Observational Study on the Diurnal Variation in Precipitable Water Associated with the Thermally Induced Local Circulation over the “Semi-Basin” around Maebashi using GPS Data

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(Manuscript received 20 November 2000, in revised form 28 June 2001)

Abstract

The processes associated with the diurnal variation of precipitable water over the “semi-basin” were studied using GPS and radiosonde data. Precipitable water over the semi-basin exhibited a pronounced diurnal variation, with a maximum around 18–20 JST and a diurnal range of 10 to 25 mm. The variation of precipitable water agreed well with the variation of ESE component of the surface wind, due to a thermally induced local circulation. The diurnal variation of water vapor was recognized in two different layers of Layer L (surface to 1.5 km), and Layer H (1.5 km to 3.0 km).

In the increasing period (09:00 to 20:00 JST), precipitable water increased simultaneously all over the south part of the mountains in the north Kanto District. The variation of precipitable water in the Layer L would be, in large part, controlled by convergence of surface wind. Furthermore, the amount of water vapor in Layer H over the semi-basin that is located on the lee side of mountains increased abruptly from evening to midnight. It was expected that the water vapor that had been transported into the mountains due to the thermally induced local circulation traveled into the semi-basin by ambient wind and/or return flow, and the moisture advection caused the increase of water vapor in Layer H over the semi-basin.

In the decreasing period (21:00 to 08:00 JST), precipitable water decreased simultaneously all over the GPS network using the present study. The decrease in water vapor coincided with increase in potential temperature in the Layer H. The large scale subsidence due to the Pacific High seemed to be necessary for the prominent diurnal variation of precipitable water over the semi-basin.

1. Introduction

The “semi-basin” refers to the area around Gunma University (GUNU), which is surrounded by mountains to the east, north and west directions, and the Kanto Plain in the southeast direction (see Fig. 1). In a region of such topographical contrast, there is often a thermally induced local circulation, which has a large influence on

the diurnal variation of the wind, water vapor, and convective activity. Precipitable water at GUNU, located in the center of the semi-basin, exhibits a pronounced diurnal variation with an evening maximum in summer sunny days (Iwasaki and Ohbayashi 1998; Iwasaki 1999). Besides the precipitable water, convective activity also exhibits a pronounced diurnal variation in the semi-basin. The local precipitation, corresponding to cumulonimbus clouds, reaches a maximum strength at about 20 JST (=11 UTC), which is a few hours later than the adjacent mountains (Fujibe 1988; Misumi 1999). The time of the convective activity maximum is close to the time of the precipitable water maximum.

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The variation of water vapor is expected to have a strong influence on the convective activity because the water vapor is an energy source of convective clouds. Iwasaki and Ohbayashi (1998) suggested that the dry atmospheric condition in the morning prevented deep convections in the afternoon over the semi-basin, when the diurnal variation of precipitable water dominated. Moisture transport due to the thermally induced local circulation seems to influence the cumulonimbus activity over the mountains in the central Japanese Islands and the northern Kanto District (Kuwagata 1997; Iwasaki 1997). As for the smaller scale, Kimura (1994) suggested diurnal variation of sunshine duration over the basin was controlled by the redistribution of water vapor associated with the thermally induced local circulation. The aspects of diurnal variation depended on the topographical features and its scale. Thus, redistribution of water vapor due to the local circulation is very important for the evolution of shallow and deep convections.

However, even the fundamental features of the diurnal variation of precipitable water and the process of redistribution of water vapor have not been studied using observational data, because ordinary observational data of water vapor are not sufficient in spatial and temporal resolution to elucidate the whole aspect of the diurnal variation of water vapor. We will adopt GPS (Global Positioning System) data provided by the Geographical Survey Institute (GSI) to obtain precise horizontal distribution of precipitable water (PW), with high temporal and spatial resolution. Since the vertical profile of water vapor cannot be obtained by GPS data, radiosondes are launched every 3 to 6 hours for two days. Using the horizontal distribution and vertical profiles of water vapor, we will reveal the features of the diurnal variation of precipitable water over the semi-basin. One of the purposes of this paper is to elucidate the whole aspect of the diurnal variation of the horizontal and vertical distribution of water vapor around the semi-basin using GPS and radiosonde data.

Kimura and Kuwagata (1995) elucidated the fundamental features of moisture transport over the large topographical contrast using a 2-dimensional numerical model. Takagi et al. (2000) and Kuwagata et al. (2001) also indicated the prominent diurnal variation of precipitable water observed at Lhasa and Amdo located in the bottom of a wide and deep valley in the central Tibetan Plateau. Kuwagata et al. (2001) concluded that the day-

time decrease of precipitable water in the valley, and the daytime increase of precipitable water over the mountains, could be accounted for by the moisture transport due to the thermally induced local circulation using the theory of Kimura and Kuwagata (1995). As for around the semi-basin, Iwasaki (1999) showed the time change in distribution of precipitable water over the Kanto District using twice daily split-window data of the NOAA Satellite. Kimura et al. (1997) also indicated the variation of the vertical profiles of water vapor and potential temperature at GUNU and Marunuma (see Fig. 1). These results were consistent with the theory of Kimura and Kuwagata (1995). However, to put it in an extreme way, their 2-dimensional numerical model assumes an ideal basin. The semi-basin in the analysis region faces a plane in the southeastern direction, which is different from the topography in the numerical model. It is an interesting problem to investigate the effects that were derived from the difference in the topographical features. Therefore, another purpose of this paper is to discuss the process of the diurnal variation of precipitable water peculiar to the semi-basin using the precise GPS-PW with high temporal, and spatial resolution.

2. Data and observation

Among the data used in this paper are GPS, radiosonde and surface meteorological data. The following are properties of the data.

2.1 GPS data

The number of GPS sites over the analysis region is more than 260 (see Fig. 4), and elevations of all GPS sites are lower than 1,500 m, so that there is no data in the mountainous region. Most GPS data used in this paper were provided by GSI. The GPS precipitable water (GPS-PW) is estimated from the values of the total zenith delay of the GPS signal, using measurements of surface temperature and pressure (Bevis et al. 1992; Businger et al. 1996). The total zenith delay of the GPS signal is directly calculated from the GPS data every 30 minutes with the use of Bernese GPS software Version 4.0. The surface temperature and pressure at each GPS site were interpolated from the data of surrounding meteorological observatories of Japan Meteorological Agency (JMA). The rms error of GPS-PW is about 2.0 mm in comparison with radiosonde, or water vapor radiometer (e.g., Iwasaki et al. 2000; Ohtani and Naito 2000; Shoji et al. 2000).

Fig. 1. Location of the sonde sites and the GPS sites except for GSI network. The elevation is indicated by the degree of shading. The contours are 0.5, 1.0 and 2.0 km, respectively.

Besides the GSI network, 5 GPS receivers were installed at important points to elucidate the water vapor variation over the semi-basin, and these GPS sites are indicated in Fig. 1. HARU is located near the mountain top of Mt. Haruna. The distance between HARU and GUNU is only 14 km, while the difference in latitude is roughly 1,000 m. The information on vertical transport of water vapor will be obtained by comparing the water vapor values at the two GPS sites.

2.2 Radiosonde and surface meteorological data

Radiosondes were launched at GUNU and Maru-numa every 3 to 6 hours from July 30 to August 1 in 1999. In addition to these observations, sonde data at Tateno and Hamamatsu (see Fig. 1) were also used to discuss the source of water vapor above the mixing layer.

Surface meteorological data were observed in the Maebashi meteorological observatory located about 2 km south of GUNU, and the Automatic Meteorological Data Acquisition System (AMeDAS) of JMA.

3. Outline of the diurnal variation of precipitable water during the analysis period

3.1 Synoptic scale and mesoscale situation

In advance of the analysis over the semi-basin, some features of the synoptic and mesoscale situation and an outline of the diurnal variation of precipitable water during the analysis period will be described. Figure 2 shows the time series of GPS-PW at KIZA, GUNU, KURA and HARU located in the semi-basin (see Fig. 1), and the surface wind at Maebashi meteorological observatory located about 2 km south of GUNU. Precipitable water from the four GPS sites exhibits a pronounced diurnal variation with similar phase from 00 JST July 30 to 00 JST August 3, even though the difference of height between HARU and GUNU is about 1,000 m. This suggested that the time variation of water vapor occurred simultaneously in the boundary layer over the semi-basin. We will focus on this period in this paper.

Figure 3a shows a synoptic weather chart at 09 JST on July 31 1999. The Japanese Islands were covered by the western part of a Pacific High, under which clear skies prevailed (Fig. 3b). Figure 3c shows the distribution of surface wind. A sea breeze developed over the coastal region and the wind vectors over the interior were directed toward the mountains. As shown in Fig. 3b, cumulus clouds had developed over the mountains. These are typical features of the thermally induced local circulation over the central Japanese Islands (e.g., Fujibe and Asai 1979; Kuwagata 1997).

In the analysis period, convective activity would be suppressed by the Pacific High. The number of grids (5 km $\times$ 5 km) exhibiting a rain intensity of more than 10 mm/hr were only 63 in the hourly radar-AMeDAS composite chart over the analysis region throughout the analysis period. All of these intense rain were observed far from semi-basin, and according to AMeDAS surface wind, the typical local circulation was well recognized around the semi-basin. Therefore, the mesoscale circulation associated with cumulonimbus-cloud groups did not modify the distribution of water vapor. In other words, it is easy to extract the mesoscale variation of precipitable water associated with the local circulation.

Fig. 2. Time series of the surface wind at Maebashi and GPS precipitable water at GUNU, KIZA, HARU and NAKA:

(a) to (b) Surface wind at Maebashi meteorological observatory of JMA

(c) ESE component of surface wind at Maebashi and GPS precipitable water at GUNU

(d) GPS precipitable water at KIZA, HARU and NAKA

Arrows indicate the time of abrupt increase in the ESE component of surface wind at Maebashi.

Fig. 3. Synoptic and mesoscale situations
 (a) Synoptic weather chart at 09 JST July 31 1999
 Contour interval is 4 hPa and a closed circle indicates the location of GUNU.
 (b) Typical visible imagery from GMS at 15 JST July 31
 White frame indicates the analysis region.
 (c) Distribution of AMeDAS surface wind at 15 JST July 31
 The elevation is indicated by the degree of shading. Contours are 1.0, 1.5, 2.0, 2.5 and 3.0 km, respectively.

3.2 Distribution of mean GPS-PW over the analysis region

Figure 4 shows the distribution of the mean GPS-PW for the analysis period. GPS sites located near the mountains exhibit low precipitable water due to high elevation. High GPS-PW areas extend over the coastal regions around Hamamatsu and the northern Niigata Plain. In spite of coastal regions, the mean GPS-PW over the southeastern to northeastern Kanto Plain is relatively low.

There is a remarkable area where the mean GPS-PW exceeded 37 mm in the interior ("H" in Fig. 4). This high GPS-PW area was recognized every day throughout the analysis period, in a greater or lesser degree. Iwasaki (1999) also indicated a similar maximum area nearby this area using satellite-derived precipitable water. In the previous studies, distinct behavior of cumulonimbus clouds were de-

scribed nearby this area; a lot of damage to crops due to large hail and strong gust were concentrated in the western part of this area (Yoshino et al. 1987), and isolated hailstorms tend to form into squall lines from 17 to 21 JST in this area (Iwasaki and Ohbayashi 1998).

3.3 Features of diurnal variation of GPS-PW over the analysis region

a. Amplitude of the diurnal variation of GPS-PW

Figure 5 indicates the time series of the GPS-PW averaged over the analysis region, excluding the mountainous region denoted as the black area in Fig. 4. The diurnal variation of precipitable water prevailed not only over the semi-basin, but over the analysis region as well, with a maximum at about 19–21 JST and minimum at about 09–10 JST on average, with an amplitude of 4 to 9 mm. The phase of the GPS-PW averaged over the analysis region is similar to the phase of GPS-PW for each site over the semi-basin as shown in Fig. 2.

Fitting the time series of GPS-PW of each site to a sine curve with a period of 24 hours using a least square method, we obtain the distribution of the amplitude and the time that precipitable water reached a maximum ($T_{\max}$) over the analysis period, as shown in Fig. 6a and 6b, respectively. The amplitude over the coastal region adjacent to the Pacific Ocean is relatively lower, values less than 3.0 mm extend over the southeastern Kanto Plain.

On the other hand, the coastal region adjacent to the Japan Sea and the interior tends to exhibit values larger than 5 mm. Two distinct areas, over the semi-basin and northern slope of the mountains to the north of the Kanto District, exhibit values greater than 7 mm in the average. As shown in

Fig. 4. Distribution of mean GPS precipitable water for the analysis period.

Small open circles indicate the GPS sites used in this paper. The shaded areas and the symbol "H" indicate the mountainous region higher than 1.3 km and high GPS-PW area in the interior, respectively.

Fig. 5. Time series of GPS precipitable water averaged over the analysis region.

Precipitable water over the mountainous region higher than 1.3 km, denoted as black area in Fig. 4, were excluded because of the absence of GPS sites.

Fig. 6. Characteristic features on the diurnal variation of precipitable water during the analysis period (00 JST July 30 to 24 JST August 3 1999). Black areas indicate the mountainous regions higher than 1.3 km. Open circles indicate the GPS sites.

(a) Distribution of the amplitude of diurnal variation of GPS-PW over the analysis region.

(b) Distribution of the time that precipitable water reached to maximum. The region where the amplitude is smaller than 3.0 mm is shaded dark gray.

Fig. 3c, it is expected that the convergence of surface winds corresponds to the local circulation over these two areas in the afternoon.

b. Phase of the diurnal variation of GPS-PW

Figure 6b shows the distribution of $T_{\max}$. Since most GPS sites where the amplitudes are larger than 3 mm exhibit a maximum of GPS-PW during 18–21 JST, the evening maximum of precipitable water is a common feature over the most of the analysis region. Comparing of $T_{\max}$ with the amplitude of GPS-PW, no correlation could be found over the analysis region. The phase of the diurnal variation would be independent of the amplitude.

GPS-PW over the northern parts of the Niigata Plain reached a maximum in the middle of the night. The phase of the diurnal variation seems to have propagated from the mountains down to the Niigata Plain, and this direction is similar to the

wind direction in the 1.0 to 3.0 km layer observed at GUNU, Hamamatsu and Tateno at 21 JST (see Fig. 10 and Table 2). Horizontal advection of water vapor might contribute to the diurnal variation of water vapor in this region.

4. Two layers relevant to the diurnal variation of precipitable water

In this section, characteristics of profiles of water vapor will be described. Figure 7 shows the time series of water vapor amount integrated every 0.5 km from surface at GUNU using sonde data for two days. Because the amount of water vapor above 3.0 km does not exhibit periodic variation, we conclude that the diurnal variation occurred from the surface to 3.0 km. The pronounced diurnal variation is recognized from 1.5–3.0 km, with a maximum at 21–24 JST. In spite of low specific humid-

Fig. 7. Time series of water vapor amount every 0.5 km layer at GUNU.

Water vapor amount in each layer is integrated every 0.5 km from the surface using sonde data.

ity, its range is 3 mm just above the mixing layer of 1.5–2.0 km. As for the lower layer, the diurnal variations become less pronounced and ranges lessen in lower height.

Figure 8 shows an example of the time change in the profiles of specific humidity, and potential temperature, at GUNU in the increasing and decreasing periods. When the mixing layer is well developed from 0.5 km to 1.3 km, the amount of water vapor from the surface to 1.5 km increase from 09 to 12 JST (A to B in Fig. 8a). After that, the amount of water vapor from the surface to 1.5 km, and the specific humidity in each level was held almost constant (B to C in Fig. 8a). A remarkable increase in water vapor occurred in the level of 1.5 km to 3.0 km at 21 JST (B to C in Fig. 8a), which was several hours later than that in the lower layer. Since the top of the mixing layer can be defined at 1.3 km clearly by the specific humidity and potential temperature, the increase of water vapor was not caused by vertical moisture transport due to dry convection.

As for the decreasing period of GPS-PW, the layer between 1.8 km to 4.0 km became remarkably dry at night and it did so a few hours earlier than that in the lower layer. In marked contrast to that, water vapor was increasing from the surface

Fig. 8. Time change in the vertical profiles of mixing ratio and potential temperature in the increasing and decreasing periods.

Arrows indicate the spiky increase of water vapor in Level H. Observation times A to D are following; A: 08:27 JST July 31, B: 11:25 JST July 31, C: 20:26 JST July 31, D: 02:28 JST August 1.

to 1.5 km (C to D in Fig. 8c). Thus, variation of water vapor was quite different in two layers, which implies existence of two distinct mechanisms for the two layers. In this paper, for convenience sake, these two layers are referred to as Layer L (surface to 1.5 km) and Layer H (1.5 to 3.0 km).

5. Increasing period of precipitable water over semi-basin

5.1 Spatial correlation in the increasing period

It is an interesting problem in what area of the region will precipitable water increase and decrease with the diurnal variation. We will examine the spatial correlation of GPS-PW in the increasing

Fig. 9. Distribution of the correlation coefficient of GPS-PW in the increasing period (a: 09:00 to 20:00 JST) and decreasing period (b: 21:00 to 08:00 JST). The reference point is GUNU, denoted by a closed circle.

period (09:00–20:00 JST) and decreasing period (21:00–08:00 JST), separately. With the GUNU sonde site taken as a reference point, Fig. 9a shows the spatial correlation in the increasing period. High correlation coefficients of more than 0.8 are recognized in the limited area of the south to mountains in the northern Kanto Plain. This implies that precipitable water over the area increased simultaneously, and the mechanisms for increase in precipitable water depended on the orographic features.

5.2 Two relationships between time change of precipitable water and surface wind

As shown in Figs. 2a and b, surface winds at Maebashi observatory also showed the clear diurnal variation as well as precipitable water at GUNU. When the thermally induced local circulation developed, a ESE wind dominated at Maebashi in the daytime. As the ESE component of the surface wind became gradually strong at 9–10 JST, GPS-PW at GUNU also began to increase. The

ESE component reached a maximum around 17 to 18 JST, and a maximum of GPS-PW occurred about the same time or a few hours later. The diurnal variation of GPS-PW agreed well with the ESE component in the analysis period.

Table 1 shows the correlation coefficient between GPS-PW and the ESE component of the surface wind, the amplitude of the diurnal variation of GPS-PW and $T_{\max}$. It is evident that the correlation coefficients were large on the days in which the amplitude was larger than 6 mm, and precipitable water reached a maximum after 19 JST. In other words, the diurnal variation of precipitable water depended on the ESE component of surface wind when the diurnal variation of precipitable water predominated.

It is noted that GPS-PW exhibited pronounced diurnal variation after 1 August although wind direction remained nearly steady in ESE. This means that the time change of the wind direction is not essential to the diurnal variation of precipitable water, and time change of the ESE component is

Table 1. Correlation between GPS-PW and the ESE component, the amplitude of the diurnal variation of GPS-PW, and $T_{\max}$ at GUNU.

Day (UTC)	27 Jul.	28	29	30	31	1 Aug.	2	3
Correlation	0.03	0.24	0.56	0.84	0.68	0.80	0.74	-0.48
Amplitude (mm)	2.3	2.2	7.6	8.19	4.6	6.6	8.9	4.1
$T_{\max}$ (JST)	12.6	20.8	17.8	18.9	19.3	20.2	19.6	2.0

rather significant for the diurnal variation of precipitable water.

Another correlation between precipitable water and the surface wind is found for a short-time scale. When the ESE component increased in a few hours denoted as "a" to "f" in Fig. 2c and 2d, GPS-PW also increased by 2–3 mm (b and c), or a decreasing rate of GPS-PW was lowered (a, d, e and f). These variations on the short-time scale occurred simultaneously not only at GUNU, near the Maebashi observatory, but also at other GPS sites in the semi-basin. It should be noted that the variation of precipitable water over the semi-basin coincided with the ESE component of surface wind for the diurnal scale and the short-time scale.

5.3 Discussion on the process of increase in precipitable water over the semi-basin

a. Increasing process of water vapor amount averaged over the analysis region

As shown in Fig. 5, the amount of water vapor averaged over the analysis region, excluding the mountainous region, increased from morning to evening. Roughly speaking, the increase of precipitable water is mainly caused by evaporation at the surface and convergence in the lower atmosphere with moisture advection from outside the analysis region.

At first, we will examine the contribution of evaporation at the surface over the analysis region. The diurnal variation of precipitable water prevailed over the analysis period, with a maximum at about 19–21 JST. The increment of the mean GPS-PW was 8 to 17 mm during 10 hours (see Fig. 5). According to observational and numerical studies (e.g., Kondo and Saigusa 1994), evaporation from soil covered by grass is as much as 4–6 mm in the warm season, which is less than the increment of water vapor estimated by GPS data. Although the water vapor evaporated from the surface must contribute to the increment of precipitable water at a considerable level, it is apparent

that the evaporation alone cannot account for the increase of precipitable water.

Secondly, we will examine moisture advection from outside the analysis region. As shown in Fig. 3c, the local sea breeze develops over the coastal regions and the surface wind is directed toward the mountains over the interior from morning to evening. As a result of the sea breeze circulation, it is apparent that convergence in the lower atmosphere occurred over the land, and water vapor also traveled from the ocean over the land at the same time. Since convergence of the water vapor that had already existed over the analysis region did not lead to an increase in water vapor amount over the land, the moisture transport from the ocean caused the increment of the water vapor amount averaged over the analysis region. In addition to the evaporation from the surface, moisture advection can account for the large increment of precipitable water averaged over the analysis region.

b. Increasing process in Layer L over the semi-basin

The variation of GPS-PW over the semi-basin agreed well with the variation of the ESE component of the surface wind (Fig. 2), and the correlation coefficients between GPS-PW and the ESE component exceeded 0.8 on typical days (Table 1). There is no doubt that the variation of precipitable water over the semi-basin was, in large part, controlled by the ESE component of surface wind. Since there are mountains on the lee side of Maebashi, a ESE wind will converge on the windward side of the mountains. As a result of the convergence and dry convection, water vapor seemed to spread into the mixing layer.

As shown in Fig. 8a, the amount of the water vapor from the surface to 1.5 km increased as the mixing layer was developing. However, the top of the mixing layer was defined clearly at a height of 1.3 km (Fig. 8a and 8b), which means that water vapor in Layer L could not be transported di-

rectly into Layer H. Therefore, over the semi-basin, the increase in water vapor due to the convergence of the surface wind and evaporation might be restricted to Layer L.

c. Increasing process in Layer H over the semi-basin

Water vapor is transported from the valley into the mountains due to the thermally induced local circulation (Kimura and Kuwagata 1995). As a result of the moisture transport, water vapor is supplied 1–2 km higher than mountains. Kimura et al. (1997) indicated that the mixing layer at Marunuma located on the mountainside (see Fig. 1) developed up to 4.5 km above sea level (2.5 km above ground level), and this observational result

demonstrates that water vapor can be transported into Layer H over the mountainous region due to the thermally induced local circulation. This process is important for the variation of water vapor in Layer H.

Figure 10 shows the profiles of specific humidity, wind speed and wind direction at GUNU and Hamamatsu at 21 JST on July 30 and 31. On July 30, specific humidity in Layer H over GUNU is larger than it is over Hamamatsu. It is noted that the wind direction in Layer H over GUNU was SW: GUNU is located on the lee side of the mountains. On July 31, a salient profile in the specific humidity denoted by arrows in Fig. 8a and Fig. 10d as observed at height of 1.8 km, where a WSW wind increased abruptly like a jet.

This salient profile in the specific humidity is not exceptional for the analysis period. Similar salient profiles in Layer H were observed from 00 to 06 JST, and 15 to 24 JST on July 31, and were also observed frequently at Marunuma around midnight (not shown). When these salient profiles and/or moisture layers were observed in Layer H at GUNU and Marunuma, the wind direction was always from W to WSW, with the mountainous region always located on the windward side.

It is expected that the water vapor that had been transported into the mountains due to the thermally induced local circulation traveled into the semi-basin by ambient wind, and the moisture advection caused the increase of water vapor in Layer H over the semi-basin. This hypothesis can explain why the water vapor in Layer H began to increase several hours later than it did in Layer L at GUNU.

When the thermally induced local circulation well developed, not only the ESE component of surface wind over the semi-basin, but the moisture transport from the plain to the mountains also increased. Furthermore, moisture advection from the mountains to the semi-basin due to the ambient wind in Layer H was also enhanced. This process would be one of the reasons why the correlation between the ESE component, and GPS-PW is high, as shown in Fig. 2c.

The profile of specific humidity at Tateno, where the amplitude of the diurnal variation of GPS-PW was less than 3 mm, is shown in Fig. 11. In contrast to the semi-basin, Layer H at Tateno was kept dry even at 21 JST. As shown in Table 2, wind direction in Layer H ranges from 200 to 230 degrees. Unlike at GUNU, in the semi-basin the moisture advection in Layer H was not expected because there

Fig. 10. Vertical profiles of mixing ratio, wind direction and wind speed at GUNU and Hamamatsu at 21 JST July 30 and 31.

Arrows indicate the salient increase of water vapor in Level H.

Fig. 11. Vertical profiles of mixing ratio and potential temperature of Tateno at 09 and 21 JST on July 31.

Table 2. Wind direction (WD) and wind speed (WS) at mandatory level at Tateno

Level (hPa)	09 JST 31 July			21 JST 31 July		
	Height (km)	WD (deg)	WS (m/s)	Height (km)	WD (deg)	WS (m/s)
1000	0.13	203	6	0.13	191	10
925	0.82	223	7	0.81	209	17
900	1.05	225	7	1.05	211	14
850	1.55	234	11	1.55	217	11
800	2.07	225	8	2.08	205	7
700	3.20	218	7	3.21	197	9
600	4.47	223	8	4.48	207	8
500	5.92	218	8	5.93	191	8

are no mountains to the windward side of Tateno. This result supports a hypothesis for the increasing process of water vapor in Layer H.

Kimura and Kuwagata (1995) also pointed out that moisture transport above the mixing layer occurred from mountains to the valley due to the return flow of the valley-wind circulation in the late afternoon. This increasing process of water vapor in the valley is similar to the process discussed in this paper. The salient profile in the specific humidity (Fig. 8 and Fig. 10) might be due to the return flow of the valley-wind circulation. However, as shown in Fig. 10 and Table 2, the ambient wind

in Layer H is not weak, so the moisture advection by the ambient wind must be more important for this analysis period.

6. Decreasing period of precipitable water over the semi-basin

6.1 The features on the decrease in precipitable water

Figure 9b shows the spatial correlations in the decreasing period. Over the analysis region, except for the Pacific coast and the northern Niigata Plain, the correlation coefficients are larger than 0.8, and the correlation at most GPS sites is larger than it in the increasing period. It is suggested that the mechanism for the decrease in precipitable water does not depend on the orographic features, on which it depends in the increasing period.

Figures 8c and 8d show the time change in profiles of specific humidity and potential temperature in the decreasing period at GUNU. Specific humidity decreased remarkably at a height of 2.0–4.0 km from 21 JST 31 July to 03 JST 1 Aug (C to D in Fig. 8). It should be noted that the increase in potential temperature by 5 K coincided with the decrease in specific humidity at the same altitude. The coincidence of low specific humidity, and high potential temperature, was also recognized by sonde data at Marunuma (not shown) and Tateno at 09 JST and 21 JST on July 31 (Fig. 11).

6.2 Discussion on the process of decrease in water vapor

a. Decreasing process in Layer H over the analysis region

The coincidence of the decrease in water vapor and increase in temperature (Fig. 8c and 8d), and the high correlation over the majority of the region (Fig. 9b) indicate the existence of a large scale subsidence in middle troposphere. Since the Japanese Islands were covered by the Pacific High when the prominent diurnal variations were observed (see, Fig. 3 a and b), synoptic scale subsidence due to the Pacific High seems to have diminished the water vapor in Layer H, and the resulting dry and warm air might have travelled into the analysis region.

The prominent diurnal variations in Layer H can be explained as follows. If moisture advection did not occur, Layer H is always dry like Tatenosue due to the large scale subsidence. If mountains are located on the windward side, water vapor is transported over the mountains due to the local circulation in the daytime, and then horizontal moist advection by the ambient wind and/or return flow increase the specific humidity in Layer H over the semi-basin from evening to midnight, even though large scale subsidence has been occurring. After the local circulation had ceased, large scale subsidence diminishes water vapor in Layer H again. The large scale subsidence due to the Pacific High seems to be necessary for the prominent diurnal variation of precipitable water over the semi-basin.

b. Decreasing process in the Layer L over the semi-basin

As mentioned above in Section 5.2, GPS-PW over the semi-basin exhibited a pronounced diurnal variation, even though wind direction held constant in ESE after August 1. This means that a local scale mountain-wind circulation in the nighttime is not essential for the decrease of precipitable water. A decrease in the ESE component of the surface wind seems to be the principal factor in

the decrease of water vapor in Layer L. However, it is considered that the mountain-wind circulation transports dry air from the mountain to the plain, so that, a mountain wind might contribute to the decrease in water vapor in Layer L from July 29 to August 1.

7. Discussion on the diurnal variation of precipitable water peculiar to the semi-basin

7.1 Comparison with wide and deep valley in the Tibetan Plateau

The diurnal variation of precipitable water had been studied at Lhasa and Amdo. Both cities are located in a wide and deep valley in the central Tibetan Plateau (Takagi et al. 2000; Kuwagata et al. 2001). Characteristics of the diurnal variation are summarized in Table 3. The diurnal range at Lhasa is very small, because the values are obtained from a 62-day average. A prominent daily diurnal variation was also observed at Lhasa (Kimura 2000: personal communication). Even though the mean precipitable water was little more than 8 mm at Amdo, the daily diurnal range reached as much as 5 mm. The ratio of the diurnal range to the mean precipitable water exceeded 0.65, which is quite larger than that of the present study.

As shown in Table 3, precipitable water at the bottom of the valley reaches a minimum (maximum) at 13–14 LST (24–04 LST), which are 4–6 hours later than in the semi-basin. The time in which precipitable water reaches a minimum at a valley depends on the depth and width of the valley (Kimura and Kuwagata 1995). Kuwagata et al. (2001) concluded that the daytime decrease of precipitable water at Amdo can be explained by the redistribution of water vapor due to the thermally induced local circulation using a 2-dimensional numerical model in which realistic depth and width around Amdo was incorporated.

Table 3. Characteristics of the diurnal variation of precipitable water in a wide and deep valley in the Tibetan Plateau and the present study. Characteristics in Lhasa and Amdo were read from Fig. 4 of Takagi et al. (2000) and Fig. 3 of Kuwagata et al. (2001). Time for Lhasa and Amdo is LST (Local Solar Time).

Site	Diurnal range	Tmin	Tmax	Season
Lhasa (Valley)	1.8 mm	17 LST	04 LST	Premonsoon (62-day average)
	1.3 mm	15 LST	23 LST	Monsoon (62-day average)
Amdo (Valley)	5–7 mm	14–18 LST	23–25 LST	Premonsoon (DOY=165–168)
GUNU (Semi-basin)	10–18 mm	09–10 JST	19–20 JST	Summer (DOY=212–216)

On the other hand, precipitable water in the semi-basin reached a minimum at 09–10 JST. It is very difficult to determine the depth and width of the semi-basin in this study. Assuming 80 km in width and 1 km in depth, according to Kimura and Kuwagata (1995), precipitable water reaches a minimum at about 16 LST, which is 6–7 hours later than the observational results. It is suggested that the effects of large-scale subsidence, and the decrease of the ESE component of the surface wind are significant for the decrease of precipitable water over the semi-basin, rather than the redistribution of water vapor due to the thermally induced local circulation.

7.2 The effect of the semi-basin

A 2-dimensional numerical model of Kimura and Kuwagata (1995) has succeeded in the clarification of the fundamental features of diurnal variation over the wide and deep valley. However, to put it in an extreme way, a 2-dimensional numerical model is assuming the ideal basin. The semi-basin in the analysis region faces the Kanto Plain to the southeast. In this section, we will discuss the topographical effect of the semi-basin.

The variation of precipitable water over the semi-basin in the present study agreed well with the variation of the ESE component of the surface wind. The variation of precipitable water over the semi-basin is considered to be controlled by the ESE component of the surface wind. If there were mountains to the southeast of the semi-basin around Maebashi like there are in an ideal basin, the ESE wind due to the thermally induced local circulation would not converge over the semi-basin, because a mountain barrier to the southeast would be an obstacle to the penetration of the surface wind.

Besides the moisture advection from mountains in Layer H, the convergence of the surface wind also plays a key role in the diurnal variation of precipitable water over the real semi-basin. When convergence of the surface wind occurs, it is easy to increase the water vapor in the mixing layer. The increase of water vapor in the mixing layer works to unstabilize atmosphere from evening to night. In this semi-basin, the local precipitation corresponding to cumulonimbus clouds exhibits a pronounced maximum around 20 JST (Fujibe 1988; Iwasaki and Ohbayashi 1998; Saitoh and Kimura et al. 1998; Misumi 1999), which is a few hours later than it is in the adjacent mountains (Fujibe 1988; Misumi 1999). It is expected that the evening maximum of precipitable water contributed to the

evening maximum of convective activity over the semi-basin. The relationship between diurnal variation of water vapor and convective activity over the semi-basin will be discussed in a forthcoming paper.

8. Summary

The processes of the diurnal variation over the “semi-basin” were studied using GPS and radiosonde data. The results are summarized as follows

- 1) Precipitable water over the semi-basin exhibited a pronounced diurnal variation with a maximum around 18–20 JST, and a range of 10 to 25 mm. Correlation coefficients between the variation of the ESE component of the surface wind associated with the thermally induced local circulation, and the variation of precipitable water exceeded 0.8 when the diurnal variation of precipitable water was pronounced;
- 2) The diurnal variation of water vapor was recognized in the two different layers, Layer L (surface to 1.5 km) and Layer H (1.5 km to 3.0 km);
- 3) In the increasing period (09:00 to 20:00 JST), precipitable water increased simultaneously over the southern mountains in the north Kanto District. It is suggested that the convergence of surface wind is one of factors in the diurnal variation of precipitable water.
Further, the amount of water vapor in Layer H over the semi-basin increased abruptly from evening to midnight, and a significant increase of water vapor was restricted to the sonde sites that were located on the lee side of the mountains. These features suggest that the water vapor had been transported to the mountainous region by the thermally induced local circulation and travelled into Layer H over the semi-basin; and,
- 4) In the decreasing period (21:00 to 08:00 JST), precipitable water decreased simultaneously all over the analysis region, and the decrease in water vapor coincided with the increase in potential temperature in Layer H. These features suggest that a large scale subsidence associated with the Pacific High is a primary factor in the decrease of precipitable water in Layer H.

Acknowledgments

This research was supported by a grant from the GPS/MET Japan (GPS Meteorology Project in Japan) funded by the Science and Technology Agency of Japan. We express our thanks to a staff

member of the Geographical Survey Institute for the supply of the GPS data, and Prof. F. Kimata of Nagoya University for providing GPS receivers. We are indebted to Prof. F. Kimura of University of Tsukuba, Prof. Nakagawa of Joetsu University of Education and their students for assisting our observation.

AMeDAS data and radar AMeDAS composite chart were provided by the Japan Meteorological Agency. GMS imageries were provided by the Center for Environmental Remote Sensing (CERES) of Chiba University.

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