Heating processes over the Asiatic landmass prior to the first transition of the summer monsoon

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Abstract

Using the GAME (GEWEX Asian Monsoon Experiment) 4DDA upper-air data, the large-scale heat source (Q_1) and moisture sink (Q_2) over the western and eastern Tibetan Plateau are examined for a 4-month period from 1 May to 31 August 1998. The computations were performed on the sigma-pressure hybrid coordinate, named η -coordinate, since the analysis area includes high-elevating mountains.

Over the western Plateau in May, there is a deep layer of heating occupying the whole troposphere with the maximum value exceeding 3K day^{-1} around 400-600 hPa. The smaller magnitude of the apparent moisture sink is confined in the lower troposphere 1 km above the ground surface. Vertically integrated heat sources of 103 Wm^{-2} over the western Tibetan Plateau are accompanied by a moisture sink of about half that (60 Wm^{-2}). These results indicate that the latent heat release associated with the condensation plays an important role in the total heating besides the sensible heat supply from the land surface. Later in July, the moisture sink over the eastern Tibetan Plateau nearly equals to the heat source indicating that the dominance of moist process associated with summertime monsoon rains.

The contrasting features of the heat source and moisture sink are closely related to the circulation fields. Throughout May and June, we observe strong upward motion along with the western and southwestern slopes of the western Plateau, while there is salient subsidence motion over the eastern Plateau. The analyses of the static stability and the lifting condensation level indicate that the release of latent heat relevant to the moist convection is a dominant factor for the tropospheric heating after the monsoon onset. While the pre-monsoon period (May) is composed of both the convective rainfall and the dry thermal convection.

Thus, the heating mechanism prior to the onset of the monsoon, especially over the western Tibetan Plateau, can be characterized by the hybrid nature of “wet” processes due to condensation heating and “dry” processes associated with the sensible heat flux from the elevated mountain surface.

Keyword: Tibetan Plateau, First transition, Q_1,Q_2, GAME reanalysis

1. Introduction

The Asian monsoon is a major component of the global climate system. A number of observational studies (Yeh et al. 1957; Staff Members Academia Sinica 1958; Yeh and Gao 1979; Nitta 1983; Yanai and Li. 1994 and many others) have recognized that the high Tibetan Plateau plays an important role in the establishment and maintenance of the Asian summer monsoon as an elevated heat source. After the First GARP Global Experiment (FGGE), there have been several observational studies of heat sources over the Tibetan Plateau and surrounding areas. Nitta (1983) described the 100-day mean vertical profiles of heat and moisture sources for the four parts of the eastern Tibetan Plateau. He found that the contribution to the total heating by the sensible heat flux from the elevated surface is nearly the same as that by the condensation heating due to latent heat release.

Luo and Yanai (1984) determined the heat and moisture budgets over the Tibetan Plateau using the FGGE data for 1979. They showed the deep mixed layer at 1200 UTC on the western Plateau and suggested that dry thermal convection is a key process which is responsible for the deep tropospheric heating in the afternoon hours. They also identified the principal components of the heat source after the onset as the addition of condensation heating over the eastern Plateau.

The seasonal evolution of the monsoon circulation exhibits distinct changes during its onset phase (Li and Yanai 1996; Ueda and Yasunari 1998; Wu and Zhang 1998 and many others). He et al. (1987) showed that the summer monsoon of 1979 commenced in two transition stages. The first transition seen in middle May is characterized by the eastward intrusion of low-level southwesterlies to the west of 120°E. The second transition is the onset of the Indian monsoon that usually occurs in early June to the west of 80°E. They inferred that these abrupt changes are responses to the differential heating between the Asian continental land mass and the adjacent oceans. Yanai et al. (1992) extended the heat and moisture budget analysis of He et al. (1987) to the warming process of the upper troposphere. They revealed that, during the first transition period, diabatic heating and warm horizontal advection plays a primary role in the temperature increase over the eastern Tibetan Plateau. During the second transition period, adiabatic warming due to large-scale subsidence is a key process that induces a temperature increase over the western Tibetan Plateau, Iran and Afghanistan region. Recently, the desert formation over these regions is attributed to the downward motion associated with Rossby-wave pattern induced by remote diabatic heating in the Asian monsoon region (Rodwell and Hoskins 1996).

The GEWEX Asian Monsoon Experiment (GAME) Intensive Observation Period (IOP) was conducted from May to August 1998. One of the purpose was to obtain high-quality four-dimensional data assimilation (4DDA) for energy and water cycle process of the Asian summer monsoon by means of four-times/day soundings of radiosonde observation at more than 100 stations covering Southeast Asia, the northern part of South Asia (India, Bangladesh, and Myanmar), the Tibetan Plateau, central Eastern China around Huai-He River, the South China Sea, Korea, and Southwest Japan (GAME International Science Plan 1998).

Based on the above enhanced experimental upper air data, as well as operational observation data, the 4DDA was conducted through collaboration between the Meteorological Research Institute (MRI), Numerical Prediction Division of the Japan Meteorological Agency (JMA) and the Earth Observation Research Center of National Space Development Agency of Japan (NASDA/EORC). The 4DDA products have hybrid vertical η coordinates, which are identical to the conventional sigma coordinates in the lower troposphere and nearly equal to the pressure coordinate in the upper troposphere. The benefit of this coordinate is that it provides a good representation of the lower boundary condition and reduction of finite difference errors of the pressure gradient force at the higher levels (e.g., Kasahara 1974; Simmons and Burridge 1981). Since the Asian monsoon region contains the high-altitude Tibetan Plateau, we performed the heat and moisture budget analysis on the vertical η coordinate.

This study attempts to determine quantitatively the horizontal and vertical distributions of heat sources and moisture sinks over and around the Tibetan Plateau through budget computations of mass, heat and moisture with the GAME reanalysis data set archived during the GAME IOP from 1 May to 31 August 1998. The other objective of the present work is to reveal the seasonal evolution process of the heat sources and moisture sinks on a pentad time scale. We compare the results of heat and moisture budget analyses by using satellite-derived precipitation data as an independent resource of the GAME reanalysis product.

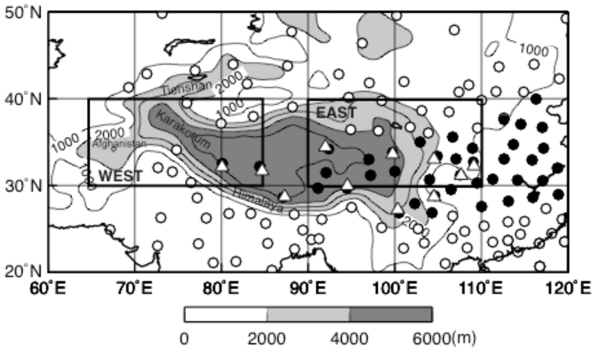

Fig. 1. Orographic structure of the Tibetan Plateau. The solid lines denote elevation contours. The ground surface with elevations > 2000 (4000) m are shown by light (dark) shading. Two areas enclosed by thick bold lines are used for budget analysis. Open triangles over the western Tibetan Plateau denote newly set up stations for four-times/day upper air observation during the enhanced observation period. The other open triangles correspond to stations where four times/day upper-air soundings were conducted but not transmitted by the GTS on-line network. Additional observations at 06 and 18 UTC (besides the routine soundings at 00 and 12 UTC) are depicted by colored circles. The operational stations usually make twice-daily observations, which are shown by open circles.

2. Data and study method

The major data used in this study are the 18 and 24-hour forecasted 4 DDA products by the GAME-reanalysis project on a 2.25° × 2.25° grid for 1 May to 31 August 1998. Temperature (T), heating rate of long-wave radiation (Q_R), zonal and meridional wind components (u, v), and specific humidity (q) are given on 30 η levels. Surface pressure (Ps) is also utilized to determine the vertical distribution of the pressure field.

The global spectral model, which was processed with the JMA operational global forecast analysis cycle model (GSM9912), has an equivalent grid spacing of about 55 km (T213) horizontally and 30 η-levels (L30) vertically with a model top of 10 hPa. The convection scheme used in the model is the prognostic Arakawa-Schubert scheme (Kuma 2000). The apparent heat source Q_1 and apparent moisture sink Q_2 (e.g. Nitta 1972; Yanai et al. 1973) are calculated from the thermodynamic and moisture budget equations in the η coordinates as follows:

$$\frac{\partial T}{\partial t} = -\mathbf{V}\cdot\nabla T + \frac{R_d}{C_p P_k}\frac{dp}{dt} - \dot{\eta}\frac{\partial T}{\partial \eta} + \frac{Q_1}{C_p},$$

$$\frac{\partial q}{\partial t} = -\mathbf{V}\cdot\nabla q - \dot{\eta}\frac{\partial q}{\partial \eta} - \frac{Q_2}{L_c},$$

where T is temperature; q, the mixing ratio of water vapor; v, the horizontal wind; R_d and C_p, the gas constant and the specific heat at constant pressure of dry air; p, the pressure; and η vertical, η velocity and L_c, the latent heat condensation.

The pressure on half levels is

$$\frac{dp}{dt} = \mathbf{V}_k \cdot \nabla p_{k+1/2} - \sum_{l=k}^{k\max} \nabla_l \cdot (\mathbf{V}_l \Delta P_l) - (\nabla \cdot \mathbf{V}_k) \frac{\Delta p_k}{2},$$

where k is the full level number and $k+1/2$ is the half level number that increases with altitude. η is computed from

$$(\dot{\eta}\frac{\partial p}{\partial \eta})_{k-1/2} = -\frac{\partial p_{k-1/2}}{\partial t} - \sum_{l=k}^{k\max} \nabla(\mathbf{V}_l \Delta p_l),$$

$$(\dot{\eta}\frac{\partial T}{\partial \eta}) = \frac{1}{2\Delta p_k}\left\{(\dot{\eta}\frac{\partial p}{\partial \eta})_{k-1/2}(T_{k-1} - T_k) + (\dot{\eta}\frac{\partial p}{\partial \eta})_{k+1/2}(T_k - T_{k+1})\right\},$$

3. East-west contrasting features over the Plateau

The budget computations were made in the western and eastern Tibetan Plateau enclosed by solid lines in Fig. 1. The western part (30°-40°N, 65°-85°E) denotes the area extending from the Plateau region to the southern foot of the Plateau. The eastern Plateau (30°-40°N, 90°-110°E) has an average surface elevation of about 3000 m. The distribution of four times/day rawinsonde observations covering over the Tibetan Plateau and its surrounding area during the GAME-IOP are shown by three symbols. Open triangles over the western Tibetan Plateau, enclosed by a bold line, denote newly set up stations for this experiment. Enhanced observation were made at 06 and 18 UTC (Coordinated Universal Time) by using the convectional (00 and 12 UTC) observation network (colored circles). In addition to these soundings, we conducted 4DDA by use of the upper-air data observed by the operational stations (open circles).

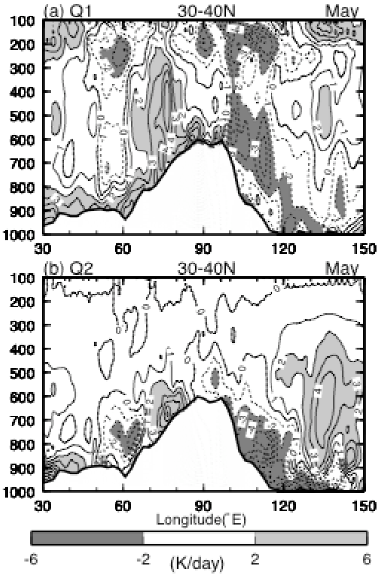

Fig. 2. Vertical-time sections of areal mean (a) apparent heat source, (b) moisture sink for the western Plateau (30°-40°N, 65°-85°E). Dark (Light) shaded regions indicate a heating rate greater (less) than +2 (-2) K day^{-1}.

Figure 2 show the seasonal evolution of heat sources (upper panel) and moisture sinks (lower panel) over the western Tibetan Plateau through the months of May and August, 1998. During May, the pre-monsoon period, the maximum heating (exceeding 3K day^{-1}) exists in the layer between the land surface and 300 hPa. The smaller magnitude of the apparent moisture sink is confined to 1 km above the near mountain surface. This smallness of Q_2 suggests that another source of heating besides the latent heat release is needed to explain the total heating. Thus, the contribution of the sensible heat flux, directly transported by dry thermal convection, may be important to the total heating. Between late June and middle July (except for early July), the heat source is relatively smaller and the evaporation exceeds the precipitation seen as negative Q_2. Until August, the large positive Q_1 recurs in the whole layer and is accompanied by positive Q_2 seen in the 2 km layer between the mountain surface and 500 hPa. These results indicate that the large heat source is be due to both effects of the condensation heating by deep cumulus convection and the sensible heat supply from the ground surface.

4. Conclusions and remarks

We have used GAME 4DDA products from the GAME reanalysis joint project between MRI, JMA and NASDA/EORC to study spatial and temporal variations of heat sources and moisture sinks over and around the Tibetan Plateau for the period from 1 May to 31 August 1998. We have mainly focused on the heat and moisture budgets over the western and eastern portion of the Plateau, including the southern and eastern foot of the high elevating mountains, The main findings of the present study may be summarized as follows:

1) During the pre-monsoon period of May, the results of heat and moisture budget analyses indicate that the western Tibetan Plateau plays an important role as one of center of the heat source in the first transition of the Asian summer monsoon, while the eastern Tibetan Plateau remains a heat sink in the same period.
2) During July, corresponding to the mature phase of the summer monsoon, there is a large heat source in the eastern Plateau with amplitude about two times those over the western Plateau in May. In contrast, the heating over the western Plateau becomes weaker compared to those in May.
3) Throughout May and June, we observe strong upward motion along with the western and

southwestern slopes of the western Plateau, while the obvious subsidence motion is found over the eastern Plateau. This paired circulation becomes weaker in July and August.

4) The condensation heating generated by convective rainfall and the sensible heat supply from the grand surface is nearly equal during May over the western Plateau. A similar relationship, but relatively larger contribution of latent heat release to the total heating, can be recognizable over the eastern Plateau in July.
5) The analyses of the static stability and the lifting condensation level indicate that the total heating is attributed to both the convective rainfall and the dry thermal convection in the pre-monsoon period (May). On the other hand, the release of latent heat relevant to the moist convection is a dominant factor for the tropospheric heating after the monsoon onset.

In conclusion, we have shown that the western Plateau in the pre-monsoon period can be characterized by the hybrid nature of "wet" processes due to condensation heating and "dry" processes associated with the dry thermal convection. Finally we should note here that the analysis period of the present study corresponds to a peculiar year. From May through August 1998, sea surface temperature was higher than normal in the whole Indian Ocean, and the Asian summer monsoon was much modulated (Matsumoto et al. 1999; Shen and Kimoto 2001). This is due to combined effects of termination of a dipole mode in the equatorial Indian Ocean and the La Niña phase in the Pacific Ocean (Ueda and Matsumoto 2000). The Asian monsoon is considered to have large interannual variability that may be responsible for the different magnitudes of budget results among several studies. In this respect, the ability to accurately observe the heat and moisture balances in the Tibetan Plateau over a complete annual cycle, as well as variability on longer timescales, would significantly promotes progress of the monsoon prediction.

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