Estimation of Precipitable Water Distribution over Land Using NOAA/AVHRR Data and GPS-derived Precipitable Water

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Abstract: Precipitable water (PW) is an important variable in climate system, hydrological system, or terrestrial ecosystem. The PW has been measured mainly by radiosondes over land, and nowadays it can also be measured by GPS. In Japan, GEONET (GPS Earth Observation Network System) has provided us with the PW data sets since 1996. However, the PW obtained from GEONET distribute discretely.

Satellite remote sensing is useful for obtaining continuous spatial distribution of the PW. Since NOAA/AVHRR has two thermal channels in the water vapor absorption region, the AVHRR is applicable to estimate total column PW. In this study, we examined the possibility of the AVHRR data in measuring PW by comparing AVHRR split window temperature difference with GPS-derived PW, and found that there was high correlation between them. Then, by using this relationship, we estimated the PW distribution over land in Japan.

Keywords: Precipitable Water, NOAA/AVHRR, GPS.

1. Introduction

Precipitable water (PW) is the total atmospheric water vapor contained in a vertical column of unit area from earth’s surface to top of atmosphere. PW is an important variable in climate system, hydrological system, or terrestrial ecosystem. For example, water vapor is one of the greenhouse gases that can lead to global warming. Water vapor influences the process of partitioning incoming solar radiation into latent and sensible heat fluxes, through its effect on stomatal conductance and evapotranspiration. In turn, the process feeds back into the Earth’s energy and water budgets. In terrestrial ecosystem modeling, since the water vapor within and just above the vegetation canopy can limit photosynthesis, near-surface water vapor is needed to calculate latent heat flux [3].

PW has been mainly measured by radiosondes over land, but these instruments offer limited opportunities for spatial and continuous measurements of PW [2]. In Japan, there are only 18 radiosonde stations and the observation is made twice per day. Nowadays it can also be measured by GPS (Global Positioning System). GEONET (GPS Earth Observation Network System) has provided us with the PW data sets since 1996, and this data set offers the average PW for every three hours. The number of GPS sites has been gradually increased to become over 1,200. The spatial resolution of GEONET is 15–25 km, but the GPS stations do not equally distribute because the primary purposes of the network are crustal deformation monitoring and geodetic surveying.

Recently, the efforts to measure PW have turned to using satellite remote sensing instruments [2]. Satellite remote sensing is useful for obtaining continuous spatial distribution of the PW since it has higher spatial resolution. Microwave remote sensing techniques have been developed using satellite instruments to estimate PW over oceans. However, these techniques cannot be applied accurately over land since the microwave land surface emissivity is highly variable [5]. MODIS (Moderate Resolution Imaging Spectroradiometer) has a channel in the water vapor absorption region, 0.94 μm. The method using this channel has high accuracy and precision for retrievals of PW over the land, but the MODIS observation period is short because its observation started in 1999.

NOAA/AVHRR(Advanced Very High Resolution Radiometer) has long observation period, about 20 years, and two thermal channels in the water vapor absorption region; channel 4(10.3- 11.3 μm) and channel 5 (11.4- 12.3 μm). In order to retrieve PW over land from currently orbiting satellite sensors, several investigations have applied techniques using the 11 and 12 channels, called the split window channels, to the AVHRR sensors. These techniques based on that AVHRR channels 4 and 5 are differentially impacted by water vapor; in other words, absorption by the water vapor continuum is higher in the channel 4 than in the channel 5. With a radiative transfer model, the radiative response of the atmosphere at
the channel 4 and 5 regions was simulated for a wide variety of atmospheric conditions. As a result, a linear relationship was found between the PW and the difference in brightness temperature measured in these channels [4].

In this study, we compared AVHRR split window temperature difference with GPS-derived PW, and found the relationship between them. Then, by using this relationship, we estimated the PW distribution over Kyusyu and Hokkaido district from 1984 to 2001.

2. Theory and data description

1) Theory

The split window approach of the AVHRR sensor can utilize the differential atmospheric effect in the two thermal wavebands in order not only to estimate surface temperature but also to estimate PW. Since AVHRR channel 5(11.4-12.3 μm) is more sensitive to water vapor than Channel 4(10.3-11.3 μm), the brightness temperature difference between Channels 4 and 5 (T4-T5) increases with increasing values of water vapor abundance. Czajkowski et al. revealed this relationship using MODTRAN3.

If the radiative transfer equation is linearized, the amount of atmospheric water vapor is proportional to the difference of the two AVHRR thermal channels [3]:

\[
PW = a(T_4 - T_5) + b\]

where PW is precipitable water, and T4 and T5 are the brightness temperatures for AVHRR Channels 4 and 5, respectively. Coefficients a and b in Eq. (1) can be derived from radiative transfer models output or observational data at specific site [3]. Usually these coefficients are computed by using some radiative transfer models together with atmospheric profiles measured by radiosonde [2]. In this study, in order to obtain these coefficients, we used GPS-derived PW as observational data.

2) GPS-derived PW

GPS-derived PW is the total atmospheric water vapor contained in a vertical inverse cone, whose radius is 30km, from GPS receiver to top of atmosphere. The PW is estimated from the GPS signal delay. When the GPS signals propagate from the GPS satellites to the receivers on the ground, they are delayed by the atmosphere. The total atmospheric delay is caused by ionosphere (ionospheric delay) and the delay by troposphere (tropospheric delay). The ionospheric delay can be removed by a linear combination of dual frequency data. The tropospheric delay also consists of two components; the dry component that is dependent on the dry air gasses in the atmosphere (dry delay) and wet component that depends on the moisture content of the atmosphere (wet delay). The dry delay can be estimated with high accuracy from a surface pressure measurement. Since the wet delay is nearly proportional to the total quantity of PW in the atmosphere directly above the GPS stations, PW can be obtained by eliminating the delays except for the wet delay from the total atmospheric delay observed at GPS stations [1].

Since 1994, the Geographical Survey Institute (GSI) in Japan has deployed a nation wide permanent GPS array, GPS Earth Observation Network System (GEONET).

The GPS-derived PW data set used in this study was made by GPS Meteorology Japan (GPS/MET Japan) project in order to develop applications of the PW derived from GEONET in various fields of research, such as meteorology, geodesy, and hydrology.

3) AVHRR data

NOAA/AVHRR images were acquired from Institute of Industrial Science, the University of Tokyo. The images of Kyusyu and Hokkaido districts in Japan (Fig.1) were used for processing. AVHRR data were calibrated to reflectance values and brightness temperature, and they were geometrically corrected based on ground control point (GCP) matching by using PaNDA software [10]. The daytime images in May and June from 1984 to 2001 were selected for processing because the accuracy of GPS-derived PW in spring is higher than that of other seasons. However, the images whose scan angle was over 30 degree were excluded. As the result, 28 images of Kyusyu and 35 images of Hokkaido could be acquired. Since the split window algorithm cannot work in cloudy condition, the pixels contaminated by clouds in all images were eliminated with a threshold method using channel 1, 2 and 4.
3. Results and discussion

1) Relationship between the \((T_4-T_5)\) and GPS-derived PW

In order to examine the relationship between AVHRR split window temperature differences \((T_4-T_5)\) and GPS-derived total column PW, 10 images of Kyusyu district and 16 images of Hokkaido from 1996 to 2001 were used. The correlation between GPS-derived PW and AVHRR split window temperature difference \((T_4-T_5)\) was examined. To overcome the problem of misregistration of pixels, brightness temperature differences of AVHRR Channels 4 and 5 were averaged over boxes of \(3 \times 3\) pixels centered at the GPS stations. The scatter plots between GPS-derived PW and the \((T_4-T_5)\) are shown in Fig.2. The correlation coefficients and root-mean-square errors (RMSE) for Kyusyu district is 0.74 and 4.31 mm, respectively. For Hokkaido district, the correlation coefficients and RMSE is 0.66 and 4.51 mm, respectively. When the data of both Kyusyu and Hokkaido were analyzed together, the correlation coefficients and RMSE is 0.67 and 4.52 mm, respectively.

However, the GPS-derived PW does not always correspond to the average \((T_4-T_5)\) over box of \(3 \times 3\) pixels centered at the GPS station, because the GPS-derived PW is the total atmospheric water vapor contained in a vertical inverse cone whose radius is 30km. To determine the box size corresponding to the GPS-derived PW, the average \((T_4-T_5)\) was calculated varying the box size from \(3 \times 3\) to \(31 \times 31\). Then the correlation between GPS-derived PW and the average \((T_4-T_5)\) was examined for each box. The correlation coefficients for each case were shown in Fig.3. GPS-derived PW became more highly correlated the average \((T_4-T_5)\) in case the box size increased, but the correlation coefficients is almost constant over \(17 \times 17\) pixels for Kyusyu and \(25 \times 25\) pixels for Hokkaido. In case the data of both Kyusyu and Hokkaido were analyzed together, the GPS-derived PW is corresponded to the average \((T_4-T_5)\) over box of \(21 \times 21\) pixels.
Thus, the relationship between the \((T_4 - T_5)\) and GPS-derived PW can be written as

\[
\text{GPS\_PW} = c(T_4 - T_5)^* + d
\] (2)

where GPS\_PW is the GPS-derived PW and \((T_4 - T_5)^*\) is the average \((T_4 - T_5)\) over box of \(N \times N\) pixels centered at the GPS station \((N = 2m+1, m \geq 1)\), \(c\) and \(d\) are constants.

Figure 2. Scatter plots between GPS-derived PW and the \((T_4 - T_5)\).

Figure 3. Correlation coefficients in varying box size.
2) Estimation of PW distribution

By comparing the AVHRR split window temperature difference ($T_4$-$T_5$) with GPS-derived PW, we found that the ($T_4$-$T_5$) has linear relationship with PW. In order to estimate PW distribution, coefficients $a$ and $b$ in Eq. (1) was derived from Eq. (2).

The PW has highly spatial variable due to the relative location of moisture source and sink regions and physical and dynamic processes of atmosphere [5]. However, the RMSE are almost same (Fig.4) whether the data of Kyusyu and Hokkaido were analyzed separately or both together. Therefore, we analyzed the data of both Kyusyu and Hokkaido together, and derived coefficients $a$ and $b$ in Eq. (1). The GPS-derived PW and the average ($T_4$-$T_5$) had high correlation when the box size is larger than 21×21 pixels. In addition, RMSE is very small when the box size becomes larger than 25×25 pixels. For these reasons, we derived coefficients $a$ and $b$ in Eq. (1) from Eq. (2) in case N is 25. In Eq. (2), where $N$ is 25, $c$ and $d$ is 7.17 and 5.65, respectively.

Thus, the PW distribution equation can be written as

$$PW = 7.17(T_4 - T_5)* + 5.65$$

where ($T_4$-$T_5$)* is the average ($T_4$-$T_5$) over box of 25×25 pixels centered at the GPS station. Using this equation, the PW distribution was estimated from 1984 to 2001. Some PW distribution images are shown in Fig.5.

4. Conclusions

In this study, we examined the relationship between AVHRR split window temperature difference ($T_4$-$T_5$) and GPS-derived PW. By comparing them, we found that the ($T_4$-$T_5$) had linear relationship with GPS-derived PW. From this relationship, we estimated the PW distribution over Kyusyu and Hokkaido district. Finally, we could obtain continuous spatial distribution of the PW before GPS-derived PW data sets were made by using GEONET.

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Figure 5. Images of PW distribution.
References


