A Method to Retrieve Precipitable Water Content Using a Microwave Spectro-Radiometer

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Abstract

A new method, utilizing a 22.235 GHz-water vapor emission line, to retrieve precipitable water content (PWC) is proposed. To obtain PWC, the method includes estimating the portion of the water vapor contribution to the brightness temperature, integrated over the microwave K-band (18–26.5 GHz) range. It is appropriate to use the K-band range in order to retrieve PWC because the emission (or absorption) in this frequency range is weak and the line strength is little dependent on atmospheric temperature and pressure.

By using several atmospheric models with typical cloud types, the following approximate relation to retrieve PWC is introduced:

$$\text{PWC} = a\hat{T}_{b,H_2O} + b \text{ (g/cm}^2\text{)}$$

where $a = 0.2135 \pm 0.0021$, $b = -0.0420 \pm 0.0251$,

$$\hat{T}_{b,H_2O} = \frac{1}{\Delta f} \int_{f_1}^{f_2} T_{b,obs}(f) df - [T_{b,obs}(f_2) + T_{b,obs}(f_1)]/2 + \Delta T_b.$$

$T_{b,obs}(f)$ is a brightness temperature observed at a frequency of f GHz, and f_1 and f_2 are lower and upper boundary frequencies for integration, which are 18 and 26 GHz, respectively, and $\Delta f = f_2 - f_1$. ΔT_b is a correction factor for the term correcting cloud and water vapor continuum emission. It is best for ΔT_b to be set at 0.2 K empirically.

By using actual radiosonde data along with clouds introduced depending on atmospheric conditions, an error is determined from the above approximate method for retrieval of PWC. The error for PWC is less than 5 % under the average atmospheric condition (PWC > 1 g/cm² and liquid water path (LWP) < 0.1 g/m²), and is about 6 % for rather cool atmospheric conditions (PWC < 1 g/cm² and LWP < 0.01 g/m²).

1. Introduction

Precipitable water content (PWC) is one of the most important parameters in understanding the physical mechanism of cloud formation, development and global water circulation. The amount of water vapor has a strong variation in time and space. A radiosonde measurement is the most popular way to measure PWC directly. Recently, according to an advance in microwave techniques, PWC can be measured from an observation of microwave emission of atmospheric water vapor. The microwave technique has the advantages of continuous measurements, easy operation and portability compared with the traditional way (Westwater, 1978; Guiraud, *et al.*, 1979; Elgered, 1982; Hogg *et al.*, 1983; Rocken *et al.*, 1991).

Two different methods have been developed in order to measure PWC, one of which is an absorption method using a near-infrared water vapor absorption band, and the other is a measurement method of microwave radiation emitted by atmospheric water vapor. The absorption method uses solar radiation as a light source and utilizes a weak absorption band of 0.94 μm in the near-infrared (Bird and Hulstrom, 1982; Thome *et al.*, 1992). This method has the disadvantage of unavailable measurements during night time and cloudy day. For microwave measurements, two absorption frequencies of 22.235 and 183.3 GHz, are mainly used. The 22.235 GHz absorption line is weak, and thus shows a low optical thickness and is relatively transparent under usual atmospheric conditions. Therefore, it is appropriate to use 22.235 GHz-line in order to obtain the PWC from a ground-based radiometer

and to map the global distribution of PWC from a satellite-borne radiometer (Staelin *et al.*, 1976). Westwater and Falls (1989) reported a good agreement between ground-based radiometer measurements and radiosonde measurements. On the other hand, using the strong absorption line of 183.3 GHz enables one to retrieve a vertical distribution of water vapor density (Schaerer and Wilheit, 1979; Rosenkranz *et al.*, 1982; Kakar, 1983). The microwave measurement has superior characteristics under cloudy skies than the near-infrared measurement.

Some algorithms have been developed to measure PWC. The representative method is a statistical inversion technique associated with a dual-frequency measurement (Ulaby *et al.*, 1986). An important point in this method is to select an appropriate set of wavelengths which give no or very small dependence on atmospheric temperature and pressure, and to estimate or correct for the effect of cloud liquid amounts (or Liquid Water Path, LWP, as a column integration). The frequencies such as 20.6 (Westwater, 1978; Guiraud *et al.*, 1979), 23.9 GHz (Rocken *et al.*, 1991) which are sensitive to water vapor and the frequency 31.4 GHz (sensitive to cloud liquid water) are employed. A great advantage in the algorithm is simultaneous determination of PWC and LWP using both optical thicknesses. The coefficients of their linear regression have some dependence on atmospheric temperature profiles, and thus modified coefficients may be required for measurements under largely different atmospheric conditions, such as in a polar or tropical region.

Since the water-vapor line strength at 22.235 GHz has weak dependence on atmospheric temperature and pressure, precipitable water content can also be derived from a spectral integration of brightness temperature over the K-band microwave frequencies, which include the water vapor absorption line. Thus the method presented in this paper shows minimal influence of the atmospheric condition in determining PWC. In Section 2, theoretical background of the microwave radiometry is summarized and, in Section 3, the estimation formula of the new method and an error analysis are described. Finally, a few concluding remarks are given in Section 4.

2. Theoretical background

The brightness temperature $T_{b,f}$, at the frequency f GHz, received by a ground-based radiometer is determined by the following equation:

$$T_{b,f} = \frac{1}{\mu} \int_0^\infty T(z) \kappa_f e^{-\tau_f(0,z)/\mu} dz + T_{\cos} e^{-\tau_f(0,\infty)/\mu},$$

where $T(z)$ denotes atmospheric temperature profile, $\tau_f(0, z) = \int_0^z \kappa_f dz$ is the atmospheric optical thickness at the altitude z from the surface at the frequency f GHz, θ is the zenith angle, $\mu = \cos(\theta)$,

and κ_f is the absorption coefficient of the atmosphere. $T_{\cos}$ represents the background radiation from outer space.

The above equation can be changed into the following expression consisting of each part of the absorbing medium, such as oxygen, water vapor, cloud liquid and rain:

$$\begin{aligned} T_{b,f} &= \frac{1}{\mu} \int_0^\infty T(z) [\kappa_{O_2,f} + \kappa_{H_2O,f} \\ &\quad + \kappa_{Cld,f} + \kappa_{Rain,f}] e^{-\tau_f(0,z)/\mu} dz \\ &= \int_0^\infty [W_{O_2,f}(z) T(z) + W_{H_2O,f}(z) \rho(z) \\ &\quad + W_{Cld,f}(z) m(z) + W_{Rain,f}(z) r(z)] dz, \end{aligned} \quad (1)$$

where

$$\begin{aligned} W_{O_2,f}(z) &= \frac{1}{\mu} \kappa_{O_2,f}(z) e^{-\tau_f(0,z)/\mu}, \\ W_{H_2O,f}(z) &= \frac{1}{\mu} T(z) \kappa_{H_2O,f}(z) / \rho(z) e^{-\tau_f(0,z)/\mu}, \\ W_{Cld,f}(z) &= \frac{1}{\mu} T(z) \kappa_{Cld,f}(z) / m(z) e^{-\tau_f(0,z)/\mu}, \end{aligned}$$

and

$$W_{Rain,f}(z) = \frac{1}{\mu} T(z) \kappa_{Rain,f}(z) / r(z) e^{-\tau_f(0,z)/\mu}. \quad (2)$$

Equation 2 expresses weighting functions for oxygen, water vapor, cloud droplets and rainfall. $\rho(z)$ is the water vapor density (g/m^3) at altitude z , and $m(z)$ and $r(z)$ indicate the liquid water content (g/m^3) and the rainfall rate (mm/h), respectively. In our current estimation, we assume that no rain falls in any place or at any time. The cloud is supposed to consist of water droplets only because the absorption coefficient of ice crystals is much smaller than that of water droplets (Ulaby *et al.*, 1981).

Figures 1a and 1b show weighting functions of water vapor ($W_{H_2O,f}(z)$), as indicated in Eq. 2 at some microwave frequencies. Two different atmospheric models, tropical (a) and mid latitude winter (b), described in McClatchey *et al.* (1972) are used in this calculation. These figures, (a) and (b), have almost the same trend in spite of a big difference in both temperature profiles and a weak dependence of weighting function on an altitude at around 21 and 23 GHz. These frequencies correspond to the water vapor channel to retrieve PWC in a dual-frequency method. However, both curves of the weighting function have a slight difference in absolute value, reflecting the difference between the two profiles, which may result in an error in the PWC estimation.

The line strength of a weak and an isolated absorption line of water vapor, which is equivalent to the integral of the absorption coefficient over the absorption line, should be proportional to water vapor

Fig. 1. The weighting function for water vapor. The figures (a) and (c) are based on the McClatchey's tropical model and figures (b) and (d) on the mid-latitude winter. Figures (a) and (b) show the weighting functions for a single frequency and Figures (c) and (d) are the frequency-averaged weighting functions.

content. Due to Kirchhoff's law, the brightness temperature integrated over the absorption line will be also proportional to water vapor content (or PWC as a columnar content of water vapor), if a radiometer can measure brightness temperature over a wide frequency range of the spectrum including the water vapor absorption line. As given in Ulaby *et al.* (1981), the absorption coefficient of 22.235 GHz is given by

$$\kappa_{H_2O,f} = \left(\frac{4\pi}{c} f \right) S_{lm} F_g(f, f_{lm}), \quad (3)$$

where c is the velocity of light, S_{lm} is the line strength of the absorption from a state l to a state m , f_{lm} is the center frequency of this transition and F_g is the line shape. Ulaby *et al.* (1981) compiled in his text that the Gross line shape agrees well with

the past experimental results. The temperature dependence of S_{lm} in Eq. 3 is as follows;

$$S_{lm} \propto T^{-5/2} e^{-\varepsilon_l/kT} \propto T^{-5/2} e^{-644/kT}, \quad (4)$$

where k is Boltzmann's constant and ε_l is the energy level of the state l . In Table 1, the temperature dependence is summarized for a temperature range expected in usual atmospheric conditions. As seen in the table, the line strength has a very weak dependence on temperature within a 5 % error for the tropospheric atmosphere. The above error will decrease because the water vapor concentrates in the lower troposphere. Thus, a spectral absorption measurement covering the water vapor absorption line can be expected to show little temperature dependence for PWC estimation, *i.e.*, the weighting

Fig. 1. (Continued)

function of water vapor should be little dependent on atmospheric temperature, as described later.

On the other hand, in this paper a microwave measurement using a radiometer is based on the emissions by absorption matter in the atmosphere. An averaged brightness temperature is then defined over a frequency range from f_1 to f_2 and calculated using the following equation with the assumption of no raining:

$$\begin{aligned}\bar{T}_b &= \frac{1}{\Delta f} \int_{f_1}^{f_2} T_{b,f} df \\ &= \bar{T}_{b,O_2} + \bar{T}_{b,H_2O} + \bar{T}_{b,Cloud},\end{aligned}\quad (5)$$

where $\Delta f = f_2 - f_1$. The mean brightness temperature $\bar{T}_{b,H_2O}$ due to water vapor over a frequency range from f_1 to f_2 GHz in Eq. 5 can be derived by putting $T_{b,f}$ of Eq. 1 into Eq. 5. We get

$$\bar{T}_{b,H_2O} = \int_0^\infty \rho(z) \bar{W}_{H_2O}(z) dz, \quad (6)$$

where

$$\begin{aligned}\bar{W}_{H_2O}(z) &= \frac{1}{\mu \Delta f} \int_{f_1}^{f_2} T(z) \kappa_{H_2O,f}(z) / \rho(z) e^{-\tau_f(0,z)/\mu} df.\end{aligned}$$

In Eq. 6, we assume four frequency combinations for f_1 and f_2 , including the 22.235 GHz absorption line. These are 10–40 GHz, 15–35 GHz, 15–30 GHz and 18–26 GHz. The frequency range of 18–26 GHz (K-band) is the maximum frequency range covered by a single unit of a variable-frequency radiometer.

Figures 1c and 1d show two examples of the frequency-averaged weighting function for the tropical and mid latitude winter atmospheric model, respectively. Both figures were calculated by the same models as in Figs. 1a and 1b. Compared with each corresponding figure, it is clear that the frequency-averaged weighting function is relatively independent of altitude, especially for the case of 4.

Table 1. Temperature dependence of 22.235 GHz water vapor line strength.

T_1 (K)	$(T_1/T_0)^{-5/2}$	EXP $(-644/T_0^*(T_0/T_1-1))$	S_{lm1}/S_{lm0}
330	0.7880	1.2155	0.9578
300	1.0000	1.0000	1.0000
270	1.3013	0.7878	1.0252
240	1.7469	0.5847	1.0214
210	2.4392	0.3985	0.9721

where $T_0=300$ K.

Table 2. Cloud models employed in the simulation.

Cloud Model	Cloud base (m)	Cloud top (m)	Density (g/m ³)	Liquid water path (g/cm ²)
Low-lying stratus	500	1000	0.25	1.25E-02
Fog layer	0	50	0.15	7.50E-04
Haze, heavy	0	1500	0.001	1.50E-04
Fair-weather cumulus	500	1000	0.5	2.50E-02
Cumulus congestus	1600	2000	0.8	3.20E-02

Thus, it is expected that the PWC is proportional to the $\bar{T}_{b,H_2O}$:

$$\text{PWC} = a \cdot \bar{T}_{b,H_2O}. \quad (7)$$

The estimation of PWC is then reduced to the derivation of $\bar{T}_{b,H_2O}$. The coefficient a in Eq. 7 is, however, required to be known for estimating PWC.

3. Water vapor estimation

3.1 Estimation formula

We simulate a relationship between mean brightness temperature and PWC using the McClatchey's atmospheric models with five cloud types (Ulaby *et al.*, 1981), as seen in Table 2. A cirrus cloud is not adopted because it consists wholly of ice crystals. These models are suitable for typical climatic regions and contain cloud types with appropriate liquid water paths. The clouds incorporated in the atmospheric models include super-cooled water droplets for atmospheric temperatures below 0°C. The absorption coefficients of water vapor, liquid water droplets and oxygen are quoted from H.J. Liebe (1985).

The computational results are summarized in Table 3 and shown in Fig. 2. The integral increment df was 1 GHz, using a trapezoidal formula. The excellent relationship between mean brightness temperature by water vapor and PWC is shown in Fig. 2 and is as expected above in spite of existing clouds. The four frequency cases mentioned earlier have almost the same deviations, and the temperature sensitivity for PWC becomes higher as the frequency range becomes narrower. The usage of the 18–26 GHz spectrum is most advantageous among the four frequency bands, because of the highest sensitivity for the $\text{PWC}/\bar{T}_{b,H_2O}$. A narrower spectrum than that

of 18–26 GHz will give improved sensitivity, but the dependency on the atmospheric temperature will get worse, coming near that for a single-frequency measurement. The relationship between PWC and the mean temperature is as follows:

$$\begin{aligned} \text{PWC} &= a \cdot \bar{T}_{b,H_2O}, \\ a &= 0.0933 \pm 0.0019 \text{ (g/cm}^2\text{/K)}. \end{aligned} \quad (8)$$

Since it is difficult to get the $\bar{T}_{b,H_2O}$ separately from observed temperature ($T_{b,obs}(f)$), a new equation is defined for the averaged brightness temperature due to water vapor and is given below:

$$\begin{aligned} \hat{T}_{b,H_2O} &= \frac{1}{\Delta f} \int_{f_1}^{f_2} T_{b,obs}(f) df \\ &\quad - [T_{b,obs}(f_2) + T_{b,obs}(f_1)]/2 + \Delta T_b, \end{aligned} \quad (9)$$

where the second term of the right-hand side of the equation shows the effects due to oxygen and cloud liquid. This term also includes a continuum absorption due to water vapor and gives a small over-subtraction, because the continuum absorption is proportional to the square of the frequency (Liebe and Layton, 1987). Only the small difference is empirically corrected by the last term ΔT_b through model calculations, being set at 0.2 K for the frequency range of 18 to 26 GHz. Thus, $\hat{T}_{b,H_2O}$ in Eq. 9 is basically proportional to the PWC.

Figure 3 depicts variations of the average brightness temperature versus precipitable water for McClatchey's atmospheric models with the five cloud types shown in Table 2. It should be noted that the sensitivity of the $\hat{T}_{b,H_2O}$ to the PWC is lower compared to that of the $\bar{T}_{b,H_2O}$ of Eq. 8. This may be caused by the effect of water vapor included in the subtraction term of Eq. 9. An extension of the

Table 3. Summary of the mean brightness temperature simulated with and without cloud models. The frequency range is from 18 to 26 GHz. The column $\bar{T}_b$ indicates the mean brightness temperature of all the emission media. The other three columns, $\bar{T}_{b,o2}$, $\bar{T}_{b,h2o}$ and $\bar{T}_{b,cl d}$, indicate the partial contribution of oxygen, water vapor and cloud to the mean brightness temperature, respectively.

Atmosphere	Cloud	PWC (g/cm ²)	LWP (g/cm ²)	$\bar{T}_b$ (K)	$\bar{T}_{b,O2}$ (K)	$\bar{T}_{b,h2o}$ (K)	$\bar{T}_{b,cl d}$ (K)	PWC/ $\bar{T}_{b,h2o}$
Tropical	No Cloud	4.168	0.00E+00	48.4	3.3	45.1	0.0	0.0925
	Low-lying Stratus	4.168	1.26E-02	50.2	3.3	44.8	2.1	0.0930
	Fog Layer	4.168	7.83E-04	48.5	3.3	45.0	0.1	0.0925
	Haze Heavy	4.168	1.50E-04	48.4	3.3	45.1	0.0	0.0925
	Fair-weather Cumulus	4.168	2.51E-02	52.0	3.3	44.6	4.1	0.0935
	Cumulus Congestus	4.168	3.21E-02	53.6	3.3	44.7	5.6	0.0933
Mid-Latitude Summer	No Cloud	2.968	0.00E+00	36.0	3.5	32.5	0.0	0.0913
	Low-lying Stratus	2.968	1.25E-02	38.1	3.5	32.3	2.3	0.0918
	Fog Layer	2.968	7.67E-04	36.1	3.5	32.5	0.1	0.0913
	Haze Heavy	2.968	1.50E-04	36.0	3.5	32.5	0.0	0.0913
	Fair-weather Cumulus	2.968	2.50E-02	40.1	3.4	32.2	4.5	0.0923
	Cumulus Congestus	2.968	3.19E-02	41.8	3.4	32.2	6.1	0.0921
Mid-Latitude Winter	No Cloud	0.867	0.00E+00	13.3	4.0	9.4	0.0	0.0927
	Low-lying Stratus	0.867	1.25E-02	16.9	3.9	9.3	3.7	0.0937
	Fog Layer	0.867	7.67E-04	13.5	4.0	9.3	0.2	0.0928
	Haze Heavy	0.867	1.50E-04	13.4	4.0	9.4	0.0	0.0927
	Fair-weather Cumulus	0.867	2.50E-02	20.4	3.9	9.2	7.4	0.0948
	Cumulus Congestus	0.867	3.19E-02	23.1	3.9	9.2	10.0	0.0944
Subarctic Summer	No Cloud	2.109	0.00E+00	26.7	3.6	23.1	0.0	0.0913
	Low-lying Stratus	2.109	1.25E-02	29.2	3.6	22.9	2.7	0.0920
	Fog Layer	2.109	7.67E-04	26.9	3.6	23.1	0.2	0.0913
	Haze Heavy	2.109	1.50E-04	26.8	3.6	23.1	0.0	0.0913
	Fair-weather Cumulus	2.109	2.50E-02	31.7	3.6	22.8	5.4	0.0926
	Cumulus Congestus	2.109	3.19E-02	34.0	3.6	22.8	7.6	0.0925
Subarctic Winter	No Cloud	0.423	0.00E+00	8.6	4.2	4.4	0.0	0.0952
	Low-lying Stratus	0.423	1.25E-02	13.3	4.1	4.4	4.8	0.0967
	Fog Layer	0.423	7.67E-04	8.9	4.1	4.4	0.3	0.0952
	Haze Heavy	0.423	1.50E-04	8.7	4.2	4.4	0.1	0.0952
	Fair-weather Cumulus	0.423	2.50E-02	17.9	4.0	4.3	9.5	0.0981
	Cumulus Congestus	0.423	3.19E-02	20.9	4.0	4.3	12.5	0.0976
								0.0932 (Average)
								0.0019 (Std Dev)

frequency range reduces the sensitivity and distinguishes the cloud effects. The K-band (18–26 GHz) has the most suitable response among the listed four spectrum bands in estimating PWC. So the linear regression equation for the K-band is given as:

$$PWC = a\hat{T}_{b,H_2O} + b,$$

(10)

where $a = 0.2135 \pm 0.0021$, $b = -0.0420 \pm 0.0251$. $\hat{T}_{b,H_2O}$ is the partial contribution of water vapor to the brightness temperature which can be derived from the observed brightness temperature, as shown in Eq. 9.

Equation 10 in the proposed method is applicable only for upward-looking use (or ground based observation). We need more information about surface emissivity covering the 18–26 GHz frequency range when this method is applied to a downward-looking observation. This is basically common with the dual-frequency method. The present method

for downward use may, however, prove able to estimate PWC by eliminating the emissivity effect, if the emissivity can be assumed to be constant within the K-band range. This assumption is not available in general. The surface emissivity strongly depends not only on surface structure (roughness), temperature and wetness but also on the microwave frequency.

3.2 Error analysis

The proposed method has a great advantage over the dual-frequency approach. There is not only little temperature dependence of the weighting function but a large tolerance of the brightness temperature because this method requires the relative spectrum shape of brightness temperature. The absolute error in brightness temperature reflects the estimation error in PWC directly for the conventional method, but has no or little relation with the PWC-

Fig. 2. Variation of the mean brightness temperature of water vapor as a function of the frequency integration range. McClatchey's atmospheric models are employed with five cloud models shown in Table 2.

Fig. 3. Same as in Fig. 2, but the mean brightness temperature is calculated from Eq. 9 in the text.

estimation accuracy for this method. This allows a large tolerance in absolute temperature calibration of the radiometer. On the other hand, more time is required to scan the frequency range for measurement. In addition, a stable atmospheric condition is required during the frequency scanning. However, these requirements should be overcome by technical progress.

The uncertainty in an estimated PWC comes from measurement errors in Eq. 9 and from the regression analysis in Eq. 10. While the error in absolute accuracy of the brightness temperature virtually reduces due to the characteristics of the relative difference expression in Eq. 9, the estimated value of the PWC in Eq. 10 has a 1 % error of the estimated value plus

$\pm 0.0251 \text{ g/cm}^2$ statistically. When it is assumed that the observed brightness temperature has a random error $\Delta T_{b,obs}$ of 0.1, 0.5 and 1.0 K, the error in PWC will be 0.021, 0.107 and 0.214 g/cm^2 plus $\pm 0.0251 \text{ g/cm}^2$, respectively.

The validity of the proposed method was checked through a simulation of Eq. 10 using radiosonde data at Sapporo (43.05N, 140.13E), Tateno (36.05N, 149.13E) and Okinawa (26.23N, 127.68E). These points represent typical climatological places in Japan; Sapporo in winter suffers from a subarctic climate and Okinawa in summer is under a tropical climate. Data used in this simulation are from the 1st of January and August in 1990 to the 31st of these in 1992. Aerogical data are basically present two times

Table 4. Statistics of the sample data used for estimating PWC from the brightness temperature simulated by employing actual aerological data. The leftmost column indicates variables which are the surface temperature (T_{sfc}), the water vapor density (H_2O_{sfc}) at the surface, PWC, LWP, the simulated total brightness temperature ($\bar{T}_b$) and the estimated mean brightness temperature due to water vapor ($\hat{T}_{b,h2o}$) only. The last row indicates the PWC estimated by this proposed method. Each column has an average and a standard deviation of all data.

Place Period	Sapporo Sapporo		Tateno Tateno		Okinawa Okinawa		Sapporo Sapporo		Tateno Tateno		Okinawa Okinawa	
	90_92.1	90_92.1	90_92.1	90_92.1	90_92.1	90_92.1	90_92.8	90_92.8	90_92.8	90_92.8	90_92.8	90_92.8
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
T_{sfc} (K)	269.9	3.3	274.8	2.6	289.8	2.1	295.0	2.2	298.1	2.8	301.7	1.1
H_2O_{sfc} (g/m ³)	2.893	0.909	3.860	1.132	10.013	2.620	14.778	2.341	18.760	2.774	22.149	1.281
PWC (g/cm ²)	0.4744	0.1934	0.7758	0.4297	2.2508	0.7777	3.4279	0.9700	4.4382	0.9477	5.2212	0.9562
LWP (g/cm ²)	0.0277	0.0289	0.0460	0.0617	0.0683	0.0570	0.0722	0.0707	0.0577	0.0540	0.0668	0.0794
$\bar{T}_b$ (K)	11.87	7.52	17.02	14.81	39.93	18.14	50.00	20.00	58.73	15.14	67.46	19.34
$\hat{T}_{b,h2o}$ (K)	2.26	0.89	3.81	1.90	10.42	3.10	16.06	3.74	20.27	3.76	23.18	3.18
PWC.est (g/cm ²)	0.4414	0.1896	0.7719	0.4059	2.1819	0.6628	3.3865	0.7988	4.2858	0.8035	4.9062	0.6782

Fig. 4. Comparison between PWCs measured by radiosonde and estimated by the proposed method. Plotted are data for $LWP \leq 0.1 \text{ g/cm}^2$.

a day, 9 and 21 o'clock JST. In Table 4, the first 4 rows show the climatological data for surface temperature, water vapor density at the surface, PWC, and LWP for the atmospheric column. Since radiosonde measurements have no information about cloud, we assume that the atmosphere has water clouds when the relative humidity in the radiosonde data is more than 85 % and the air temperature of the layer is over -10°C . The cloud liquid content is assumed to be 0.5 g/m^3 for any temperature and height. The cloud content such as of cumulus (see Table 2) is fairly dense and is enough to validate the

cloud effect on the estimated PWC. The fifth ($\bar{T}_b$) and sixth ($\hat{T}_{b,h2o}$) rows in Table 4 present mean simulated brightness temperatures of Eq. 5 and that of water vapor from Eq. 10. The last row presents the mean values of PWC estimated using this method. Figure 4 shows the relation between the simulated and the original PWC for all data except $LWP > 0.1 \text{ g/cm}^2$. About 87 % of all samples are within $LWP \leq 0.1 \text{ g/cm}^2$ and about 32 % of samples have no cloud atmosphere. Samples with LWP over 0.1 g/cm^2 are excluded in the figure because a cloud with such a heavy LWP is rare for an actual atmo-

Fig. 5. Error dependence on LWP. Figure (a) is for the absolute error and Figure (b) for the relative error.

sphere and can have a severe effect on the estimated PWC, as described later. The estimated PWCs have a tendency toward lower values and are widely scattered as the PWC increases. This may be due to two reasons, one of which is non-linearity between the PWC and the $\hat{T}_{b,H_2O}$, and the other is the cloud effect.

In order to clarify the cloud effect, the estimated absolute errors (standard deviation) of the PWC are shown in Fig. 5a for every 0.01 g/cm² of LWP. The relative errors (standard deviation divided by the mean estimated value) are shown in Fig. 5b. It should be noted that the sample number is not the same for each LWP step, *e.g.*, sample numbers with no cloud (LWP=0) are about 66 % for Sapporo during the winter, and about 8 % for Okinawa during the summer. A time with no error in Figs. 5a and 5b means no sample data. Table 4 shows a summary of these basic data for the three places and the two months.

The mean error is about 7.5 % for all cases with a LWP < 0.1 g/cm² and about less than 5 % for PWC > 1 g/cm². The PWC can be also estimated with an error of less than 6 % for all the samples with LWP < 0.01 g/cm². The cloud effect becomes severe with small PWC, because the contribution of the cloud liquid to brightness temperature is larger than that of the water vapor.

The proposed method has the great advantage that the PWC can be estimated without knowledge of the LWP. However, we can improve the accuracy of PWC when the cloud liquid content can be inferred from the same spectrum.

4. Summary

By using a spectro-radiometer at the K-band (18–26 GHz) including the 22.235 GHz water vapor absorption line, a new method for estimating precipitable water content (PWC) was presented. The essence of this method is that the emission power

integrated over the K-band is basically proportional to PWC. In addition, the integrated power is little dependent on atmospheric temperature. The approximation formula of Eq. 10 to infer PWC is obtained by a regression analysis using McClatchey's atmospheric models with several cloud types.

The validity of the formula is estimated using radiosonde data for several kinds of climate expected in tropic and subarctic regions. As a result, the estimated PWC is in good agreement with the actual PWC even for a cloudy atmosphere with LWP $< 0.1 \text{ g/cm}^2$. The mean error is less than 5 % for the case of PWC $> 1 \text{ g/cm}^2$. Even for the case of PWC $< 1 \text{ g/cm}^2$, the PWC can be inferred within an error of 5–6 % for light clouds with LWP $< 0.01 \text{ g/cm}^2$.

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周波数可変型マイクロ波放射計を用いた可降水量の推定方法

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22.235 GHzの水蒸気吸収線を利用した可降水量(PWC)を求める新しい方法を提案する。この方法は、マイクロ波のK-バンド(18–26.5 GHz)全域で測定された輝度温度を積分し、平均の輝度温度を求めこれから水蒸気の寄与を推定するものである。これは、この周波数域が比較的弱い水蒸気の吸収と、吸収線強度が温度、圧力に強く依存しないことによる。

典型的な雲モデルをもつ大気モデルを用いて、PWCを求める関係式をもとめた：

$$\text{PWC} = a\hat{T}_{b,H_2O} + b \text{ (g/cm}^2\text{)}$$

ここで $a = 0.2135 \pm 0.0021$, $b = -0.0420 \pm 0.0251$,

$$\hat{T}_{b,H_2O} = \frac{1}{\Delta f} \int_{f_1}^{f_2} T_{b,obs}(f) df - [T_{b,obs}(f_2) + T_{b,obs}(f_1)]/2 + \Delta T_b.$$

$T_{b,obs}(f)$ は、周波数 f GHzで観測された輝度温度、 f_1, f_2 は積分範囲を示し、ここで18及び26 GHzである。 $\Delta f (= f_2 - f_1)$ は両周波数の差を示し、 ΔT_b は右辺第2項で雲及び酸素の影響を除去するが、その補正のための係数であり0.2 Kである。この推定式の精度を、種々の大気状態を示す実際のラジオゾンデデータを利用して調べた。その結果、通常の大気状態($\text{PWC} > 1 \text{ g/cm}^2$, $\text{LWP(雲水量)} < 0.1 \text{ g/cm}^2$)では、5%以内で再現され、やや冷たい大気条件下($\text{PWC} < 1 \text{ g/cm}^2$, $\text{LWP} < 0.01 \text{ g/cm}^2$)でも、およそ6%程度で再現できることがわかった。