Estimation of Precipitable Water distribution over northeast Asia using NOAA AVHRR

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ABSTRACT: In this study, we estimated precipitable water(PW) distribution over land in northeast Asian region using NOAA AVHRR data and evaluated the results by comparing with PW estimated from radiosonde observations. The PW estimation method using AVHRR is useful for obtaining continuous spatial distribution of the PW in the area where there are few ground observation points of PW. In previous study, we authors developed the method to estimate PW distribution using AVHRR and estimated it over land in Japan from 1984 to 2004. The method is based on the relationship between brightness temperature difference of AVHRR and GPS-derived precipitable water over land in Japan. In order to reveal the applicable area of this method in northeast Asian region except for Japan, we applied this method to northeast Asian region and compared the PW estimated from AVHRR using this method with the PW from radiosondes in northeast Asia. The means of the difference between radiosonde PW and AVHRR PW in Japan and in other area of northeast Asian region were 5.6 mm and 3.7 mm, and the standard deviations were 6.9 mm and 5.8 mm, respectively. Therfore, the PW can be estimated in northeast Asia by using the estimation method at the same level of accuracy in Japan.

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. Atmospheric water vapor is one of the greenhouse gasses 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. Nowadays it has revealed that the amount of atmospheric water vapor has been increasing with air temperature increasing.

The PW is usually measured by radiosondes over land, but they offer limited opportunities for spatial and continuous measurements of PW(Cuomo et al., 1997). Nowadays it can also be measured by another instrument; Global Positioning System(GPS). It calls GPS-derived PW and GPS-derived PW means the total atmospheric water vapor contained in a vertical inverse cone, whose radius is about 40 km and height is 10 km, from GPS receiver to top of atmosphere. In Japan, GPS measuring network has provided us with the GPS-derived PW data sets since 1996, and this data set is composed of the three-hour average PW. The spatial resolution of the PW measurement has advanced by using GPS network in Japan, but the GPS stations do not equally distribute because the primary purposes of the network are crustal deformation monitoring and geodetic surveying.

Satellite remote sensing is useful for obtaining continuous spatial distribution of the PW in the area where ground observation points of PW, such as radiosondes and GPS, has not been densely-developed. There are some approaches for estimating PW using currently orbiting satellite sensors.

Microwave remote sensing technique has been developed using satellite instruments to estimate PW over oceans, but it cannot be applied accurately over land since the microwave land surface emissivity is highly variable(Eck and Holben, 1994). Terra/Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) has a channel in the water vapor absorption region(0.94 ㎛) 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, and two thermal channels in the water vapor absorption region for PW retrieving. The PW estimation method from AVHRR uses the channel 4(11 ㎛) and 5(12 ㎛), called the split window channels. This method based on a linear relationship between the PW and the difference in brightness temperature measured in these channels(Dalu, 1986).

We authors estimated PW distribution over land in Japan from 1984 to 2004 by using PW estimation formula derived from the relationship between brightness temperature difference of AVHRR and GPS-derived PW from 1996 to 2001(Akatsuka et al., 2008). The root-mean-square error of the PW estimation is approximately 6 mm, and our AVHRR-based estimation has a fairly good result compared with that of radiosondes in Japan. However, it is not clear that the applicable area of this estimation formula in other region of northeast Asian.

In this study, in order to reveal the applicable area of this formula in northeast Asian region except for Japan, we applied this formula to northeast Asian region and compared the PW estimated from AVHRR using this formula with the PW from radiosondes in northeast Asia.

2. METHODOLOGY

2.1 Data description

NOAA AVHRR images were acquired from Institute of Industrial Science, the University of Tokyo. The daytime images from 1996 to 2001 were used for deriving PW estimation formula and those in 1998 were used for mapping PW in northeast Asia. 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 (Takeuchi et al., 2002). The area whose scan angle was over 30 degree was excluded form each image. 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.

The GPS-derived PW data set was made by GPS Meteorology Japan (GPS/MET Japan) project in order to develop applications of the PW in various fields of research, such as meteorology, geodesy, and hydrology. The data set from 1996 to 2001 can be acquired from "GPS/MET Japan Homepage"(http://dbx.cr.chiba-u.jp/Gps_Met/GpsHome.html). The three-hour average PW corresponding to satellite acquisition time was downloaded from the web site.

The PW estimated from radiosondes in northeast Asia for evaluation was downloaded from "Wether Web" of University of Wyoming(http://weather.uwyo.edu/upperair/sounding.html). The radiosonde stations which were used for analysis are shown in Figure 1.

2.2 PW estimation formula

If the radiative transfer equation is linearized, the amount of atmospheric water vapor is proportional to the difference of the two AVHRR thermal channels (Czajkowski et al., 2002):

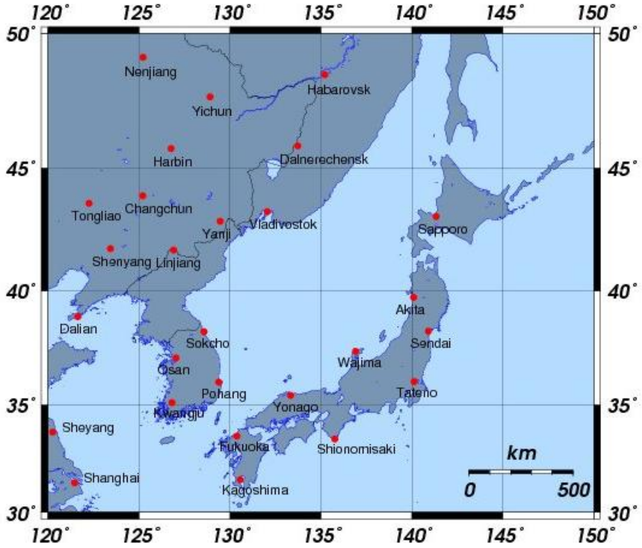

Figure 1. The radiosonde stations in northeast Asia.

$$PW = a(T_4 - T_5) + b \quad (1)$$

where PW is precipitable water, and T_4 and T_5 are the brightness temperatures for AVHRR Channels 4 and 5, respectively. Coefficients *a* and *b* in Eq. (1) are usually computed by using some radiative transfer model together with atmospheric profiles measured by radiosonde(Cuomo et al., 1997). In this study, in order to obtain these coefficients, the regression analysis between the ($T_4 - T_5$) and GPS-derived PW was used.

However, the brightness temperature difference between AVHRR channel 4 and 5 in Eq.(1) increases along with atmospheric water vapor abundance, scan angle and land surface temperature(LST). In order to estimate PW using the relationship of Eq.(1), the effect caused by scan angle and LST needs to be eliminated from ($T_4 - T_5$). Therefore, its effect was simulated using radiative transfer model and the correction formulas to eliminate theses effects from ($T_4 - T_5$) were developed(Akatsuka et al., 2008). The corrected relationship between ($T_4 - T_5$) and GPS-derived PWcan be written as:

$$PW = a(T_4 - T_5)^{*}\cos\theta + b \quad (T^{*}_4 \leq 25) \quad (2)\text{-a}$$

$$PW = a\{(T_4 - T_5)^{*}\cos\theta - (0.0034PW - 0.011)(T_4 - 25)\} + b \quad (T^{*}_4 > 25) \quad (2)\text{-b}$$

where ($T_4 - T_5$)* is the average ($T_4 - T_5$) over box of 25×25 pixels and θ is sacan angle, and T^{*}_4 is the average T_4 over box of 25×25 pixels. We used ($T_4 - T_5$)* in the regression analysis between the brightness temperature difference and GPS-derived PW because the GPS-derived PW is corresponded to the average ($T_4 - T_5$) over box of 25×25 pixels centered at the GPS stations.

3. RESULTS AND DISCUSSION

3.1 Derivation of PW estimation formula

By the regression analysis between the AVHRR split window temperature difference and GPS-derived PW in Japan, coefficients *a* and *b* in Eq.(2) were derived. The coefficients *a* and *b* are 12.45 and 1.36 respectively. The scatter plot of GPS-derived PW and corrected brightness temperature difference is shown in Figure 2.

Thus, the PW estimation formula can be written as:

$$PW = 12.45(T_4 - T_5)^* \cos\theta + 1.36 \quad (T^*_4 \leq 25) \qquad (3)\text{-a}$$

$$PW = 12.45\{(T_4 - T_5)^* \cos\theta + 0.011(T^*_4 - 25) + 1.36\} / \{1 + 0.0423(T^*_4 - 25)\} \quad (T^*_4 > 25) \qquad (3)\text{-b}$$

where $(T_4 - T_5)^*$ is the average $(T_4 - T_5)$ over box of 25×25 pixels, and T^*_4 is the average T_4 over box of 25×25 pixels.

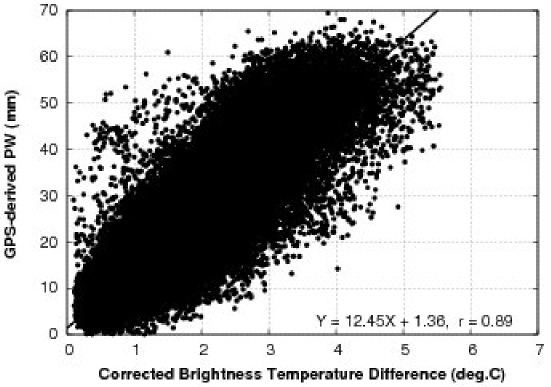

Figure 2. The scatter plot of GPS-derived PW and corrected brightness temperature difference.

3.2 Comparing PW from AVHRR with PW from radiosondes

Using the PW estimation formula, the PW distribution over northeast Asian region(lat:30-50N, lon:120-150E) was estimated in 1998. Some PW distribution images are shown in Figure 3.

The PW at radiosonde stations were extracted from the PW distribution images to compare with PW estimated from radiosonde observation. The PW extracted from the PW distribution images are averaged over box of 25×25 pixels centered at the radiosonde station.

The mean and standard deviation of the difference between radiosonde PW and AVHRR PW in Japan and other area were calculated respectively. The number of radiosonde stations in Japan, which we used for analysis, is nine and that in other area is sixteen. The results are shown in Table 1. The radiosonde PW measured at 00:00 UTC was used for comparing AVHRR PW. The means in Japan and other area in northeast Asian region were 5.56 mm and 3.63 mm, respectively. The standard deviations were 6.88 mm and 5.67 mm, respectively. It revealed that this formula overestimated the PW in northeast Asia. The PW can be estimated in northeast Asia by using the estimation formula at the same level of accuracy in Japan and this formula can be applied to northeast Asian region except for Japan region.

4. CONCLUSIONS

In this study, we estimated the PW distribution in northeast Asia using PW estimation formula based on the relationship between brightness temperature difference of AVHRR and GPS-derived precipitable water over land in Japan. In order to reveal the applicable area of this formula, we compared the PW estimated from AVHRR with the PW from radiosondes in northeast Asia. The means of the difference between radiosonde PW and AVHRR PW in Japan and in other area of northeast Asian region were 5.6 mm and 3.7 mm, and the standard deviations were 6.9 mm and 5.8 mm, respectively. Therfore, the PW can be estimated in northeast Asia by using the estimation method at the same level of accuracy in Japan.

The atmospheric water vapor amount is input as parameter into numerical forecasting system for improvement of forcst accuracy. The system requires 10 percent accuracy in estimating the amount of water vapor(Aoki, 1993). In this study, PW was overestimated and the error is large when the true value of PW is approximately less than 20 mm. Therefore, we must improve the estimation accuracy of this method, or develop more sensitive estimation method in drier condition.

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References

Aoki, T., 1993. Remote Sensing, III. Satellite, TENKI, 40(7), pp.51-56.

Akatsuka,S., Oyoshi, K., Takeuchi, W., Sawada, H. and Yasuoka, Y., 2008. Mapping of precipitable water over land in Japan using NOAA AVHRR, Journal of the Japan Society of Photogrammetry and Remote Sensing, 4, pp.29-41.

Cuomo, V., Tramutoli, V., Pergola, N., Pietrapertosa, C. and Romano, F., 1997. In place merging of satellite based atmospheric water vapour measurements, INT. J. Remote Sensing, 18(17), pp.3649-3668.

Czajkowski, K. P., Goward, S.N., Shirey, D. and Walz, A., 2002. Thermal remote sensing of near-surface water vapor, Remote Sensing of Environment, 79, pp. 253-265.

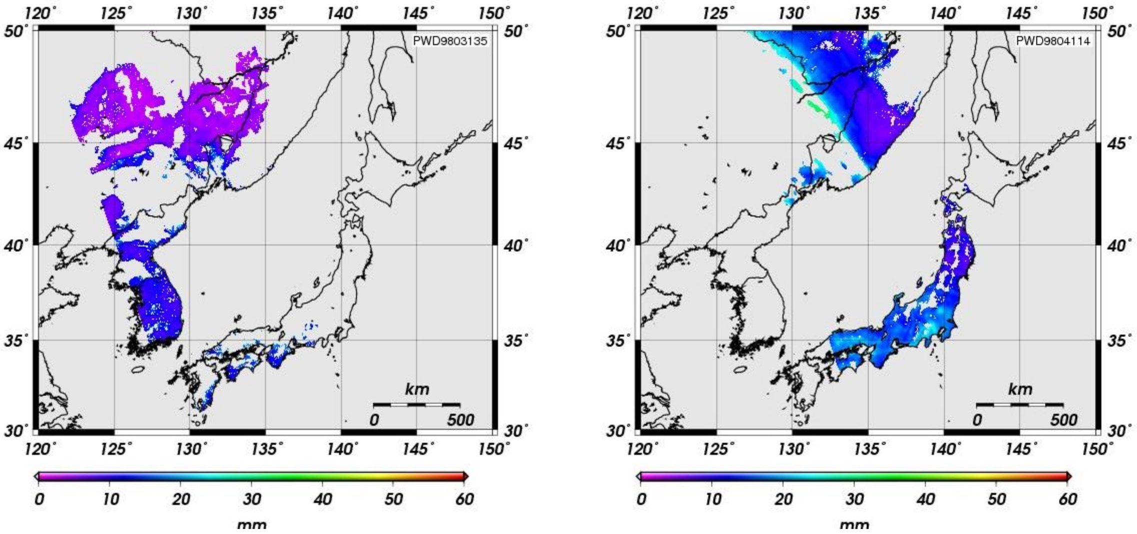
Dalu, G., 1986. Satellite remote sensing of atmospheric water vapour, INT. J. Remote Sensing, 7(9):, pp.1089-1097.

Eck, T. F. and Holben, B. N., 1994. AVHRR split window temperature differences and total precipitable water over land surfces, INT. J. Remote Sensing, 15(3), pp.567-582.

Takeuchi, W., Nemoto, T., Ochi, S., and Yasuoka, Y., 2002. Development of AVHRR data processing system on WWW, J. Japan Society of Photogrammetry and Remote Sensing, 41(3), pp.23-27

URL: GPS/MET Japan. Available at: http://dbx.cr.chiba-u.jp/Gps_Met/GpsHome_j.html

URL: Weather Web. Available at: http://weather.uwyo.edu/upperair/sounding.html



(a)March 13, 1998 (b)April 11, 1998

Figure 3. Precipitable water images. ((a)March 13, 1998, (b)April 11, 1998)

Table 1. The mean and standard deviation of the difference between radiosonde PW and AVHRR PW. ((a) Japan, (b) Other region)

(a) Japan

RPW (mm)	(AVHRR − Radiosonde)		
	Mean(mm)	SD(mm)	Sample Number
0～10	5.13	4.1	108
10～20	7.48	9.37	50
20～30	3.24	10.24	17
30～40	1.2	6.52	5
Total	5.56	6.88	180

RPW : precipitable water from radiosonde at 00:00 UTC

(b) Other region

RPW (mm)	(AVHRR − Radiosonde)		
	Mean(mm)	SD(mm)	Sample Number
0～10	3.02	4.3	208
10～20	4.91	6.87	96
20～30	2.9	8.31	23
30～40	4.36	7.48	12
Total	3.63	5.66	339

RPW : precipitable water from radiosonde at 00:00 UTC