

# Structure of Moist Layer and Sources of Water over the Southern Region Far from the Meiyu/Baiu Front

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## Abstract

We investigate structure of a moist layer and sources of water in the southern region far from the Meiyu/Baiu front using GAME reanalysis data. In the period from July 4 to 15, 1998, the Meiyu/Baiu front was located over northern China and the Korean Peninsula. Both regions over both the plain area of mainland China (the eastern region of 112°E line) and the East China Sea had moist air masses; the total precipitable water was about  $45\text{kgm}^{-2}$ . However, the structure of these moist layers is quite different. The moist layer over mainland China is deep, reaching 600 hPa. On the other hand, the moist layer over the East China Sea is shallow, with a thickness of up to 800 hPa. This difference in the structure of the moist layers can be attributed to the development of a moist convective mixing layer and the generation of shallow convective clouds in the daytime over mainland China as a result of the supply of abundant latent and moderate sensible heat fluxes from the land surface.

We also examine the sources of water supplied into the Meiyu front using Colored Moisture Analysis (CMA). Though water vapor to generate the deep moist layer over mainland China is mainly transported from the upstream regions of the Asian summer monsoon, which include the Indian Ocean, the Indochina Peninsula, and the South China Sea, the rate of the contribution of water from the southeastern region of mainland China is also over 15% of the total precipitable water, when the Meiyu front is located over northern China. This shows that the land surface over southeastern China is also regarded as a major source of water.

## 1 Introduction

The Meiyu/Baiu front is a boundary between wet and dry regions in the eastern Asia. Water vapor that causes heavy rainfall events around this front originates in the southern region far from the front (wet region) and is transported northward by the southwesterly monsoon (e.g., Akiyama 1973). Akiyama (1973) also considered that the horizontal transport of water vapor is mainly restricted to the lower troposphere (below 700 hPa) both over mainland China and the East China Sea. Shinoda and Uyeda (2002) have hypothesized that the development of the convective mixing layer and shallow convective clouds transported water vapor from the atmospheric boundary layer to the middle troposphere; this process should form a deep moist layer over mainland China. However, we could not confirm the structure and horizontal extension of the moist layer in the lower troposphere not only over mainland China, but also over the East China Sea. The first purpose of this study is to confirm the structure of moist layers over both regions.

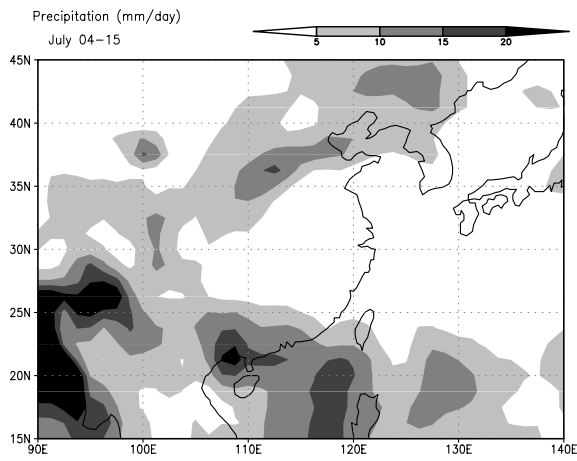
Shinoda and Uyeda (2002) also indicated that the latent heat flux from the land surface over the wet region of mainland China, especially from the paddy fields that are widely distributed around the Yangtze and Huaihe River Valleys, was responsible for moistening the lower troposphere and would be the source of water into the Meiyu front. The second purpose of this study is to quantitatively confirm the contribu-

tion of the land surface over mainland China to the source of water into the Meiyu front.

## 2 Data

The GAME (GEWEX Asian Monsoon Experiment, GEWEX: Global Energy and Water Cycle Experiment) conducted intensive observations around the east and southeast Asian regions in summer season in 1998. The results of these intensive observations are included in GAME reanalysis data. Thus, we use 6-hourly GAME reanalysis data version-1.5 developed by Yamazaki et al. (2000) in this study. The GAME reanalysis data are on a  $1.25^\circ \times 1.25^\circ$  grid and cover the period from April to October 1998. In this study, we define a term of a “moist layer” as relative humidity is larger than 60% in the lower and middle troposphere.

In order to explore the source of water supplied into the Meiyu front, we employ a “Colored Moisture Analysis (CMA)” developed by Yoshimura et al. (2004). The CMA is an analytic method that allows for the estimation of atmospheric moisture advection from specific source regions in daily time scale. The CMA’s water transport model includes atmospheric water balance equations and vertically well-mixed assumption, and uses external meteorological forcings (precipitation, evaporation and horizontal advection) obtained from GAME reanalysis. Water evaporating from earth surface is tagged as one of 16 kinds of wa-



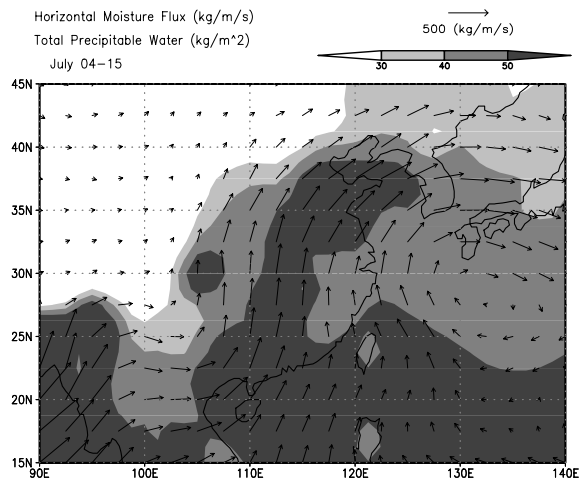
**Fig. 1** Surface precipitation rates ( $\text{mmday}^{-1}$ ) averaged from July 4 to 15, 1998, using GAME reanalysis data. The values above  $5\text{mmday}^{-1}$  are shaded.

ter and is mixed into precipitable water. The total precipitable water in each grid can be presented by the sum of tagged water from any sections. The calculation is started at 00 UTC April 1, 1998. Thus, we can identify the source of water at the specific grid over mainland China near the Meiyu front.

### 3 Difference in the structure of the moist layers

This study will focus on the water circulation in the southern region far from the Meiyu/Baiu front from July 4 to 15, 1998 (Fig. 1). The Meiyu front is located over the Yellow River Valley and the Korean Peninsula during this period. Figure 2 shows the horizontal distribution of total precipitable water (vertically integrated water vapor amount) and of the vertically integrated horizontal moisture flux averaged from July 4 to 15, 1998. There is a steep gradient of precipitable water along the Meiyu front. The horizontal moisture flux shows moisture transport toward the Meiyu front from the South China Sea through to the plain region of mainland China (the eastern region of  $112^\circ\text{E}$  line) and the East China Sea. The total precipitable water values over the plain region of mainland China and the East China Sea are both larger than  $45\text{kgm}^{-2}$ . This result shows that there are moist air masses over both the plain region of mainland China and the East China Sea.

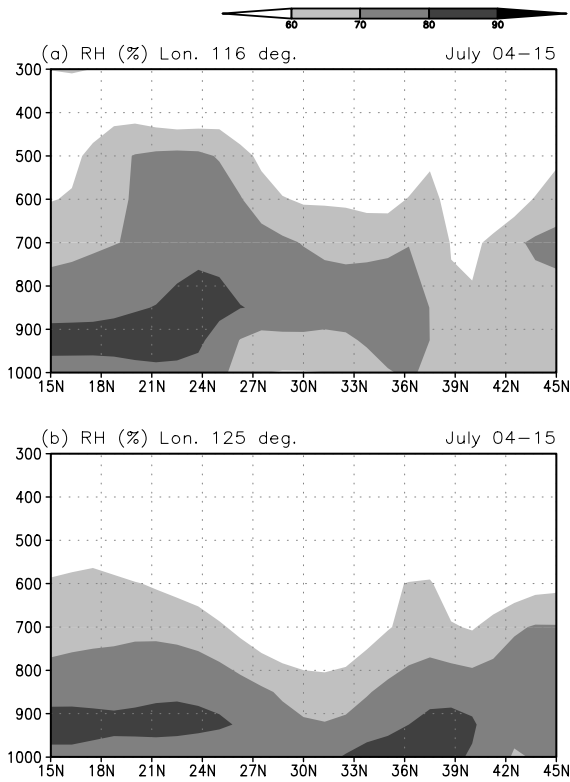
However, there are significant differences in the structure of moist layers over mainland China and the East China Sea. Mixing ratio of water vapor near the surface over mainland China is less than that over the South China Sea and over the East China Sea (not shown). That above 800 hPa over mainland China is larger than that over the East China Sea. Figure 3 shows vertical cross sections of relative humidity along  $116^\circ\text{E}$  (over mainland China) and  $125^\circ\text{E}$  (over



**Fig. 2** Horizontal distribution of total precipitable water ( $\text{kgm}^{-2}$ ) and vertically integrated horizontal moisture flux vectors ( $\text{kgm}^{-1}\text{s}^{-1}$ ) averaged from July 4 to 15, 1998, using GAME reanalysis data. The total precipitable water values above  $30\text{kgm}^{-2}$  are shaded.

the East China Sea) averaged from 4 to 15, 1998. There is a significant deep moist layer; that is, relative humidity is larger than 60%, between  $18^\circ\text{N}$  and  $25^\circ\text{N}$  along  $116^\circ\text{E}$  in this period (Fig. 3a). This region of the moist layer corresponds to two tropical depressions that are recognized in the distribution of surface precipitation (Fig. 1). The moist layer over the plain region of mainland China (from  $25^\circ\text{N}$  to  $37^\circ\text{N}$  along  $116^\circ\text{E}$ ) reaches up to 600 hPa. On the other hand, the moist layer over the East China Sea (from  $25^\circ\text{N}$  to  $33^\circ\text{N}$  along  $125^\circ\text{E}$ ) reaches up to 800 hPa, except for the deep moist region extending from the South China Sea, that is, the area between  $15^\circ\text{N}$  and  $24^\circ\text{N}$  along  $125^\circ\text{E}$  (Fig. 3b).

In order to develop a deep and moist convective mixing layer, the supply of the sensible and latent heat fluxes from the surface is necessary. Figure 4a shows the horizontal distribution of the latent heat flux averaged from July 4 to 15, 1998. Over the East China Sea, the value of the latent heat flux is about  $80$  to  $100\text{Wm}^{-2}$ , and there is no diurnal variation. In the southern region far from the Meiyu front over mainland China, the latent heat flux exceeds  $180\text{Wm}^{-2}$ . Surprisingly, this value is twice that over the East China Sea. A large amount of latent heat flux from the land surface over mainland China should moisten the atmospheric boundary layer and increases the amount of total precipitable water over this region (Fig. 2). Figure 4b shows the horizontal distribution of the sensible heat flux averaged in the same period. Over the East China Sea, there is no sensible heat flux throughout the day. On the other hand, the sensible heat flux is about  $40$  to  $60\text{Wm}^{-2}$  over mainland China. The supply of the sensible heat flux from the land surface over mainland China should contribute to the development of the convective mixing layer.



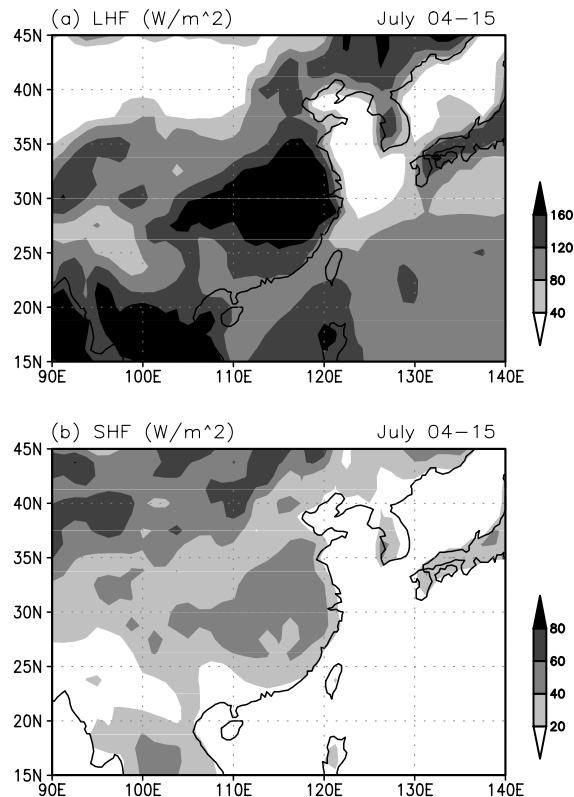
**Fig. 3** Vertical cross sections of relative humidity along  $116^{\circ}\text{E}$  (a) and  $125^{\circ}\text{E}$  (b) averaged from July 4 to 15, 1998, using GAME reanalysis data. Relative humidity values above 60% are shaded.

The supply of abundant latent and moderate sensible heat fluxes from the surface should form the deep and moist convective mixing layer over mainland China.

## 4 Source of water vapor into the Meiyu front

As shown in the previous section, a large amount of latent heat flux from the land surface causes the generation of the moist layer over mainland China. In this section, we confirm whether the land surface over mainland China can be regarded as a source of water into the Meiyu front. In order to explore the sources of water supplied into the Meiyu/Baiu front, we employ the “Colored Moisture Analysis (CMA).” We organized 16 sections that are closely related to the water circulation in the east Asian region.

Figure 5 shows a daily time series of the water sources of the total precipitable water in a grid including the center of the GAME-HUBEX region over mainland China. As the Meiyu front approached over this region after June 23, 1998 (days of year = 174), water sources dramatically change from those in the earlier period. Instead of the remarkable decrease of the contribution of the northern part of the Eurasian Continent (northeastern and northwestern China and the Central Eurasian Continent) to the total precip-



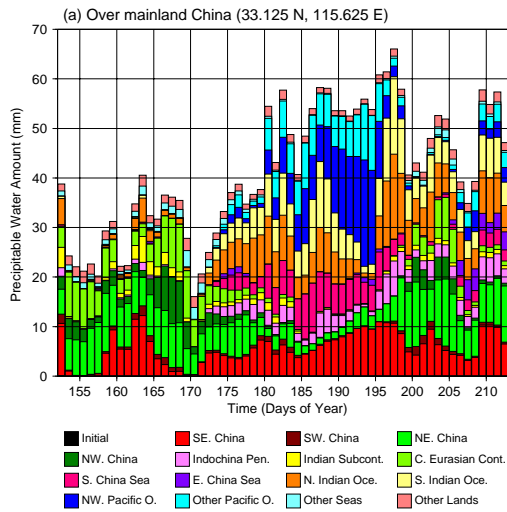
**Fig. 4** Horizontal distributions of the latent heat flux (a) and the sensible heat flux (b) from the surface averaged from July 4 to 15, 1998, using GAME reanalysis data. The latent heat flux above  $40\text{Wm}^{-2}$  and sensible heat flux above  $20\text{Wm}^{-2}$  are shaded, respectively.

itable water, water from the upstream regions of the Asian summer monsoon; that is, the Indian Ocean, the Indochina Peninsula, and the South China Sea, increases over the GAME-HUBEX region. The sum of the contribution amount (rate) of these regions on July 14 (days of year = 195), 1998 occupies 25.54 mm (41.99%). This result shows that water that generates the moist layer over mainland China is mainly supplied from the upstream regions of the Asian summer monsoon.

However, the contribution amount (rate) of the southeastern region of China to the total precipitable water is about 10 mm (over 15%) after the passing of Meiyu front. This shows that the land surface over southeastern China is one of the most important sources of water to form the moist layer over this region and can be regarded as a major source of water into the Meiyu front.

## 5 Concluding Remarks

The structure of the moist layer in the lower troposphere in the southern region far from the Meiyu/Baiu front over mainland China and the East China Sea are investigated by using GAME reanaly-

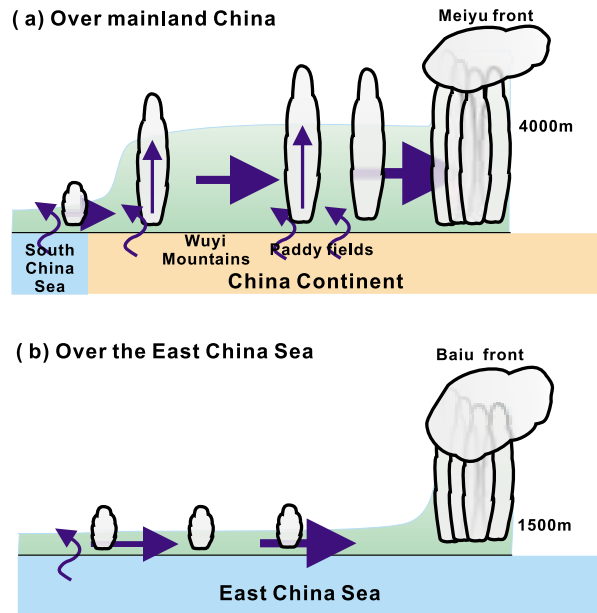


**Fig. 5** Daily time series of water sources of the total precipitable water at the grid including Fuyang (33.125°N, 115.625°E) over mainland China.

sis data. In the period from July 4 to 15, 1998, the Meiyu/Baiu front was located over the Yellow River Valley and the Korean Peninsula. Both regions over both the plain area of mainland China (the eastern region of 112°E line) and the East China Sea had moist air masses; their amount of the total precipitable water was larger than  $40\text{kgm}^{-2}$ . However, the structure of these moist layers, which is defined as the relative humidity is larger than 60% in the lower and middle troposphere, is quite different as shown in Fig. 6.

The moist layer over mainland China is deep, reaching 600 hPa. This deep moist layer is probably formed by the development of the convective mixing layer and shallow convective clouds in the daytime. The moist convective mixing layer is formed by the supply of abundant latent heat flux from the land surface, especially from the paddy fields that are widely distributed over southeastern China, and by the supply of moderate sensible heat flux. Shallow convective clouds generated around the top of the convective mixing layer transport water vapor from the convective mixing layer to the middle troposphere (Shinoda and Uyeda 2002); consequently, the moist layer becomes deep. Though water vapor to generate this deep moist layer is transported from the upstream regions of the Asian summer monsoon, the land surface over southeastern China is also regarded as a major source of water. The amount (rate) of the contribution of water from the southeastern region of mainland China is about 10 mm (over 15%) of the total precipitable water. Finally, this deep moist layer merges into the Meiyu front and supplies water vapor into it.

On the other hand, the moist layer over the East China Sea is shallow, reaching 800 hPa. There is no supply of the sensible heat flux over the East China



**Fig. 6** Schematic illustration of the transport of water and the structure of the moist layer over mainland China (a) and over the East China Sea (b). Arrows show the transport of water.

Sea; thus, the deep moist layer cannot be formed. The mixing ratio of water vapor near the surface is larger than that over mainland China. Finally, this shallow moist layer also merges into the Baiu front and supplies water vapor into it.

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