NOTES AND CORRESPONDENCE

Drastic Evening Increase in Precipitable Water Vapor over the Southeastern Tibetan Plateau

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Abstract

A drastic increase in precipitable water vapor (PWV) in the evenings was repeatedly confirmed in October 2000, by an analysis of GPS observational data at Lhasa in the southeastern Tibetan Plateau, China. In order to investigate its mechanism, a numerical simulation was performed for a typical day using a regional atmospheric model. During the daytime, moisture is transported toward the summits of the Himalayas from the Hindustan plain along the southern slope of the mountain range by thermally-induced upslope winds. The moist air mass penetrates the Tibetan Plateau, through some cols of the Himalayas. Moisture accumulates over the northern foot of the Himalayas. Then a horizontal gradient of moisture increases north of the Himalayas, and a stationary moisture front forms between the moist air mass and dry air on the Tibetan Plateau. In the evening, the frontal structure begins to gradually decay until the midnight, and a large amount of moisture bursts toward the inner Tibetan Plateau in the lower atmosphere as a gravity current, causing a rapid increase in PWV. It is speculated, therefore, that the drastic evening increase in PWV, extending widely along the Himalayas, is generated by the plateau scale diurnal wind induced by the thermal effects between the Tibetan Plateau and the Hindustan plain. During the following day, the PWV level decreases over a wide area of the inner Tibetan Plateau, since dry air advection is intensified in the lower atmosphere by the synoptic scale westerly winds, because of the growth of the mixed layer accompanied by the vertical transportation of momentum.

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1. Introduction

The Tibetan Plateau has a high mean altitude of 4500 m above sea level (ASL), and influences the surrounding atmospheric circulation thermally and dynamically. During the Asian monsoon period, latent heating plays an important role as the major heat source over the eastern Tibetan Plateau (Yanai et al. 1992), and intense cloud activity frequently occurs in the evenings. The convective index, calculated from equivalent black-body temperature (T_{bb}) data derived from infrared images of the Geostationary Meteorological Satellite (GMS), has been analyzed in a large number of studies (Murakami 1983; Nitta and Sekine 1994). Fujinami and Yasunari (2001) discussed the diurnal cycle of T_{bb} over the Tibetan Plateau, which shows an evening peak of cloud development. They also analyzed long-term variations in the convection with the diurnal cycle. Kurosaki and Kimura (2002) examined the diurnal cycle of cloud-cover frequency, estimated from visible GMS images, and described a relationship between the diurnal cycle and local orography during pre-monsoon and monsoon periods.

Diurnal variations in moisture over the Tibetan Plateau, were also clarified by previous studies using observational data. These studies showed that low-level moisture tends to show a clear diurnal cycle, which is at its lowest in the daytime. Yanai and Li (1994) examined sounding data, and surface observational data, obtained by the Qinghai-Xizang Plateau Meteorological Experiment (QXPME), which was carried out from May to August 1979. They stated that there is less low-level moisture in the evening than in the morning because of an intensification of dry air advection by large-scale westerly winds during the daytime. Using satellite data, they also showed that cloud activity could be observed more frequently in the evening, in spite of less moisture in the lower atmosphere.

In contrast, Kuwagata et al. (2001), analyzing sounding data, indicated that the daytime decrease in precipitable water vapor (PWV) is due to thermally-induced local circulation during the summer. Takagi et al. (2000) indicated that PWV reaches its minimum level in the evening. Their finding was based on Global Po-

sitioning System (GPS) observational data, obtained in Lhasa during the pre-monsoon and monsoon periods in 1998. Intense cloud activity in the evening does not agree with the diurnal PWV cycle, which is at a minimum in the evening over the Tibetan Plateau. They speculated that most meteorological observation stations are located in the valley region, so observed moisture may be strongly affected by the descending motion of the local circulations, while clouds can be observed by satellites around the mountains near the valleys. However, they did not elaborate on the effect of the plateau scale circulation upon the diurnal moisture variations.

2. GPS-PWV data analysis

2.1 Data and method

Recently, a technique to estimate PWV from GPS data has been developed (Businger et al. 1996). Routine GPS observations are done by the International GPS Service (IGS), for the purpose of the detection of crustal movements. One of the IGS observational stations is in Lhasa (91.10 degree E, 29.66 degree N, 3659 m ASL), which is located in a narrow valley bottom in the southeastern Tibetan Plateau (Fig. 1c). The hourly total atmospheric delay was calculated from GPS data using Bernese GPS Software Version 4.2 (Hugentobler et al. 2001). Then, the amount of PWV was estimated from the surface pressure and temperature, also observed by IGS, in addition to the total atmospheric delay (Davis et al. 1985; Bevis et al. 1992). Thus, PWV data derived from GPS have high time resolutions and make it possible to analyze diurnal variations in detail on the Tibetan Plateau.

2.2 Diurnal variation of observed PWV

Figure 2 represents the 15-day average diurnal cycle of PWV, estimated from GPS data obtained in Lhasa in October (thin line), as well as hourly data observed on 23 October 2000 (thick line), the day on which the most prominent clear diurnal cycle was shown. Error bars plotted on the average PWV indicate estimated standard deviations of the 15-day mean, which were derived from standard deviations of daily means divided by the square root of 14 (the number of samplings minus one). Throughout the 15 day period, the synoptic scale westerly

Fig. 1. Model domains for (a) a coarse grid system (Domain A; grid interval 75 km), (b) a semi-fine grid system (Domain B; 25 km) and (c) a fine grid system (Domain C; 5 km). The location of Lhasa is shown as an inverse triangle, and the positions of cross sections (Figs. 5 and 6) are shown as Line 1 and 2, respectively, in Domain C.

winds were quite strong, over 400 hPa. Cloud cover was rarely observed by GMS, over the southern half of the Tibetan Plateau during this period.

The average PWV did not vary much in the early morning. It began to decrease before noon and then increased each evening. On 23 October 2000, the PWV continuously decreased by about 6 mm during the daytime, and reached a minimum level in the evening. Then the PWV abruptly increased by almost the same amount as the daytime decrement, within 4 hours. Takagi et al. (2000) reported a similar diurnal cycle for PWV, with the daily minimum at about 1700 Local Solar Time (LST) in Lhasa during the pre-monsoon period in 1998.

3. Numerical simulation

3.1 Design of numerical simulation

The numerical model in the present study is a modified RAMS (TERC-RAMS, Yoshikane et al. 2001; Sato and Kimura 2003). The original RAMS (Regional Atmospheric Modeling System) was developed at Colorado State University (Pielke et al. 1992). The numerical model was modified at TERC (Terrestrial Environ-

Fig. 2. Diurnal cycle of PWV estimated from GPS data in Lhasa averaged for 15 days, from 10 to 24 October 2000 (thin line), and hourly data observed on 23 October 2000 (thick line). Error bars plotted on the average PWV indicate estimated standard deviations of the 15-day mean.

ment Research Center, University of Tsukuba). Specifications of the model, and the design of the numerical simulation are shown in Tables 1 and 2, respectively. The numerical simulation was conducted for the case study observed on 23 October 2000, starting at 0000 UTC of the

Table 1. Specifications of the model.

The Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992) modified at TERC (Terrestrial Environment Research Center, Univ. of Tsukuba)	
Dynamical process	Physical process
Non-hydrostatic equations Polar-stereo, Z* terrain-following coordinate	Radiation scheme (Nakajima et al. 2000) Surface process (Louis 1979) Soil model (Tremback and Kessler 1985) Cloud microphysics (Walko et al. 1995)

Table 2. Design of the numerical simulation.

Calculation time	48 hours integration (start at 0000 UTC, 22 Oct. 2000)
Horizontal grid interval	75 km (Domain A), 25 km (B), 5 km (C)
Vertical layers	30
Top of the level	21 km ASL
Depth of the lowest layer	110 m
Soil layers	11
Initial soil water content	0.4 (ratio of soil water content to saturated soil water content)
Vegetation type	Crop/mixed type (uniform over the whole domain)
Initial and boundary condition	NCEP/NCAR reanalysis data (6-hourly)
Sea surface temperature	NOAA-CIRES CDC* monthly mean Reynolds SST (Oct. 2000) (Reynolds and Smith 1994)

*National Oceanic and Atmospheric Administration (NOAA)-Cooperative Institute for Research in Environmental Sciences (CIRES) Climate Diagnostics Center (CDC)

previous day, and integrating during 48 hours. Vegetation and soil types were assumed to be uniform over the whole domain. Figure 1 shows model domains for (a) a coarse grid system (Domain A; grid interval 75 km), (b) a semi-fine grid system (Domain B; 25 km) and (c) a fine grid system (Domain C; 5 km). These grid systems are two-way nested. Domain C includes the Himalayas at a latitude of 28 degrees north, with a very steep slope on the southern side of the Himalayas. Initial and boundary conditions were assumed by using 6-hourly NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data, while the nudging technique was applied only in the lateral boundary of Domain A.

3.2 Diurnal variation of simulated PWV

Figure 3 represents the time variation of PWV, simulated by the model (thick line) in Lhasa after 24 hours of spin-up integration. The thin line in Fig. 3 indicates the PWV observed by GPS on the same day, which is shown by the thick line in Fig. 2. While simulated PWV changes were small during the early morning, they decreased remarkably from 1100 LST to 1500 LST and then abruptly increased in the evening. The range and shape of the di-

Fig. 3. Time variation of PWV simulated by the model in Lhasa on 23 October 2000 after 24 hours of spin-up integration (thick line). The thin line indicates PWV observed by GPS on the same day (same as the thick line shown in Fig. 2).

urnal cycle of the simulated PWV agree well with those of the observed one.

Figure 4 shows horizontal distributions of the simulated PWV and low-level wind velocity (roughly 50 m above ground) over Domain C. In the daytime, the PWV level is larger and southerly winds prevail along the southern slope of the Himalayas. A large PWV area also exists around the northern foot of the Himalayas at 1500 LST (Fig. 4b). The enhanced PWV area, a few hundred kilometers long, and about one hundred kilometers wide, is almost parallel to the Himalayas. The enhanced area extends northward, or northeastward in the evening (see Fig. 4c and d). The broken lines in the figures indicate the frontal position of the enhanced area.

The increased PWV during the evening tends to be restored during the following day, when strong westerly winds become predominant in the lower atmosphere, and the PWV decreases over a wide area in the inner Tibetan Plateau.

4. Discussion

In general, the diurnal cycle of moisture is affected by thermally-induced local circulations. Kimura and Kuwagata (1995), and Kuwagata et al. (2001) simulated the phase and amplitude of the diurnal PWV cycle associated with mountain-valley circulations. The daily minimum of PWV appears around noon in a narrow (20 km or 40 km) valley bottom, while it appears later in the bottom of a wider valley. Although Lhasa is located in a narrow valley

Fig. 4. Horizontal distributions of PWV (gray shading grade) and wind velocity in the lower atmosphere (roughly 50 m above ground) simulated by the model over Domain C at (a) 1300 LST, (b) 1500 LST, (c) 1700 LST and (d) 1900 LST, 23 October 2000. The wind velocity is shown by arrows, and the altitude is shown by contour lines with an interval of 500 m. The broken lines indicate the frontal position of the moist air.

(about 30 km width), the daily minimum PWV is observed around sunset. It is hard to explain the mechanism of the diurnal PWV cycle in Lhasa, only by the mountain-valley circulation.

The present numerical simulation shows southerly winds along the southern slope of the Himalayas (Fig. 4). The southerly winds seem to be the thermally-induced upslope winds gen-

Fig. 5. Meridional-height cross sections of the mixing ratio (contour lines, with an interval of 0.5 g kg^{-1}) simulated by the model along Line 1 in Fig. 1c at (a) 1500 LST and (b) 2000 LST, 23 October 2000. The gray-shaded area indicates a moist area with a mixing ratio larger than 3 g kg^{-1} . The vertical axis indicates height (m ASL). The black area shows a cross section of the topography. The broken line in (a) indicates the frontal position of the moist air (corresponding to the line shown in Fig. 4b).

erated over the slope. In the daytime, a large amount of moisture on the Hindustan plain is transported by the upslope winds toward the summits of the Himalayas. The moisture further penetrates the Tibetan Plateau, through some cols of the Himalayas. The penetration of moisture is remarkable, especially over the eastern Himalayas. Extremely strong upvalley winds have been observed in the daytime by pilot balloons, and aircraft soundings in the Himalayan Kali Gandaki valley in Nepal (Egger et al. 2000; Zangl et al. 2001; Egger et al. 2002). They have also simulated the strong upvalley winds by a numerical model. By this wind system, moisture accumulates over the northern foot of the Himalayas until the evening, when the moist air mass extends northward, and then turns northeastward, because of strong westerly winds prevailing in the lower atmosphere over the inner Tibetan Plateau.

Figure 5 shows the meridional-height cross sections of the mixing ratio along Line 1 in Fig. 1c simulated by the model. The moist area of a mixing ratio larger than 3 g kg^{-1} is shaded in gray in the figure. At 1500 LST, a moist air mass extends over the Himalayas and reaches the northern foot of the Himalayas. The horizontal gradient of the moisture becomes large north of the Himalayas, and a stationary moisture front forms between the moist air mass, and dry air on the Tibetan Plateau (broken line, corresponding to the line shown in Fig. 4b). The formation mechanism of the front is similar to that of a sea breeze.

In the evening, the frontal structure begins to gradually decay until midnight, and a large amount of moisture bursts toward the north, or northeast, into the inner Tibetan Plateau in the lower atmosphere. As the moist air mass reaches Lhasa, the PWV increases drastically

Fig. 6. Longitudinal-height cross sections of the mixing ratio (contour lines, with an interval of 0.5 g kg^{-1}) and the westerly component of wind velocity (gray shading grade, greater than 10 m s^{-1}) simulated by the model along Line 2 in Fig. 1c at (a) 1000 LST and (b) 1500 LST, 23 October 2000. The vertical axis indicates height (m ASL). The black area shows a cross section of the topography.

there. The moisture burst is somewhat analogous to a gravity current converted from a sea breeze in the late afternoon (Simpson et al. 1977).

Additional simulation, which only includes a coarse grid system (Domain A), and a semi-fine grid system (Domain B), was conducted. The results also indicate similar moisture penetration into the Tibetan Plateau from the Hindustan plain. However, the frontal structure was quite ambiguous.

Figure 6 shows the same information as Fig. 5, except for the longitudinal-height cross sections along Line 2 in Fig. 1c. The westerly component of wind velocity greater than 10 m s^{-1} is shown by the gray shading. At 1000 LST, the wind is weak in the lower atmosphere. Since the mixed layer has not developed well, the mixing ratio is larger in the lower atmosphere.

At 1500 LST, the westerly wind becomes strong, and the mixing ratio decreases in the entire mixed layer. The decrement of the mixing ratio is caused by the large-scale advection of a dry air mass. The reason for the acceleration of the low-level westerly wind, is the vertical transportation of momentum by the turbulence in the mixed layer. The ventilation effect extends across the entire Tibetan Plateau. This fact agrees with Yanai and Li's (1994) finding that the low-level moisture decrease in the Tibetan Plateau during the daytime is caused by large-scale westerly winds. In the valley around Lhasa, the daytime decrease of the mixing ratio is locally enhanced by strong westerly winds from the windward mountains, intensified by the mechanism of the downslope wind, as a part of a non-linear mountain wave. The drastic evening increase in PWV seems to extend widely along the Himalayas, and is generated by the plateau scale diurnal wind induced by the thermal effects between the Tibetan Plateau, and the Hindustan plain, rather than the local scale mountain-valley winds.

The importance of plateau scale circulation may depend on the season. The effect of local circulation on the diurnal cycle of PWV may be stronger in mild ambient wind. Analyses similar to those presented here, will be necessary in other seasons. An evening increase in PWV has been directly observed, only by GPS in Lhasa. More GPS stations are necessary in the Tibetan Plateau to clarify the horizontal structure of the phenomena, and detailed interaction with orography. More detailed meteorological data are also necessary, to verify the simulation results.

5. Conclusion

PWV estimated from GPS at Lhasa in the southeastern Tibetan Plateau frequently showed a drastic increase in the evenings in October 2000. The mechanism of the drastic increase in PWV cannot be explained only by local scale mountain-valley winds, because Lhasa is located in a narrow valley bottom, which means that theoretically the PWV should have begun to increase much earlier. In order to investigate the mechanism of the increase, a numerical simulation was conducted for a typical day. The simulated PWV indicated almost the same variation as the observed one.

From the simulation, it was concluded that the following process occurs:

- (1) In the daytime, the moisture on the Hindustan plain climbs along the southern slope of the Himalayas by thermally-induced upslope winds;
- (2) the moisture further penetrates the Tibetan Plateau through some cols of the Himalayas;
- (3) moisture accumulates over the northern foot of the Himalayas parallel to the mountain range;
- (4) a horizontal gradient of moisture becomes large north of the Himalayas, and a stationary moisture front forms between the moist air mass, and dry air on the Tibetan Plateau;
- (5) in the evenings, the frontal structure begins to gradually decay until the midnight, and a large amount of moisture bursts toward the inner Tibetan Plateau in the lower atmosphere;
- (6) the drastic increase in the PWV seems to extend widely along the Himalayas, generated by the plateau scale diurnal wind, induced by the thermal effects between the Tibetan Plateau and the Hindustan plain; and,
- (7) during the following day, the PWV decreases again over a wide area of the inner Tibetan Plateau, since dry air advection by westerly winds is intensified in the lower atmosphere.

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