Diurnal Variation of Precipitable Water over a Mountainous Area of Sumatra Island

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ABSTRACT

Diurnal variations in atmospheric water vapor at Koto Tabang, a mountainous area of Sumatra Island, Indonesia, are studied by analyzing the GPS-derived precipitable water, radiosonde data, and surface meteorological observation data. A permanent GPS receiving station was established at Koto Tabang in March of 2001. Radiosonde soundings were carried out at 3-h intervals to study the atmospheric water and energy cycles in the Maritime Continent of Indonesia. A distinct diurnal variation in water vapor is observed. The precipitable water increases during daytime, reaching its maximum in the late afternoon. The results of the radiosonde observations indicate that the increase in water vapor occurs up to an altitude of approximately 3 km. Water vapor is transported by turbulent mixing with the development of the boundary layer in the afternoon. The diurnal cycle of water vapor is affected by the intensity of incident solar radiation. It is suggested that the diurnal variation in water vapor is caused by the horizontal transport of water vapor by local circulation. The diurnal range of the precipitable water on days with heavy rain was larger than that on days without rain. Rainfall often occurs as intensive showers during a short period in the late afternoon and early evening in the Koto Tabang area; daily shortwave radiation is still sufficiently strong to generate the local circulations and to induce large diurnal variation in precipitable water, even on the heavy-rain days.

1. Introduction

Water vapor is a crucial element in weather and climate. By continually cycling through evaporation and condensation, water vapor transports latent heat energy between the surface and the atmosphere. This process plays a crucial role in the global energy and hydrological cycles. Convective cloud activity is very strong in the Maritime Continent of Indonesia because of the abundant supply of water vapor. Condensation heating generated in a large number of cumulus clouds in this region plays an important role in the earth's general circulation system.

Diurnal variation in convection and rainfall in the tropical Asia region have been investigated by many researchers. Convection attains its maximum intensity in the late afternoon over continents and large islands. Over sea areas in the vicinity of large islands, the maximum convective activity generally occurs in the morning (Murakami 1983; Nitta and Sekine 1994). On the other hand, the diurnal variation in rainfall has been investigated using precipitation data observed at surface meteorological stations in tropical Asian countries. Inland regions have a pronounced peak in rainfall in the late afternoon (Oki and Musiake 1994). However, at some stations, large daily maxima of rainfall are often found between late night and early morning (Ohsawa et al. 2001). They suggested that the diurnal variations of rainfall are caused by the interaction between the local circulation and monsoon wind.

Water vapor is essential for cloud convective activity. Knowledge of the distribution and temporal variation of atmospheric water vapor is, therefore, important in forecasting regional weather and for understanding of the global climate system. However, monitoring the variation of water vapor with high temporal and spatial resolution by conventional techniques, such as radiosondes and water vapor radiometers, is difficult. Because of the lack of observational data, there are few published investigations of the diurnal variation of water vapor in tropical Asia. Previous investigations of the diurnal variation in convection in this region are mostly based on Geostationary Meteorological Satellite infrared (IR) data.

The global positioning system (GPS) technology,

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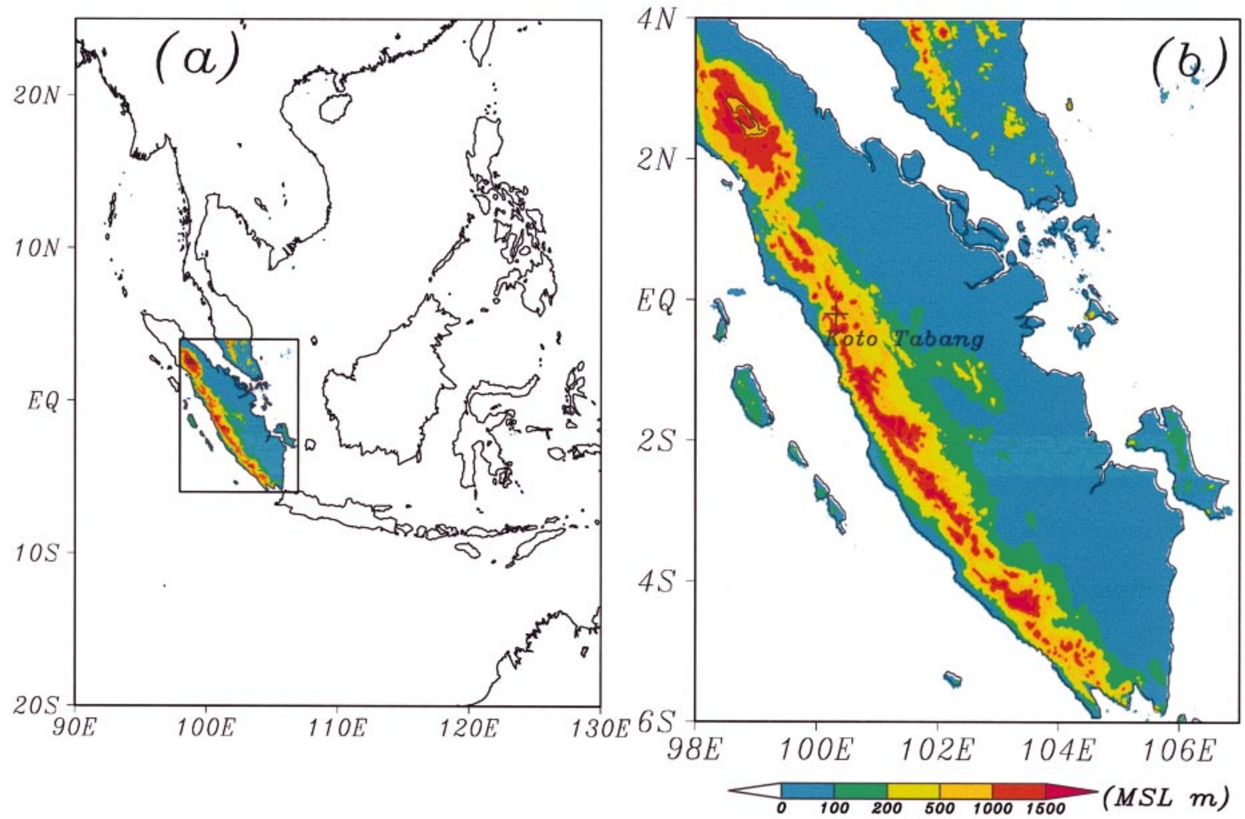

FIG. 1. Map of Southeast Asia showing the location of Koto Tabang, showing also contours of orography (m).

which is typically used for geodesy and precise geographic positioning, provides an effective, alternative technique to measure water vapor in the atmosphere with a high time resolution. The ability to estimate accurately the precipitable water (PW, the total atmospheric water vapor above the surface) by GPS has been well established (Bevis et al. 1992; Rocken et al. 1993; Duan et al. 1996; Ohtani and Naito 2000).

Dai et al. (2002) studied the diurnal variation in atmospheric water vapor with GPS and radiosonde data over 54 stations in North America. Their results indicated that most of the stations are characterized by significant diurnal variations in precipitable water. Kimura et al. (1997) and Ohtani (2001) investigated the diurnal cycle of rainfall and GPS-derived precipitable water around the central part of the main island of Japan. Their results showed that precipitable water increases in the mountainous area during daytime on calm summer days because of the convergence of anabatic winds and sea breezes. A zone of abundant precipitable water formed in the mountainous area shifts toward the Kanto plain in the evening and frequently gives rise to thunderstorms along the foot of the mountains. The results of a two-dimensional numerical model (Kimura and Kuwagata 1995) show that daytime, thermally induced local circulations play an important role in the transport of heat and water vapor from the plains to the mountainous areas.

To elucidate the atmospheric and hydrologic circulations in the Asian monsoon region, the Frontier Observational Research System for Global Change has established a GPS station network in the tropical Asian region and the Tibetan plateau. A permanent GPS receiving station was established at Koto Tabang in a mountainous region of Sumatra Island, Indonesia, in March of 2001. Radiosonde balloon observations were carried out at 3-h intervals in intensive observation periods in May, August, and November of 2001. In this paper, we describe our preliminary examination of the diurnal variation of precipitable water at this site. A distinct diurnal variation in water vapor with a maximum in the late afternoon is observed. The results show that the diurnal cycle of water vapor is related to the intensity of incident solar radiation at the surface.

2. Data and analysis

The climate of Indonesia is generally determined by the variation of rainfall because its temporal variability is much greater than that of temperature (Bayong and Zadrach 1996). The weather is influenced strongly by the behavior of the local and mesoscale circulation (Tien and Surjadi 1996). Koto Tabang (0.20°S, 100.32°E) is located in the mountainous area of western Sumatra Island, about 60 km from the west coast (see Fig. 1).

The altitude is 853 m above sea level. Because it is located approximately on the equator, the monthly mean temperature varies little throughout the year. In contrast to temperature, seasonal changes in rainfall are marked. The Koto Tabang region has two rainy seasons: March–April and October–November. The period from June to August is the dry season. In this paper, we examine the variation of water vapor at Koto Tabang in the annual dry season.

Radiosonde observations were made eight times per day at Koto Tabang in the intensive observation period of 1–27 August 2001. Vaisala, Inc., RS80- G and -H radiosondes were used for the observations. Surface meteorological data, including pressure, temperature, relative humidity, wind direction and speed, rainfall, and global solar radiation were measured with an automatic weather station (AWS; Vaisala model MAWS 201) with a time interval of 1 min. The global solar radiation, measured by a pyranometer (Vaisala model CM3), is the solar energy that is received from the entire hemisphere (180° field of view).

The GPS receiving station at Koto Tabang consists of Dorne–Margolin-type antenna-plus-choke-ring assemblies with a radome. The choke-ring design reduces ground-based multipath error, thereby improving the quality of the GPS observables. The GPS receiver recorded the tracking data from seven–eight satellites in view every 30 s.

The GPS atmospheric delay was estimated at 5-min intervals from the GPS data using the analytic software package, GPS-Inferred Positioning System (GIPSY) Orbit Analysis and Simulation Software (OASIS) (Webb and Zumberge 1993), with an analysis strategy of ''precise point positioning'' (Zumberge et al. 1997). Precise orbits of GPS satellites, satellite clock error information, and Earth rotation parameters provided by the Jet Propulsion Laboratory were used.

The path delay data were used to derive the 5-min-averaged path delay using a cutoff elevation angle of 10°. The wet path delay induced by water vapor was obtained by subtracting the hydrostatic delay from the total path delay using the dry mapping function of Niell (1996). The wet path delay was mapped into zenith wet delay by using the wet mapping function of Niell (1996).

The zenith wet delay was converted into precipitable water by using the Π parameter (Bevis et al. 1992, 1994). The weighted atmospheric mean temperature T_m was estimated from the surface temperature T_s observed by the AWS. The T_m–T_s relationship from Bevis et al. (1994) was used for these calculations. The geographic and seasonal variability of T_m was investigated by Ross and Rosenfeld (1997, 1999). The difference between PW estimated by Bevis's regression and that by a more reliable mapping function is estimated to be less than 0.5 mm. The error caused by Bevis's regression should be much smaller than the signal in the variation of precipitable water vapor in this study.

Figure 2 shows the scatterplots of precipitable water derived from GPS and from radiosonde for 162 observations during the period of 1–27 August 2001. A good correlation between GPS-derived PW and PW from radiosonde is obtained (correlation coefficient = 0.86). However, the overall root-mean-square difference between GPS and radiosonde is 4.7 mm, which is somewhat poorer than those reported over North America (1–2 mm) and Japan (3.7 mm) (Duan et al. 1996; Ohtani and Naito 2000). The overall bias (mean of the PW difference) of the GPS-derived PW with respect to radiosonde is 5.0 mm. One of the main causes of this large difference may be the uncertainty in the calibration of radiosonde moisture sensors.

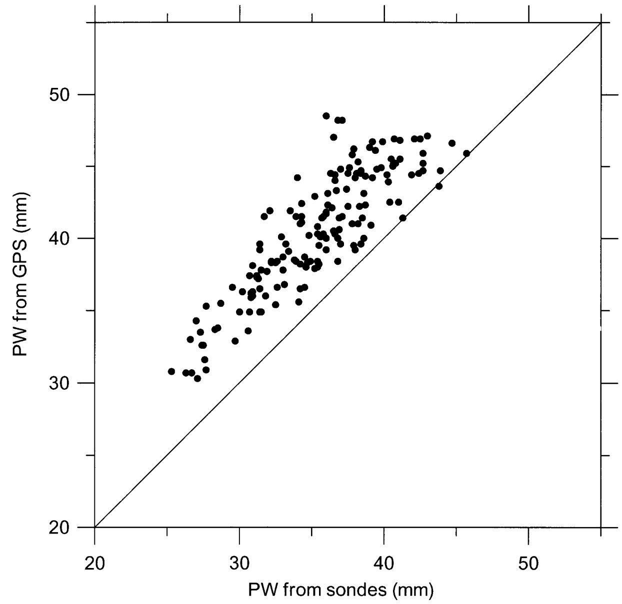

FIG. 2. Scatterplot of PW derived from GPS vs that from radiosondes for 162 soundings during the period of 1–27 Aug 2001.

Because a dry bias was found in the humidity data observed by Vaisala radiosondes during the Tropical Ocean and Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE) (Zipser and Johnson 1998), a number of studies were performed to estimate and correct the bias (Wang et al. 2001, 2002). It was found that the Vaisala humidity sensors contained a chemical contamination error and a temperature-dependence error. The chemical contamination error generally increases with age of radiosondes and relative humidity. The 1-yr-old RS80-H sondes have about 4% contamination error at 50% RH. The temperature-dependence error mainly exists at temperatures below −20°C and also introduces a dry bias (Wang et al. 2001). Turner et al. (2003) also point out that there is significant variability in the moisture calibration of RS80-H radiosondes after analyzing nearly 2000 radiosondes in detail. Therefore, the systematic biases between the PW data estimated by the GPS and by radiosonde may be caused mainly by the dry bias in the humidity sensors of the radiosondes. Meanwhile, the

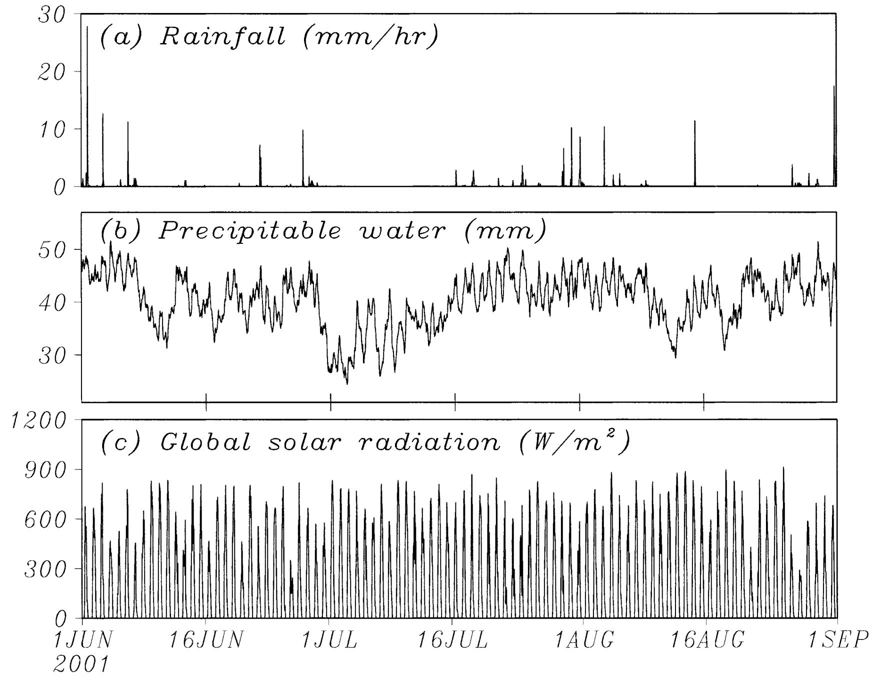

FIG. 3. Time series of (a) hourly rainfall, (b) GPS-sensed PW, and (c) global solar radiation observed at Koto Tabang during the period from 1 Jun to 31 Aug 2001.

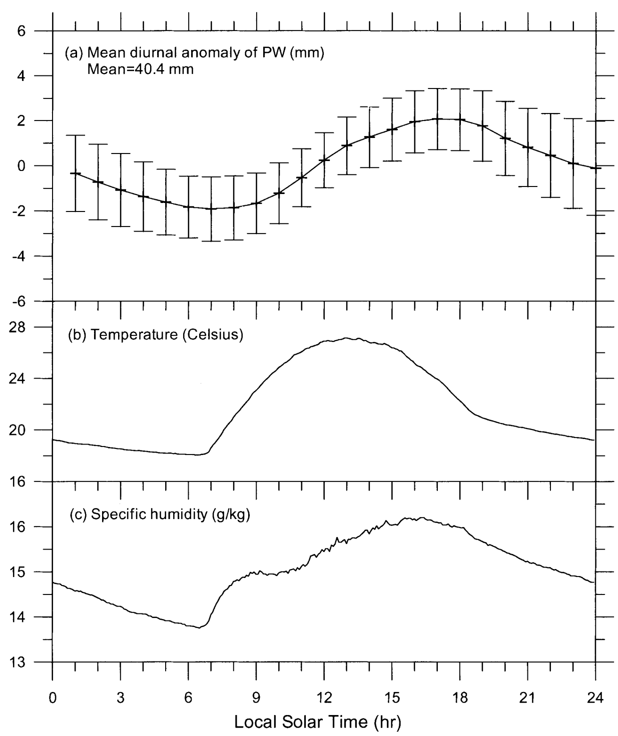

FIG. 4. Three-monthly mean diurnal variations of (a) GPS-sensed PW, (b) temperature observed at a level of 1.5 m, and (c) specific humidity observed at a level of 1.5 m. The error bars indicate one standard deviation of the day-to-day variation.

complex mountainous topography surrounding Koto Tabang may cause a high spatial variability in water vapor. This spatial variability may add more scatter to the GPS–radiosonde comparison.

3. Results and discussion

Figure 3 shows the time series of rainfall, precipitable water, and the global solar radiation observed at Koto Tabang from 1 June to 31 August 2001. The rainfall and solar radiation data were averaged to 1-h means from data obtained at 1-min intervals, and precipitable water data were averaged to 1-h means from data at 5-min intervals.

The variation of precipitable water is very large, ranging from 25 to 52 mm at Koto Tabang during the observation period. Rainfall is observed frequently in this period. Most of the rainfall occurs as intensive showers in the late afternoon with a time period of less than 1 h. The daily maximum of the global solar radiation was 600–800 W m^{-2} on most days, although occasionally maximum values of less than 300–400 W m^{-2} were recorded.

Three-monthly mean diurnal variations of precipitable water estimated from GPS, temperature, and specific humidity observed at a level of 1.5 m are shown in Fig. 4. The air temperature increases rapidly from about 0630 local solar time (LST) immediately following sunrise and reaches a maximum of 27°C at around 1300 LST. Specific humidity also abruptly increases from about 0630 to about 0900 LST, and then the rate of increase is reduced. The starting time of the abrupt increase of specific humidity is almost the same as that of air temperature; the increase is due to solar heating of the land surface, which causes evaporation of water from the surface. The reduction of the rate of increase in surface specific humidity about 2 h after sunrise is attributable to the vertical mixing of water vapor caused by development of the turbulent mixed layer. These processes will be discussed in a following section using radiosonde observation data (see Fig. 6 below).

The mean precipitable water shows a clear diurnal cycle. The minimum and the maximum of precipitable water appear at around 0600 and 1700 LST, respectively. The average increment in precipitable water is 4.0 mm during the period from the morning to late afternoon. The moisture may be transported from lower levels by the daytime upslope winds. Chen and Wang (1994) studied the diurnal variation in the surface thermodynamic field over the island of Hawaii. They found that large positive mixing-ratio anomalies exist on the slope over the entire island. These positive anomalies on the slope are caused by the development of the daytime upslope flow that brings low-level moisture to higher elevations.

The increase of precipitable water during daytime and its maximum value in the late afternoon are consistent with the results of a numerical model study simulating the thermally induced local circulation by Kimura and Kuwagata (1995). Their simulation indicates that the total amount of water vapor transported to the mountainous areas depends on the horizontal scale of the mountains. The largest amount of water vapor should be accumulated over the mountains in the late afternoon when the horizontal scale is about 100 km, which is close to the east–west scale of the Barisan Mountains on Sumatra Island. Over mountains smaller in horizontal scale, the maximum will appear earlier and the amplitude will be smaller.

Sasaki and Kimura (2001) examined the PW data obtained at 10 GPS stations in the major mountain ranges around the Kanto plain in Japan on five fine, clear days in the summer of 1996 and 1997. In their analysis, precipitable water shows a clear diurnal cycle, with an amplitude of about 6 mm. They discussed the mechanism of the diurnal cycle of PW by comparing it with the evolution of surface wind systems and concluded that the main reason for the clear diurnal cycle is the convergence of lower-layer wind systems generated by the heating of the mountains.

The phase of the diurnal cycle in valleys is very different from that in mountains. Takagi et al. (2000) reported the diurnal variation of PW at Lhasa, located in a deep valley on the Tibetan plateau, during the premonsoon and monsoon seasons. The daily maximum appears at midnight and the minimum appears at 1800 LST, almost the reverse of the diurnal cycle over mountains.

Because the meteorological and geographical conditions around Koto Tabang are similar to those of the mountains around the Kanto plain, we conclude that the increase of precipitable water at Koto Tabang during daytime is likewise caused by transport of water vapor from the plains or the ocean by thermally induced local circulations.

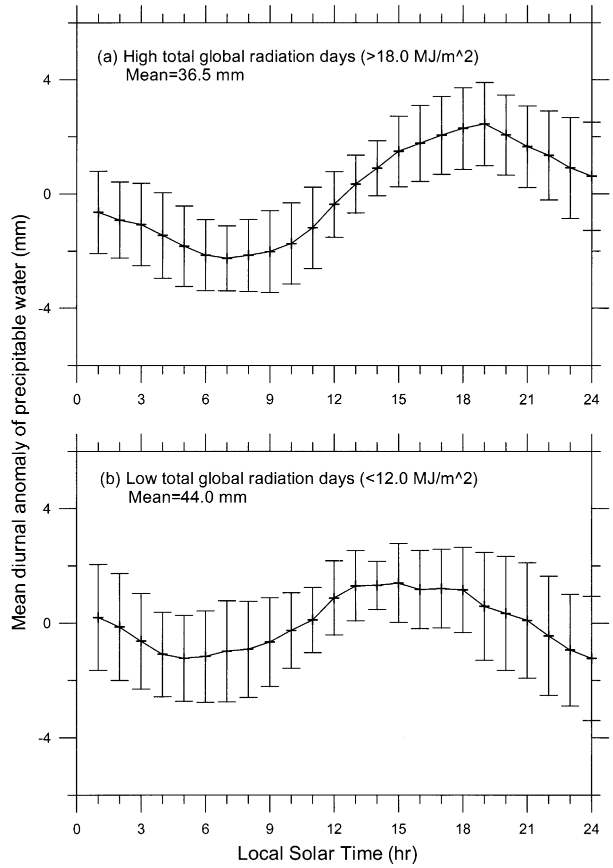

FIG. 5. Mean diurnal variations of GPS-sensed PW on high (>18.0 MJ m^{-2}; 27 days) and low (<12.0 MJ m^{-2}; 15 days) total global radiation days. The error bars indicate one standard deviation of the day-to-day variation.

Figure 5 shows the mean diurnal variation of precipitable water for days categorized by high and low total global solar radiation, greater than 18.0 (Fig. 5a) and less than 12.0 MJ m^{-2} (Fig. 5b), respectively. The lower global solar radiation category corresponds to sky conditions characterized by thicker and/or spatially extensive clouds. These figures indicate that the amplitude of PW is smaller in the case of lower levels of total global solar radiation.

Although the difference in the starting time of the increase in precipitable water between low and high total global radiation days is very small, the daily maxima appear at different times in these two cases, that is, at about noon on low-radiation days and at about 1900 LST on high-radiation days.

Weaker solar radiation reduces not only the intensity of the thermally induced local circulations but also their thickness, so that the convergence of the low-level winds around the mountains, that is, anabatic winds, is reduced. Stronger solar radiation enhances the intensity and thickness of local circulation, especially with respect to the larger horizontal-scale circulations, which would sustain the low-level convergence until the late afternoon.

Surface moisture observations and GPS-derived precipitable water cannot provide a measure of the vertical variation of water vapor, but radiosondes can give profiles of both temperature and water vapor. Figure 6 shows profiles of potential temperature and specific humidity during a strong radiation day (12 August 2001, for which the total global solar radiation is 23.1 MJ m^{-2}) and a weak radiation day (26 August 2001, for which the total global solar radiation is 9.3 MJ m^{-2}) at Koto Tabang. At 0700 LST on both of these days, the potential temperature increases with height through all levels. The specific humidity at the surface is about 13.0 g kg^{-1} and decreases rapidly with height.

On the weak radiation day, the depth of the mixed layer is only about 500 m, about 1300 m MSL (above mean sea level). Specific humidity at 1300 is larger than that at 0700 LST at levels lower than 3000 m MSL. By 1900 LST, however, it decreases and achieves similar values to those at 0700 LST. In a deep layer above the mixed layer, the humidity is higher than in the morning. The reason for this variation in humidity above the mixed layer is unclear. Deep convection near the observing station may contribute to moisture in the upper layer.

On the strong radiation day (12 August 2001), the depth of the mixing layer is more than 1000 m at 1300 LST and the top of the mixed layer is at nearly 2000 m MSL. The potential temperature is almost vertically uniform because of the strong turbulent mixing. Moisture is also mostly vertically uniform throughout the mixed layer. At 1300 LST, specific humidity near the surface is lower than that observed at 0700 LST, because of transport of water vapor to the upper layer by turbulent mixing. Water vapor evaporated from the surface has been transported to the upper atmosphere. Despite a decrease in the lower-layer moisture, the total amount of moisture throughout the mixed layer, from about 1000 to 2000 m, increases considerably, which means that PW is also increasing.

At 1900 LST, the specific humidity has increased remarkably, even over the mixed layer, although the humidity profile has a large vertical variation in contrast to that in the mixed layer. The humid layer extends up to an altitude of about 2800 m. It is obvious that the moisturization above the mixed layer is not due to vertical turbulent diffusion but may be caused by advection from the moist region above higher mountains located somewhere around the observing point. Similar moisturization has been observed above the northern mountain range of the Kanto plain by frequent sounding with radiosondes, as reported by Kimura et al. (1997). They found that the humidity above the mixed layer shows a clear diurnal cycle with a maximum in the evening and concluded that this cycle is a result of moisture advection by thermally induced local circulations.

Figure 7 shows the time–height cross section of specific humidity observed at Koto Tabang during the period of 1–27 August 2001. Near the surface, specific humidity varies from 11.3 to 17.5 g kg^{-1} during the observation period. Clear diurnal variations are often observed in specific humidity, with maxima in the late afternoon. The 9.0 g kg^{-1} contour in specific humidity exceeds an altitude of 3 km in the late afternoon on most days. The increase in humidity associated with the diurnal cycle can be seen even up to 5–6 km during the period of 1–7 August.

Figure 8 shows the mean diurnal variations of GPS-derived precipitable water on days with heavy rain (10 days on which daily total precipitation is larger than 10.0 mm) and days without rain (49 days) during the period from 1 June to 31 August 2001. The figure shows that the amplitude of precipitable water on days with heavy rain is larger than that on days without rain. Meanwhile, the maximum in precipitable water on days with heavy rain appears 1–2-h later than that on days without rain.

Because cloud activities tend to be very strong on days with heavy rain, one might expect that thermally induced local circulations would be reduced and that the diurnal variation in PW would be suppressed on these days. However, these figures suggest that clouds and precipitation do not prevent the diurnal cycle of PW in the Koto Tabang area. On these days, rainfall often occurs as intensive showers within a short time period of less than 1 h in the late afternoon and early evening. As a consequence, the daily total shortwave radiation is still sufficiently strong to generate local circulations and to induce large diurnal variation in precipitable water, even on days with heavy rain.

The rainfall often occurs in the late afternoon and early evening because heating from the surface of the earth and moisture supplied by the local circulations reduce moist static stability over Koto Tabang. Because the latter occurs only over mountains, rainfall due to deep convection is limited in mountainous areas. Deep convection causes a strong convergence in the lower layer and sustains moisture in the atmosphere, so that high precipitable water in these areas will be retained during rainfall. Therefore, the amplitude of precipitable water on days with heavy rain is larger than that on days without rain. The maximum in precipitable water on days with heavy rain appears 1–2-h later than that on days without rain.

4. Summary

This paper investigates the diurnal variations in atmospheric water vapor at Koto Tabang, a mountainous area of Sumatra Island, in the dry season from June to August of 2001 on the basis of GPS-derived precipitable

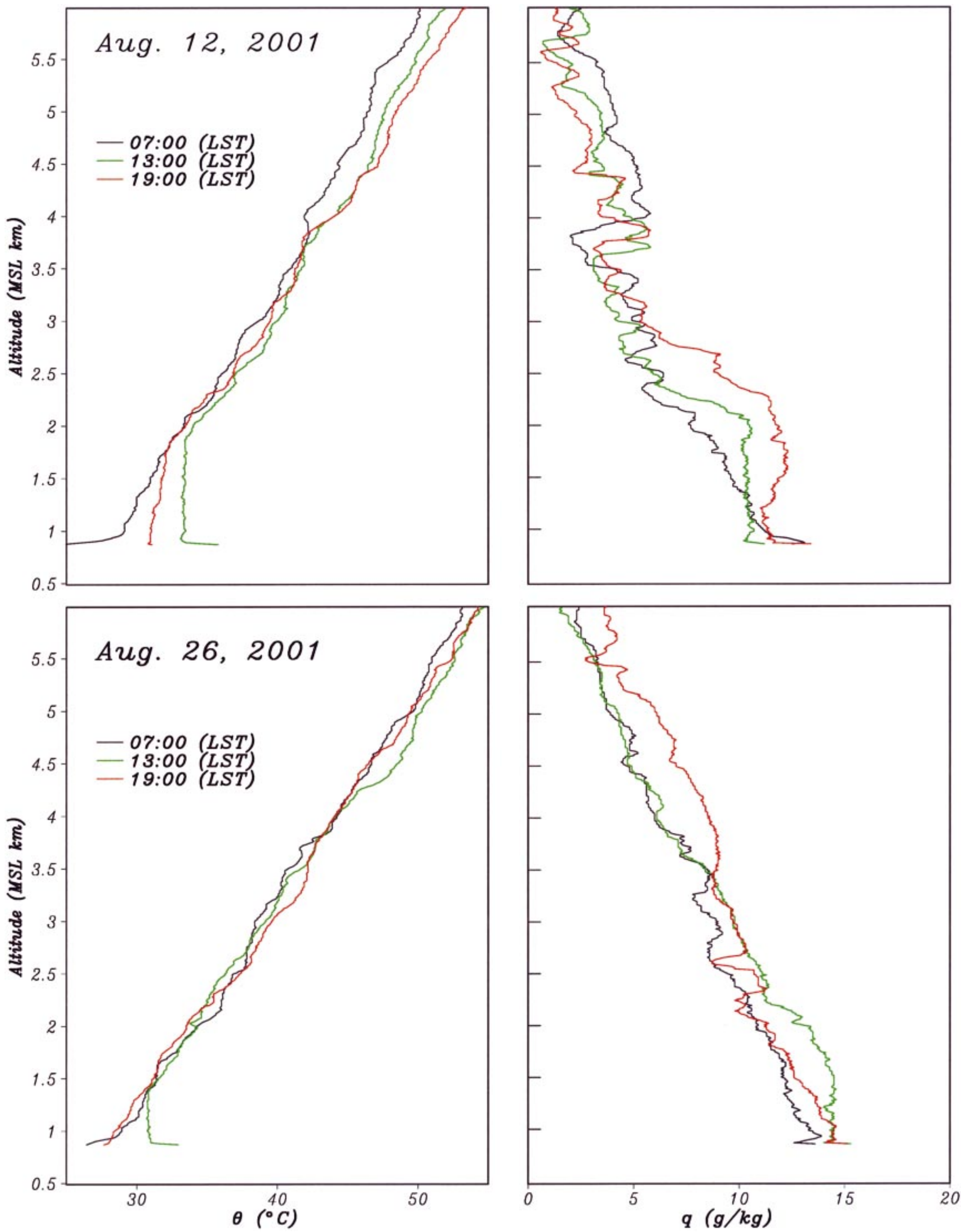

FIG. 6. Diurnal variation in the vertical profiles of (left) potential temperature and (right) specific humidity observed at Koto Tabang on 12 Aug 2001 (a fine-weather day) and 26 Aug 2001 (a cloudy day). The altitude of the land surface is indicated at the bottom of the profiles.

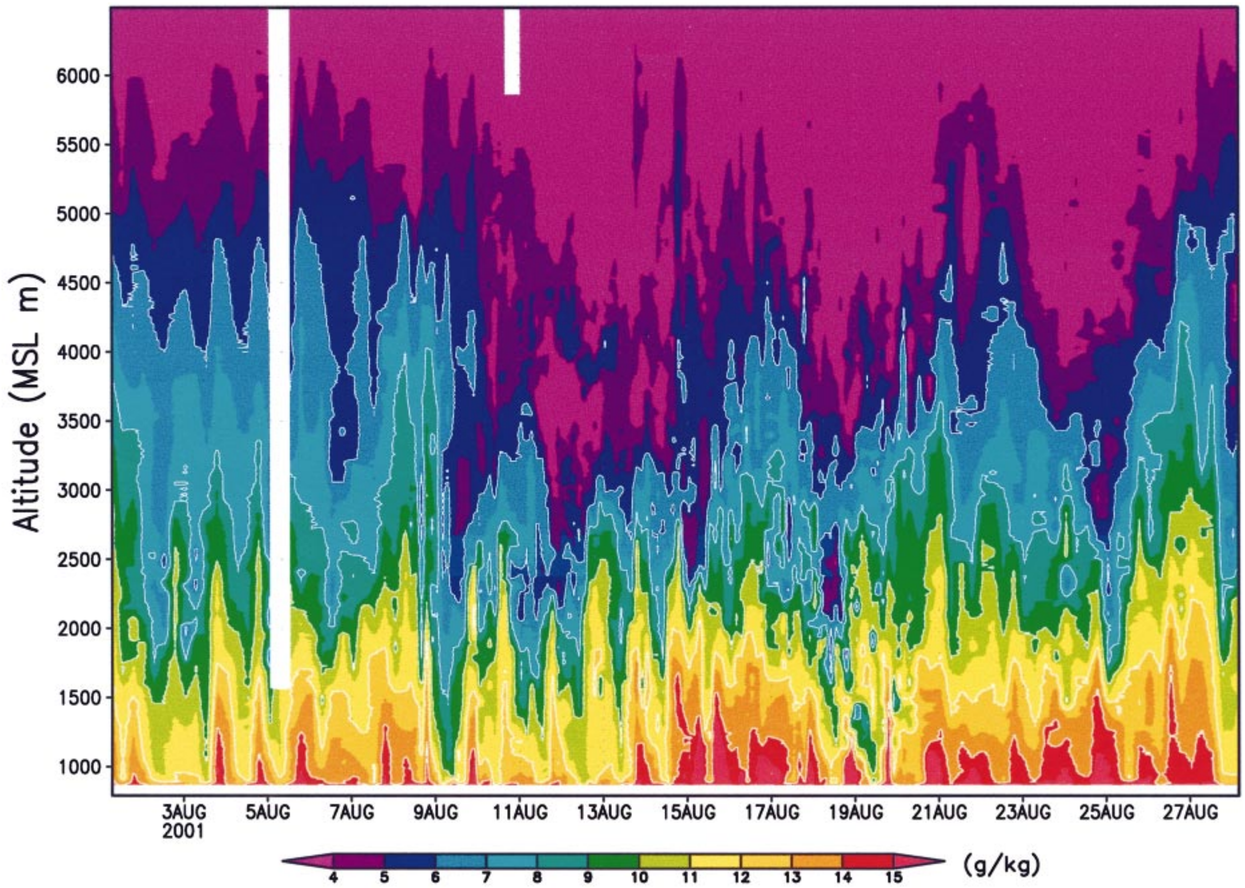

FIG. 7. Time–height cross section of specific humidity observed by radiosonde at Koto Tabang during the period of 1–27 Aug 2001.

water, radiosonde, and surface meteorological observation data.

A distinct diurnal variation in water vapor is observed. Precipitable water increases during daytime, reaching its maximum in the late afternoon at about 1700 LST. The diurnal variation of water vapor occurs up to an altitude of nearly 3 km, concurrent with the development of the mixed layer in the afternoon. The amplitude of the diurnal cycle of the local circulation and precipitable water depends on the intensity of incident solar radiation at the surface. The amplitude of PW is smaller on the days of lower total global solar radiation. Considering that the east–west width of the Barisan Mountains on Sumatra Island is about 100 km, the increase of precipitable water during daytime and its maximum value in the late afternoon are consistent with the results of a numerical model study simulating the thermally induced local circulation. These results suggest that the diurnal variation of water vapor is caused by the transport of water vapor by thermally induced local circulations.

The diurnal range of the precipitable water on days with heavy rain is larger than that on the days without rain. Rainfall often occurs as intensive showers during a short period in the late afternoon and early evening in the Koto Tabang area, and daily shortwave radiation is still sufficiently strong to generate the local circulations and to induce large diurnal variation in precipitable water, even on days with heavy rain. In these cases, deep convection may cause a strong convergence in the lower atmosphere.

The hydrological cycle should have seasonal and interannual variation, which play an important role in the atmospheric water and energy cycles in the Maritime Continent of Indonesia. The relationship between the diurnal cycle and seasonal and interannual variation is an important issue to be studied in the future. We performed radiosonde observations eight times per day at Koto Tabang in the intensive observation periods in May, August, and November of 2001. The water transport processes and structure of the planetary boundary layer will be investigated in a longer timescale using these observation data.

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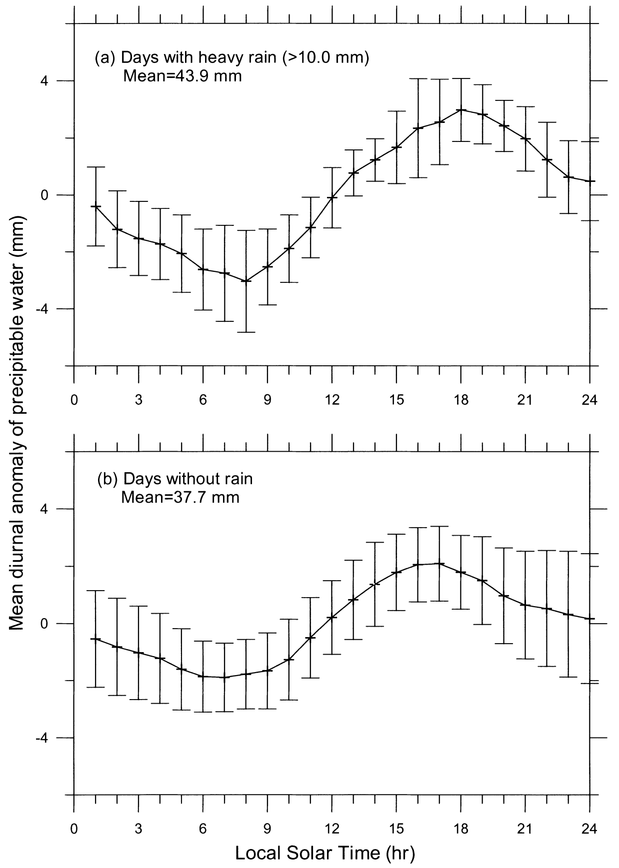

FIG. 8. Mean diurnal variations of GPS-sensed precipitable water on days with heavy rain (total precipitation $>$ 10.0 mm; 10 days) and days without rain (49 days) during the period from 1 Jun to 31 Aug 2001. The error bars indicate one standard deviation of the day-to-day variation.

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