a near-concurrent tropical development. For the monsoon onset, the Northern Hemispheric cyclogenesis appears to follow a sequential development that progresses from the southern China coast southwestward to the equator, but the southern Indian Ocean development lags only slightly

(24 h, see Figs. 10a,b) the southern China cyclogenesis. Thus, it is not clear whether the entire teleconnection pattern develops from north to south, or if there is nearly concurrent development over China and the southern Indian Ocean. The chronological order in the Tropics during the June surges is less ambiguous. The simultaneous development of anticyclonic circulations over Indochina and the southern Indian Ocean is concurrent with the arrival of the midlatitude trough in southern China. The steady westward propagation of this anticyclogenesis couplet, and their symmetry about the equator, resemble forced equatorial Rossby waves (Matsuno 1966; Gill 1982). The westward propagating disturbances that develop in the Bay of Bengal or move in from the western Pacific during summer monsoon discussed in previous studies (e.g., Krishnamurti et al. 1977; Saha et al. 1981) are mostly cyclonic depressions. More studies are required to investigate the source of this anticyclonic, equatorial Rossby wave generation and to determine whether it is a response to the midlatitude forcing or if it is part of the response to a larger-scale forcing that also leads to the southward intrusion of the midlatitude Mei-Yu front.

Murakami et al. (1986) suggested that the monsoon onset in the South China Sea is triggered by the wet phase of the 30–60-day Madden-Julian oscillation and/or the 10–20-day oscillation. Our study does not preclude a possible relationship between the monsoon onset or surges with these tropical intraseasonal oscillations. Both oscillations have a rather large range of periods, with the maximum period twice the minimum. It is therefore possible that a midlatitude-triggered event can locally amplify the intraseasonal oscillations and results in the appearance of an onset triggered by these oscillations. Further research, with better data from field experiments, will be needed to clarify the cause and effect of this type of midlatitude-tropical interaction during the monsoon onset and surges.

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