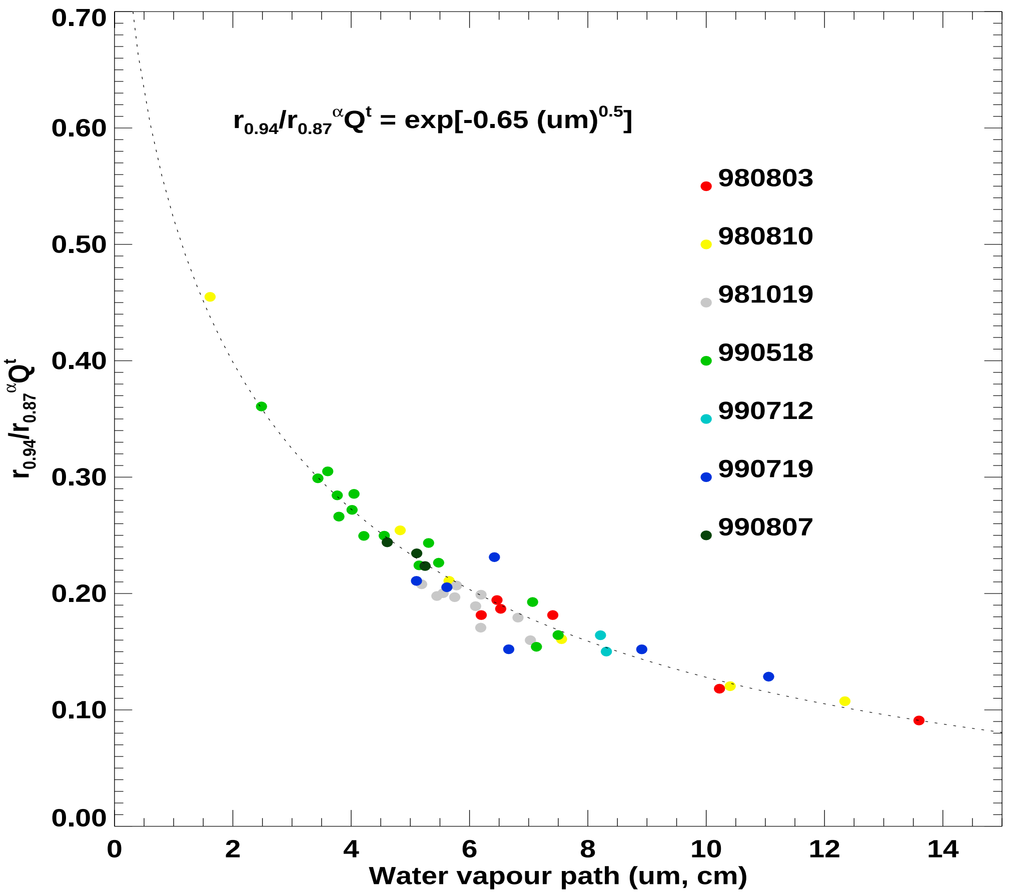
Precipitable Water Retrieval from Multi-Filter Rotating Shadowband Radiometer Measurements

A. J. Prata



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Precipitable Water Retrieval from Multi-Filter Rotating Shadowband Radiometer Measurements.

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Abstract

A method has been developed to utilise 940-nm measurements from a ground-based sunphotomter (the Multi-Filter Rotating Shadowband Radiometer–MFRSR) to determine the column water vapour amount. The accuracy of the method, when compared to coincident, collocated radiosonde measurements is $\approx$3 mm of precipitable water. Details of the method and some example results are provided in this report.

1 Introduction

A MultiFilter Rotating Shadowband Radiometer (MFRSR; Harrison *et al.*, 1994) has been installed at the Continental Integrated Ground-Site Network (CIGSN; Prata *et al.*, 1998) satellite calibration and validation sites near Hay, (34.39 °S, 145.30 °E), NSW, Amburla (23.39 °S, 133.12 °E) and Thangoo (18.18 °S, 122.36 °E), WA. These instruments measure the total sky and diffuse sky solar radiation in six narrow channels between 0.4 μm and 0.96 μm, and in one broadband channel. The principal purpose of the measurements is to obtain the aerosol optical depth of the atmosphere for use in atmospheric correction of satellite radiances and for radiation budget studies.

A single channel centred at 0.94 μm is used to obtain an estimate of the atmospheric water path (precipitable water x airmass) . This paper describes the method used to retrieve precipitable water (u) from the MFRSR measurements at Thangoo.

2 Measurements

2.1 MFRSR

Table 1 lists the MFRSR band-centres and band-widths for the instrument deployed at Thangoo, and Figure 1 shows the response functions.

Table 1: The MFRSR band-centres and band-widths.

Channel	Band-centre (nm)	Band-width FWHM (nm)	Purpose
1	400–1000		solar radiation
2	415.4	10	aerosol
3	501.5	10	aerosol
4	615.8	10	aerosol/ozone
5	672.4	10	aerosol/ozone
6	871.8	10	aerosol
7	939.6	10	water vapour

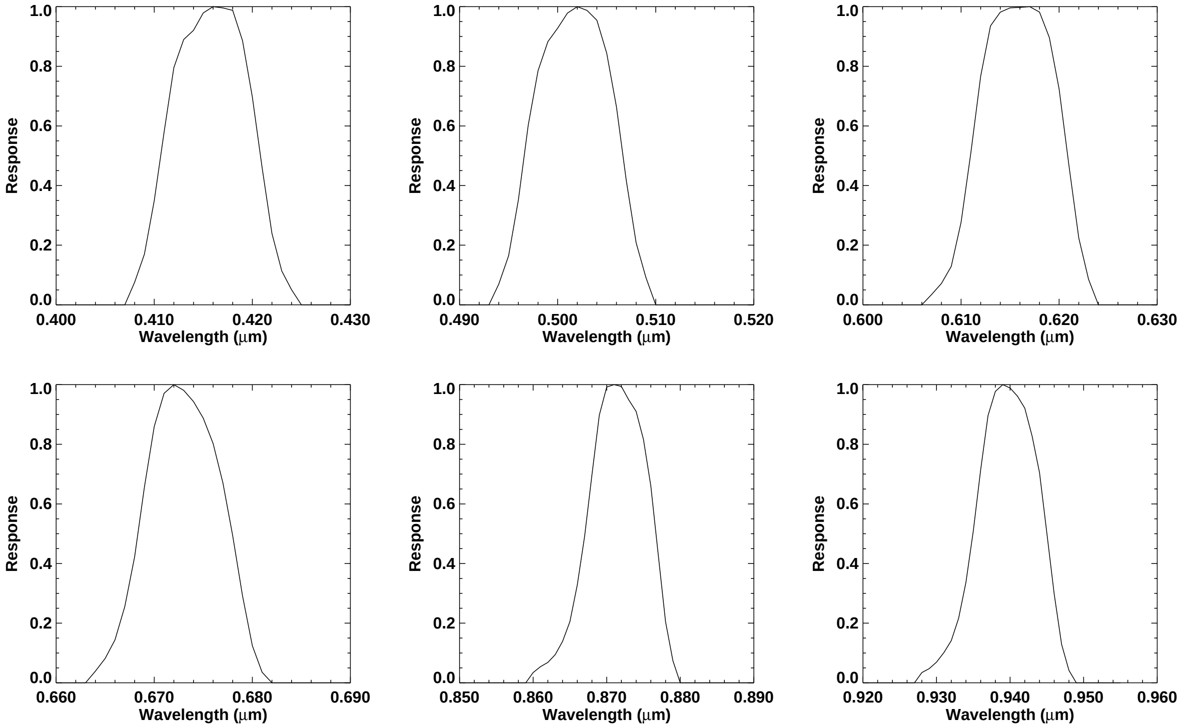

Figure 1. Response functions for the six narrow bands of the Thangoo MFRSR.

The instrument is located on the Thangoo homestead at 18.183°S, 122.357°E, 30-m elevation, and has an unobstructed view of the sky. Data are logged continuously as 60-s averages, collected every 60-s. The files are downloaded via modem to CSIRO Atmospheric Research and processed using software provided by Yankee Environmental Systems (YES) Inc. The processed data consist of irradiance values for the direct and diffuse beams for each channel throughout the day. Data for the period October 1998 to August 1999 are utilised here.

2.2 Radiosonde data

The Bureau of Meteorology operate a radiosounding launching facility near Broome airport (located at 17.949°S, 122.234°E, 10 m) approximately 28 km (line-of-sight) from the Thangoo MFRSR. Launches are made at 0000 UT[1] each day and on some days a second launch is made at 12UT. The 0000 UT launch occurs around 0800 to 0900 hours local time. Data from the morning sonde are used to calculate the vertically integrated precipitable water each day. The precipitable water is defined as the total mass of water vapour per unit area in the atmospheric column and is calculated using

$$u = \frac{1}{g}\int_{p_s}^{p_o} m_r dp, \tag{1}$$

where,

$$m_r = \frac{\rho_{wv}}{\rho_{air} + \rho_{wv}}$$

is the mass mixing ratio, ρ_{wv} is the water vapour density and ρ_{air} is the density of dry air. The integration is from the surface at pressure p_s up to a pressure designated by p_o, which depends on the final altitude reached by the sonde.

3 Water vapour absorption at 0.94 μm

Channel 7 of the MFRSR is placed near the centre of the strong $\rho\sigma\tau$ near-infrared water vapour absorption band. Figure 2 shows the variation of transmission across this band from 10400 cm^{-1} to about 11000 cm^{-1} (0.91–0.96 μm) for an atmosphere containing 2.83 cm of precipitable water, derived using the Modtran 3 radiative transfer code (Berk *et al.*, 1989). The MFRSR

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[1] Local time (WST) = UT+8 hours.

0.94 μm filter response function covers a large part, but not all, of this band.

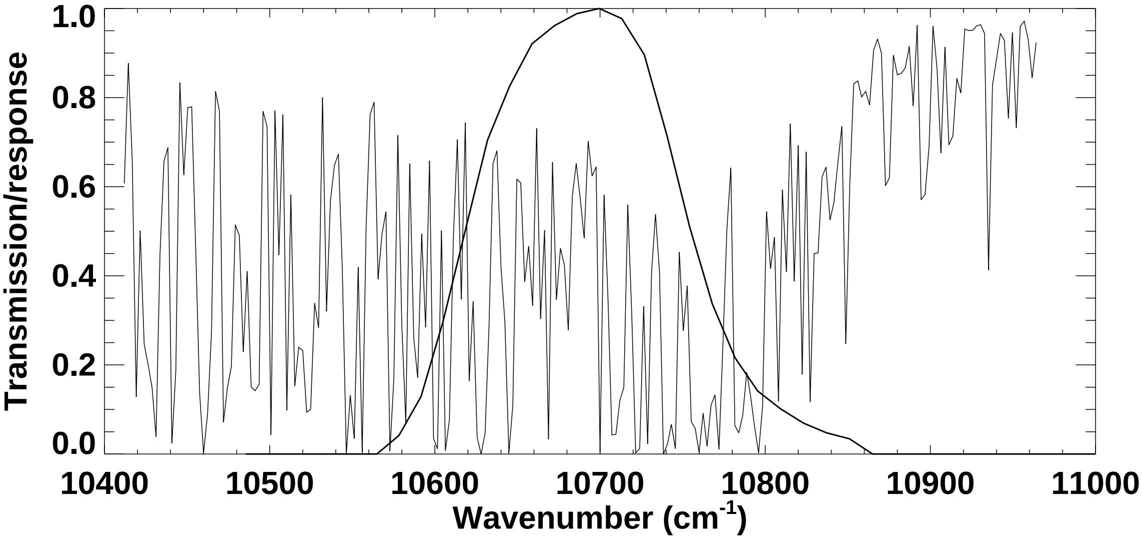

Figure 2. Modtran 3 transmission calculated at 2 cm^{-1} resolution for an atmosphere with 2.83 cm of precipitable water. The thick line shows the MFRSR 0.94 μm filter response function.

4 MFRSR precipitable water retrieval

The basis for retrieving u from measurements of the attenuation of the direct beam irradiance, relies on knowledge of the variation of transmission with u over the 0.94 μm MFRSR channel, and correction for attenuation in this band due to aerosol and molecular scattering.

A method, described as the modified Langley method, for retrieving u from sun photometer measurements has been described by Bruegge *et al.* (1992). The idea behind this method is to assume that the attenuation of the direct beam irradiance follows the Lambert-Beer-Bouguer law for aerosol and molecular scattering, and a power law for water vapour absorption. Thus,

$$r_{0.94} = r_{t,0.94} \exp[-\tau_{s,0.94} m - k(um)^{\beta}], \qquad (2)$$

where $r_{0.94}$ is the band integrated direct beam irradiance measured by the MFRSR, $r_{t,0.94}$ is the (band integrated) top-of-atmosphere irradiance, m is the airmass, $\tau_{s,0.94}$ is the optical depth due to aerosol and molecular scattering, u is precipitable water, and k and β are parameters to be determined. In the modified Langley approach $\tau_{s,0.94}$ is obtained by fitting a straight line to aerosol optical depth measurements at 0.50 μm and 0.87 μm and extrapolating the fit to obtain $\tau_{aer,0.94}$ at 0.94 μm. Molecular scattering is assumed to follow a λ^{-4} dependence and calculated using a Rayleigh scattering formula. The parameters k and β are determined from modelling (e.g. using Modtran or Lowtran). Using Lowtran, Bruegge *et al.* found k = 0.655, and β = 0.57, whereas Michalsky *et al.* (1995), using Modtran 2, found k = 0.344 and β = 0.578 for u = 0 to

6 cm, and k = 0.374, β = 0.493 for a larger range of water vapour paths (up to 25 cm). Once the parameters have been established, u can be retrieved from a plot of $\ln[r_{0.94}/r_{t,0.94}]$ versus um.

If the sun photometer has a second band covering the water vapour absorption, but broader than the first band, then a differential absorption technique due to Frouin *et al.* (1990) can be used.

Another, related method can be used to retrieve u using direct beam irradiances from the 0.87 μm and 0.94 μm channels. At 0.87 μm it is assumed that there is negligible water vapour absorption within the band. Then,

$$r_{0.87} = r_{t,0.87} \exp[-\tau_{s,0.87} m], \tag{3}$$

where $\tau_{s,0.87}$ is the total optical depth (aerosol + molecular scattering) at 0.87 μm. If we assume that,

$$\tau_{s,0.94} = \alpha \tau_{s,0.87}, \tag{4}$$

where α is a constant, then combining (2)-(4) yields, after manipulation

$$\ln\left[\left(\frac{r_{0.94}}{r^{\alpha}_{0.87}}\right) Q_t\right] = -k(um)^{\beta}, \tag{5}$$

where,

$$Q_t = \frac{(r_{t,0.87})^{\alpha}}{r_{t,0.94}}.$$

Q_t is a constant factor for a given instrument (the earth-sun distance variation cancels out), depending only on the in-band solar extraterrestrial irradiance and the factor α.

This analysis can be improved by assuming the linear relationship (4) holds for aerosol scattering and the Rayleigh scattering can be calculated separately. The aerosol optical depth varies as $\approx \lambda^{-1.3}$, whereas the molecular scattering varies as $\approx \lambda^{-4}$, but both are small at these wavelengths. Hence the improvement will be marginal. This method still requires an estimate of the parameters k and β and the optical depth scaling factor, α.

5 Radiative transfer modelling

To investigate the relationship between transmission and precipitable water, the transmission integrated over the 0.94 μm channel bandpass was calculated for 207 atmospheric profiles obtained from the Broome radiosonde facility. The Modtran 3 code (Berk *et al.*, 1989) was used with 5 cm^{-1} resolution. Vertically integrated precipitable water was calculated using (1). Figure 3 shows the variation of the transmission with u for all 207 profiles.

An excellent fit to these data is obtained with k = 0.65 and β = 0.62. These values are quite close to those reported by Bruegge *et al.* (for a different instrument, presumably with a different response function), but differ from Michalsky *et al.*'s values. This is odd because Michalsky *et al.* used a similar instrument and Modtran, albeit an earlier version of the code used here.

Nevertheless, the difference between this analysis and Michalsky *et al.*'s is of concern. The radiative transfer modelling suggests that it is reasonable to assume absorption in this band obeys a power law, not very different from the square-root dependence expected on theoretical grounds (0.62 *vs* 0.50).

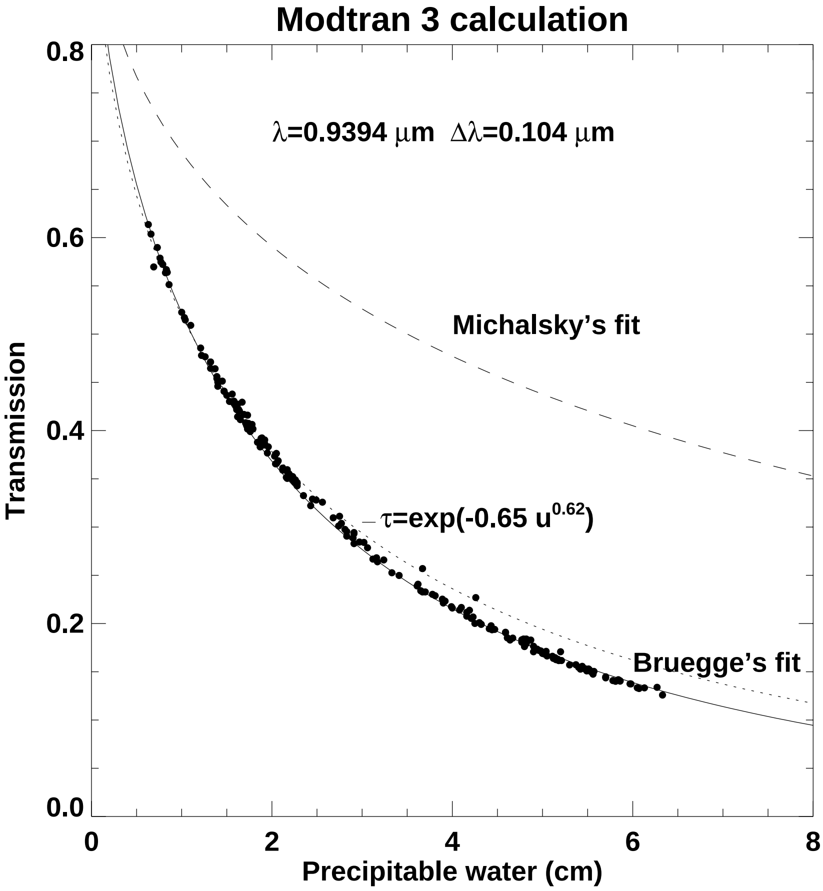

Figure 3. Modtran 3 transmission calculated at 5 cm^{-1} resolution integrated over the MFRSR 0.94 μm filter response function and plotted against vertically integrated precipitable water, u in cm. The fits obtained by Bruegge *et al.* (1992) and Michalsky *et al.* (1995) are shown for comparison.

6 MFRSR analysis

If not for the differences between the k and β values obtained by various authors and the values found here, it would be sufficient to proceed to retrieve u directly from (5). It remains to find a value for α, the optical depth scaling factor. Straight line fits of total optical depth at 0.87 μm and 0.50 μm against wavelength suggest an Angstrom dependence of $\lambda^{-1.27}$, in agreement with previous work. This gives a value of $\alpha \approx 0.91$. We adopt this value as a starting point, and then use it as a free parameter to tune the retrieval procedure.

The retrieval method proposed here differs slightly from previous studies. Here we use a hybrid methodology that utilises the near simultaneous precipitable water derived from the radiosonde to provide a fit to the power law water vapour absorption found from the modelling study. Retrieval of water vapour using this method is quite sensitive to the signal-to-noise ratio (SNR) of the MFRSR measurements. The SNR is greatest when the sun is high in the sky and least at sunrise and sunset. The decrease in SNR is evident in the retrieval by the introduction of *curvature* in the profile of water vapour variation through the day. We show that the parameter α can be tuned by constraining the diurnal variation of u to be free of curvature, any curvature in retrieved u being caused by inadequate correction of the aerosol and molecular scattering resulting from poor SNR in the MFRSR measurements.

6.1 Data analysis

Six periods from October 1998 to August 1999 were chosen for analysis. From these periods, 48 days were selected based on the clarity of the atmosphere on those days and the absence of clouds from 0730 LT to 1730 LT. The radiosonde launch takes upwards of an hour to complete the sounding, but since most of the water vapour is contained within the first 2-3 km of the surface, only the first 15 minutes of the MFRSR data were used. Fifteen minute averages of the 60-s averaged data were obtained for the direct beam irradiances at 0.50 μm, 0.87 μm and 0.94 μm. These averages were then plotted onto the 60-s averaged data and checked 'by eye' to ensure that there were no undetected drop-outs, clouds or other anomalies.

Figure 4 shows the variation of the 0.94 μm direct beam irradiance for the observations used, plotted with the vertically integrated precipitable water, u, obtained from the radiosonde data.

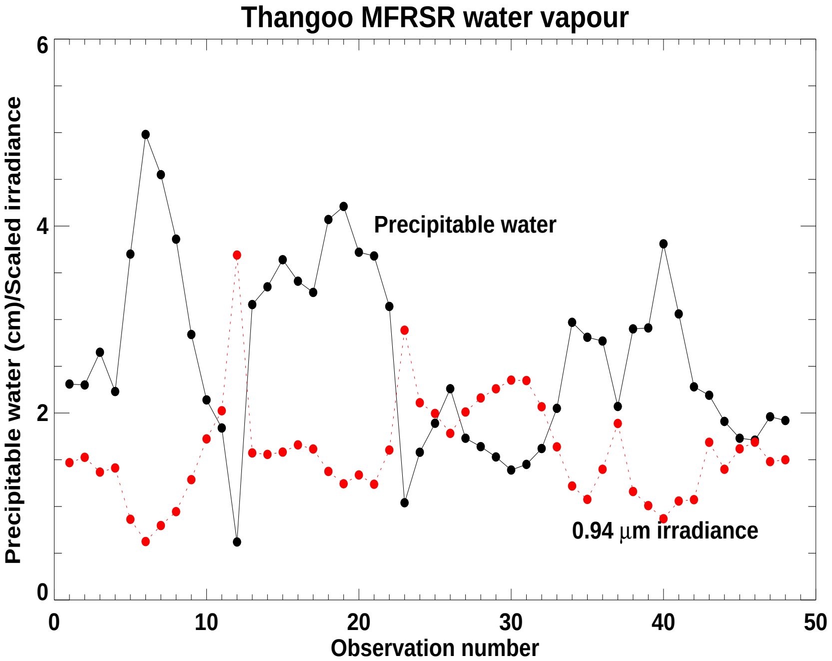

Figure 4. Precipitable water (u, cm) and 0.94 μm direct bean irradiance variation with observation number. Note the high degree of anti-correlation between the two measurements.

There is a strong anti-correlation between the two measurement series – this is the basis for the retrieval of water vapour from 0.94 μm irradiance measurements.

The value of Q_t is determined from extraterrestrial spectral solar irradiance tables (e.g. Iqbal, 1983), and the MFRSR response functions. A plot of $Q_t[r_{0.94}/(r^{\alpha}_{0.87}]$ *vs.* u is shown in Figure 5. The best fit to the data give β = 0.5 and k = 0.65, values not too different to the modelling results.

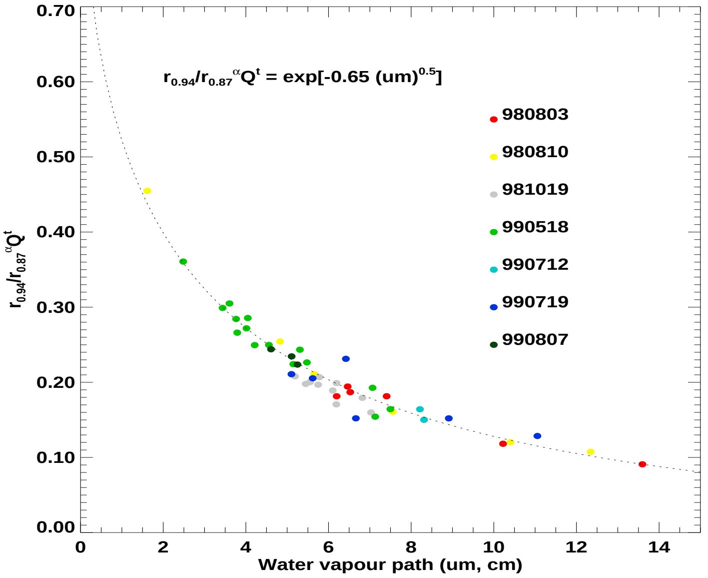

Figure 5. Direct bean irradiance at 0.94 μm and precipitable water variation for 48 coincident clear days at the Thangoo field station.

Taking the natural logarithm of the left-hand-side of (5) and plotting this quantity against the natural logarithm of the water vapour path (um), yields a straight line as shown in Figure 6. The slope and intercept of this line provides the parameters β and k^{-1}.

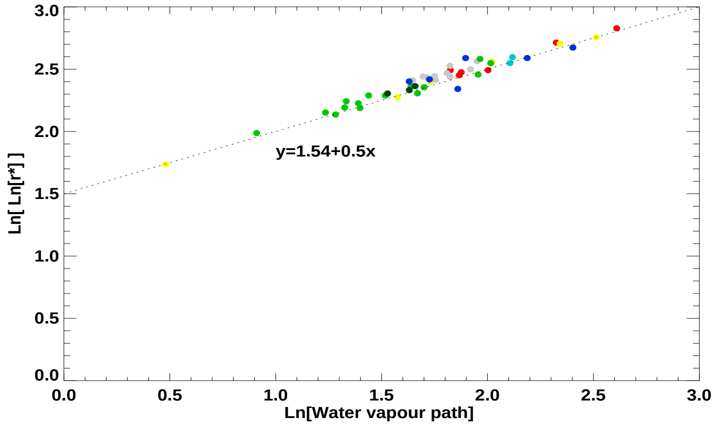

Figure 6. Linear dependence of the logarithm of the logarithm of direct beam irradiance at 0.94 μm with the logarithm of the water vapour path. This plot is used to determine the band parameters β and k.

7 Water vapour retrieval

Equation (5) has been used to retrieve water vapour amount from the MFRSR for 14 days during May 1999. Figure 7 shows the results. The $+$ symbols indicate precipitable water derived from the radiosonde at Broome. In the retrieval algorithm the parameter α has been used as a free parameter. A value of 0.91 is suggested from theoretical reasoning, but when this value was used, a slight curvature was introduced into the temporal profile of u. This kind of variation is not expected, based on the meteorology of the region. Consequently, we assume that the retrieval is somewhat sensitive to α, presumably because α scales the effect of aerosol scattering in the retrieval. Varying α by $\pm$10 % about its expected value allows tuning of the retrieval. A value of α = 0.9 gives the results shown in Figure 7. This value appears to give minimum curvature in the temporal profile of u, but better results can be obtained by setting α differently on each day.

The results look reasonable with the mean difference and standard deviation for all 14 days being δm = $+$0.05 cm and σ = $\pm$0.25 cm. Generally there appears to be little variation of precipitable water with time through the day, except on a few occasions. Day 134 (14 May) shows a small increase in precipitable water at around midday; this is believed to be due to the onset of a sea breeze carrying air with a greater moisture content. The eventual rise from around 2 cm to almost 3 cm is significant in terms of the effects on satellite sensed radiances, particularly for infrared measurements.

The variation of precipitable water through the day can also be examined using humidity and air temperature measurements made at the Thangoo field site. Under stable atmospheric conditions the total precipitable water content in a vertical column is related to surface values of the partial pressure of water vapour and near surface air temperature. This relation occurs through the hydrostatic variation of pressure with height, the ideal gas law and an assumed constant lapse rate. Using these relations, Prata (1996) was able to show that the precipitable water can be obtained from,

$$u = \zeta \frac{e_o}{T_o}, \tag{6}$$

where e_o is the partial pressure of water vapour (in mb) and T_o is the surface air temperature (in K). The constant ζ depends on the lapse rate and the water vapour scale height. For mean global conditions Prata found $\zeta \approx$ 46.5. Relative humidity and near-surface air temperature (both at approximately 2-m height above the surface) are routinely measured at the Thangoo field site. Using (6) with these measurements gives an indication of the time dependent behaviour of precipitable water from an independent data source. Figure 8 shows the variation of u with time derived from (6) on 8 May, 1999. These estimates may be compared with the MFRSR retrievals for the same day (Day 128).

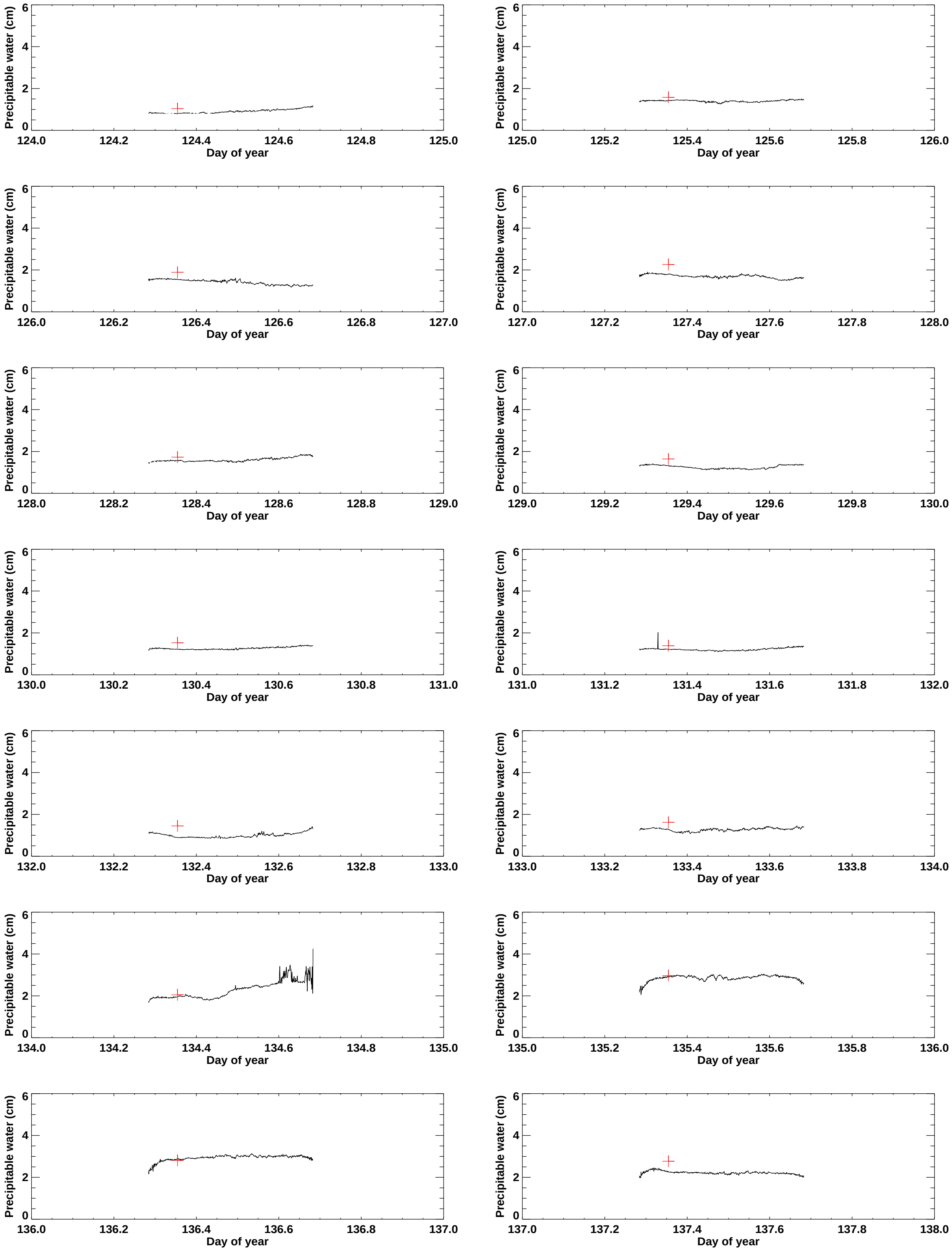

Figure 7. Precipitable water (u, cm) retrieval from the MFRSR. The symbol $+$ indicates radiosonde precipitable water estimates.

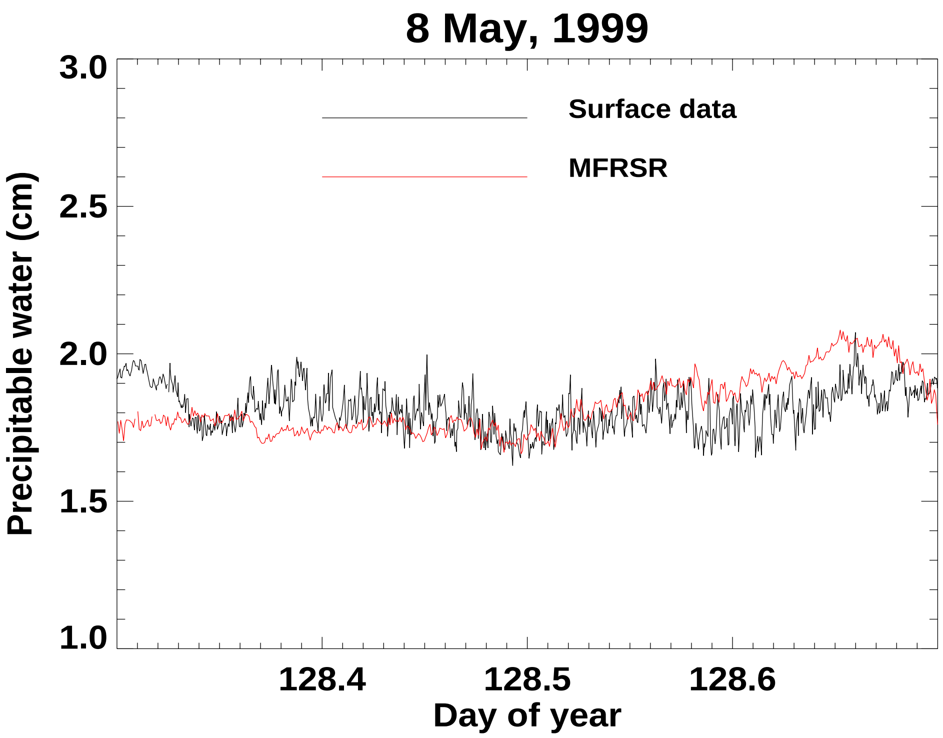

Figure 8. Precipitable water (u, cm) derived from surface humidity and air temperature data obtained at Thangoo field station.

8 Conclusion

A simple method has been described and tested for determining precipitable water from direct beam irradiance measurements at 0.94 μm. The accuracy of the method was found to be $\approx$ 0.3 cm of precipitable water with a bias of less than 0.1 cm for a range of precipitable water of 1.0 cm to 3.5 cm. Although the retrieval algorithm used water vapour amounts of up to 6 cm, the validation has been done for amounts much less. This may affect the applicability of the algorithm for use in other areas, however we note that Michalsky *et al.* also validated their algorithm over a similar water vapour range (1.0 cm – 3.5 cm).

Retrievals for a period of about two weeks during May 1999 show that there is little variation of precipitable water through the day and that it is reasonable to assume that the precipitable water measured at 0800 WST from the local radiosonde launch is representative of the precipitable water at all other times during the daylight hours. Changes in u occur with the onset of the sea breeze, a common phenomenon at the coastal Thangoo field site.

The algorithm will be tested on data from the Hay MFRSR installation (a grassland site, well away from the ocean) and, at a later date, on data from the arid Amburla site.

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