Diurnal Variation of Water Vapor Mixing between the Atmospheric Boundary Layer and Free Atmosphere over Changwu, the Loess Plateau in China

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Abstract

We investigated the diurnal variation of water vapor mixing between the atmospheric boundary layer (ABL) and the free atmosphere over the Loess Plateau in China. Water vapor and wind velocity in the troposphere were observed using a ground-based microwave radiometer and a wind profiler radar in 2005 and 2006. On sunny days in early summer, a strong vertical wind was generated in the afternoon followed by ABL development. Strong convection was enhanced when active cumulus convection developed in the afternoon. In such cases, water vapor decreased in the lower atmosphere from the early morning until late afternoon, while water vapor increased in the upper atmosphere. This finding suggests that water vapor was exchanged diurnally between the ABL and the free atmosphere. The strong convection in the ABL, which was developed by sensible heat from the land surface, played critical roles with link to cumulus convection in such vertical mixing of water vapor. Influences of other processes such as a local circulation and advection of cloud systems were also discussed.

1. Introduction

Water plays an important role in the Earth's climate by transporting energy over long distances, forming clouds and rainfall, and thereby influencing biological and ecological activities worldwide. Water is also crucial for human lives and activities. It is especially critical in arid and semi-arid regions where water resources are limited.

In East Asia, vast areas of such severe climate regimes are distributed across northern China. Located in the middle part of the Yellow River basin, the Loess Plateau significantly affects the water cycle in the Yellow River basin (Zhang and Liu 2005).

The Loess Plateau experiences dry conditions in most periods of the year. Over the dry surface exposed to intense solar radiation, the atmospheric boundary layer (ABL) can develop to high altitudes (Gamo 1996). A strong vertical wind, which can reach the free atmosphere, develops in the ABL over the plateau in early summer (Nishikawa et al. 2005). Over the Tibetan Plateau, dry convection in the ABL and cumulus convection have been shown to play significant roles in heating the upper troposphere in spring (Taniguchi and Koike 2007). Thus, the developments of the ABL and clouds are critical factors in atmospheric dynamics and water cycles.

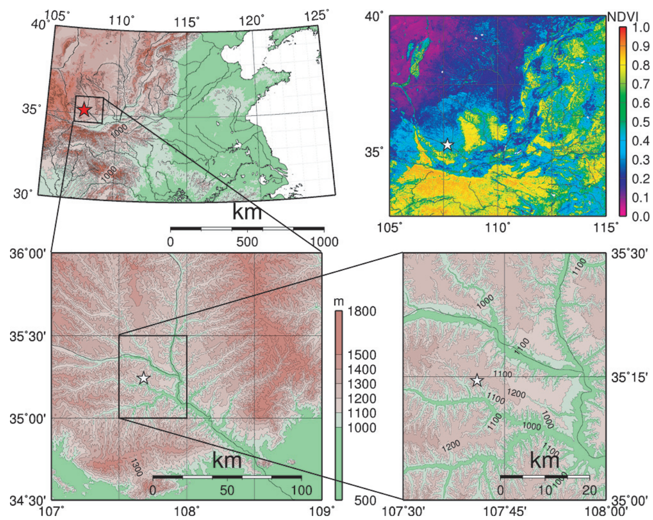

Fig. 1. Topographical maps of the observation site, which is marked by an asterisk in each map. The upper right figure shows the MODIS-derived normalized difference vegetation index (NDVI) values for July 2002 (resolution: 250 m). The lower left figure was made using data from the global digital elevation model GTOPO30 (resolution: 1 km), and the lower right figure was made using data obtained by the Space Shuttle (resolution: 90 m).

To clarify the role of cloud activity, it is necessary to investigate the temporal variation of the atmospheric thermodynamic state. Recent progress in collecting *in situ* observation variables has made it possible to measure precipitable water vapor (PWV) at a high time resolution (e.g., Takagi et al. 2000). Passive microwave radiometry, which was adopted in this study, is an efficient method to retrieve continuous profiles of atmospheric humidity and temperature (Lohnert et al. 2007). In this study, data were also obtained using a wind profiler radar to assess the kinematic structures of the ABL and the free atmosphere.

The aims of this study were 1) to clarify the diurnal variation of the atmospheric water vapor over the Loess Plateau in early summer in 2005 and 2006, and 2) to investigate interactive influences of the ABL development and cumulus convection on the vertical transport of water vapor.

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2. Observations and data set

In May 2004, we established systems for measuring the ABL over a wheat field of the Changwu Agro-Ecological Experimental Station [35.24°N, 107.68°E, 1224 m above sea level (a.s.l.)] in the southern part of the Loess Plateau in China (Fig. 1). Complex terrain with a flat tableland and steep gullies spreads over the plateau. Broad areas of the tableland are occupied by crop fields of wheat, maize, and apples.

The ABL observation systems were installed in May 2004 (Hiyama et al. 2005). Vertical profiles of atmospheric water vapor were measured from the ground to a height of 10 km using the ground-based microwave radiometry (MR) equipment (TP/WVP-3000, Radiometrics Corp., Boulder, CO, USA) with a time step of 1 min. Vertical profiles of wind velocity were also observed using a 1290-MHz wind profiler radar (WPR; L-28, Sumitomo Electric Industries, Inc., Osaka, Japan) up to a height of about 8 km. Turbulence measurements were also conducted at this site to estimate sensible heat (SH) and latent heat (LH) fluxes on the ground based on the eddy correlation method (EC). An ultrasonic anemometer/thermometer (1210R3, Gill Instruments, Ltd., Lymington, UK) and an open-path type H_2O/CO_2 gas analyzer (LI-7500, Li-Cor, Inc., Lincoln, NE, USA) were installed on the system at a height of 32 m. Additionally, 30-min average air temperature (T_a) at a height of 2 m was measured using a temperature/relative humidity probe (HMP-45A, Vaisala, Helsinki, Finland). Precipitation was measured using a tipping-bucket rain gauge. Visual observations of the amount and types of clouds that appeared in the daytime were conducted every 1 h from 8:00 Beijing Standard Time (BST) to 18:00 BST during the intensive observation periods (IOPs) from 11 May to 13 July 2005 and from 15 May to 10 July 2006.

The neural network of the MR was trained with use of radiosonde data at YanAn (36.60°N, 109.50°E, 959 m a.s.l.), located about 224 km from our observation site. To check the validity of our MR data, further, the vertical profiles of humidity and air temperature measured by the MR were compared to radiosonde data measured at Pingliang (35.55°N, 106.67°E, 1348 m a.s.l.), located about 98 km from our observation site. We used data measured at 7:00 BST in 32 cases of fine days. The data from the three measurement sets agreed well with each other. Root mean square errors were 1.47 g m^{-3} (r^2 = 0.78) for humidity and 2.27 K (r^2 = 0.83) for air temperature in the atmosphere lower than a height of 2 km from the ground, and 0.32 g m^{-3} (r^2 = 0.71) for humidity and 2.74 K (r^2 = 0.97) for air temperature in the atmosphere higher than 2 km. Atmospheric conditions could be taken as being closely homogeneous in the area including the three sites on fine days. Thus, we judged that the MR data were suitable for use in examining the seasonal and diurnal changes in atmospheric water vapor and air temperature over the observation site.

3. Results

The upper panel of Fig. 2 shows the seasonal variation in daily averaged values of atmospheric water vapor content (WVC) integrated vertically from the surface to a height of 2 km (light blue line and circles) and to 10 km (black line and circles) in unit space (1 m^2) and T_a (green line) at a height of 2 m. Here, we use WVC to represent the amount of water vapor in a certain depth of the atmospheric layer in order to distinguish this amount from PWV. Data were missing for the period from 13 July 2005 to 8 April 2006 due to problems with the electric power to the measurement equipment. The WVC varied drastically in the course of the seasonal march. Compared with WVC below a height of 2 km, the integrated WVC below 10 km fluctuated greatly, especially in the warm season. The maximum peak of WVC appeared around July and August in 2006. During the period when WVC was high, precipitation occurred frequently and the soil-water content increased.

The middle panel of Fig. 2 shows the seasonal variation of the daily-averaged fluxes of SH and LH based on the EC method at a height of 32 m. Moderate maximum peaks of SH occurred in spring. When surface soil was moistened by precipitation in the rainy seasons beginning around July, LH reached its maximum peaks, and SH decreased gradually.

As depicted in the lower panel of Fig. 3, which shows the amounts and types of clouds during the IOPs over the observation site in daytime, the frequency of appearance of active cumulus clouds increased with increases of T_a and WVC (upper panel of Fig. 3) from late June in each year. In this study, we defined active cumulus as cumulus congestus or cumulus castellanus clouds that developed massively to a high altitude, in

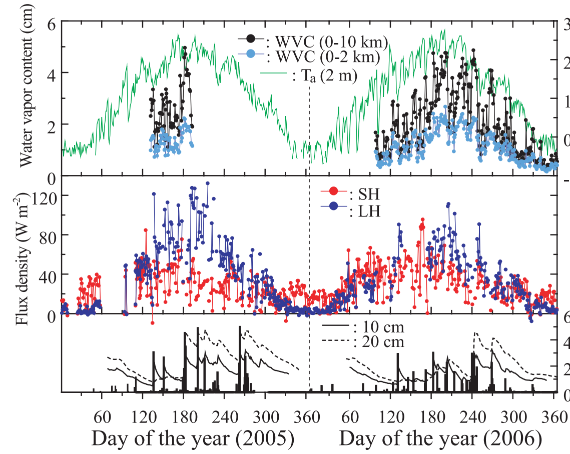

Fig. 2. Seasonal variations in (upper panel) daily-averaged values of water vapor content (WVC) in the troposphere, 30-min average air temperature (T_a) at 2 m, (middle panel) flux densities of sensible heat (SH) and latent heat (LH), and (lower panel) surface soil water contents. Seasonal variation in daily precipitation is shown as black bars in the lower panel.

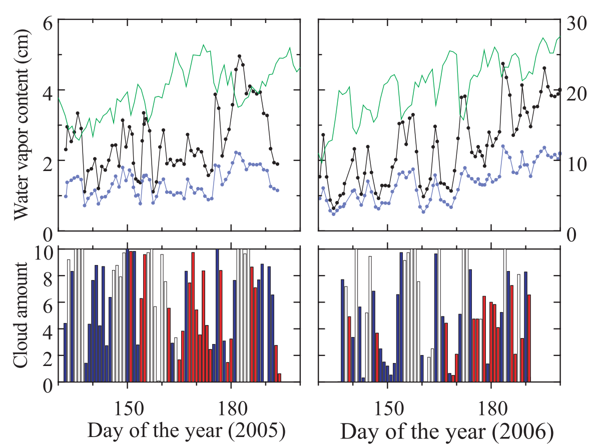

Fig. 3. Seasonal variation in (upper panel) daily-averaged values of water vapor content (WVC) in the troposphere, 30-min average air temperature (T_a) at 2 m, and (lower panel) the amounts and types of clouds. The meanings of each line are the same as those for the upper panel of Fig. 2. In the lower panels, red bars indicate the presence of active cumulus, blue bars indicate the presence of forced but not active cumulus, and the white bars indicate other types of clouds.

contrast to fair weather cumulus.

In the presence of active cumulus clouds, characteristic diurnal variation in WVCs was observed in the lower and upper atmospheric layers, as shown in the upper panel of Fig. 4 illustrating the time series of WVCs during days of the year (DOY) 168–172 in 2005. Ther grey bar was depicted for showing occurrence of precipitation, since accuracy of measurement of humidity profile decreased during events of precipitation. The WVC decreased in the lower layer in daytime and increased in the upper layer clearly on the DOY 168, 169, and 170. The minimums in the lower layer and maximum in the upper layer appeared in the evenings. Such diurnal variations of WVCs had been observed during the periods from spring to early summer in 2005 and 2006. We could observe 15 and 19 cases in 2005 and 2006, respectively. Especially, it occurred frequently in June in both of years. The lower panel of Fig. 4 shows the variation of cloud amount and types. Active cumulus appeared in the afternoon of each day. Note that the observations of cloud amount and type by visual survey of the sky from the ground were made only during the daytime. To compare this information with the cloud amount for a larger area, cloud amount was also estimated using equivalent black body temperature (Tbb) data derived from the Geostationary Operational Environmental Satellite 9 (GOES-9); these cloud amounts are depicted by open circles with lines in the lower panel of Fig. 4. The larger area covered 5°× 5°, the center of which was our observation site, and the resolution was 0.05°×0.05°. Areas in which Tbb was below 270 K were treated as cloud areas. The estimations using GOES-9 data indicated that the cloud amount tended to increase in the afternoon, which was apparent on DOY 168, 170, and 171, but was relatively weak on DOY 169 and 172. These differences might relate to development of active cumulus in the afternoon on each day. Thus, these cloud developments also likely related to the development of the ABL.

Figure 5 shows the time-height sections of the vertical wind velocity measured by the WPR on DOY 168, 169, and 170. The wind velocity showed strong vertical mixing. Updrafts sometimes reached a height of about 5 km, in the afternoons of DOY 169 and 170. The vertical motion in the lower layer was due to development of the ABL. However, the strong vertical motion of the upper layer cannot be explained only by the ABL development. Active cumulus clouds, which appeared in the afternoon as shown in the lower panel of Fig. 4, may have caused the strong vertical motion, which might have been linked to the vertical motion in the ABL. Active cumulus can be considered to act as a pump that transports water vapor from the lower to the upper atmosphere. This feature can be seen in Fig. 6 (a) illustrating the diurnal variation of the vertical profiles of absolute humidity on DOY 170 in 2005, when the vertical winds were strong in the afternoon. Four profiles at different times are shown. Upward transport of air, which may be caused by convective clouds, can also affect the atmospheric humidity. Water vapor can heat the upper layer by releasing its latent heat to the surrounding air as a consequence of condensation. Thus, the potential temperature increased in the free atmosphere above around 4 km under the condition of cumulus convection (figure not shown). Such atmospheric heating in the upper troposphere was also observed in spring at the Tibetan Plateau (Taniguchi and Koike 2007). In contrast to this case, the vertical

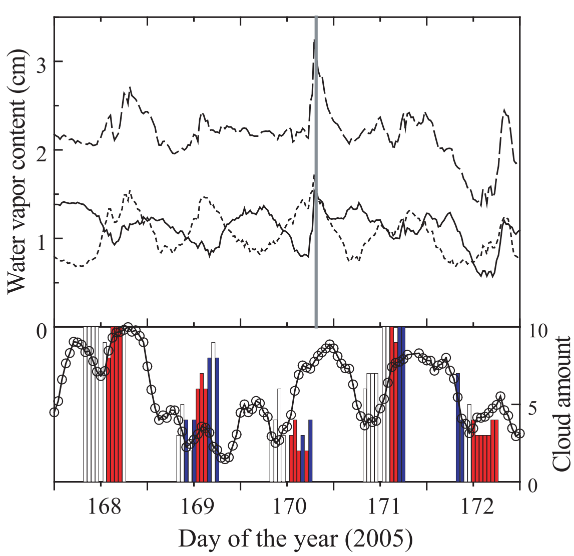

Fig. 4. Diurnal variation in atmospheric water vapor content (WVC) measured on days of the year (DOY) 168–172 in 2005 (upper panel). The dashed broken line shows WVC from the ground to a height of 10 km, the solid line shows WVC integrated from the ground to a height of 2 km, and the dotted line shows WVC integrated from 2 to 10 km in height. Grey bar shows event of precipitation. The lower panel shows the amounts and types of clouds. The colors of the bars have the same meaning as in Fig. 3. Open circles with lines are cloud amounts estimated using black body temperature (Tbb) measured by the GOES-9 satellite.

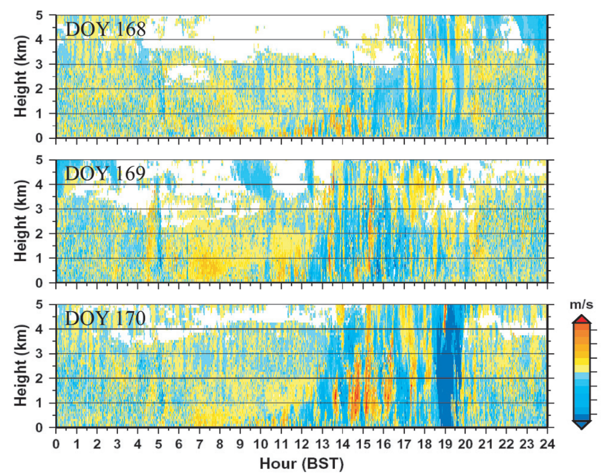

Fig. 5. Time-height sections of the vertical winds observed on 168, 169, and 170 DOY in 2005. The colors indicate the vertical wind velocity. Red colors indicate upward wind and blue color indicates downward wind.

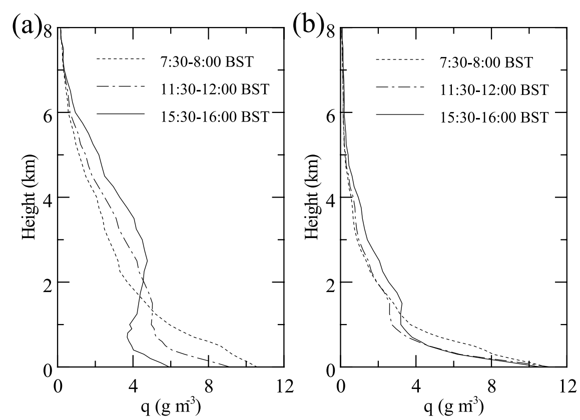

Fig. 6. Vertical profiles of 30-min-averaged absolute humidity on day of the year (DOY) 170 (a) and 158 (b) in 2005. Dotted line: 7:30–8:00 BST, dashed-dotted line: 11:30–12:00 BST, and solid line: 15:30–16:00 BST.

winds were weak and a cumulus cloud was not observed on DOY 158 in 2005. As shown in Fig. 6 (b), the diurnal variations of humidity were relatively small in both of the upper and lower atmosphere in such a case.

4. Discussion

In addition to the contribution from vertical mixing, the horizontal advection of water vapor may influence atmospheric profiles. DOY 168 was cloudy and active cumulus clouds were observed in the afternoon (lower panel of Fig. 4). In this condition, WVC also showed diurnal variation (upper panel of Fig. 4), although strong vertical mixing was not captured by the WPR (upper panel of Fig. 5). In this case, the contribution of horizontal advection of clouds might have been dominant in the variation of WVC, although our observations were limited to vertical distribution, assuming homogeneity in the horizontal direction.

Several previous studies have reported decreases in PWV in the daytime over inland, mountainous, and coastal areas and have concluded that local circulations are important to this process (Takagi et al. 2000; Bastin et al. 2007). Under such conditions, convective activity might be closely related to a local circulation. In this study, WVC in the lower layer began to decrease in early morning on DOY 168, 169, and 170, as shown in Fig. 4. A weak upward wind occurred in the lower layer from the ground to about 1 km in the morning each day in Fig. 5. Such air motion may also have contributed to decreasing the WVC in the lower layer. Thus, a local circulation may have formed over the tableland and influenced the diurnal variation in WVC (e.g., Zängle and Chico 2006), which also might influence diurnal change of potential temperature above a height of about 4 km.

On the other hand, diurnal variation of atmospheric water vapor due to cloud development is also likely to be influenced by weak synoptic subsidence reaching a height of about 3 km, which helps active cumulus to develop easily, and also by the convective activity that is transported eastward from the Tibetan Plateau (Asai et al. 1998). The active cumulus clouds on cloudy days (e.g., DOY 168 and 171) and during the nighttime on DOY 170 in Fig. 4 were likely caused by active cloud convection transported from the eastern Tibetan Plateau, which was shown in the Tbb data from GOES-9 (figures not shown). In this context, the period with weak activity of cumulus clouds until mid-June (lower panel of Fig. 3) may have been related to a resting phase of cloud activity over the eastern Tibetan Plateau; such a phase was reported by Fujinami and Yasunari (2001) and Yasunari and Miwa (2006). These findings suggest that the convective activity over the Loess Plateau is influenced by that of the eastern Tibetan Plateau. However, in the daytime on DOY 169 and 170, active cumulus was considered to have developed locally, since the GOES-9 Tbb data showed no horizontal advection of active cloud convection from the outside region (figures not shown). In such a situation, development of the ABL over the plateau was related to cloud development, and cumulus cloud convection had a critical role in the vertical transport of water vapor.

5. Summary

This study revealed characteristic diurnal variations of WVC in the atmosphere over the southern part of the Loess Plateau in summer. Water vapor decreased from early morning until late afternoon in the atmosphere within the ABL and increased in the free atmosphere when active cumulus clouds developed. A strong vertical wind was generated in the afternoon followed by the development of the ABL. Such strong convective activity was especially apparent when cumulus clouds developed in the afternoon. The enhanced vertical wind induced by the active cumulus clouds may play a critical role in diurnal variation in atmospheric water vapor, although a local circulation may also be generated and contribute to the diurnal variation in WVC. Future research should investigate whether a local circulation is formed over the complex terrain of the Loess Plateau. Further studies will also be needed to clarify the diurnal variations in water vapor in the troposphere over the Loess Plateau, detailing how such variation is generated and how it influences the water vapor transport for this region.

Acknowledgments

We thank the two anonymous reviewers and the editor for their helpful comments to improve this study significantly. This study was conducted with financial support from the "Recent Rapid Change of Water Circulation in the Yellow River and Its Effects on the Environment" research project of the Research Institute for Humanity and Nature, Japan.

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Manuscript received 11 January 2008, accepted 27 March 2008
SOLA: http://www.jstage.jst.go.jp/browse/sola/