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GPS observations in Thailand for hydrological applications

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We report the delineation of the onset of the Asian Monsoon based on GPS sensing of water vapor in Thailand. We conducted GPS observations at five sites in Thailand since March 1998 under the hydrological project called GAME-T. The objective of the project is to clarify the water and energy cycle system in the Asian Monsoon area. As a preliminary analysis, we used data from March to June 1998 and estimated the water vapor content in the zenith direction (PWV) every 30 minutes using GIPSY software (GPS-PWV). A comparison of the resultant PWV with those estimated from rawinsonde data (Sonde-PWV) suggested that, generally, the long term trends of both GPS-PWV and Sonde-PWV are consistent and a rapid increase of water vapor content is visible in May, which corresponds to the onset of the Monsoon. However, systematic differences between GPS-PWV and Sonde-PWV are eminent. The RMS of the difference (RMSD) between Sonde-PWV and GPS-PWV reaches about 8.7 mm. This large RMSD can be reduced to about 5 mm by removing some unreliable sonde data and making a linear correction to Sonde-PWV. In addition, a comparison of GPS-PWV with other meteorological data (temperature, humidity, and rainfall) showed that there is a strong correlation between a rapid increase of GPS-PWV and heavy rainfall in Bangkok and in Chiang Mai, which may be used to judge the onset of the Monsoon in the area accurately.

1. Introduction

Recently, GPS (Global Positioning System) has been used not only for precise positioning but also in many other fields in Earth science. A sophisticated software system for GPS baseline analysis enables us to estimate tropospheric delays in the GPS signal and minimize positioning errors. The tropospheric delay is then converted into precipitable water vapor at the site, which can be applied to various research fields in the atmospheric sciences. This new research field is conveniently called "GPS Meteorology" (e.g., Bevis *et al.*, 1992, 1994). However, the technique can also be applied to other atmospheric sciences such as climatology or hydrology.

The present study applys GPS techniques in a climatological and hydrological study for the tropical Monsoon area of Thailand and addresses its possible contribution to clarifying the mechanism of the Asian Monsoon, especially the delineation of its onset.

GPS observations in Thailand have been conducted under the auspices of an international project called GAME (GEWEX Asian Monsoon Experiment)-Tropics (hereafter GAME-T). GAME-T mainly targets the water cycle in the tropical monsoon area and Thailand was selected for the field of study. Among various observation programs in the project, GPS and rawinsonde were used for examining spatial and temporal changes of water vapor content over the area.

The present study first examines temporal changes of water vapor in Thailand. We compare temporal changes of the estimated tropospheric water vapor using GPS and rawinsonde data to see if both techniques are compatible and if GPS is capable of detecting the onset of the Monsoon. Then, GPS data are compared with other meteorological data to see if there is any meaningful correlation between them. A brief discussion is added on whether or not GPS can detect the onset (or withdrawal) of the Monsoon accurately, whose prediction and monitoring is especially important from the standpoint of agriculture and thus socio-economic effects in Thailand. This short report first tests if GPS techniques are useful for such hydrological and/or climatological studies.

2. Observation

We established five GPS sites in a large area of Thailand and started observations in March 1998. Selected sites are Bangkok (Code: BNKK), Chiang Mai (CHMI), Ubon Ratchathani (UBRT), Si Samrong (SISM) and Phuket (PHKT). About two months later, the site at Phuket was moved to Nongkhai (NNKI) for a better distribution in the EW direction. Figure 1 shows the locations of sites. We used five dual-frequency GPS receivers (four Trimble 4000SSI and one Trimble 4000SSE); each attached to a microstrip antenna with a ground plane. All of the sessions were 24 hours in length with a 30-second sampling interval and a 5-degree minimum elevation angle. Each session file was downloaded by automatic logging software run on a PC attached to the receivers. Since many of sites were left unattended, the system often suffered from long-term failures with mechanical problems and/or power line failures.

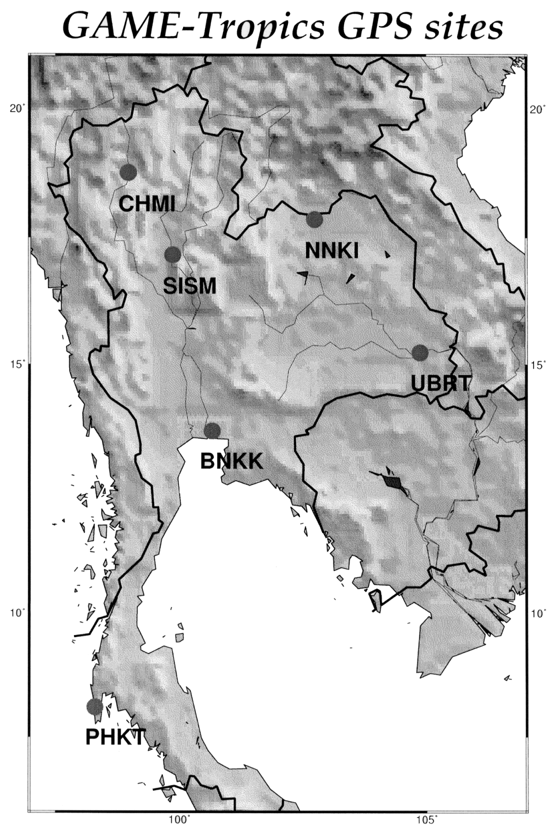

Fig. 1. GPS observation sites in Thailand.

All of the sites were established at meteorological stations where rawinsonde observations and/or other meteorological observations are conducted. A rawinsonde, IS-5A-403AG made by AIR Company, U.S.A., was used for the sonde observations. Since the GAME-T project conducted Intensified Observation Period (IOP) for the period from April 15–June 15 and August 15–September 14, 1998, we were able to use rawinsonde data to compare estimated water vapor content. Sonde observations were conducted four times a day (00, 06, 12, and 18 UTC) with the exception of the May–June period at Nongkhai where only two rawinsonde observations were made. Previous studies have shown that the RMS of precipitable water vapor (PWV) differences between rawinsonde and GPS (which we call RMSD, hereafter) is between 1.5 mm to 3 mm (e.g., Rocken *et al.*, 1995; Businger *et al.*, 1996; Duan *et al.*, 1996; Ohtani, 1999). Thus, first, in the following sections, we examine how both techniques are consistent with each other in the present study field.

3. Data Analysis

3.1 GPS

We employed GIPSY-OASIS II ver2.5.2 baseline software for data analysis. This software has a function called PPP (Precise Point Positioning), which enables point positioning using the carrier phase to centimeter accuracy, together with estimates of zenith tropospheric delay (Zumberge *et al.*, 1997). Unlike other types of software, PPP does not use double difference observables for parameter estimates, so the zenith delay can be estimated independently at each site. This is preferable for better estimates of precipitable water vapor at each site.

In the present analysis, we first estimated the ITRF coordinates of all sites over about ten days. Then we fixed these site coordinates and estimated the zenith delay (TZD) for every five minutes (Ohtani, personal communication). Estimated values were averaged for every 30 minutes. We used Niell's mapping function (Niell, 1996) with 15 degree of the minimum elevation angle to make the effects of low elevation angle minimum, instead of 5 degree in the observations.

Then the zenith wet delay (ZWD) was obtained from TZD by subtracting hydrostatic part ZHD as;

$$\mathrm{ZWD} = \mathrm{ZTD} - \mathrm{ZHD},$$

where ZHD can be estimated precisely from the latitude, ellipsoidal height of the site, and atmospheric pressure.

Finally, estimated ZWD were converted into precipitable water vapor (PWV) using the following formula (Askne and Nordius, 1987):

$$\mathrm{PWV} = \Pi \cdot \mathrm{ZHD},$$

$$\Pi = \frac{10^5}{R_v \left(k_2 - k_1 \dfrac{m_v}{m_d} + \dfrac{k_3}{T_m} \right)}$$

where m_v and m_d [kg/kmol] are molecular weights of water vapor and dry air, respectively R_v [J · K/kg] is the specific gas constant of water vapor. Refractive constants, k_1, k_2, and k_3 are given by Boudouris (1963) as 77.60 ± 0.08 [K/hPa], 71.98 ± 10.82 [K/hPa], and $(3.754 \pm 0.036) \times 10^5$ [K^2/hPa], respectively. T_m [K] is weighted mean temperature of the atmosphere and is given by Bevis *et al.* (1992).

In order to make these conversions, we need surface meteorological data; temperature, and surface pressure. In the present study we used those data obtained by the initial value of rawinsonde at the surface and estimated values at every 30 minutes by interpolation using a spline function.

3.2 Sonde

Precipitable water vapor content based on rawinsonde observation can be estimated using the following formula (e.g., Curry and Webster, 1999);

$$\mathrm{PWV} = \frac{1}{g} \sum q_i \delta p$$

where g [cm/s^2] is the acceleration of gravity, δp [hPa] is the difference of measured atmospheric pressure between layers, and q_i [kg/kg] is the discrete specific humidity measured from sonde observations and taken from the ground.

We then compare the resultant precipitable water vapor derived from GPS (called GPS-PWV, hereafter) at every 6 hours averaged for 30 minutes with that obtained from rawinsonde (called as Sonde-PWV) at every 6 hours.

4. Result

Figure 2 shows a comparison between GPS-PWV and Sonde-PWV at GPS sites for the analyzed time periods. At a first glance, general trends of both of techniques are consistent. Asian Monsoon starts in the middle of May, which is recognized by a rapid increase of the water vapor content

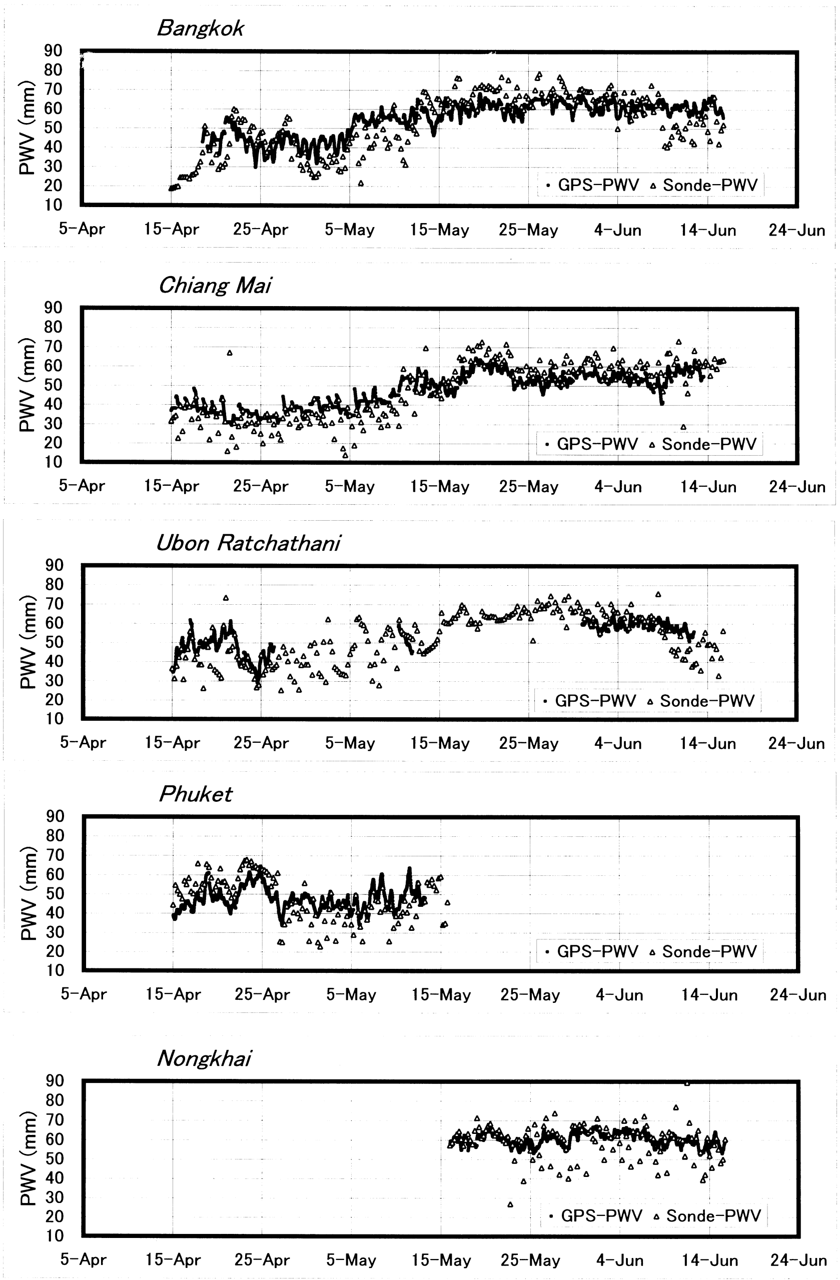

Fig. 2. Time series of GPS-PWV (black circle) and Sonde-PWV (white triangle) from April 15 to June 15, 1998.

in the figure. Onset of the Monsoon is visible for both time series of GPS-PWV and Sonde-PWV. However, a closer examination suggests that the variation of Sonde-PWV is a little bigger than GPS-PWV. PWV using GPS is a little larger than Sonde before the Monsoon begins in the middle of May, while the offset is the opposite after the onset of the Monsoon. Moreover, the diurnal variation of Sonde-PWV looks larger compared with that of GPS-PWV.

Figure 3 shows a comparison of Sonde-PWV and GPS-PWV. If both techniques are consistent (or ultimate correlation) the plots should lie on the line $y = x$. However, the regression line is significantly inclined from the ideal case. RMSD between Sonde-PWV and GPS-PWV is 8.72 mm (Fig. 3), which is much larger than the case in other studies in the mid-latitude region (e.g., Ohtani, 1999). If we examine Sonde-PWV plots, there are some anomalous values that show unrealistic jumps from surrounding data.

5. Discussion

The climate in Thailand is tropical Monsoon with the wet season from May to October and the dry season from November to April. As was indicated by Matsumoto (1997), the onset of the Monsoon is abrupt within one month than gradual. Therefore, it may be possible to detect exact timing of its onset by short duration of data from April to June. As can be seen in Fig. 2, the increase of water vapor in May appears to indicate the onset of the Monsoon season. The combination of water vapor together with rainfall, evaporation from land or river runoff provides invaluable data for investigating water cycle and mechanism of the Monsoon in this area. Precise

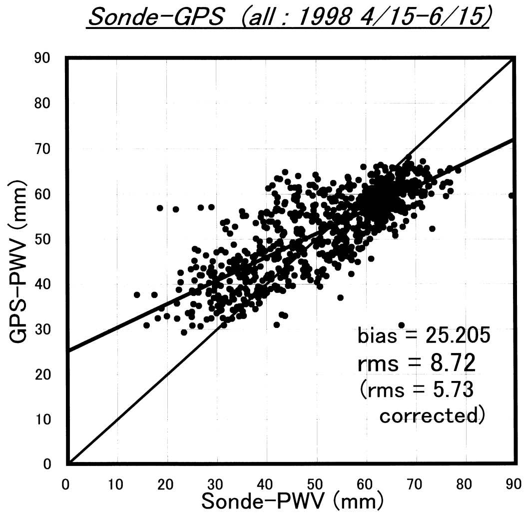

Fig. 3. GPS-PWV vs. Sonde-PWV. A linear regression line (thick line) is drawn using the least-squares method. Thin line is $y = x$.

estimates of water vapor are thus important. In this chapter, first we discuss possible causes of errors in estimating PWV both in GPS and in rawinsonde. Then, we propose a possible mean to correct Sonde-PWV data. Finally, discussion on the onset of the Monsoon is added combining with other type of data.

5.1 Possible error sources in GPS-PWV and Sonde-PWV

Both rawinsonde and GPS in this study may include some error sources like other studies such as those in Japan (Ohtani, 1999). Large RMSD between them shown in the previous section may have to be studied carefully.

First, GPS estimates would have to be examined. In a computational technique for estimating TZD using PPP, corrections using surface meteorological data would be possible error sources. Kobayashi (1999) examined several possible parameter settings in a TZD estimation using the same GPS data. His results, however, did not show any distinguishable differences in estimated TZD from the results of this study.

In the PPP analysis, we used surface meteorological data given by interpolating sonde data at surface. This would be more problematic. Surface meteorological data especially pressure data from other sources such as more reliable measurements or global objective analysis data may be useful for better estimates of GPS-PWV. However, this does not explain the large RMSD because we compared results at the time when rawinsonde observation was done. Other observational errors may have to be examined, though they appears to be smaller compared to the above ones considering the previous studies such as Ohtani (1999).

Errors in T_m could also be an error source, as was indicated by Ross and Rosenfeld (1997). We simply employed the linear relationship of T_m for the surface temperature by Bevis *et al.* (1992). Since its coefficients are determined empirically using sonde data for the North American continent, Ross and Rosenfeld (1997) investigated possible error using global sonde data over 23 years. They suggested the importance of using site specific regression including seasonal and climatological considerations. However, even if such a correction is made, its effects on the estimate of PWV are only 0.1–0.5 mm (Ross and Rosenfeld, 1997), which is much smaller than the RMSD shown in this study.

Kobayashi (1999) examined rawinsonde data used for GAME-T experiments in detail. He found that there are many cases in which vertical profiles of relative humidity in sonde data are not reasonable. He classified such erroneous data into four cases;

- Case 1: first relative humidity of sonde data has offset with surface meteorological data,
- Case 2: first temperature of sonde data has offset with surface meteorological data,
- Case 3: relative humidity shows saturation that may be due to passage in the cloud,
- Case 4: strange profiles such as termination of records at the mid altitude *etc*.

The percentage of data that applies to the above cases reached 45% among the data used. A comparison with GANAL PWV data, which is based on a global objective analysis, suggested that the PWV is between Sonde and GPS in Thailand (Kobayashi, 1999). In conclusion, we suspect that the difference in PWV estimates between Sonde and GPS are mostly due to sonde data, though a part might come from GPS.

5.2 Correction of Sonde-PWV

Since the sonde data can delineate profiles of PWV, whereas GPS gives integrated PWV over the observation sites, a combination of sonde and GPS may be necessary for the most reliable estimates of PWV. One simple approach to combination is to correct sonde data by GPS empirically. We used a simple linear model that does not require a detailed quality check of sonde data, where (GPS-PWV) $=$ $a + b \times$ (Sonde-PWV). First, using all of the data in this study, we estimated a and b in the least square sense, to be $a = 25.21$ and $b = 0.52$, respectively. Post-fit RMSD became 5.73 mm, which is much smaller than the original RMSD of 8.72 mm (Fig. 3). Then, we discarded sonde PWV data that lie outside 2.5 sigma of residuals and re-estimated a and b as $a = 25.12$ and $b = 0.52$, respectively. Postfit RMSD in this case was 5.62 mm.

This simple correction allowed considerable improvements in PWV estimates without conducting laborious quality check of sonde data. Basically, however, close corrections of Sonde-PWV based on Case 1 to 4 should be made for better estimations of Sonde-PWV. A large diurnal variation of Sonde-PWV relative to GPS-PWV was also improved by this correction (Fig. 4). Diurnal variations might come from the effects of solar radiation on sonde, which were revealed recently. Further examination is clearly necessary for sonde observations. Even if we remove bad sonde data, RMSD is still larger than in other studies, where RMSD is only about 3 mm or less. Since Thailand is tropical area where water vapor is constantly higher for the whole year compared with other mid-latitude areas such as Japan or the US, the correlation may be worse in terms of RMSD in Thailand. Extensive studies, however, are clearly necessary to clarify differences between these techniques. Results from the Global Objective

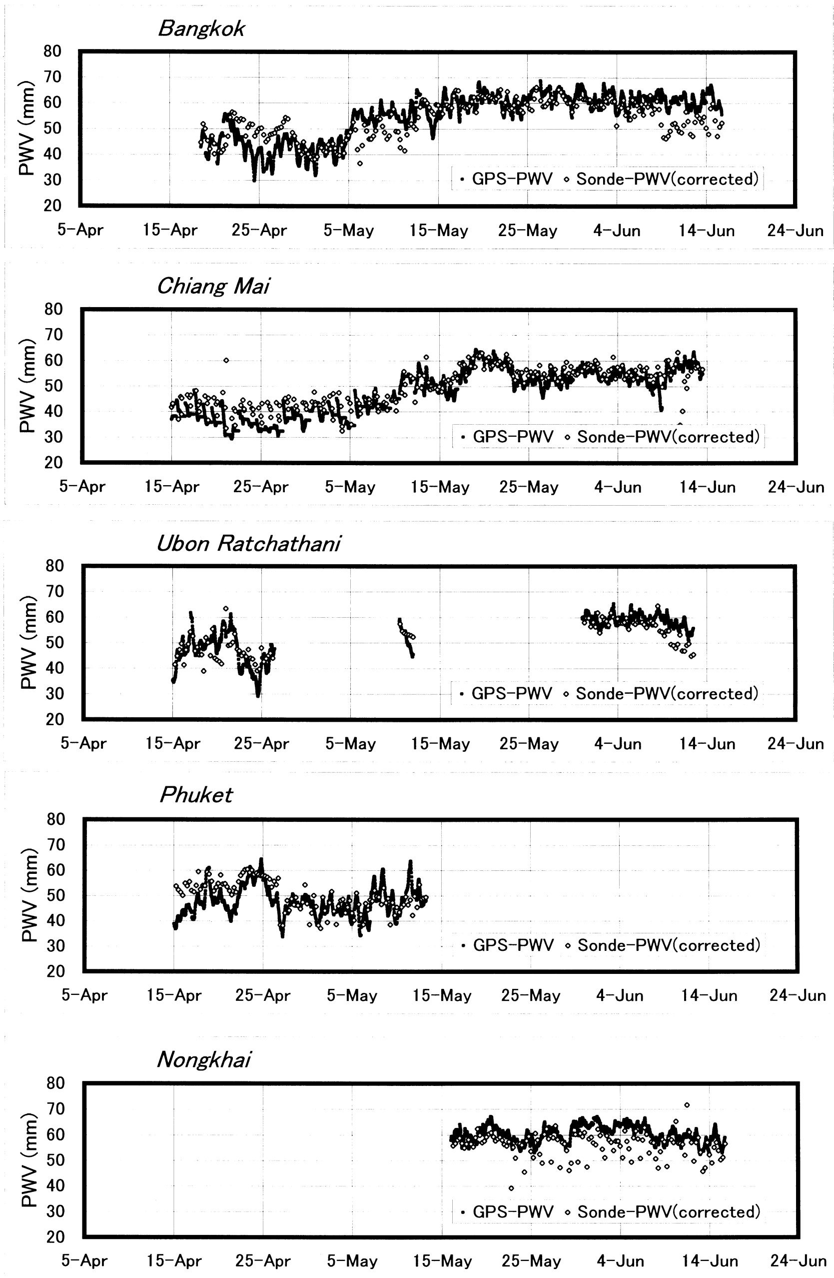

Fig. 4. Time series of GPS-PWV (black circle) and Sonde-PWV (white diamond) after correction by linear regression analysis. Bad sonde data with greater than 2.5 sigma RMS were also discarded.

Analysis may have to be included, though they are left for future studies. In this study, we tentatively consider GPS results as being representative for PWV estimates in Thailand.

5.3 Onset of the Asian Monsoon in Thailand

Finally, let us discuss further about the onset of the Monsoon comparing GPS-PWV with other meteorological data (temperature and humidity, and rainfall). Figure 5 shows the time series of daily mean GPS-PWV (thick lines), temperature (thin lines), humidity (dots lines), and rainfall (bar) at Bangkok and Chiang Mai from April 15 to June 15, 1998. First, in Bangkok, a rapid increase in PWV is seen around May 5th, 1998, from about 40 mm to 60 mm. At Chiang Mai, on the other hand, the rate of increase of PWV is a little slower, yet it is clear that the increase started at around the same day as in Bangkok. During these periods, the temperatures at both sites are rather stationary and do not show any significant change or offsets. Humidity, on the other hand, shows somewhat interesting differences between sites; a good correlation with PWV in Chiang Mai, whereas there is no visible correlation in Bangkok. Since Bangkok is closer to the ocean than Chiang Mai, the humid air may be transported from the sea by land and sea breezes even in the dry season, which keeps the humidity in Bangkok rather stationary throughout the year.

Rainfall plots in Fig. 5 show an interesting correlation with the PWV time series. An instantaneous large rainfall is concordant with the onset of the increase of PWV both in Bangkok and in Chiang Mai. Traditionally, the onset of

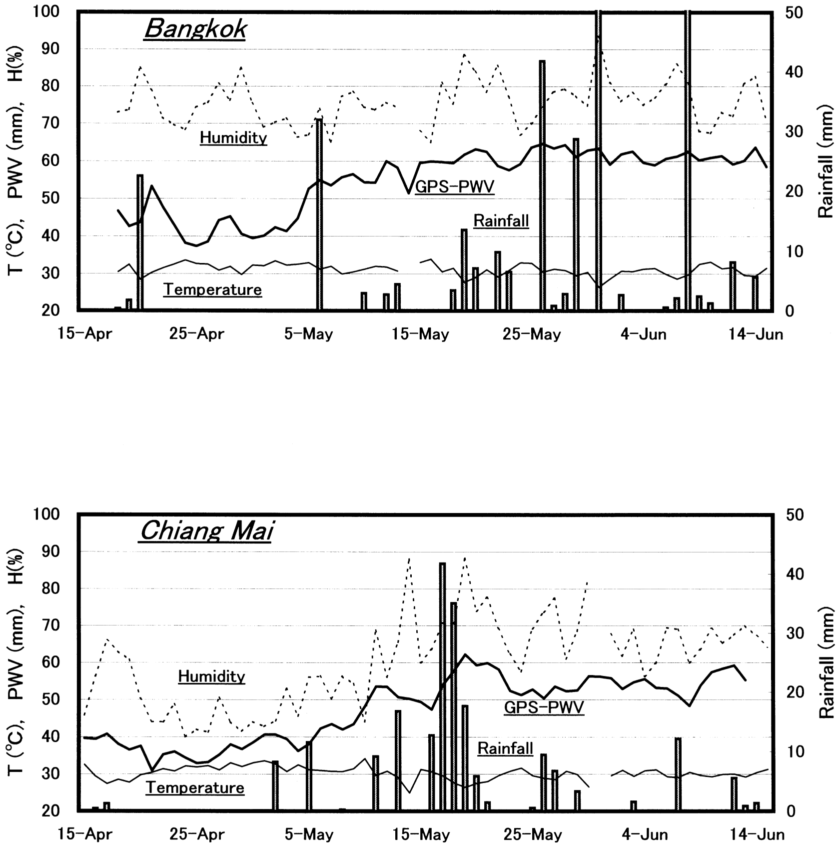

Fig. 5. Daily mean time series of GPS-PWV (thick lines), Temperature (thin lines), Humidity (dots) and Rainfall (bars) from April 15 to June 15, 1998.

the Monsoon has been identified by this increase of rainfall, as well as the change in wind direction or other data (Nakaegawa *et al.*, 2000, in preparation). Continuous monitoring of the GPS-PWV may add further indispensable data to judge the exact timing of the onset of the Monsoon in the area. Moreover, a combination of continuous monitoring of PWV using GPS, together with other meteorological data, will provide a powerful tool for monitoring the whole process of the Monsoon for the season of a year. Finally, combining our research field with other areas of GAME projects or global projects, further investigations to clarify the water and energy circulation on the Earth would be possible based on GPS-PWV data.

Further new findings may be possible using temporally high resolution of PWV using GPS. For example, closer look of Bangkok PWV might suggest that amplitude of diurnal change decreases after the onset of the Monsoon. Such fine structure in the temporal change of PWV may then be compared with the surface flux data, for example, to clarify diurnal water circulation in the studied region, though it is left for our next study. We believe that the combination of GPS-PWV with other climatological data will lead to a new approach in the study of the tropical Monsoon as well as other study areas related to the global water circulation.

6. Conclusion

We conducted GPS observations in Thailand, which is located in the Asian Monsoon area, and estimated PWV. A comparison of estimated PWV based on GPS with that from rawinsonde data suggested the following:

1) Time series of GPS and rawinsonde are generally consistent with each other in the long term and show a clear increase of PWV, which corresponds to the onset of the Monsoon season in the middle of May.
2) There are systematic offsets in estimates of PWV between rawinsonde and GPS. Sonde-PWV is larger than GPS-PWV when PWV is large and *vice versa*. Rawinsonde data were suspected to include low quality data.

In addition, GPS-PWV was compared with other meteorological data to closely examine the onset of the Monsoon. A rapid increase of GPS-PWV is consistent with the otherwise estimated onset of the Monsoon, especially the rapid increase in rainfall. Thus, the continuous monitoring of GPS together with other meteorological data will provide better data sets for investigating the onset of the Monsoon, as well as its withdrawal and the water circulation in the tropical area.

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