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EFFECTS OF LOW-LATITUDE MONSOON SURGE ON THE INCREASE IN DOWNPOUR FROM TROPICAL STORM BILIS

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Abstract: By using the dataset of CMA-STI Tropical Cyclone Optimal Tracks, NCEP/NCAR reanalysis and intensive surface observations, a study is performed of the influences of a low-latitude monsoon surge on the longer persistence and increase in torrential rains from the landing tropical storm Bilis. Results suggest that the southwest monsoon was anomalously active after Bilis came ashore. The westerly winds in Bilis's south side might give rise to the poleward movement of the SW monsoon, thus enlarging the pressure gradient between Bilis and the anticyclonic circulation to the south with the result of greatly intensified SW monsoon, which fueled plentiful water vapor, heat and momentum into the declining Bilis and allowed its long stay over land instead of erosion and disappearance. Before Bilis's landfall, the 2006 East Asian monsoon surge, characterized by the atmospheric ISO, experienced remarkable northward propagation. After landfall, the strong surge and powerful low frequency vapor convergence were just on the south side of Bilis, resulting in sharply increased rainfall. In addition, a broad belt of high-valued vapor fluxes extended from the eastern Arabian Sea via the Bay of Bengal, Indochina Peninsula and the South China Sea into the south of China. The belt was linked with the SW monsoon surge forming a moist tongue stretching from the Bay of Bengal to the south of China, which supplied continuously abundant vapor for Bilis along with the surge propagating poleward.

Key words: monsoon surge; tropical storm Bilis; increase in torrential rains; water vapor

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1 INTRODUCTION

China is a country that has the most landfall of typhoons and is most seriously affected by them in the world. It is also situated in the famous East Asian monsoon area, the largest in the world, which is, not by chance at all, consistent with this area of high-frequency typhoon activity.

Of a range of typhoon affecting factors, the East Asian summer monsoon is an innegligible one. The typhoon and summer monsoon fall into different kinds of tropical weather systems but are nonetheless interrelated (Wang et al.[1]). In the early 1960s, Tao et al.[2] claimed that when meridional circulation prevails in Eastern Asia, it is quite possible for air to be transported northward from southern equatorial latitudes and the strong southerly-wind component is linked with activities of Australian cold air. In his monograph "Monsoon Meteorology," Ramage[3] quoted the work of Tao et al. as stating that offshore typhoons are active when the southern longitudinal circulation crosses the equator. He showed that the typhoon-triggering low-level cross-equatorial current is the southerly monsoon surge. The monsoon onset and reinforcement are manifested as an intensified low-level jet which carries water vapor and unsteady energy. Interactions of landfalling typhoons with mid-latitude westerly systems as well as with low-latitude monsoon jets are, as a rule, two principal approaches for a typhoon to gain additional energy.

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The former denotes the typhoon-obtained kinetic energy transformed from baroclinic effective potential energy, in which the typhoon plays a role as a vapor provider that carries vast amounts of tropical disturbance energy and warm, wet air into midlatitudes; the latter is a means for the typhoon to get abundant energy via latent heat released from monsoon jets, permitting it to enhance or maintain its vigor, an ingredient that is of crucial importance to torrential rains[4-7]. Little is reported regarding the interplay between the typhoon and low-latitude monsoon jet stream due to limited cases. Based on a typhoon in July, 2006 (known as Bilis) that went deep into the land, persisted long and triggered downpours on its way, leading to heavy damage, research is performed on the impact of low-latitude monsoon surge upon the long-lived tropical cyclone and increased resultant rainfall by use of the datasets of CMA-STI Tropical Cyclone Optimal Tracks, NCEP/NCAR reanalysis and intensive surface observations in an attempt to gain insight into the causes of intensified precipitation for prognostic purposes.

2 OUTLINE OF THE TROPICAL STORM BILIS AND RAINFALL DISTRIBUTION BEFORE AND AFTER LANDFALL

Bilis, a tropical cyclone coded in the Chinese convention as 0604, formed on July 9, 2006 over waters east of the Philippines (13.5°N, 136.8°E). Afterwards, it moved northwestward, intensifying gradually and turning into an intense tropical storm on the afternoon of July 11. It landed at 2300 (Beijing Time, or BT, the same below), July 13 on the county of Yilan, Taiwan Island, followed by its sweeping path across the Taiwan Strait to make another landfall on the county of Xiapu, northern Fujian at 1250, July 14, with the near-center maximum sustained wind at the force scale of 11. Thereafter the storm migrated northwest by west, degrading into a tropical storm on the afternoon of the same day, traveling into Jiangxi in the evening. Later, on the afternoon of July 15, it became a tropical depression in SW Jiangxi. Subsequently, the low curved in motion west by south at a slow pace, traveling through southern Hunan and northern Guangxi, and disintegrating in eastern Yunnan on the evening of July 18. The tropical storm "Bilis" was on land for as long as 5 days, sweeping over Fujian, Zhejiang, Jiangxi, Hunan, Guangdong and Guangxi, causing heavy floods consecutively on its way, exposing 29,622,000 people to its attack (including 612 deaths and 208 missing) and resulting in an inundated cropped area of $115.8\times10^4 hm^2$ and causing direct economic loss of 26.6 billion *Yuan* (RMB)[8]. Bilis set a record of the heaviest rain rate, longest rainfall and widest affected area which is rare in history.

Under the effect of Bilis and its subsequent declining depression heavy rains or exceptional downpours occurred in southern Zhejiang, Fujian, southern Jiangxi, south Hunan, Guangdong, Guangxi, SE Guizhou and eastern Yunnan from July 14 to 18, with accumulated rainfall arriving at 300 to 500 mm in some of the regions. Typically, after landfall, heavy rain is likely to occur in the near-center area, in the north side of, or in the inverted trough in the NE side of the typhoon[9]. In contrast, downpour centers were mainly in the south side of Bilis after its landing. As shown in the distribution of successive 6-hr rainfall (figure not shown), the rain belts were largely in the NW and north of the intense tropical storm core (central to south of Zhejiang and coastal northern Fujian) before and during the landfall, but after landing intense precipitation cloud clusters were developing over southern Jiangxi, southern Hunan and eastern Guangdong, with greatly reduced rainfall in Zhejiang and Fujian, completing the shift of the rainfall center from the north to south side of Bilis in a short time. Afterwards, the precipitation belt moved into Guangxi and Yunnan with the Bilis's farther southwestward migration. No strong rainfall took place in the north of the storm, while exceptional torrential rains had persisted in the southern segment of Bilis for five days[10], especially from 2000 July 14 to 1400 July 15, during which rainfall increased sharply. From 0200 to 1400, July 14 (i.e., before and during landing, respectively), rainfall to the north of the storm's core ranged generally over 40 to 80 mm, with the central value exceeding 140 mm (Fig. 1a). From 0200 to 1400, July 15, precipitation occurred chiefly in the south of the storm's center, being mostly 100 to 160 mm, with the greatest value in excess of 240 mm (Fig. 1b).

3 CAUSES OF PERSISTENCE OF BILIS OVER LAND

The tropical storm Bilis, although weakening into a depression after landfall, had its structure unchanged as a low-pressure circulation and moved slowly. Studies show that[11] Bilis was blocked by the western Pacific subtropical high to the east, a high-pressure dam to the north and low-latitude anticyclonic circulation to the south after landfall. The northeastern airflows on the southeast side of the continental high, southerly air on the west side of the subtropical high and southwest flows on the north side of the low-latitude anticyclone were connected to form a situation in which Bilis had a long-time stay and slow southwestward movement.

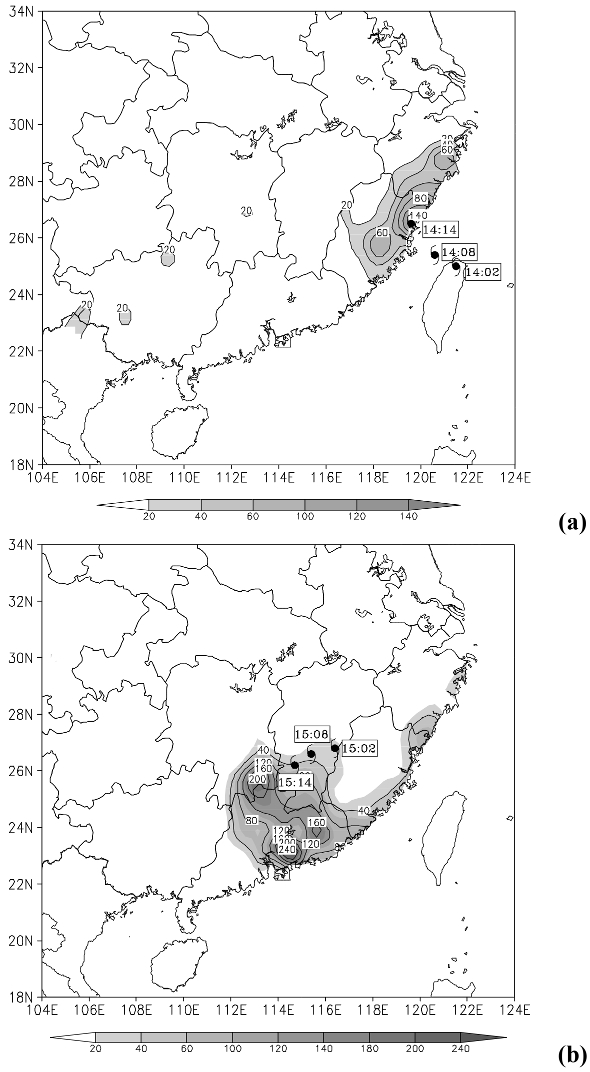


Fig.1 Cumulative rainfall (mm) for 0200 to 1400, July 14 (a) and 0200 to 1400, July 15, 2006 (b), with a legend for rainfall given below.

After making landfall, the lifespan, related rainfall intensity and domain of a typhoon are associated not only with its own intensity, size and structure but closely with the environmental field[12]. One of the salient features of Bilis ambient field was the abnormally intense SW monsoon. In 2006 the South China Sea (SCS) summer monsoon established in mid-May and began to intensify from mid-July[13]. Figure 2a delineates that at 0800, July 13, as the storm's center approached the island of Taiwan, the SW monsoon from the southern SCS started to invade the south side of Bilis. The Northern Hemisphere SW summer monsoon originated in austral winter monsoon and the SW winds joined the Somali jet stream at 40°E to 50°E, increasing the speed over the Arabian Sea, and arrived at the SCS by way of the Bay of Bengal. At 0200, July 15 (Fig. 2b), besides the vigorous Somali jet stream, the cross-equatorial airflows at 80°E to 90°E got reinforced to some degree, leading to re-intensified SW monsoon. There was a broad stretch of SW winds covering the Arabian Sea, Bay of Bengal and the whole SCS regions, with the maximum wind in excess of 27 m/s in the southeast side of Bilis (i.e. in the northern SCS).

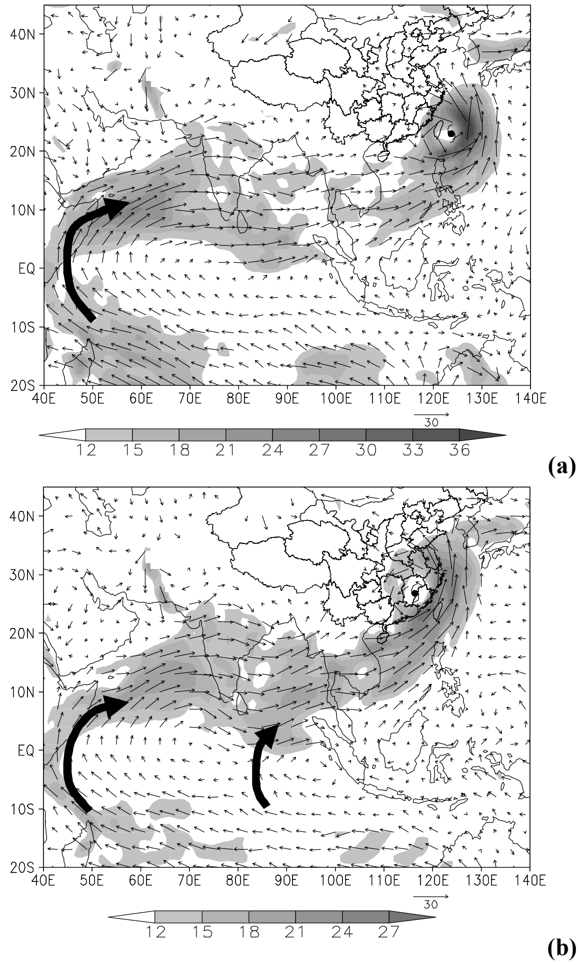


Fig.2 850-hPa winds (m/s) for 0800, July 13 in a) and 0200, July 15 in b). The shading denotes a zone of winds at >12 m/s.

Figure 3 shows the time-latitude section of 850-hPa zonal wind and vectors along 115°E, which indicates that prior to July 12, high-value zones of westerly wind were dominantly in the southern SCS south of 15°N, migrating northward starting with July 13, arriving at the south China coast on July 15, and at the same time the coastal southerly wind component intensified, too. Then the strong westerly and southerly winds flowed into the low-pressure circulation of Bilis. In association with the high-value westerlies, the coastal rainfall got augmented sharply. Afterwards, the westerly wind zone made a farther northward shift and the southerly component re-increased. The main body of SW monsoon stayed around 22°N to 27°N before July 17.

On the time-longitude section of 700-hPa meridional wind departures along the equator (Fig. 4) we see that there were positive anomalies in Somali and around 70°E from July 11. The anomalous cross-equatorial airflows propagated eastwards as a function of time and weakened somewhat on July 13 and re-intensified thereafter to continue its way towards the east. On July 15, in association with the period of Bilis-produced maximum rainfall were the positive departures of 6 to 8 m/s for the equatorial meridional winds, particularly the cross-equatorial airflows at 80°E, enhancing the SW monsoon downstream in the SCS. It followed that it was only due to the enhanced SW monsoon that vast amounts of water vapor, heat and momentum were fueled into the declining Bilis, thereby making its long stay over land instead of its quick decay.

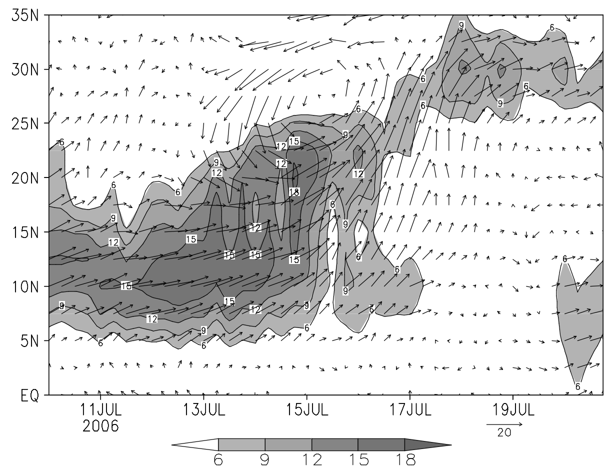


Fig.3 Time-latitude cross section of 850-hPa zonal wind and vectors along 115°E. The shading denotes a region of zonal winds at >6 m/s.

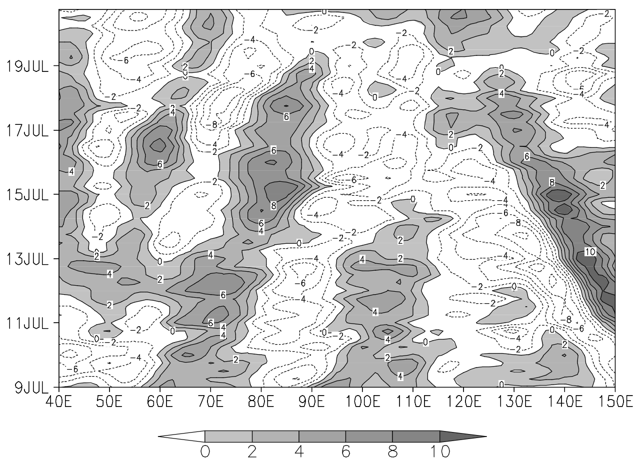


Fig.4 Time-longitude section of 700-hPa meridional wind departures along the equator. The shading denotes the positive departure zone.

In addition, after Bilis came ashore, the westerly winds in its south side might give rise to the SW monsoon movement poleward, thus enlarging the pressure gradient between Bilis and the anticyclonic circulation to the south with the result of greatly intensified SW monsoon (Fig. 2b), which, in turn, led to even stronger transport of vapor into the southern Bilis. Thus, interactions between Bilis and the SW monsoon are also a cause of the storm's long stay over land.

4 IMPACTS OF SW MONSOON SURGE UPON THE INCREASE IN RAINFALL FROM BILIS

4.1 *ISO-featured monsoon surge*

Studies show that, on a synoptic and seasonal basis, activities of summer monsoon have substantial influence on the yearly frequency of typhoons and their vigor. In the year of strong monsoons the frequency is higher than the mean of tropical cyclones in the western North Pacific and typhoons hitting Chinese southern coastline are earlier and more in comparison to normal, with positive contribution made by monsoon going inside the tropical cyclone to its development[14, 15]. Either a typhoon or a powerful summer monsoon is able to produce downpour and their combination is responsible for a stronger increase in precipitation over the inland regions[16].

As a matter of fact, summer monsoon is changeable in strength after its onset in both strong and weak monsoon years. Whenever the wind velocity is appreciably enhanced, various weather phenomena will experience great change, which is called a "monsoon surge episode"[17]. According to Ju et al.[18, 19], there is pronounced northward propagation of a monsoon surge in the period of East Asian summer monsoon. The surge is actually quasi-30-to-60 day oscillations (i.e., intraseasonal oscillation, ISO) of the monsoon and the ISO exerts innegligible impact on floods in the south of China in the years of strong monsoon surge. Figure 5 presents the wavelet power spectrum of 850-hPa zonal winds in this part of China, showing that in the summer of 2006 the quasi-30-to-60 day oscillations of zonal winds prevail at lower levels. Figure 6a gives 850-hPa ISO-treated zonal winds, which depicts that the intensity of ISO evolves as a wave with time and comparison with the mean daily rainfall (Fig. 6b) yields that there is good correspondence between June-July ISO trend and precipitation. ISO is in a positive phase from July 4 to mid-July, suggestive of the monsoon in an active interval, with its peak in mid-July well related to the maximal rainfall on July 15-16, meaning that ISO activities are in an extremely active stage, i.e., during a strong monsoon surge, there is considerable effect on the increase in rainfall from Bilis.

Ju et al.[18] claimed that the longitudinal propagation of atmospheric ISO is characterized by the northward propagation of tropical monsoon surge. From Fig. 7, it is found that there occurred a salient northward propagation of the surge in July of 2006. Beginning from early July, a new event of monsoon surge emerged in the form of positive-value ISO instead of its negative counterpart around 5°N and the low- frequency west winds started to propagate northward (shown by the arrow). When the high-valued core of the winds was positioned around 22°N about July 15, the surge was the strongest and just on the south side of Bilis, corresponding to the sharp increase in precipitation there. Subsequently, the surge continued to propagate northward, staying till late July southward of 25°N, thus allowing Bilis to stay long over land and intense rainfall to take place where it was.

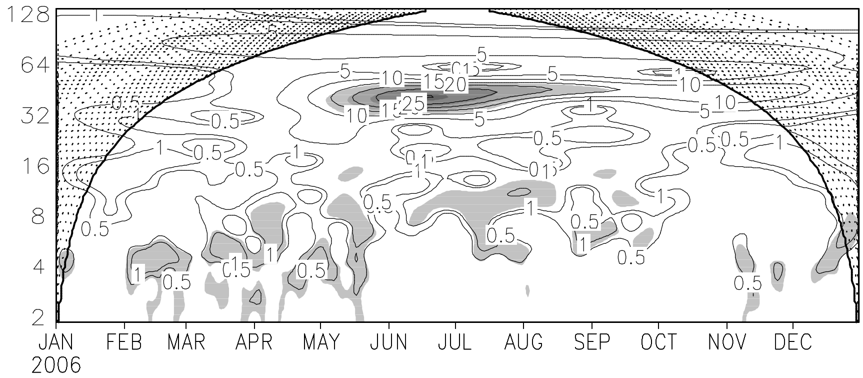


Fig.5 The wavelet power spectrum of 850-hPa zonal winds in 2006 over the south of China (18°N-25°N, 110°E-120°E). The shading represents a significant zone.

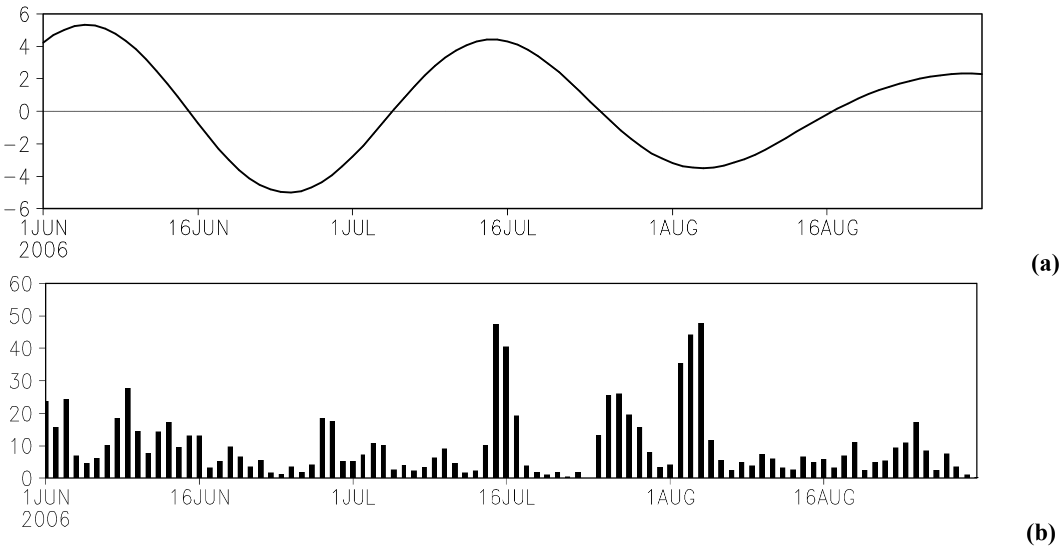


Fig.6 The 30-60 day filtered curve of 850-hPa zonal wind (a) and regionally averaged daily rainfall (b) from June to August, 2006 over the south of China.

Referring to Chan et al.[20] and the ISO filtered curve (Fig. 6a), the event of the monsoon surge is separated into eight phases, which are June 15 (phase I), June 20 (II), June 25 (III), June 30 (IV), July 4 (V), July 10 (VI), July 15 (VII) and July 20 (VIII). Phase I (V) is for the transition of the oscillation from an active to a break (from a break to an active) phase; phase III (VII) denotes the valley (peak) of the lull (active) stage, with the other phases denoting the halfway values between the trough and peak. Analysis of the phased 850-hPa low-frequency winds (Fig. 8) yields that starting from July 4 (phase V), the monsoon began its transition from the lull to active stage (Fig. 8a), with a feeble low-frequency anticyclone over the south of China and low-frequency westerlies mainly in the southern SCS in contrast to a low-frequency cyclone over waters east of the island of Taiwan, which gradually migrated northwestward to the waters offshore the south of China (phase VI) and at that time westerlies over the southern SCS spread northward to the coastal part of the region (Fig. 8b). In phase VII as the extremely active stage the low-frequency cyclone covered most of this region (Fig. 8c), with low-frequency northerly air to the west meeting low-latitude westerlies in southeastern Guangdong, thus responsible for increased vapor convergence at lower levels there, in association with the sharp increase in rainfall from Bilis at that time interval. This demonstrates the innegligible impact of the monsoon surge upon the sharp increase in rainfall from the landing storm.

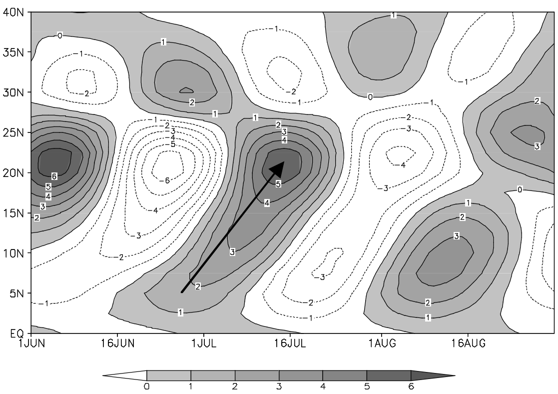


Fig.7 Time-latitude section of the 30 to 60 day filtered 850-hPa zonal winds along 115°E. The shading denotes the low-frequency west wind.

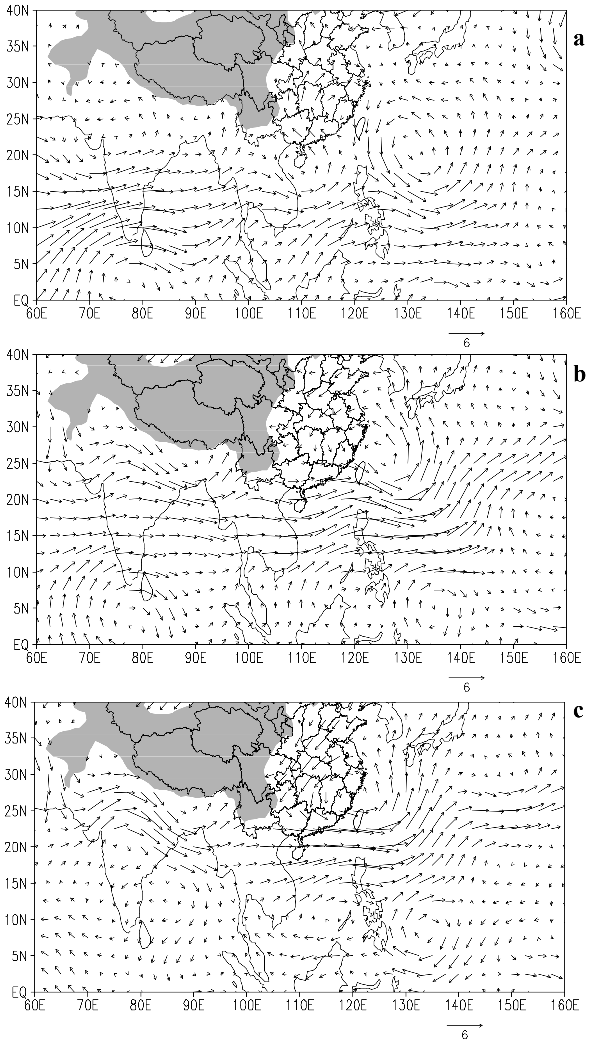


Fig.8 Evolution of low-frequency winds (m/s) at phases V-VII, with phase V in (a), VI in (b) and VII in (c).

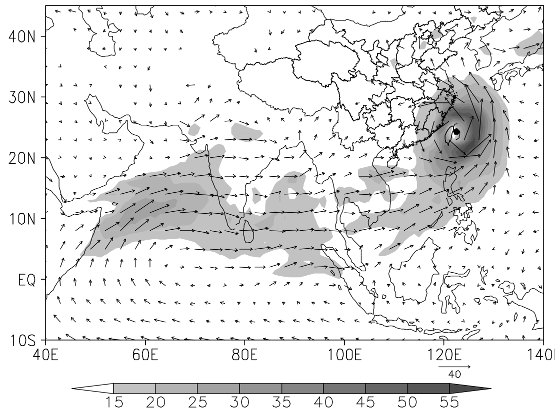
4.2 *Flux of vapor transport*

The strength of precipitation from a landing tropical cyclone is strongly linked to its long-time stay over land. Generally, when the supply of oceanic vapor and energy to the landing typhoon is cut off, the storm fails to be maintained. But it can survive for a long time if there are other approaches to gaining supplies, which permit vigorous convection to happen in the spiral rain belts of the typhoon, increasing rainfall strength[11].

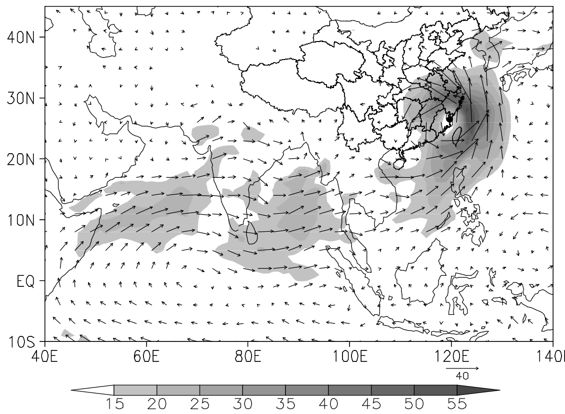
Analysis of 850-hPa vapor fluxes before, during and after the landfall indicates that the vapor had different origins. Before (during) the Bilis landing, as given in Fig. 9a (9b), vapor came dominantly from the SCS. The high-valued band of vapor from the Bay of Bengal broke to some degree at the Indochina Peninsula. And after its landfall a broad high-valued zone of vapor fluxes stretched from the eastern Arabian Sea via Bay of Bengal, Indochina Peninsula and SCS into the south of China. At 0200, July 15 (Fig. 9c) the high-valued core in the SE side of the storm had the maximal magnitude in excess of 45 g/ (s. hPa. cm), well corresponding to the increased precipitation in that period. The central intensity declined somewhat therefrom till 0200, July 17 (Fig. 9d), but nevertheless the broad vapor belt remained, on the whole. Note that the time (0200, July 17) was more than 50 hours away from the landing. It is evident from Fig. 9c that this broad belt connected to the low-level SW monsoon surge, thus forming a wet tongue stretching from the Bay of Bengal to the south of China, with high-value vapor fluxes into the surge band and vapor was constantly transferred into the Bilis circulation as the surge moved northward, thus providing plentiful vapor for torrential rains in the moist region ahead of the monsoon surge.

Inspecting the phase-dependent vapor flux shows that starting with July 4 (phase V), the monsoon was changing from the break to an active stage (Fig. 10a), with the vapor convergence zone dominantly in the region south of the Yangtze River (Jiangnan region) and northern Fujian, due mainly to the meeting of western Pacific warm, wet airflows. The divergence zones were located in central to western Guangdong and central to eastern Guangxi. With the northward shift of the passage of westerly vapor transport in the SCS and southern Taiwan island, the vapor fluxes from the western Pacific declined gradually and the vapor convergence zone that had been in the Jiangnan region spread southwestward (phase VI) into Fujian and eastern Guangdong. But the divergence area were still located in central to eastern Guangxi (Fig. 10b). In the extremely active stage (phase VII) the monsoon surge was quite vigorous, making the vapor transfer from the

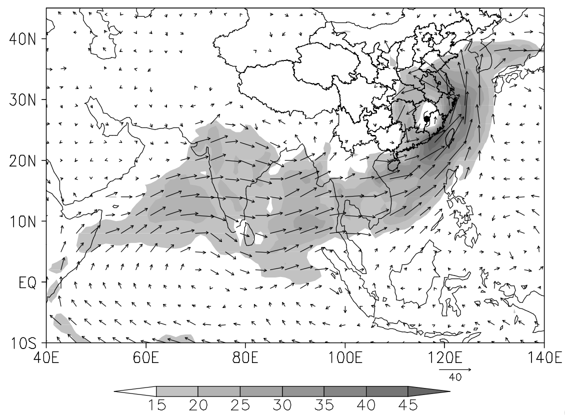
SCS reinforce greatly and spread northward gradually, leading to a powerful vapor convergence in southeastern Guangdong and central to western Fujian (Fig. 10c), in agreement with the increased precipitation over there. It follows that the propagation northward of ISO-characterized monsoon surge supplied plentiful vapor for downpour, really contributing greatly to Bilis rainfall augmentation.



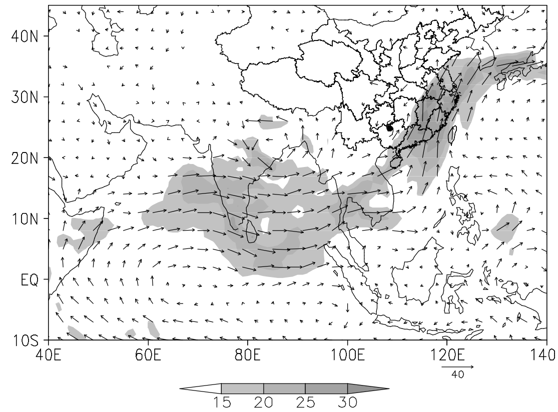
(a)



(b)



(c)



(d)

Fig.9 850 hPa vapor fluxes (g/ (s hPa cm)) at 2000, July 13 in a), 1400, July 14 in b), 0200, July 15 in c) and 0200, July 17 in d). The shading denotes a zone of vapor flux at > 15 g/ (s hPa cm).

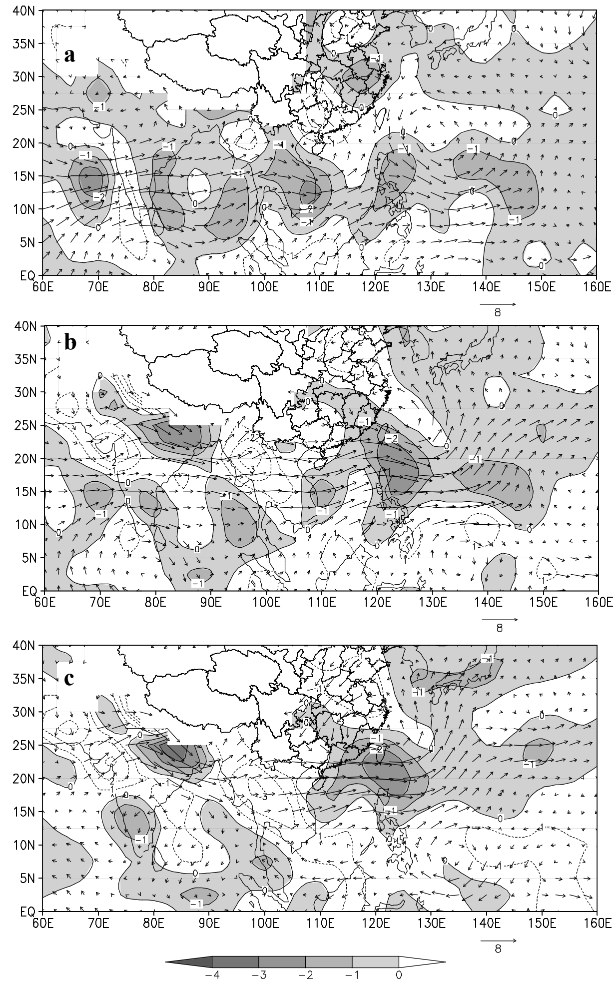


Fig.10 Evolution of 850-hPa low-frequency vapor fluxes at phases V to VII, with phase V in (a), VI in (b) and VII in (c). Units: g/(s hPa cm). The shading denotes the flux convergence zone.

5 CONCLUDING REMARKS

The tropical storm Bilis (coded 0604 in China) was not so strong during its landfall but it stayed long enough over land, producing sufficiently intense rainfall on its way to be a rare event in history. The ambient conditions and causes of the long-range maintenance of the storm and the sharp increase in downpours are explored. We come to the conclusions as follows.

(1) The southwest monsoon was anomalously active after Bilis came ashore. The westerly winds in Bilis's south side might give rise to the poleward movement of SW monsoon, thus enlarging the pressure gradient between Bilis and the anticyclonic circulation to the south with the result of greatly intensified SW monsoon, which fueled plentiful water vapor, heat and momentum into the declining Bilis, allowing its long stay over land instead of decay and disappearance.

(2) Before the Bilis's landfall, the 2006 East Asian monsoon surge, characterized by the atmospheric ISO, experienced remarkable northward propagation. After its landing, the strongest surge and powerful low frequency vapor convergence were just on the south side of Bilis, resulting in sharply increased rainfall.

(3) There was difference in vapor source before, during and after the Bilis landing. Prior to and during the landfall the vapor came largely from the SCS and after landfall a broad belt of high-valued vapor fluxes stretched from the eastern Arabian Sea, via the Bay of Bengal, Indochina Peninsula and the SCS into the south of China. The belt was connected with the SW monsoon surge, thereby forming a moist tongue stretching from the Bay of Bengal to this part of China. Vast amounts of vapor were supplied for the tropical storm as the monsoon surge propagated northward.

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