Column water vapor from diffuse irradiance

P. Kiedron, J. Berndt, J. Michalsky, and L. Harrison
Atmospheric Sciences Research Center, SUNY at Albany, Albany, New York, USA

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[1] We investigate the possibility of measuring water vapor column from diffuse irradiance, and thus the extension of optical retrievals to cloudy days. Data from the rotating shadowband spectroradiometer (RSS) during its winter deployment at the North Slope of Alaska (NSA) site are used: 20 days in March 1999 that include clear, partly cloudy and overcast days. During these days water vapor column varied between one and five mm according to the NSA site's microwave radiometer (MWR). The diffuse transmittance in the 760-nm oxygen absorption band is used to obtain the effective air mass. The end result is a correlation of 0.97 and 0.95 between MWR and RSS retrievals using 820-nm and 940-nm diffuse transmittances, respectively. These results, which are based on empirical data analysis only, imply that the diffuse irradiance may contain sufficient information to retrieve water vapor column. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0394 Atmospheric Composition and Structure: Instruments and techniques; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Kiedron, P., J. Berndt, J. Michalsky, and L. Harrison, Column water vapor from diffuse irradiance, *Geophys. Res. Lett.*, *30*(11), 1565, doi:10.1029/2003GL016874, 2003.

1. Introduction

[2] An intensive observation period (IOP) was conducted during the late winter/early spring of 1999 at the North Slope of Alaska (NSA) Atmospheric Radiation Measurement (ARM) site near Barrow to compare various techniques to retrieve water vapor column in dry conditions. The rotating shadowband spectroradiometer (RSS), deployed by the Atmospheric Sciences Research Center, was the only solar radiometer taking part in this experiment. In addition to the ARM 23.8 GHz microwave radiometer (MWR), NOAA Environmental Technology Laboratory and NASA Goddard Space Flight Center deployed two radiometers covering the 183 GHz band. The comparison between the optical and microwave methods was limited to 11 days of clear and semi-clear sky when solar direct beam measurements and retrievals could be performed. The retrievals show very good agreement between optical and microwave measurements [*Kiedron et al.*, 2001].

[3] This RSS provides continuous direct irradiance spectra over 512 pixels covering the wavelengths 350–1080 nm [*Harrison et al.*, 1999]. A better estimate of transmittance in water absorption bands than with filter radiometers is therefore possible. By removal of a baseline from the spectrum, the transmittance in the water absorption band is greatly desensitized to aerosols and radiometric calibration uncertainties allowing water vapor retrieval even when the sun is partially obscured. However, as the direct beam extinction becomes large, the signal-to-noise ratio of the direct beam becomes small, making retrievals impossible.

[4] In addition to the direct horizontal irradiance, the RSS also measures the diffuse irradiance. The latter is obtained even during overcast conditions or for very high solar zenith angles and has a relatively high signal-to-noise ratio. In this paper, we explore the possibility of using the diffuse irradiance to retrieve the water vapor column.

2. Methodology

[5] We try to find a function of diffuse irradiance I_{dif} that predicts the water vapor column w that correlates with the water vapor w_{MWR} retrieved by the MWR. We concentrate on only two spectral elements of the diffuse irradiance: One at the water absorption band near 820 nm or 940 nm and the second at the oxygen absorption band near 760 nm. We create an estimator F of water vapor column w:

$$w = F\left(I_{dif}(\lambda), I_{dif}(760), y\right) \tag{1}$$

where λ = 820-nm or λ = 940-nm, I_{dif} is diffuse irradiance and y is the vector of parameters that are derived through the process that minimizes residuals $r = w - w_{MWR}$.

[6] To eliminate sensitivity to aerosols and radiometric calibration errors, transmittances, instead of irradiances, are used. The irradiance is divided by the extraterrestrial irradiance and the baseline is removed. In Figure 1 we show diffuse irradiance divided by the extraterrestrial irradiance. The anchor points for each band's baseline are indicated. The value of the baseline $B(\lambda)$ at wavelength λ is interpolated using values at anchor points λ_1 and λ_2 with the formula

$$B(\lambda) = I_{dif}(\lambda_1)\left(\frac{I_{diff}(\lambda_2)}{I_{diff}(\lambda_1)}\right)^{\frac{\lambda-\lambda_1}{\lambda_2-\lambda_1}} \tag{2}$$

Then the transmittance at the absorption wavelength is given by

$$T_{dif}(\lambda) = I_{dif}(\lambda)/B(\lambda) \tag{3}$$

The oxygen profile and its total column are invariant. Thus the absorption at the oxygen band is dependent on geometry, cloud coverage, and surface albedo and it is independent of variable atmospheric constituents. By incorporating the diffuse transmittance at 760 nm we hope

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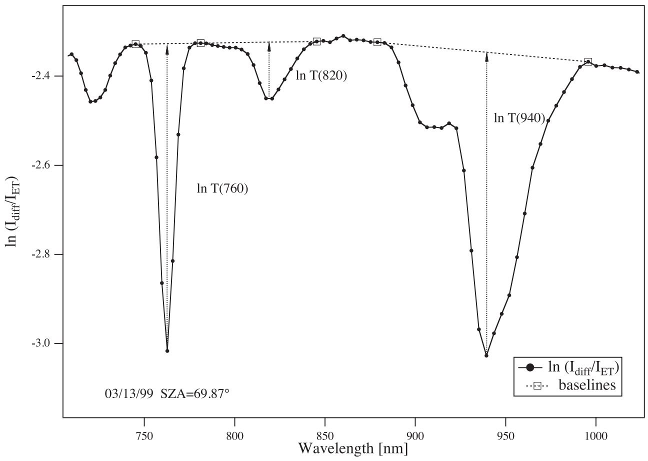

Figure 1. Example of diffuse irradiance. The anchor points used to define baselines for each absorption band are marked.

to compensate for the effects of varying pathlength with different atmospheric conditions and with the varying sun position. For the solar direct beam the air mass m is related to the transmittance at 760 nm through a curve of growth:

$$m = g(T_{dir}(\lambda)) \tag{4}$$

Once the function $g()$ is established, we define the effective diffuse air mass as

$$m^* = g\left(T_{dif}(760)\right) \tag{5}$$

Next we try to find the functional relationship between the diffuse transmittance at the water vapor absorption band and the product of the water vapor column with the effective diffuse air mass

$$w_{MWR}m^* = h\left(T_{dif}(\lambda)\right) \tag{6}$$

The function $h()$ is found in the least square sense by minimizing the root-mean-square (rms) difference between the two sides of the equation (6). The $h()$ can be considered a curve of growth that relates the equivalent diffuse water column $w_{MWR}m^*$ to diffuse transmittance. Finally, from equations (5) and (6) we can define the estimator $F()$ of water vapor column as follows

$$w = F\left(I_{dif}(\lambda), I_{dif}(760), y\right) = h\left(T_{dif}(\lambda)\right)/g\left(T_{dif}(760)\right) \tag{7}$$

where y is a vector that consists of parameters defining functions $g()$ and $h()$.

3. Curve of Growth Model

[7] We use *Moskalenko*'s [1969] model of the curve of growth for both functions $g()$ and $h()$, however, we must emphasize that the selection of the model function is not critical to our task as we derive an estimator that is essentially empirical. However, by using a curve of growth with parameters that may have a physical interpretation we hope to facilitate tying our results with future theoretical calculations.

[8] The model relates transmittance T to the air mass $x = m$ or $x = w_{MWR}m^*$ as follows:

$$lnT = -kx^{f(x)} \tag{8}$$

where $f(x)$ varies between 1 and 0.5. We chose $f(x)$ in the following form

$$f(x) = 1 - ax/(x - b) \tag{9}$$

with two positive parameters a and b. Always $f(0) = 1$ and $f(\infty) = 1 - a$. However, we did not limit a to assure the physical limit $f(\infty) \leq 0.5$ of an infinite band of Lorentzian lines *Goody* [1952].

4. Results and Discussion

[9] The 20-day data set includes over 12,000 diffuse and direct irradiance spectra. Six days were clear. We added data from two clear days in April to generate the curve of growth $g()$ from the direct transmittance at 760 nm. In Figure 2 the air mass according to *Kasten* [1965] is plotted against the logarithm of measured transmittance (3). The fitted $g()$ produces residuals within ±2% for small and medium air masses and ±4% for large air masses. The values of parameters (k, a, b) of function $f()$ can be found in Figure 2.

[10] The parameters (k, a, b) of curves of growth $h()$ for diffuse transmittances at 820 nm and 940 nm are derived in Figure 3. Finally for each data point we calculate two estimates of water vapor column using equation (7). The results are presented in correlation plots in Figure 4 and as a function of time in Figure 5.

[11] The correlations between MWR and diffuse RSS retrievals using 820-nm and 940-nm transmittances, respectively, 0.97 and 0.95, are very high. The slightly higher correlation for the 820-nm band possibly may stem from the fact that photons at this wavelength travel a more similar path to the photons at 760 nm than the 940-nm photons and also from the fact that the transmittance in the 820-nm band

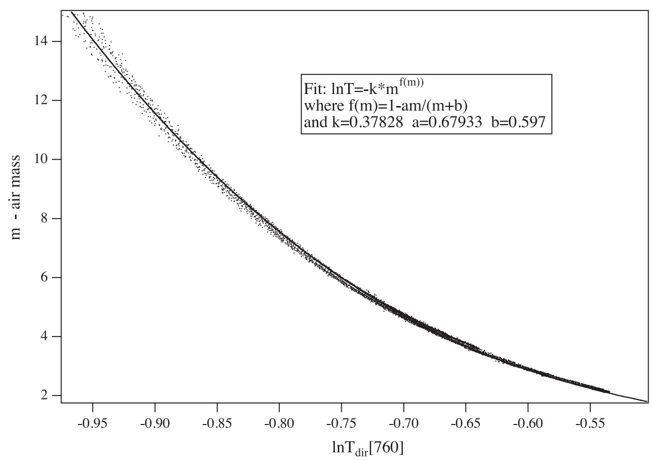

Figure 2. Empirical derivation of curve of growth at 760 nm.

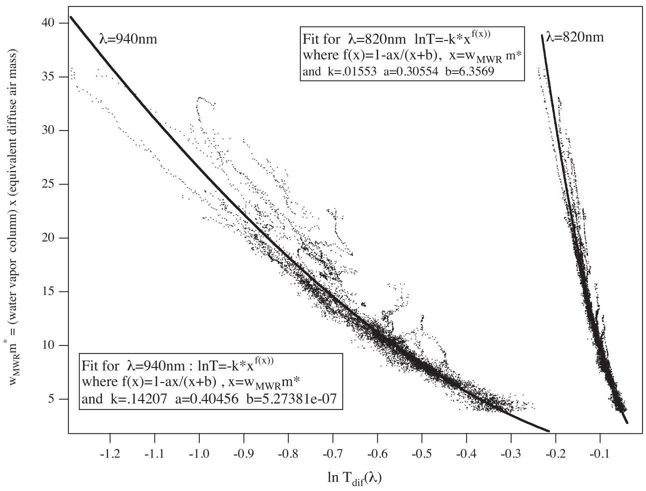

Figure 3. Derivation of effective diffuse curves of growth at 820 nm and 940 nm.

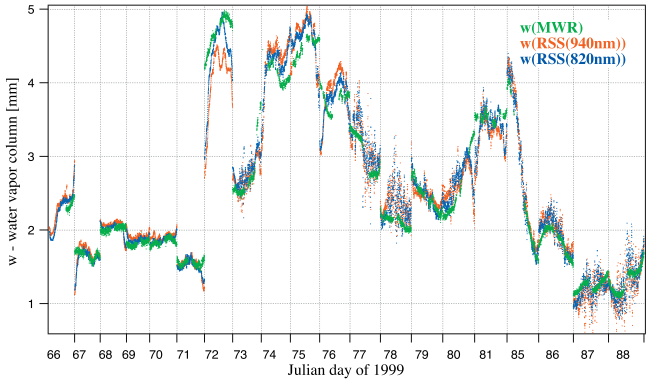

Figure 5. Water vapor column as function of time for 20 concatenated days.

is affected by water 4 times less and by ice 2.5 times less than the transmittance in the 940-nm band.

[12] The retrieval errors have a random component with zero mean and a systematic component:

$$\Delta w = \Delta w_{RND} + \Delta w_{SYST} \tag{10}$$

[13] The random error is particularly large on clear days 77, 78, 87 and 88 (see Figure 5). This is because the shadowbanding cycle of the RSS is performed with one fixed exposure that is determined at the beginning of the cycle by the signal of the unblocked measurement. Consequently, the blocked signal that determines the diffuse irradiance is measured with too short an exposure during clear sky days.

[14] We are chiefly concerned with the systematic errors as their magnitude determines the viability of our approach. The results indicate that the retrieval of water vapor column from diffuse irradiance with a rms error better than 0.24 mm is possible. However an objection can be raised that conditions during the IOP are not sufficiently representative of all climatological conditions. For instance the surface albedo in March 1999 remained relatively constant due to snow coverage. One can imagine that parameters of the *h*() may be different in summer when the surface albedo changes. Also, we did not analyze the prevailing type of cloud coverage during the overcast days. In particular, we do not know whether single-layer or multi-layer cloud conditions prevailed. The distinction between the two types of clouds is very important as photon pathlength changes dramatically between the two cloud conditions. When the extra photon pathlength is accrued above the top of the water vapor profile, the expected reduction at 760-nm transmittance will not be congruent with the transmittance at water bands. Therefore, the compensation that function *g*() in equation (7) is supposed to accomplish might be insufficient. In fact closer evaluation of Figure 4 shows that some large outliers are not due to the random errors.

[15] We do not have sufficient empirical data or valid radiative transfer simulations to quantify these effects. Instead we can envision improvements that will reduce these effects. The method presented is the simplest one among those that take advantage of information in the irradiance at the oxygen band. Only two spectral elements are used and the parameter vector *y* has only six dimensions. However, one is not limited to a method with the same parameters for clear, cloudy and overcast days. For instance,

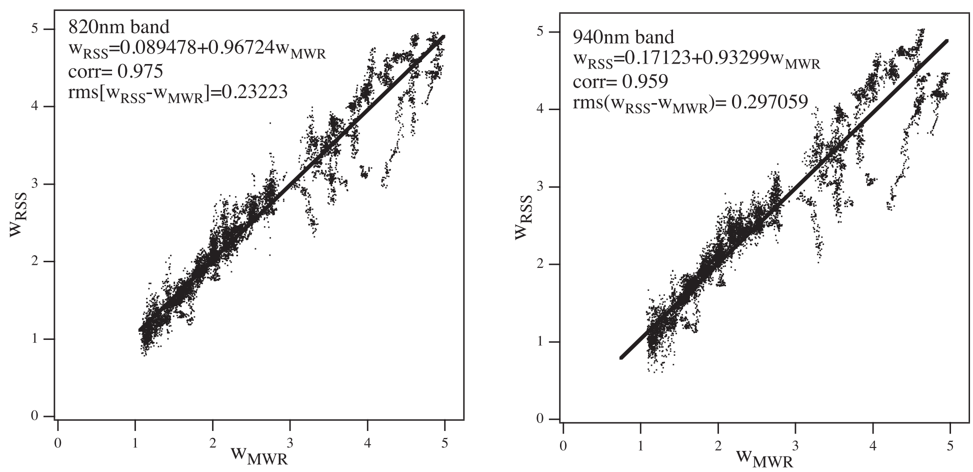

Figure 4. Correlation plots between water vapor column from diffuse irradiance from RSS and from MWR.

one may add an additional parameter of direct-to-diffuse ratios

$$R = T_{dir}(781)/T_{dif}(781) \quad (11)$$

at a non-absorbing wavelength of 781-nm to estimate cloud fraction. A reliable method that predicts cloud fraction from the direct-to-diffuse ratio was devised by *Long et al.* [1999]. Then the parameters (k, a, b) that define the function $h()$ would be R dependent. By adding additional spectral elements one can retrieve from the direct-to-diffuse ratio relative surface albedo change between the oxygen and water absorption bands. Also the solar zenith angle dependence could be diminished by normalization of the diffuse irradiance with a model clear sky irradiance.

[16] Finally the photon pathlength probability distribution function or at least its first and second moments could be derived from the shape of the 760-nm absorption band. It was demonstrated by *Min et al.* [2001] that the first and the second moments could be used to differentiate between single and multi-layer clouds. Thus the RSS diffuse spectrum contains a multitude of implicit information that could be used to reduce systematic errors.

[17] Furthermore we can imagine improvements by adding memory into the estimator. The method presented retrieves water vapor in a real time from an instantaneous spectrum regardless of the preceding or succeeding condition. The atmospheric and climatological changes occur in a finite time. For instance, changes of the surface albedo are gradual, and they can be detected with more sophisticated analysis from the wavelength dependent diffuse-to-direct ratio. This detection would be more robust if performed on successive spectra.

[18] We want to emphasize that all the possible improvements suggested in the previous paragraphs would not utilize information beyond what the RSS is already providing. For these reasons, we believe that the retrieval from the diffuse irradiance of water vapor as well as other constituents, such as ozone, is not limited only to the dry winter Arctic conditions that were studied in this paper. Wider applications for more diverse conditions are possible and warrant further investigations.

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References

Goody, R. M., A statistical model of water vapor absorption, *Q. J. R. Meteorol. Soc.*, *78*, 165–169, 1952.

Harrison, L., M. Beauharnois, J. Berndt, P. Kiedron, J. Michalsky, and Q. Min, The rotating shadowband spectroradiometer (RSS) at SGP, *Geophys. Res. Lett.*, *26*, 1715–1718, 1999.

Kasten, F., A new table and approximation formula for relative air mass, *Arch. Meteorol. Geophysics. Bioklimatol. Ser. B*, *14*, 206–223, 1965.

Kiedron, P., J. Michalsky, B. Schmid, D. Slater, J. Berndt, L. Harrison, P. Racette, E. Westwater, and Y. Han, A robust retrieval of water vapor column in dry arctic conditions using the rotating shadowband spectroradiometer, *J. Geophys. Res.*, *106*, 24,007–24,016, 2001.

Long, C. N., T. P. Ackerman, J. J. DeLuisi, and J. Augustine, Estimation of fractional sky cover from broadband SW radiometer measurements, *Proc. 10th Conf. on Atmos. Rad., June 28–July 2, 1999*, Madison, Wisconsin, 1999.

Min, Q., L. C. Harrison, and E. E. Clothiaux, Joint statistics of photon pathlength and cloud optical depth: Case studies, *J. Geophys. Res.*, *106*, 7375–7386, 2001.

Moskalenko, N. L., The spectral transmission function in the bands of water vapor, O_3, N_20 and N_2 atmospheric components, *Izv. Akad. Nauk. SSSR Fiz. Atmos. Okeana*, *5*, 678, 1969.

P. Kiedron, J. Berndt, J. Michalsky, and L. Harrison, Atmospheric Sciences Research Center, SUNY at Albany, Albany, NY 12203, USA. (Kiedron@asrc.cestm.albany.edu; jerry@asrc.cestm.albany.edu; joe@asrc.cestm.albany.edu; lee@asrc.cestm.albany.edu)