Contrasting feature of the seasonal heating between the Indochina Peninsula and the Bay of Bengal

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Abstract

Based on GAME reanalysis data set, we attempt to reveal seasonal evolution of large-scale heat source (Q_1) and moisture sink (Q_2) over and around the Indochina Peninsula. The pre-monsoon rainfall occurs inland area of the Indochina Peninsula prior to the large-scale monsoon onset in middle May. In this season, positive Q_1 in excess of 2 K day^{-1} can be found over the eastern part of the Indochina Peninsula (EIP). In contrast, negative $<Q_1>$ less than -100 W m^{-2} is discernible over the Bay of Bengal (BoB), which is collocated with the strong downward motion.

Once the large-scale monsoon commences, the value of $<Q_1>$ in EIP is roughly same as those of the pre-monsoon season. On the other hand, the whole troposphere over BoB is abruptly occupied by deep heating associated with condensation processes as shown by positive Q_1 and Q_2. These results indicate the existence of the regional difference of the atmospheric heat budget between EIP and BoB especially in the pre-monsoon season.

Keywords: pre-monsoon, Indochina, Q_1, Q_2

1. Introduction

The Asian summer monsoon (ASM) features a stepwise seasonal evolution as characterized by an abrupt enhancement of convection and eastward intrusion of the low-level monsoon westerlies (e.g., He et al. 1987; Matsumoto 1992; Wang and Xu 1997; Webster et al. 1998; Ueda and Yasunari 1998; Wang and LinHo 2002; Zhang et al. 2002). Numerous studies have focused on the first transition of the ASM, usually occur in middle May, since the physical processes involved in the monsoon onset exhibit similar to those of the ASM establishment. It has been revealed that the first transition is concurrent with the reversal of meridional temperature gradient in the upper troposphere between the Tibetan Plateau and the neighboring regions (e.g., Yanai et al. 1992; Ueda and Yasunari 1998).

The monsoon has been interpreted as an atmospheric response to the south Asian deep heat sources, manifested as the Matsuno–Gill pattern (Matsuno 1966; Gill 1980; Ose 1998). On the other hand, the heating processes over and around the Tibetan Plateau have received much attention relevant to the tropospheric temperature increase over the Asiatic landmass (e.g., Nitta 1983; He et al. 1987; Yanai et al. 1992; Li and Yanai 1996; Hsu et al. 1999; Ueda et al. 2003).

Recently, there is growing evidence that the heating mechanism prior to the first transition in the Southeast Asia exhibits complex regional characteristics (e.g., Hsu et al. 1999). For instance, based on in-situ observations of rainfall, it is indicated that the rainy season starts over the inland area of the Indochina Peninsula relatively earlier than the surrounding regions (Matsumoto 1997). However, there are a small number of papers that document the heat sources around the Indochina Peninsula and its vicinity in view of the atmospheric heat budget. Thus the objective of the present study is to examine the seasonal evolution of the heating processes of the atmosphere based on objectively analysed data of GAME reanalysis. We shall determine quantitatively the horizontal and vertical distributions of the heat sources and moisture sinks between April 1998 through July 1998.

2. Data and Method

The major data used in this study is the GAME reanalysis ver. 1.5 at a resolution of 2.5° in latitude and 2.5° in longitude. For the analysis of heat and moisture budget, we apply the widely accepted definition proposed by Yanai et al. (1973). The apparent heat source Q_1 and apparent moisture sink Q_2 are computed by use of the thermodynamic and moisture budget equations as follows:

$$Q_1 = c_p \left(\frac{p}{p_0}\right)^{\frac{R}{c_p}} \left(\frac{\partial\theta}{\partial t} + \mathbf{V}\cdot\nabla\theta + \omega\frac{\partial\theta}{\partial p}\right), \quad (1)$$

$$Q_2 = -L_c\left(\frac{\partial q}{\partial t} + \mathbf{V}\cdot\nabla q + \omega\frac{\partial q}{\partial p}\right), \qquad (2)$$

where θ is potential temperature; q the mixing ratio of water vapor; $\mathbf{V}$ the horizontal wind; ω the vertical p–velocity; L_c the latent heat of condensation; p the pressure; R the gas constant; c_p the specific heat at constant pressure of dry air; and p_0 1000 hPa respectively.

We estimate ω by accumulating horizontal divergence under an assumption of the adiabatic condition near the tropopause as follows:

$$\omega = \omega_T = -\left(\frac{\partial \theta}{\partial t} + \mathbf{V}\cdot\nabla\theta\right) \Big/ \left(\frac{\partial\theta}{\partial p}\right). \qquad (3)$$

The suffix T means the tropopause. The original estimates of the horizontal divergence, D_0, are adjusted by adding

$$D' = \left(\omega_T - \omega_s - \int_{p_T}^{p_s} D_0 dp\right) \Big/ \left(p_s - p_T\right), \qquad (4)$$

where the suffix s means the surface. Then the adjusted divergence as represented $D = D_0 + D'$ is used to obtain ω.

As shown by Yanai et al. (1973), integrating Q_1 and Q_2 from p_T to p_s, we obtain

$$< Q_1 >=< Q_R > +LP + S, \qquad (5)$$

$$< Q_2 >= L(P - E). \qquad (6)$$

In Eqs. (5) and (6), Q_R is the radiative heating rate, P the amount of precipitation, S the supply of sensible heat, and E the evaporation rate at the surface, respectively.

3. Seasonal evolution of Asian summer monsoon in 1998

The southern Indochina Peninsula features relatively flat in comparison with the surrounding mountains. From April to middle May, the tropical easterlies merge with the weak monsoon westerlies over and around the Indochina Peninsula and the resultant southwesterly wind directed to Japan (not shown). We observe upward motion associated with the orographic effect over the eastern part of the Indochina Peninsula (EIP), while the Bay of Bengal (BoB) undergoes strong subsidence motion, especially confined to the lower troposphere. In this period the precipitation can be found limited in EIP, which is nearly consistent with in-situ observation (Matsumoto 1997).

The low-level flow pattern in the Southeast Asia exhibits abrupt change around pentad 28 (May 16–20) in concurrent with the large-scale monsoon onset. The salient upward motions dominates over the eastern BoB and the west coast of the Indochina Peninsula, which is accompanied by a large amount of rainfall in excess of 20 mm day^{-1}. While, the vertical motion over EIP is rather weak as compared with those of the pre-monsoon season. It is recognizable that the precipitation decreases over EIP in June.

The horizontal distributions of 15-day mean $<Q_1>$ and $<Q_2>$ shows contrasting features between EIP and surrounding areas. The horizontal distributions of $<Q_1>$ are similar to those of $<Q_2>$ in excessive quantities (about 160 %) throughout the period. As for the pre-monsoon season (April to middle May), positive $<Q_1>$ can be found over EIP which is factor 2 greater than moisture sink $<Q_2>$. This indicates that the release of latent heat of condensation, associated with the pre-monsoon rainfall, could be equivalent to the sensible heat from the surface. On the other hand, the whole region of BoB and the South China Sea exhibit large negative $<Q_1>$ and $<Q_2>$. It is also quite important to note that the strong descending motion dominates over BoB, which might cause to suppress the in-situ convection and resultant negative $<Q_2>$.

In the post-monsoon period, in contrast, the large area including BoB and western coast of the Indochina Peninsula is covered by salient positive $<Q_1>$. The maximum $<Q_1>$, in excess of 400 W m^{-2}, can be found over the Andaman Sea and Gulf of Thailand. The distribution of $<Q_1>$ is similar to those of $<Q_2>$, indicating dominant role of condensation heating relevant to the post-monsoon rainfalls.

4. Contrasting feature between the Indochina Peninsula and adjacent oceans

The budget computations were made of the seasonal evolution of the heating field in view of the regional differences between EIP (102.5°–110°E, 10°–17.5°N) and BoB (85°–97.5°E, 10°–20°N). Figure 1 shows the vertical distribution of 5-day mean Q_1 and Q_2 over EIP from April through May 1998. During the pre-monsoon season, EIP exhibits the maximum Q_1, in excess of 2 K day^{-1}, in the layer between 500 hPa and 600 hPa, which is accompanied by positive Q_2 slightly bellow the peak level of Q_1 (Fig. 1b). This suggests the presence of a cumulus type convection, associated with the vertically eddy heat flux between these peaks (e.g., Yanai et al. 1973; Thompson et al. 1979).

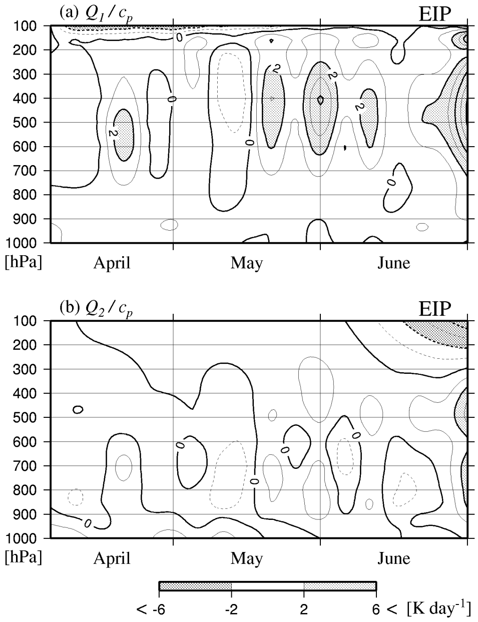

Fig. 1: Vertical-time sections of (a) heating rate Q_1/c_p (K day^{-1}) and moistening rate Q_2/c_p (K day^{-1}) for the eastern part of the Indochina Peninsula (EIP; 102.5–110°E, 10–17.5°N). Light (dark) shaded regions indicate a heating rate greater (less) than $+2$ (-2) K day^{-1}.

On the contrary, BoB (Fig. 2) is characterized by negative Q_1 throughout the pre-monsoon season. The vertical distribution of Q_2 is also negative, indicating moisture increase, especially in the lower troposphere. This means that the radiative cooling dominates in comparison to the sensible heat flux and the latent heat release. Once the summer monsoon commences, the whole troposphere is drastically occupied by large positive Q_1 as shown in large-scale wind field. Concurrent with this, large positive value of Q_2 are recognizable which implies the increased condensation. The peak levels of Q_1 and Q_2 are indicative of the existence of cumulus type convection over BoB. This atmospheric heating occurs within about 10 days, exhibiting strong interseasonal variation, toward the mature phase of the summer monsoon as well as EIP.

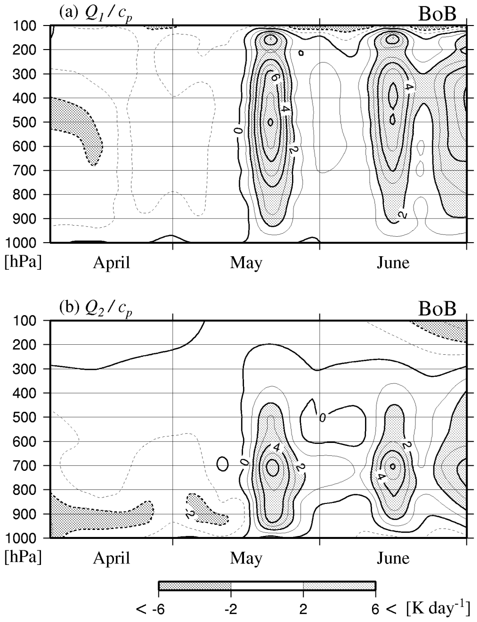

Fig. 2: Same as Fig. 6 but for the Bay of Bengal (BoB; 85–97.5°E, 10–20°N).

Figure 3 shows the seasonal evolution of Q_1 and Q_2 over BoB and EIP. The major difference between EIP and BoB can be found in the pre-monsoon season. In EIP during the pre-monsoon season, the value of $<Q_1>$ exceeds 200 W m^{-2}, which is nearly equivalent to those of post-monsoon season (Fig. 3a). Compared with the variation of $<Q_2>$ (Fig. 3b), the tropospheric heating in April can be attributed to the condensation heating. In BoB however, the apparent cooling is clearly identified before the first transition. The value of $<Q_2>$ is also negative, indicating moisture increase. It is inferred that this is attributable to the prevailing descending motion and ensuing suppressed convection. The values of $<Q_1>$ and $<Q_2>$ are abruptly increase after the first transition, which is consistent with the seasonal evolution of the vertical profiles (Fig. 2). The above results indicate that the heating processes prior to the first transition exhibit stark difference between the Indochina Peninsula and the Bay of Bengal. Especially it should be emphasized here that the pre-monsoon rainfall, presumably associated with a presence of land surface, play a crucial role in the atmosphere heating.

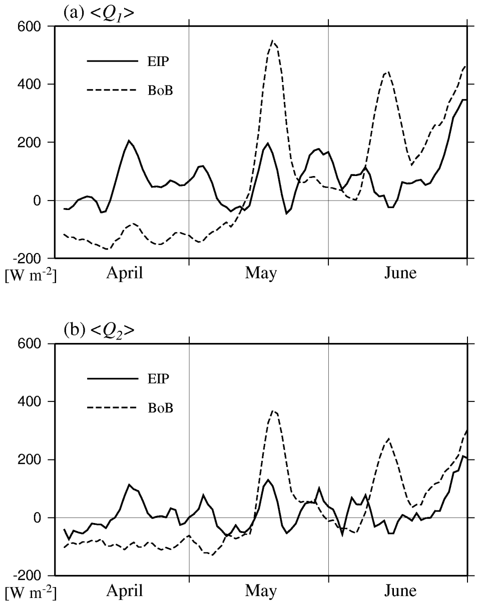

Fig. 3: Time series of $< Q_1 >$ and $< Q_2 >$ for EIP (solid line) and BoB (dashed line).

5. Conclusions and remarks

Based on the GAME reanalysis data, the heating processes over and around the Indochina Peninsula are studied during April through June 1998. The first transition of the Asian summer monsoon, defined by westerly intrusion of the low-level flow, is recognizable at pentad 28 (May 16–20) whereas the pre-monsoon rainfall occurs inland area of the Indochina Peninsula prior to this planetary-scale monsoon onset.

During middle April, the apparent heat source, in excess of 200 W m^{-2}, can be found over EIP. The value of $<Q_1>$ is two times larger than those of $<Q_2>$. This suggests that the sensible heating from the land surface is nearly equivalent to the latent heating, which is consistent with the in-situ observed precipitation (Matsumoto 1997). The difference of the peak level of Q_1 and Q_2 implicates vertical transport of eddy heat flux. The value of $<Q_1>$ around EIP after the monsoon onset features similar to those of the pre-monsoon season.

It should be also noted here that the negative $<Q_1>$ less than -100 W m^{-2} over BoB region is discernible during the pre-monsoon season, in which the strong descending motion dominates. This suggests a key role of the downward motion over BoB in triggering abrupt onset (Hung and Yanai 2004). The origin of the subsidence is obscure and thus more detail analysis should be conducted for further understanding of the mechanism that is responsible for the monsoon onset. Once the large-scale monsoon commences, the whole troposphere is abruptly occupied by positive Q_1, which is accompanied by positive Q_2 slightly below the peak level of Q_1. These results indicate that the condensation heating associated with the cumulus type convection may contribute significantly to the total atmospheric heating.

In this manner, the atmospheric heating processes in the pre-monsoon season exhibits salient regional difference between the Indochina Peninsula and the Bay of Bengal. It is worth mentioning here that the pre-monsoon rainfall may caused by the upward motion relevant to the geophysical configuration, as well as moisture convergence due to large-scale circulation.

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