Retrieval of precipitable water in a continental scale using split window data.

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1. Introduction

Water vapor is one of the most dominant greenhouse effect gases as well as the most influential atmospheric components in remote sensing studies targeting at land and ocean. It is important to understand water vapor behavior in a global scale consequently. Water vapor also has great variability in spatial and temporal domain, and then it is optimal to retrieve globally the water vapor amount using satellite data, such as polar orbiters and geostationary satellites at frequent observational intervals. Several sensors, such as optical and microwave radiometers, have been used to retrieve the precipitable water (i.e., vertically integrated water vapor amount). It is said that microwave radiometer data are useful to retrieve precipitable water only over ocean because they are not well available over land due to the complexity of land surface emissivity.

Jedlovec (1990) illustrated the Split Window Variance Ratio (SWVR) method is applicable to the airborne Multispectral Atmospheric Mapping Sensor (MAMS) data. He suggested that the Visible and Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) suffers in its lager spatial resolution and limited dynamic range.

Kleespies and McMillin (1990) analyzed Advanced Very High Resolution Radiometer (AVHRR) and VAS to retrieve the precipitable water. They addressed that the optimal instrumentation was the geostationary satellite with the quality of error reduced as much as AVHRR instrument aboard National Oceanic and Atmospheric Administration (NOAA) satellite. They also suggested that the subpixel cloudiness was critical factor for the VAS application.

Iwasaki (1994) has developed the retrieval algorithm for mesoscale water vapor variation using AVHRR / NOAA data. In the method, air temperature effect was corrected with atmospheric model calculations.

In this study, an algorithm has been under development to retrieve precipitable water in a continental scale using split window data (11 and 12 μm spectral bands) based upon Iwasaki (1994). The algorithm was applied to the VISSR aboard Geostationary Meteorological Satellite - 5 (GMS-5). The retrieved results were compared to the in situ radiosonde observation.

2. Data description

The three types of data were used in this study: One is VISSR / GMS-5 data and others are radiosonde and Automated Meteorological Data Acquisition System (AMeDAS) data as references for precipitable water and surface air temperature around Japan, respectively.

As to the VISSR data, the analyzed region ranges from 70 °N to 20 °S in latitude and from 70 °E to 160 °E in longitude. The spatial resolution is around 5 ° by 5 °, and then there exist 1800 by 1800 pixels in total. The analyzed scene number is 228 for 00 and 12 UTC, which extends from January, April, July, and October in 1997 in particular.

As for the reference data, on the other hand, both radiosonde and AMeDAS data from 1988 to 1997 around a calibration site of Japan in this study, were collected to estimate precipitable water and surface air temperature, respectively.

The algorithm under development utilizes the split window channels (11 and 12 μm spectral bands). In general, these spectral channels contains information in lower troposphere (i.e., boundary layer) where almost all water vapor exists. A 6.7 µm spectral band (so to speak, a water vapor channel), is also available in VISSR / GMS-5 data, which is sensitive to the relative humidity around 200 to 500 hPa (middle troposphere to tropopause) (Soden and Bretherton 1993). The water vapor channel is expected to add some information on a water vapor profile which is not inferred only from split window channels. It is also interested to compare the water vapor distribution pattern of the upper troposphere in a global scale to that of the lower troposphere using aboard the same sensor / satellite.

3. Analysis and results

The algorithm utilizes a transmittance ratio of two split window bands, rather than difference of those brightness temperatures, based upon AVHRR analysis over land by Iwasaki (1994). In the first step of the algorithm, a calibration curve with statistical regression is made between precipitable water and the transmittance ratio parameter, so as to simply retrieve initial precipitable water with split window data. In the second step, air temperature effect is corrected and then apparent surface temperature (i.e., surface air temperature in the model atmosphere in this study) is derived as a by-product.

The algorithm has several new features such as 1) both 11 and 12 µm channels response function are taken into account, 2) not only water vapor continuum absorption but also line absorption with water vapor and other absorbing gases, are taken into consideration and 3) apparent surface temperature is also retrieved and compared to in situ observation such as surface air temperature.

The retrieval algorithm was preliminarily applied to VISSR / GMS-5 data on 00 UTC, October 19, 1997 in particular of all data described in previous section.

a. Retrieval with regressive curve (first step)

In the first step of the algorithm, SWVR method is utilized (Jedlovec 1990). At first, an unit, which contains 32 x 32 pixels around Cape Shionomisaki (33.45 °N, 135.77 °E), was set to make segment analysis. And then, available pixels, judged as least cloud-contaminated, were picked up among the 228 scenes, and then, the statistical value (SWVR) was calculated to retrieve precipitable water for the unit. Fig. 1 illustrates the relationship between the SWVR and precipitable water estimated from the radiosonde data (00 and 12 UTC) at the Cape Shionomisaki.

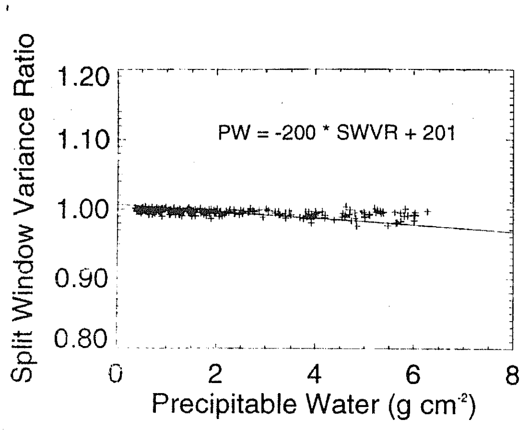

Fig. 1 The relationship between SWVR calculated from VISSR and precipitable water estimated from radiosonde data at Cape Shionomisaki. Dots are the actual data and regressive line is overlaid.

Fig. 1 indicates that linear relationship exists between SWVR and precipitable water. A regressive line was then determined with a least square fitting method:

$$PW = -200 * SWVR + 201. \qquad (1)$$

And then, precipitable water is expected to be retrieved from SWVR for all units of the all scenes. For example, precipitable water, retrieved using Eq. (1), is shown in Fig. 2 for the case of 00 UTC October 19, 1997 around Japan.

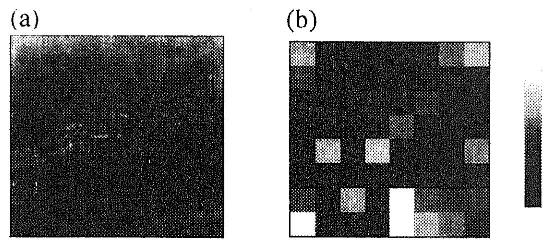

Fig. 2 (a) Water vapor channel (6.7 µm) imagery VISSR / GMS-5 and (b) retrieved precipitable water on 00 UTC (09 JST) October 19, 1997. Displayed region of these panels covers from the left top corner (42.8 °N, 129.2 °E) to the right bottom one (30.0 °N, 142.0 °E) in a uniform interval coordinate in latitudinal and longitudinal directions, and then there exist 256 x 256 pixels in total. A level slice is normalized from white to black with which corresponds from maximum to minimum value for panel (b) and vice versa for panel (a).

Precipitable water is retrieved for one unit which consists of 32 x 32 pixels, then it is found that in Fig. 2 the retrieved precipitable water distribution (panel b) is coarser than the spatial variation of water vapor channel image (panel a). Comparing them, tendency of overall distribution is not very different. But the precipitable water retrieved at the units, which contain mountain region, is smaller than that of their surroundings. The precipitable water retrieved at the units, which seems to contain cirrus, has also the same tendency

Precipitable water estimated from radiosonde data around Japan and that retrieved from the units corresponding to the radiosonde observation sites, are compared to validate the retrieved results on the same scene in Fig. 2. The comparison is illustrated in Fig. 3.

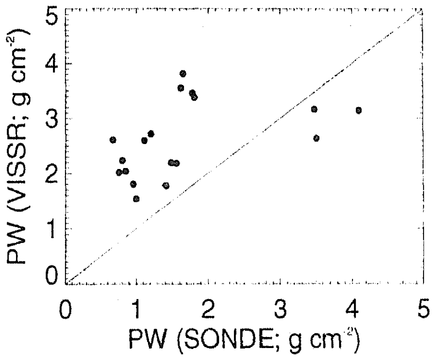

Fig. 3 The comparison of precipitable water (PW) on 00 UTC (09 JST) October 19, 1997 for the same scene in Fig. 2. The abscissa shows the precipitable water estimated from radiosonde data and the ordinate does the one retrieved using split window channels on VISSR. The one-to-one line is drawn as reference.

From Fig. 3, it is found that the retrieved precipitable water using VISSR data overestimates (underestimates) for small (large) precipitable water by about 2 (1) g cm^{-2} around 18 radiosonde observational sites in Japan.

Fig. 4 illustrates the result that the same retrieval method was applied to the VISSR data in a continental scale.

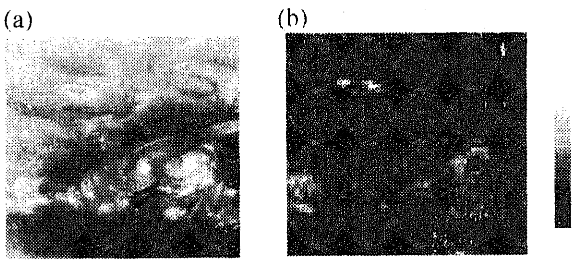

Fig. 4 (a) Water vapor channel (6.7 μm) imagery VISSR / GMS-5 and (b) retrieved precipitable water on 00 UTC (09 JST) October 19, 1997 for the same scene in Fig. 2. Displayed region of these panels covers from the left top corner (70 °N, 70 °E) to the right bottom one (20 °S, 160 °E) in a uniform interval coordinate in latitudinal and longitudinal directions and then, there exist 224 x 224 pixels in total. A level slice is normalized from white to black with which corresponds from maximum to minimum value for panel (b) and vice versa for panel (a).

In Fig. 4, displayed region is as follows: The left panel a (water vapor channel) consists of 224 x 224 pixels whose one pixel is made from average of 8 x 8 original pixels. The right panel b (retrieved precipitable water) also consists of 224 x 224 pixels after each retrieved unit is magnified by factor 4 for each direction, and then 56 x 56 units result in 224 x 224 pixels.

Comparison between Fig. 4a and Fig. 4b, the spatial variation pattern is well consistent at a glance. But there are several regions where variation pattern in each panel is inconsistent: One is the region at the Himalayas and Tibet plateau where topographic effect is not negligible and the other is where high-level clouds exist with typhoons and deep convective cloud system in tropical region.

b. Correction of air temperature (second step)

In the second step of the algorithm, sensitivity of SWVR to precipitable water was examined with model atmosphere. In the model atmosphere, water vapor and other gaseous absorption were taken into consideration as well as water vapor continuum absorption. Response functions of VISSR split window was weighted in the radiance simulation. Fig. 5 illustrates a simulation result.

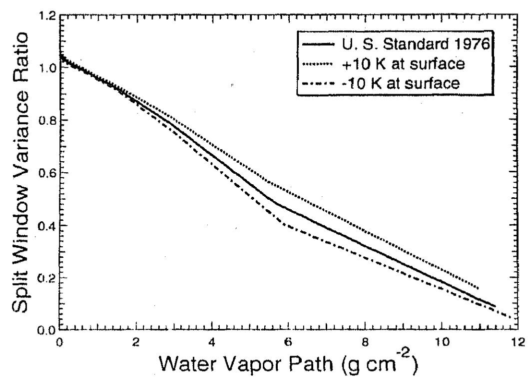

Fig. 5 The relationship between SWVR (ordinate) and Water Vapor Path (abscissa). The U. S. Standard atmosphere 1976 (hereafter USS76), incorporated into the LOWTRAN-7, was assumed as a atmospheric model. It was also assumed that surface radiative temperature in the model ranges from 285 to 295 K uniformly. Solid line is the case for USS76. Dashed line (dotted-dashed) line is the case for which air temperature profile is scaled as the surface air temperature is higher (lower) than USS76 by 10 K.

From Fig. 5, it is found that SWVR estimated using

VISSR data is sensitive to precipitable water in a simply decreasing manner. It is also found that the relationship between SWVR and precipitable water is remarkably affected by air temperature when precipitable water is greater than 2 g cm^{-2}.

As a result, it is desirable to correct air temperature effect and then improve accuracy of the retrieval of precipitable water. The correction method is also based upon Iwasaki (1994) in principle, but a few devices are added: Precipitable water is modified in iterative procedure as air temperature changes under the condition that water vapor volume mixing ratio is constant. A profile of air temperature is also multiplied for all level by the factor of the variation of surface air temperature in the iterative procedure.

As a result of the correction, retrieval accuracy was not improved at all and then the root mean square error was about 2 g cm^{-2}. This indicates that the exactness of regressive curve in the first step is more critical than the correction of air temperature when the retrieval method is applied to the VISSR / GMS-5 split window channel data.

It is now turned out that the regressive curves are different very much between from the actual VISSR data (Fig. 1) and from the simulation with a model atmosphere (Fig. 5). This discrepancy is attributed to the uncertainty of selection of clear sky (uncontaminated with cloud) pixel at this stage. It is then necessary to revise this portion of the algorithm: For example, the analysis unit size will be changed from current 32 x 32 pixels to smaller size (e.g., 16 x 16 pixels) to examine to select the clear sky pixels in the first step of the algorithm.

It is also found that in the second step of the retrieval algorithm, apparent surface temperature is retrieved as well as the improved precipitable water. Compared with an in situ observation, the retrieved apparent surface temperature as a by-product at the unit around the Cape Shionomisaki, was lower by about 2 K than the air temperature of AMeDAS data on that scene.

4. Summary and concluding remarks

To retrieve the precipitable water in a continental scale, a retrieval algorithm has been developed. The algorithm is going to be applicable in principle to the sensor which has the split window channel information such as VISSR / GMS-5 and AVHRR / NOAA. The retrieval algorithm was preliminary applied to the VISSR / GMS-5 data. The retrieved results were not well consistent with the precipitable water estimated from radiosonde observation around Japan. The inconsistency is attributed to the less exactness of regressive curve, rather than the influence of the atmospheric temperature at this stage. Further investigation is required to resolve this discrepancy.

Recently, Barton and Prata (1999) has showed that transmittance ratio method, which was identical to the SWVR method, did not work well and then they recommended to use the approach of split window brightness temperature difference.

The results in this study actually are consistent to their recommendation. It is, then, required the comparison with two retrieval method using the same VISSR / GMS-5 data: One is the brightness temperature difference in split window and the other is the split window variance ratio method.

The retrieval algorithm may also be applicable to AVHRR / NOAA data which has also split window channels, and then it is useful to compare the results each other using both sensor / satellite data. It is planned to compare the retrieved precipitable water to Objective Analysis Data in a continental scale as well. The apparent surface temperature, estimated as a by-product with the atmospheric temperature correction, will be compared with in-situ observational data in detail.

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REFERENCES

Barton, I. J., and A. J. Prata, 1999: Difficulties associated with the application of covariance-variance techniques to satellite imagery. *Remote Sens. Environ.*, **69**, 76-83.

Iwasaki, H., 1994: Estimation of precipitable water over land using the split-window data from the NOAA satellite. *J. Meteor. Soc. Japan*, **72**, 223-233.

Jedlovec, G. J., 1990: Precipitable water estimation from high-resolution split window radiance measurements. *J. Appl. Meteor.*, **29**, 863-877.

Kleespies, T. J., and L. M. McMillin, 1990: Retrieval of precipitable water from observations in the split window over varying surface temperatures. *J. Appl. Meteor.*, **29**, 851-862.

Soden, B. J., and F. P. Bretherton, 1993: Upper troposphere relative humidity from the GOES 6.7 μm channel: Method and climatology for July 1987. *J. Geophys. Res.*, **98**, 16,669-16,688.