SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

January 2011 Vol.54 No.1: 1–9
doi: 10.1007/s11430-010-4125-6

Vortex genesis over the Bay of Bengal in spring and its role in the onset of the Asian Summer Monsoon

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Received May 10, 2010; accepted August 12, 2010; published online December 6, 2010

Physical processes associated with onset of the 1998 Asian summer monsoon were examined in detail using multi-source datasets. We demonstrated that strong ocean-atmosphere-land interaction in the northern Indian Ocean and tropical Asian area during spring is a fundamental factor that induces the genesis and development of a monsoon onset vortex over the Bay of Bengal (BOB), with the vortex in turn triggering onset of the Asian summer monsoon. In spring, strong surface sensible heating over India and the Indochina Peninsula is transferred to the atmosphere, forming prominent *in situ* cyclonic circulation, with anticyclonic circulations over the Arabian Sea and northern BOB where the ocean receives abundant solar radiation. The corresponding surface winds along the North Indian Ocean coastal areas cause the ocean to produce the *in situ* offshore currents and upwelling, resulting in sea surface temperature (SST) cooling. With precipitation on the Indochina Peninsula increasing from late April to early May, the offshore current disappears in the eastern BOB or develops into an onshore current, leading to SST increasing. A southwest-northeast oriented spring BOB warm pool with SST >31°C forms in a band from the southeastern Arabian Sea to the eastern BOB. In early May, the Somali cross-equatorial flow forms due to the meridional SST gradient between the two hemispheres, and surface sensible heat over the African land surface. The Somali flow overlaps in phase with the anticyclone over the northern Arabian Sea in the course of its inertial fluctuation along the equator. The convergent cold northerlies on the eastern side of the anticyclone cause the westerly in the inertial trough to increase rapidly, so that enhanced sensible heat is released from the sea surface into the atmosphere. The cyclonic vorticity forced by such sensible heating is superimposed on the inertial trough, leading to its further increase in vorticity strength. Since atmospheric inertial motion is destroyed, the flow deviates from the inertial track in an intensified cyclonic curvature, and then turns northward toward the warm pool in the northern BOB. It therefore converges with the easterly flow on the south side of the anticyclone over the northern BOB, forming a cyclonic circulation center east of Sri Lanka. Co-located with the cyclonic circulation is a generation of atmospheric potential energy, due to lower tropospheric heating by the warm ocean. Eventually the BOB monsoon onset vortex (MOV) is generated east of Sri Lanka. As the MOV migrates northward to the warm pool it develops quickly such that the zonal oriented subtropical high is split over the eastern BOB. Thus, the tropical southwesterly on the southern and eastern sides of the MOV merges into the subtropical westerly in the north, leading to active convection over the eastern BOB and western Indochina Peninsula and onset of the Asian summer monsoon.

air-sea interaction, spring BOB warm pool, monsoon onset vortex, inertial oscillation, Asian summer monsoon onset

Citation: Wu G X, Guan Y, Wang T M, et al. Vortex genesis over the Bay of Bengal in spring and its role in the onset of the Asian Summer Monsoon. Sci China Earth Sci, 2011, 54: 1–9, doi: 10.1007/s11430-010-4125-6

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The monsoon is an atmospheric phenomenon where circulation responds to large-scale land-sea thermal contrasts due to the annual cycle of solar heating. The land surface warms quickly during spring because of increased solar radiation. During the Asian summer monsoon onset, the atmospheric meridional temperature gradient in the lower latitudes in winter changes its sign from negative to positive, accompanied by vigorous convective precipitation. To characterize the Asian summer monsoon onset and seasonal transition, Li and Yanai [1] defined an index of the upper tropospheric (200–500 hPa) temperature difference between 5°N and 30°N, and Webster and Yang [2] defined another as the vertical shear of zonal winds between 850 and 200 hPa. Mao et al. [3] pointed out that these two indices were essentially identical, with each reflecting one of the two aspects in the thermal wind relation. They then proposed variation in the tilting of the ridge surface of the subtropical high as a new index to represent seasonal transition and the Asian summer monsoon onset. They demonstrated that in winter near 12°N over the southern Asian region, the ridge surface of the zonal subtropical high tilted southward with increasing height, while in summer it tilted northward over the region. Thus, the seasonal transition from winter monsoon to summer monsoon or the Asian summer monsoon onset arises where the ridge surface becomes perpendicular to the earth's surface.

Usually, the seasonal transition from winter monsoon to summer monsoon firstly occurs over the eastern Bay of Bengal (BOB) [3–5], accompanied by a cyclonic vortex generating and developing over the BOB [6]. Therefore, such a vortex is referred to as the BOB monsoon onset vortex (MOV) [7]. The MOV arises generally over the southern BOB, and then migrates northward such that the lower tropospheric southwesterlies on the southern and eastern sides of the MOV merge into subtropical westerlies to the north of the subtropical high ridge surface. The initially continuous zonal ridgelines in the lower troposphere is thus split into two segments, with the western segment moving northward and the eastern segment moving southward, forming a summer pattern of the subtropical high with northward tilting of the ridge surface over the eastern BOB and western Indochina Peninsula. Consequently the earliest Asian summer monsoon onset occurs over the eastern BOB. In this regard, the triggering mechanism for onset of the Asian summer monsoon is related closely to MOV genesis and development. The question which meteorologists have to resolve is why the MOV firstly arises over the BOB, thereby the Asian summer monsoon onset occurs earliest over the eastern BOB.

In investigating the Indian summer monsoon onset, which appears usually in early June, Krishnamurti et al. [8] asserted that barotropic instability of zonal flow is responsible for the genesis and development of the MOV, while Mak and Kao [9] suggested that baroclinic instability is another mechanism for MOV development. However, barotropic or baroclinic instabilities reflect merely atmospheric internal energy conversion. As an open and dissipative monsoon system, it is necessary for the occurrence of the MOV to initially gain external energy from outside the atmosphere. In other words, the MOV must arise in a warm (high T) and heating (Q>0) area. Within such an area S, positive energy is created $(\int_S (Q\cdot T)\mathrm{d}s>0)$. Gray [10] pointed out that tropical cyclones occur usually over warm oceans. In fact, warm sea surface temperature (SST) is only a necessary condition for tropical cyclogenesis. The sufficient condition is an unstable atmosphere heated by the warm ocean. From this perspective and based on a case study, the objective of this paper is to identify the roles of air-sea interaction in the Asian summer monsoon onset. It is the unique air-sea interaction in the BOB that favors the MOV to first develop there, and where the Asian summer monsoon onset initially arises over the eastern BOB.

In 1998, two large-scale observational experiments were conducted in China: the second Tibetan Plateau Experiment of Atmospheric Sciences (TIPEX) [11] and the South China Sea (SCS) Summer Monsoon Experiment (SCSMEX) [12]. These provided many sound datasets for examining onset processes of the Asian summer monsoon and related physical mechanisms. The development of the summer monsoon in 1998 was selected as a case study. Much research has shown that in 1998 a MOV was generated east of Sri Lanka on May 13 [6, 13]; the Asian summer monsoon onset arose over the BOB on May 15 [14]; and subsequent onset occurred over the SCS on May 21 [15–17].

In this study we employed reanalysis of the National Center for Environment Predictions (NCEP). Other data used included pentad-mean heat fluxes and ocean currents from the NCEP Global Ocean Data Assimilation System (GODAS), and weekly SST and surface wind data from the National Oceanic and Atmospheric Administration (NOAA).

1 Air-sea processes in South Asia during spring

Figure 1 shows the evolution of surface sensible heat flux along 10°–20°N for the period January–July 1998 and is characterized by:

(1) Evident sensible heating >75 W m^{-2} over the eastern portion of the African continent from January to July.

(2) Prior to May 10, strong sensible heating >75 W m^{-2} occurred over the Indian Peninsula and Indochina Peninsula, and sensible heating over the Arabian Sea and the BOB was relatively weak, <25 W m^{-2}.

(3) From mid-May to late June, sensible heating over the Indochina Peninsula became negative, although the sensible heating remained positive over the African continent and Indian subcontinent.

Evolution of surface winds at a height of 10 m is also shown in Figure 1. Northeasterly winds prevailed over the southern portion of Asia before early March, and southwesterly winds became dominant after June. During the period from mid-March to early May, low-level circulation over South Asia was influenced mainly by the *in situ* land-sea thermal contrast. Because intense surface sensible heating can induce strong surface cyclonic vorticity [18], cyclonic circulation appeared over the subcontinents while anticyclonic circulation occurred over the oceanic areas. Therefore, southerlies prevailed along the western coastal ocean region, while northerlies prevailed along the eastern coastal ocean region.

The above features of the relationship between the surface heating and wind field are illustrated clearly in Figure 2. During April (Figure 2(a)), intense sensible heating existed over all the South Asia tropical continents, with anticyclones dominating the Arabian Sea and northern BOB. Thus strong southwesterlies prevailed along the eastern coasts of the Arabian Peninsula and Indian Peninsula, with strong northwesterlies prevailing over the western coast of the Indian Peninsula. Only the northwestern coast of the Indochina Peninsula was dominated by northwesterly winds because distinct sensible heating only occurred over the northwestern Indochina Peninsula. In May (Figure 2(b)), surface sensible heating weakened and became negative over the Indochina Peninsula, leading to the disappearance of the northerlies along its western coast.

Within the Ekman layer of the upper ocean, the Sverdrup relationship [19] between surface wind stress $\vec{\tau}$ and forced ocean current $\vec{M}_E$ can be expressed as:

$$\vec{M}_E = \frac{\vec{\tau}}{\rho f} \times \vec{k},$$

where ρ is sea water density, f the Coriolis parameter, and $\vec{k}$ the unit vector with up being positive. According to this relationship, offshore ocean currents were created around the western coastal ocean of the Arabian Sea and BOB with upwelling of cold sea water (Figure 2(c) and (d)), since the prevailing surface winds were southwesterlies in spring (Figure 2(a) and (b)). The SST difference between the last week (23–29 April) and the first week (2–8 April) of April increased a little in cold water upwelling areas and exhibited even negative temperature differences, while a signifi-

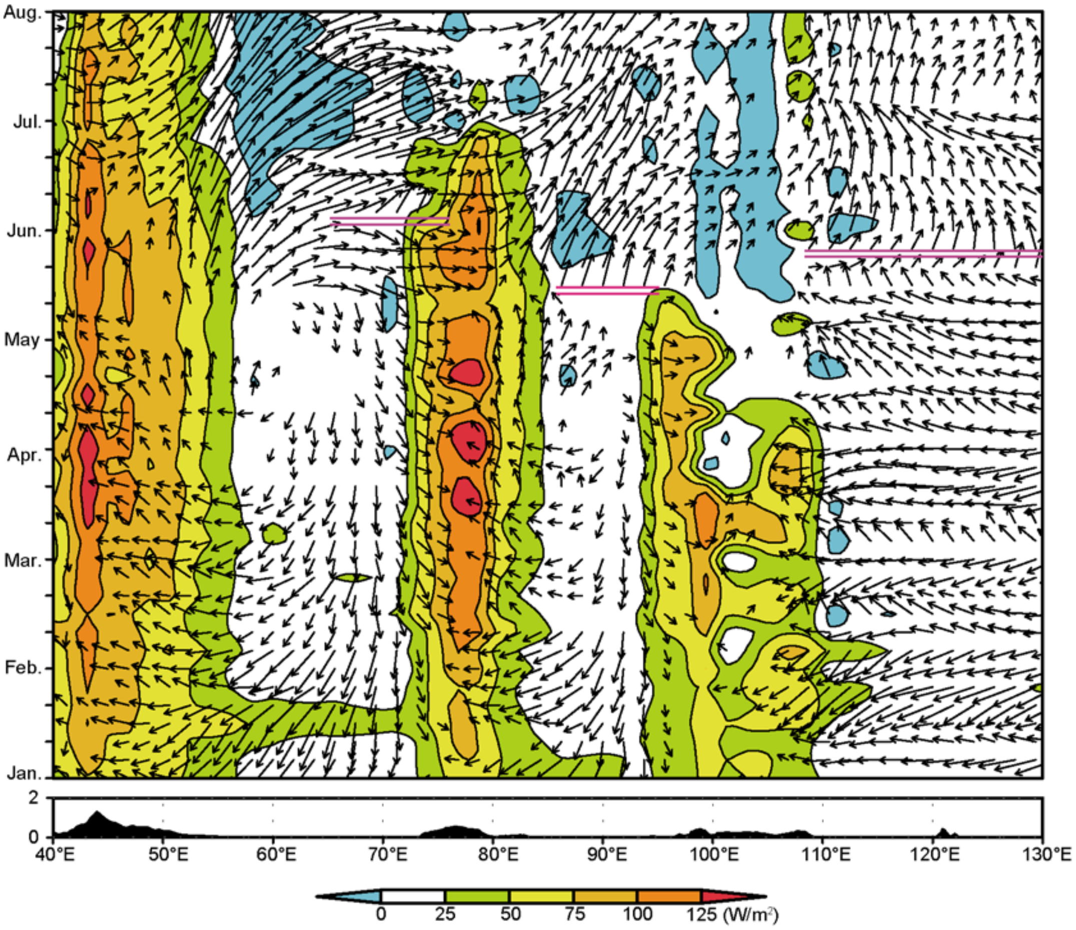

Figure 1 Time-longitude cross section averaged between 10°N and 20°N of 10-meter-height surface wind (vectors, m s^{-1}, wind velocity >2 m s^{-1} shown only) and surface sensible heating flux (contours and shading) from January to August 1998. Horizontal segments indicate the summer monsoon onset dates over the Bay of Bengal, South China Sea, and India. The bottom panel shows orographic height (km) averaged between 10°N and 20°N.

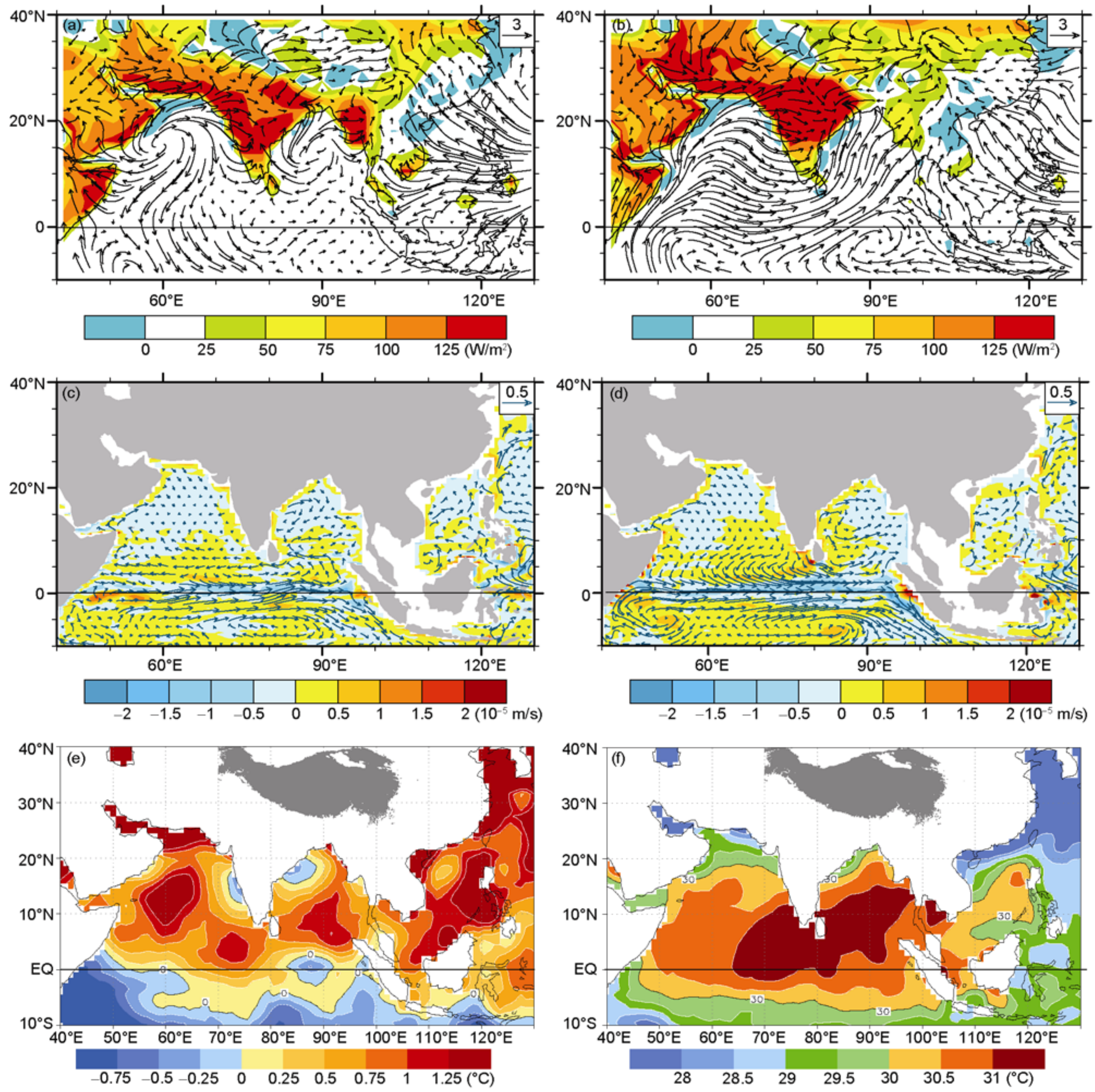

Figure 2 The 1998 distributions of surface sensible heat flux and 10-m-height surface wind (vectors, m s^{-1}) in April (a) and May (b); vertical velocity in the oceanic mixed-layer and oceanic current (vectors, m s^{-1}) 5 m below sea surface in April (c) and May (d); SST increase in April from the first week (April 2–8) to the last week (April 23–29) of the analysis (e); and weekly mean SST for the first week of May (April 30–May 6) (f).

cant increase in SST occurred in the central and eastern Arabian Sea, central BOB, and eastern SCS (Figure 2(e)). As a consequence, in early May (Figure 2(f)) a warm pool with SST >31°C formed in the northern Indian Ocean (from southeastern Arabian Sea to central BOB), with a warm center around Sri Lanka. This analysis also suggests that intense sensible heating forced prominent surface cyclonic circulations over the tropical Asian continents, with strong winds along the coasts of Arabian Sea and the western coast of the BOB. These stronger coastal winds induced *in situ* offshore ocean currents and upwelling, resulting in a colder SST. The relatively lower SST in most of the Arabian Sea, northern BOB and SCS was not conducive for MOV genesis in these areas in early spring.

2 Air-sea coupling processes prior to MOV formation

Air-sea interactive processes continued to develop till May 10 (3 days prior to the MOV genesis). Surface sensible heating flux exceeded 125 W m^{-2} over the Indian subcontinent, and 100 W m^{-2} over the Arabian Peninsula and the northwestern Indochina Peninsula (Figure 3(a)). Strong winds >3 m s^{-1} were forced along both eastern and western coasts of Arabian Sea and the eastern coast of India, causing the Arabian Sea and northern BOB to be dominated by surface anticyclones. This in turn induced *in situ* offshore ocean currents and upwelling along both the eastern and western coasts of the Arabian Sea and the western coast of the BOB (Figure 3(b)), and retained roughly the characteristics of spring air-sea interaction.

Notable changes in atmospheric circulation occurred the day before MOV formation. A significant cross-equatorial flow developed along 50°E, with inertial fluctuation along the equator (Figure 3(c) and (d)). The inertial anticyclone over the equatorial Arabian Sea overlapped with the anticyclone that existed originally over the northern Arabian Sea, leading to an increase in westerly wind speed due to confluence of the two westerly branches around the southeast-

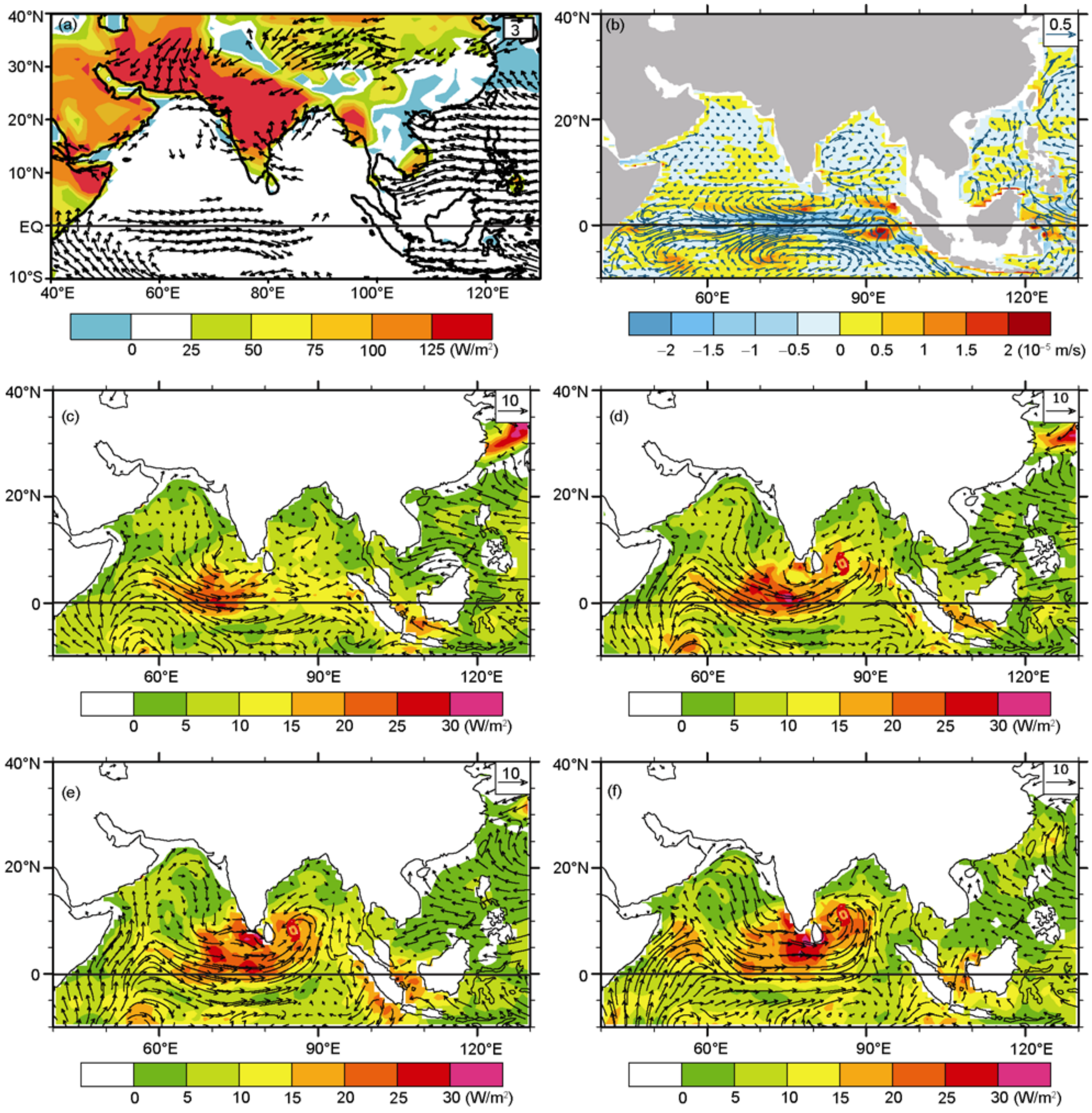

Figure 3 The 1998 distributions of the Pentad mean (May 6–10) surface sensible heat flux and 10-m-height surface wind (vectors, m s^{-1}) (a); vertical velocity in the oceanic mixed-layer and oceanic current (vectors, m s^{-1}) at 5 m below sea surface (b); and surface sensible heat flux and 10-m-height surface wind (vectors, m s^{-1}) on May 12 (c), May 13 (d), May 14 (e), and May 15 (f). The symbol “🌀” denotes position of MOV (monsoon onset vortex) center.

ern Arabian Sea. Cold northerlies ahead of the anticyclone ridge entered into warm pool area and enhanced sensible heating from ocean into atmosphere, which caused sensible heating to exceed 20 W m^{-2}. Based on thermal adaptation theory, such surface heating would create surface cyclonic vorticity [18]. This cyclonic vorticity generation was superimposed on the low pressure trough of the inertial fluctuation, resulting in deformation of the inertial wave. With wind speed increasing along the inertial trough, by May 13 (Figure 3(d)) the region of large surface sensible heating expanded notably, with a heating center >25 W m^{-2}. Such strong sea surface heating caused the deformed inertial trough to develop and widen further, enabling air particles east of the trough to overcome the inertial motion to veer northward, and eventually enter the region over the BOB warm pool. This cyclonic southerly flow encountered cold northeasterly air from the anticyclone over the northern BOB, generating a MOV over the northern Indian Ocean east of Sri Lanka, accompanied by strong sea surface sensible heating of >20 Wm^{-2}. The range and intensity of large sensible heating increased further by May 14, and the MOV ahead of the trough also strengthened further and migrated toward the central BOB warm pool (Figure 3(e)). By May 15 (Figure 3(f)), a strong MOV dominated most of the BOB, and the southerlies on its southern and eastern sides prevailed over the southern BOB extending to north of 10°N.

3 MOV development and Asian summer monsoon onset

Before summer monsoon onset, the 700-hPa wind field showed that the entire subtropical high exhibited a zonal oriented configuration along 15°N–20°N, with a continuous ridgeline connecting several anticyclone centers (Figure 4). The ridgeline separated clearly the tropical easterly to its south from the subtropical westerly to its north (Figure 4(a) and (b)). When the MOV was generated over the southwestern BOB on May 13, 1998, the corresponding cyclonic center at 700 hPa appeared over the southern tip of Sri Lanka, with heavy precipitation >15 mm day^{-1}, whereas the anticyclonic center over the northern BOB disappeared (Figure 4(b)). The northward migration of the MOV toward the BOB warm pool caused the geopotential height in the vicinity of the ridgeline to reduce. The ridgeline broke into two segments over the BOB (Figure 4(c)), accompanied by strong precipitation >20 mm day^{-1}. The eastern segment of the ridgeline over Indochina Peninsula moved southward to approximately 10°N, so that the southwesterly on the eastern side of the MOV merged into the subtropical westerly. The Asian summer monsoon onset thus occurred firstly over the eastern BOB. Subsequently the MOV moved northward, causing the western segment of the ridgeline over India to migrate north of 25°N. The eastern segment of the ridgeline moved further southward to approximately 5°N, and the summer monsoon was established over Indochina Peninsula (Figure 4(d) and (e)). By May 21, the MOV disappeared, leaving behind a deep trough dominating the whole BOB so that the westerly to the east of the trough intruded into the entire SCS, leading to SCS summer monsoon onset.

4 Summary and discussion

Air-sea coupling in South Asia during spring drives the entire MOV lifecycle: its genesis, movement and decay. The genesis and northward migration of the MOV over the BOB is an important mechanism triggering the onset of the Asian summer monsoon.

The gradually increase in land surface sensible heating over the tropical continents of eastern Africa and South Asia from winter to spring in 1998 induced strong cyclonic circulations near the surface, with anticyclone circulations occurring over the Arabian Sea and the northern BOB. Such surface coastwise winds forced the ocean to generate the *in situ* offshore currents and upwelling, forming unfavorable environmental conditions for MOV genesis over the Arabian Sea and northern BOB.

Significant changes in air-sea interaction occurred in South Asia since early May. Because persistent rainfall occurs over the Indochina Peninsula (Figure 4) the *in situ* surface sensible heating decreased rapidly and exhibited negative values (Figure 1), resulting in the weakening of the surface cyclone. Thus the northwesterlies over the eastern coast of the BOB disappeared (Figure 3(a)), and the offshore current and upwelling also weakened or vanished (Figures 2(d) and 3(b)), leading to downwelling and SST increase. Under control of the surface atmospheric anticyclone, the northern BOB sea surface received strong solar radiation and lost less surface sensible and latent heat. Consequently, a spring BOB warm pool with SST >31°C formed in a band oriented southwest-northeast from the southeastern Arabian Sea to eastern BOB (Figure 2(f)). The MOV genesis and development are summarized below and demonstrated schematically in Figure 5.

In the western Indian Ocean, cold SST exists south of the equator while warm SST exists to its north. Such SST distribution induces a cross-equator surface pressure gradient and southerly winds [20]. Surface sensible heating over the African continent also contributes to occurrence of a prominent cross-equatorial southerly flow along 45°E–55°E, accompanied by inertial oscillation along the equator (Figure 3(c) and (d)). This inertial anticyclonic circulation overlaps in phase with the anticyclone existing over the northern Arabian Sea and the two cold air flows ahead of the anticyclone converge over the southeastern Arabian Sea (Figure 5), This enhances wind speed around the southern end of the trough and induces large sea surface sensible heating >20 W m^{-2} (pink area in Figure 5) of the atmosphere. The cyclonic vorticity forced by such sensible heating is super-

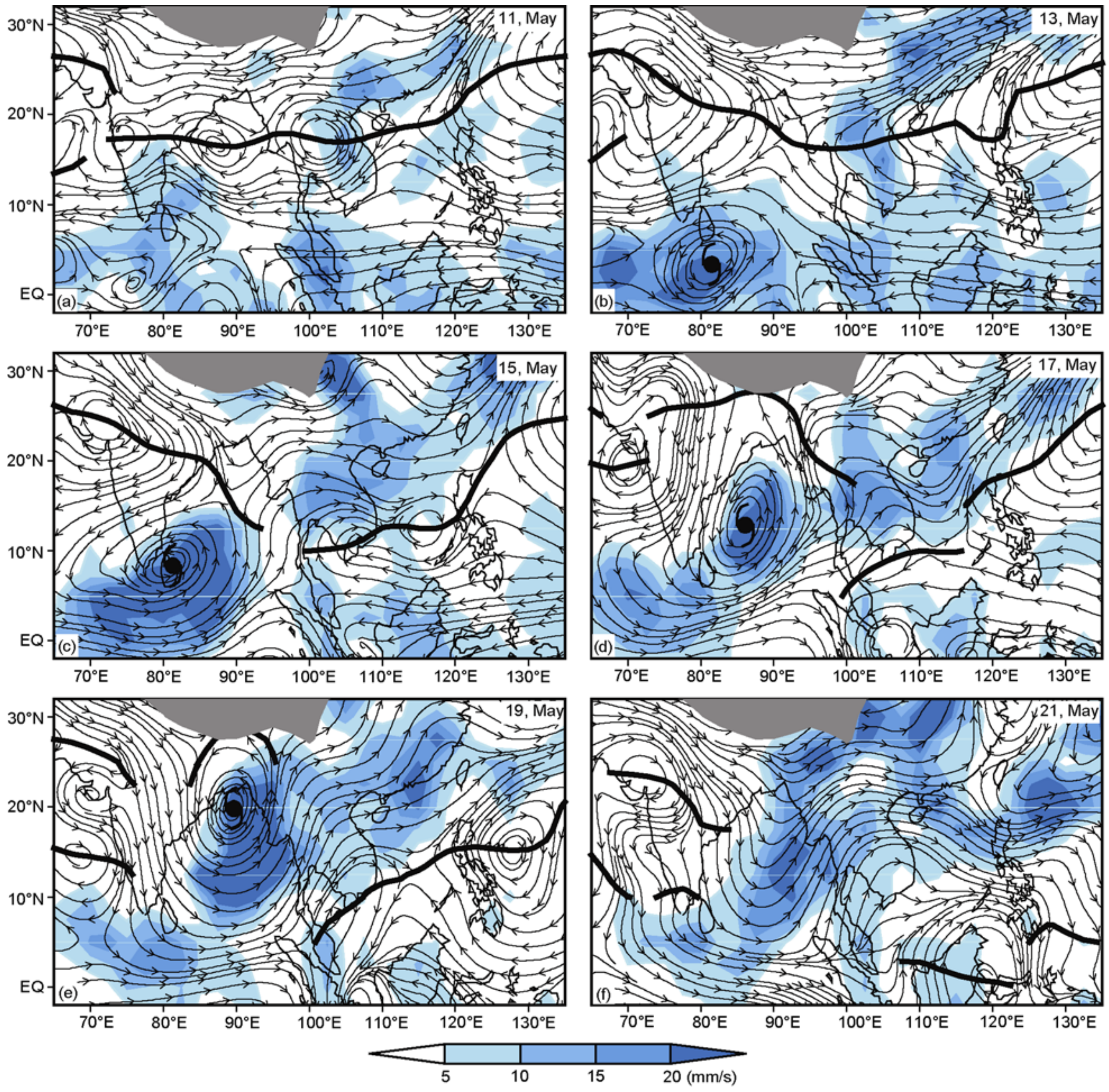

Figure 4 Evolution of daily rainfall, streamline and the ridgeline of the subtropical high at 700 hPa (thick curve) for the period May 11–21 1998 ((a)–(f)). The symbol “🌀” denotes the position of the 700-hPa low geopotential height center. Terrain above 3 km is hatched.

imposed on the inertial trough, causing the trough to strengthen further (Figure 3(d) and (f)). The inertial anticyclonic motion of air particles is suppressed. Instead, particles move northward in cyclonic curvature and enter the BOB warm pool (orange area in Figure 5). This cyclonic flow also converges with the easterly on the southern side of the anticyclone over the northern BOB. Finally, a MOV is generated over the northern Indian Ocean east of Sri Lanka. Because the MOV center is located within a higher SST area with large sensible heating of >20 W m^{-2}, air temperature (T) is correlated positively with heating (Q), thus creating net available potential energy, which is transferred to atmospheric kinetic energy for the MOV development.

The evident ascending motion and heavy precipitation are also noted (Figure 4(b)). The MOV intensifies continually when it migrates northward, causing the continuous ridgeline of the zonal subtropical high to disconnect over the eastern BOB. The tropical southwesterly on the southern and eastern sides of the MOV joins with the subtropical westerly, leading to active convection over the eastern BOB and western Indochina Peninsula, and thus Asian summer monsoon onset (Figure 4).

In 1998 the origin site of the MOV was not far from the equator. However, it is not clear if MOV was triggered by “inertial instability”, which is used commonly to interpret development of convective activities near the equator [21–

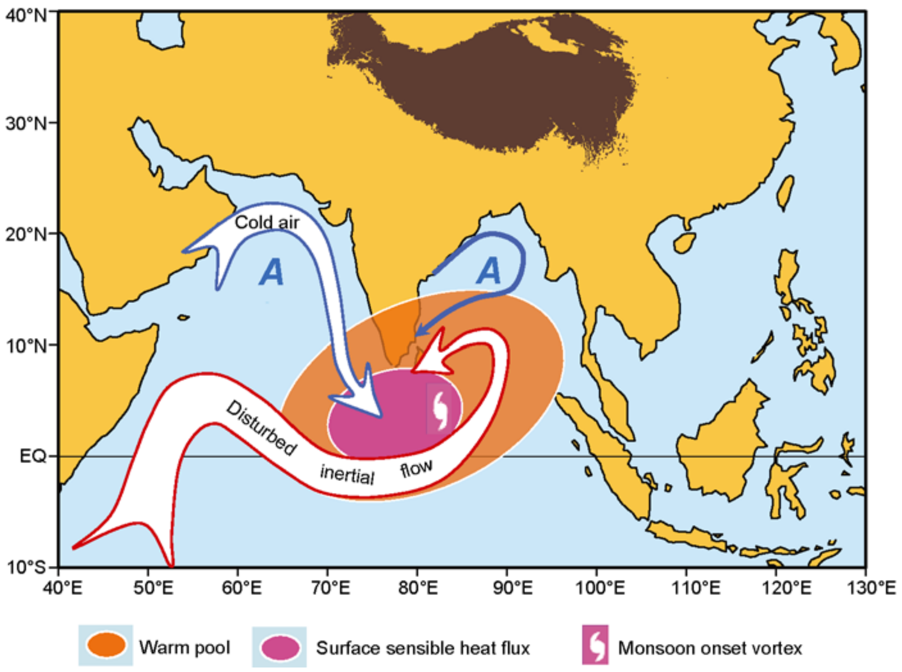

Figure 5 Schematic diagram showing the genesis of the Bay of Bengal monsoon onset vortex (BOB MOV) as a consequence of *in situ* air-sea interactions modulated by land-sea thermal contrast in South Asia in spring. Southward-moving cold air (blue hollow arrow) from the Arabian anticyclone overlaps the cross-equatorial inertial flow, inducing pronounced sea surface sensible heating from the ocean to the atmosphere south of India where the inertial trough (red hollow arrow) is located, resulting in enhancement and transformation of the inertial trough. Consequently, particles ahead of the inertial trough move northward in the form of cyclonic curvature and enter the region above the BOB warm pool (orange area). This cyclonic flow then converges with the easterly (blue solid arrow) on the southern side of the anticyclone occurring over the northern BOB. The warm ocean releases large sensible heating to the atmosphere to create net available potential energy, which in turn is transformed to atmospheric kinetic energy, thereby generating the BOB MOV.

23] For the case of inertial instability, there is a cross-equator meridional pressure gradient near the surface. When the necessary condition $(f(f-\partial u_g/\partial y)<0)$, where u_g is the zonal component of the geostrophic wind, is satisfied near the equator, on the equatorward side of the zero absolute-vorticity contour there is a horizontal divergence, whereas on the other side there are horizontal convergence and convection development. To examine the possible contribution of inertial instability to MOV development, we calculated the daily distribution of the near-surface absolute vorticity for the period May 12–15. We demonstrated that the absolute vorticity zero contours oscillated usually in a stable and regular manner around the equator. In the longitude domain 65°–85°E, the zero contour was located south of the equator. The southern edge of the inertial trough was already in the southern hemisphere, and the absolute vorticity north of the equator in this longitude domain was positive (Figure 3(c) to (f)). The necessary condition for inertial instability occurrence is unsatisfied. Thus the contribution of inertial instability to MOV genesis can be excluded.

This study demonstrated that the BOB MOV is generated as a consequence of air-sea interaction in South Asia during spring, and its genesis and development are the important factors leading to the Asian summer monsoon onset. The time of MOV occurrence is related closely to development of cross-equatorial flow from the Southern Hemisphere. These findings differ from traditional notions that simple "land-sea thermal contrast" leads to the summer monsoon onset, and help further elucidate the dynamical characteristics of summer monsoon evolution.

The MOV in 1998 was generated around Sri Lanka, while the majority of MOVs in other years occurred usually around southeastern BOB (unpublished data), which may be associated with the longitudinal position where the spring cross-equatorial flow first occurs. In most years the cross-equatorial flows occur generally between 65°E and 85°E, but in 1998 occurred in a more westward position (west of 50°E). Since the evolution of the land-sea thermal state in South Asia as shown in Figure1 represents the typical situation, we infer that the results obtained from the present study reflect the general principle. More case studies are needed to better understand MOV activities in relation to the onset of the Asian summer monsoon.

This study was supported jointly by National Basic Research Program of China (Grant No. 2006CB403600), the Chinese Academy of Sciences (Grant No. KZCX2- YW-Q11-01), and National Natural Science Foundation of China (Grant Nos. 40875034, 40925015, 40821092, 40975052, and 40810059005).

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