Case Study on the Distribution of Precipitable Water Associated with Local Circulation Using the Split-Window Data of a NOAA Satellite

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Abstract

The algorithm of Iwasaki (1994 a) to estimate precipitable water over land was applied to 12 analysis units of a 30×30 array of pixels (about $33 \text{ km} \times 33 \text{ km}$ at the nadir point for NOAA satellites) including mountainous regions, and retrieved volume was compared with microwave radiometer data. The correlation between satellite and radiometer precipitable water was 0.81, slope and the y interception of the regression line are 1.08 and -1.68 mm , respectively.

Using the algorithm, the mesoscale distributions of precipitable water and its time change associated with thermally induced local circulations were visualized under the cloud-free conditions. Precipitable water on the coast increased by 5–20 mm from morning to afternoon. At the same time, precipitable water increased by 0–20 mm over the mountains and decreased by 0–15 mm at the foot of the mountains.

1. Introduction

In regions of topographical contrast, there is often a thermally induced local circulation, which has a large influence on the diurnal variation of wind, water vapor, and convective activity. Precipitable water at Maebashi, located in the center of the semibasin (Fig. 1), exhibits a pronounced diurnal variation in summer days, as shown in Fig. 2. It is considered that the local circulation induced by thermal imbalance between the Kantoh Plane and the surrounding mountains causes the diurnal variation of water vapor (Kimura and Kuwagata, 1995; Kimura and Tanikawa, 1997). The moisture transport from the plane to the mountainous area influences the cumulonimbus activity over the mountains (Kuwagata, 1997; Iwasaki, 1997). Further, Iwasaki and Ohbayashi (1998) suggested that the dry atmospheric condition due to the mesoscale-compensating downdraft of the local circulation prevents deep convection over the semibasin in the afternoon. Although the redistribution of water vapor is very important for the evolution of deep convection, there are few studies on the effect of the variation of water vapor, because of insufficient information about water vapor over the land. It is

necessary to clarify the variation of moisture distribution in order to investigate the influence of the redistribution of water vapor on diurnal convective activity.

Satellite data are useful to elucidate the mesoscale distribution of water vapor over the land, and some algorithms were developed using the split-window channel data (Chester *et al.*, 1983; Kleespies and McMilline, 1990; Jedlovec, 1990; Guillory *et al.*, 1992; Iwasaki, 1994a). Since the methods of Chester *et al.* (1993) and Guillory *et al.* (1992) require information about the vertical profile of temperature, these are not suitable for the semibasin where the diurnal variation is pronounced as shown in Fig. 2. The algorithm of Iwasaki (1994a: referred to as I94) is an extension of Kleespies and McMilline (1990) and Jedlovec (1990), and can estimate precipitable water using only satellite data. Using the algorithm, satellite precipitable water was in good agreement with the sonde observation data launched at Tsukuba (see Fig. 1) with slight undulations. However, the amount of radiosonde data in I94 (4 cases) was far from sufficient to demonstrate the reliability of the algorithm. In estimating precipitable water over the mountains, the variation of precipitable water attributed to the difference of elevation in the “analysis unit” must have considerable contamination, requiring sufficient validation data and some considerations to eliminate the contamination due to mountains.

This paper focuses on the validation of the al-

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Fig. 1. Location of microwave radiometer at the observation site, Maebashi. Symbol (+) indicates the observation site at Gunma University. Contour interval is 500 m.

Fig. 2. Time series of precipitable water observed with the microwave radiometer at Maebashi.

gorithm of I94 for mountains, and application to mesoscale moisture patterns associated with thermally induced local circulation.

2. Satellite data and air-truth data

The data used in this study are the split-window channel data ($11\ \mu\text{m}$ and $12\ \mu\text{m}$) from the Advanced Very High Resolution Radiometer (AVHRR) mounted on NOAA satellites. The spatial resolution at the nadir point, and the temperature resolution, are 1.1 km and about 0.1 K, respectively.

In order to obtain important air-truth data, the observation of precipitable water about every two minutes was carried out using a microwave radiometer from 20 July to 31 August 1995 at Maebashi (Fig. 1). Further, the precipitable water derived from the microwave radiometer was calibrated by radiosonde data launched at the same site.

Data of wind and sunshine duration obtained by the Automated Meteorological Data Acquisition System (AMeDAS) stations of the Japan Meteorological Agency, were used to discuss the reliability

of the mesoscale features of precipitable water.

3. Theory and algorithm

3.1 Theory

The algorithm of I94 is an extension of the two-points technique (Kleespies and McMillin, 1990) and the split-window variance ratio technique (Jedlovac, 1990). These algorithms assume the atmospheric conditions in which temperature and water vapor are invariant for all pixels in an analysis unit, and the surface condition in which the emissivity of each pixel for 11 μm and 12 μm channels are the same. The main variables of the two-points technique is satellite observed blackbody brightness temperature (T_{BB}) and total atmospheric transmittance (τ). The square of the transmittance ratio of 11 μm and 12 μm can be written as,

$$\left(\frac{\tau_{12}}{\tau_{11}}\right)^2 = \left(\frac{T_{BB}^A{}_{12} - T_{BB}^B{}_{12}}{T_{BB}^A{}_{11} - T_{BB}^B{}_{11}}\right)^2, \quad (1)$$

where the subscripts refer to the 11 μm and 12 μm channels, the superscripts A and B refer to two observation points where surface temperatures are markedly different. Since precipitable water is directly related to the transmittance ratio, precipitable water can be estimated from satellite data. This technique is the key to estimating the first-guess transmittance ratio and checking the quality of satellite data (see Fig. 5) in the algorithm of I94. Jedlovac (1990) extended this idea for a small unit where the variation of surface temperature is not large enough for use of the two-points technique. Eq. (1) can be rewritten as,

$$\left(\frac{\tau_{12}}{\tau_{11}}\right)^2 = \left(\frac{\sigma_{12}}{\sigma_{11}}\right)^2, \quad (2)$$

where, σ is the spatial variance of T_{BB} over a unit. The precise transmittance ratio is calculated using Eq. (2).

Using this algorithm of I94, precipitable water is estimated for a unit of a 30×30 array of pixels (about $33 \text{ km} \times 33 \text{ km}$ at the nadir point for NOAA satellites). The algorithm has three advantages in comparison with the previous technique:

- 1) low-confidence pixels contaminated with sub-grid scale clouds and some noise are removed in the process of determining the first-guess variance ratio using the two-points technique,
- 2) the quality check of satellite data is simple using the transmittance ratio,
- 3) the first-guess temperature profile does not have a serious influence on the accuracy, because the temperature profile in the model atmosphere is adjusted to the actual temperature

profile using the modified averaged air temperature in the linearized form of the radiation transfer equation.

3.2 Elimination of noisy pixels in advance of main procedure

Mt. Akagi and Mt. Haruna are over 1600 m above sea level and about 20 km from the observation site of the microwave radiometer (see Fig. 1). The difference of elevation between the mountains and the observation site reaches over 1400 m in a unit. Since the algorithm assumes that the atmospheric conditions are invariant for all pixels in the unit, the variation of precipitable water due to the difference of elevation in the unit must have considerable contamination. The influence is more serious for the estimation over the mountains.

In addition, a water surface also lowers the accuracy of the estimation because of the different characteristics of surface emissivity compared to a land surface. Elimination of these noisy pixels before the main procedure can result in higher accuracy.

Determination of these noisy pixels in this paper is as follows. The position of each pixel is calculated by orbit prediction considering the variation of the three-dimensional satellite posture, and then the elevation and surface type of the pixel are determined using digital map data. Any pixels 250 m higher or lower than the center of the unit, as well as the pixels corresponding to water surfaces and clouds, were removed before the main procedure. If noisy pixels occupied more than 80 %, the calculation did not execute for the analysis unit. These elimination of noisy pixels were new consideration in this paper.

4. Comparison of satellite precipitable water with precipitable water derived from a microwave radiometer

The algorithm was applied to 12 cases, and the retrieved values of precipitable water were then compared with radiometer data. Figure 3 shows the results of the comparison. The symbols of closed circles and triangles indicate retrieved values with (Case A) and without (Case B) the elimination of pixels corresponding to high elevation, respectively. Table 1 shows regression equations for two cases by least square method.

The results of the algorithm for Case B show a smaller correlation than Case A, and underestimation for the conditions of higher precipitable water. Further, slope of the linear regression is less than 0.6 and the y interception is larger than 13 mm. On the other hand, the satellite precipitable water for Case A are in better agreement with the radiometer observations. The correlation is 0.81, and slope of the regression line is nearly 1.0 and the y interception is only -1.68 mm . These results indicate that the

Fig. 3. Scatter diagram of the relationship between satellite precipitable water and precipitable water from the radiometer. The closed circles (Case A) and triangles (Case B) indicate the precipitable waters using the algorithm with and without the elimination of mountains, respectively.

algorithm with the elimination of mountainous pixels has the ability to clarify the moisture variation associated with thermally induced local circulation.

5. Mesoscale features of precipitable water distribution over the Kantoh District

The distributions of precipitable water in this section are computed by shifting the center of the unit by 0.1 degree in latitude and longitude. Figure 4 shows the distribution of satellite-precipitable water over the Kantoh District at 1440 LST on 27 July. The distribution of albedo is also superimposed in Fig. 4. White areas over the land correspond to shallow clouds.

5.1 A quality check

The mesoscale variation of precipitable water is well recognized over the land. Some smaller areas of low precipitable water less than about 25 mm, and of high precipitable water more than about 45 mm around cloud areas and over the mountains, must be noise due to cloud and/or orographic contamination. Such a fine spatial resolution is not anticipated using the algorithm.

A large gradient of precipitable water exists between units A, B, and C. Although the difference reaches 15 mm between units A and B separated by the distance of only 50 km, these features are qualitatively reliable at least. A quality check of NOAA satellite data for the three units was made following

Table 1. Regression equations for Cases A and B.

Case	Regression equation	R	RMS
A	$PW_{NOAA} = 1.08 * PW_{MWR} - 1.68$	0.81	3.65 mm
B	$PW_{NOAA} = 0.58 * PW_{MWR} + 13.3$	0.73	3.78 mm

I94. Figure 5 shows the histogram of the square of the transmittance ratio calculated by Eq. (1) using the two-points technique. All transmittance ratios should be equal to each other under ideal conditions. The frequency of the transmittance ratio expands due to the lack of uniformity of surface emissivity, air temperature and water vapor in the analysis unit; however, clear peaks in the histograms should be recognized as long as the noise is not serious (see Fig. 7 in I94). Clear peaks for all units are evidence of the sufficiently high quality of satellite data.

Although the peak frequency for unit B is very low, it does not necessarily mean serious noise. The reason for the low peak is that the number of pixels decreased due to elimination of many apparent cloud and ocean pixels before the main procedure. It is considered that cloud contamination, and/or mechanical noise, do not have a serious influence on the large gradient of precipitable water in Fig. 4.

5.2 Mesoscale distribution of precipitable water

There is a cloud line corresponding to the sea-breeze front over the Bouso Peninsula in Fig. 4. Surface winds obtained by AMeDAS suggest that strong convergence occurred on the coastal side of the front (not shown), where high precipitable water over 45 mm is observed. Besides the Bouso Peninsula, precipitable water over the coast tends to be large.

Observational studies revealed that the sea breeze transports moister air inland (*e.g.*, Simpson *et al.*, 1977; Yoshikado and Kondo, 1989). It is considered that moisture transport and surface convergence due to the sea breeze contribute to high precipitable water along the coast.

Over the interior, high precipitable water around unit A and low precipitable water around unit B are recognized for daytime satellite observations on 26 and 28 July 1995 (not shown). These high and low precipitable water areas will be discussed in the next section. However, it should be noted that mesoscale features in precipitable water appear over the land under the cloud-free conditions, which has much in common with the results of Jedlovec (1990) and Iwasaki (1994b).

6. Discussion on the time change of precipitable water associated with local circulation

The Kantoh District was observed by NOAA satellites at 0730 and 1430 LST on 28 July. Fig-

Fig. 4. Distribution of precipitable water from satellite at 1240 LST on 27 July. Albedo is also superimposed.

ure 6 shows the time change of precipitable water during about 7 hours. Yellow areas indicate ocean and cloud units on either imagery. The increment of radiometer precipitable water at Maebashi is about 4 mm as shown in Fig. 2, which is consistent with the satellite observations.

6.1 Remarkable increment in precipitable water over the interior

Over the coasts of both the Pacific Ocean and the Japan Sea, precipitable water generally increased due to the progress of the sea breeze. Over the interior, mesoscale variations were apparent in the increment and decrement of precipitable water. As shown in the previous section, a high precipitable water area is often observed north of the Tokyo Metropolitan area. The remarkable increment in precipitable water around (35.9N, 139.4E) in Fig. 6 corresponds to the high precipitable water area. According to Fig. 7, the wind field seems to converge south of the high precipitable water area in Fig. 4. This convergence was observed from 1200 to 1900 LST.

The relationship between the mesoscale convergence zone and the high precipitable water area is similar to the results of Iwasaki (1994b). Sunshine duration around the high precipitable water decreased markedly due to shallow convection at

1500 LST. The relationship between the high precipitable water area and the evolution of shallow convection is consistent with the results of Jedlovec (1990).

Kuwagata (1997) showed that strong convergence north of the Tokyo Metropolitan area is a common feature of summer days, and the sea-breeze front in this region is intensified by the heat island effect of the city. The numerical studies of Kimura and Takahashi (1991), and Yoshikado (1992) support his idea. It can be expected that the sea-breeze front affected by the heat island contributes to the high precipitable water area. However, it does not seem that this high precipitable water area is directly related to the initiation of deep convection during the analysis period of 1995.

6.2 Time change of precipitable water over the mountains

Figure 8 indicates the increment of precipitable water and averaged elevation along band A-B in Fig. 6. Besides the coast, a significant increment of precipitable water was recognized over the mountains ($X = 80\text{--}130$ km). An increase of 5–15 mm over the mountains was also observed around (36.8N, 138.7E) and (35.6N, 138.2E) in Fig. 6. Kimura and Tanikawa (1997) revealed that sonde

Fig. 5. Histogram of the square of the transmittance ratio for units A, B, and C in Fig. 4.

precipitable water increased by 7–9 mm from 0600 to 1500 LST on 26 and 27 July 1995 at Marunuma. The time change of satellite precipitable water over the mountains is consistent with their sonde observation.

At the same time, precipitable water changed little or decreased at the foot of the mountains around 500–1000 m above sea level ($X = 50$ – 80 km and 130 – 160 km). When thermally induced upward motion dominates over the mountains on fine summer days, a compensating subsidence occurred in the surrounding area, which has the role of transporting dry air to the lower troposphere. The contrast of precipitable water would be attributed to the moisture transport due to the thermally induced local circulation. Split-window data now, for the first time, provide observations of the whole feature of the redistribution of water vapor studied by Kimura and Kuwagata (1995) and Kimura and Tanikawa (1997).

6.3 Time change of precipitable water over the basin and coastal regions

Precipitable water decreased over the Kofu Basin around (35.4°N , 138.5°E) and north of Tokyo Bay. Kimura (1994) showed that sunshine duration at the Kofu Basin has a tendency to increase around

Fig. 6. Distribution of the increment of precipitable water from 0730 to 1430 LST on 28 July. Contour is 1000 m.

8–12 LST due to the compensating mesoscale downdraft on fine summer days. Fujibe and Asai (1979) pointed out that clear divergence was recognized in the afternoon over Tokyo Bay associated with a regional-scale sea breeze. The decreases of precipitable water were consistent with these previous analyses.

These mesoscale features of precipitable water are consistent with the surface wind field and the previous studies. However, precipitable water over the convergence zone is somewhat large, where the atmospheric conditions are variant. Further validation is required over the areas of variable atmosphere and surface conditions.

7. Summary

The algorithm to estimate precipitable water over the land using split-window data from the NOAA satellites was developed in order to obtain data over the mountains. The following results were obtained.

- 1) Satellite precipitation water was compared with precipitable water from a microwave radiometer 12 cases, and the correlation and root-mean-square error are 0.81 and 3.65 mm, respectively.
- 2) Mesoscale variation in precipitable water was well recognized over the land even under cloud-free conditions.

Fig. 7. Distribution of wind vectors and sunshine duration. (a) wind field at 1400 and sunshine duration from 1300 to 1400 LST on 27 July. (b) wind field at 1500 and sunshine duration from 1400 to 1500 LST on 27 July.

Fig. 8. Increment of precipitable water and averaged elevation along line A₁₋₃-B₁₋₃ in Fig. 6.

- 3) Over the coasts of the Pacific and Sea of Japan, precipitable water increased by 10–20 mm from morning to afternoon.
- 4) The algorithm can visualize the variation of precipitable water due to thermally induced local circulation from morning to afternoon. Precipitable water over the mountains increased by 0–20 mm; at the same time, precipitable water decreased by 0–15 mm at the foot of the mountains at 500–1000 m above sea level.

These features are consistent with the previous observational studies of the thermally induced local circulation. The results from the present study indicate that this algorithm has the ability to clarify the evolution of moisture variations in the pre-storm stage.

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NOAA 衛星の Split-window データを用いた熱的局地循環に伴う 可降水量分布に関する事例解析

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NOAA 衛星の Split-window データを用いて陸域の可降水量を見積もる Iwasaki (1994) のアルゴリズムを 30 画素×30 画素からなる山岳域を含んだ解析単位について応用し、マイクロ波放射計で得られた可降水量と比較した。12 事例について比較した結果、回帰直線の傾きは 1.0 に近く、y 軸切片も -1.68 mm と小さく、相関係数は 0.81 と良好な結果を得た。

このアルゴリズムを使うことで、熱的局地循環に伴う晴天域のメソスケールの可降水量分布とその時間変化を可視化できた。熱的局地循環が卓越した 1995 年 7 月 28 日の 07 時 30 分から 14 時 30 分の間に、海岸付近では可降水量が 5-20 mm 増加していた。山岳域では可降水量は 0-20 mm 増加し、逆に、山麓では可降水量が 0-15 mm 減少していた。