Determination of atmospheric water vapour content from direct measurements of radiance in the thermal infrared region

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Abstract

Atmospheric water vapour content (W) is a required parameter in thermal infrared (TIR) to carry out processes such as atmospheric correction or retrieving atmospheric factors (downwelling or upwelling irradiance, transmittance of the atmosphere, etc.). The present study proposes an alternative method to ones already in use to calculate W from direct measurements of downwelling atmospheric radiance ($L^{\downarrow}_{atm}$) in the TIR range. It was possible to lay down a linear relationship between W and $L^{\downarrow}_{atm}$ by means of a simulated study, based on data from a radiosoundings database. A subsequent validation concludes that it is possible to obtain W with an uncertainty of 0.5 cm, using *in situ* measurements of $L^{\downarrow}_{atm}$ in the thermal range of 11.5 – 12.5 μm.

1. Introduction

At the present time it is possible to retrieve a value of the atmospheric water vapour content (W) by measurements *in situ* through instruments like sunphotometers (Estellés *et al*. 2007), for instance, obtaining W with an uncertainty of ±0.15 cm. This direct technique usually works in the visible or near infrared spectral range. It is also possible to obtain W through satellite sensors, for instance MERIS (Guanter *et al*. 2008), MIPAS (Milz *et al*. 2009) or SCIAMACHY (Noël *et al*. 2004), all onboard the ENVISAT platform. The present study offers an alternative method to measure W in case of an unavailability of a specific instrument to do it with and against the inability to obtain W from satellite data. This method consists of obtaining W with direct measurements of the sky radiance using a radiometer working in the thermal infrared (TIR) region 8 -14 μm.

The original idea starts from the *diffusive approximation* proposed by Rubio *et al*. (1997) which states that the atmospheric downwelling radiance in the upper hemisphere ($L^{\downarrow}_{atm}$) could be obtained from a direct measurement of the sky radiance at a nadir view ($L^{\downarrow}_{atm}(0°)$) by:

$$L^{\downarrow}_{atm,\lambda} = \gamma_{\lambda} L^{\downarrow}_{atm,\lambda}(0°) \tag{1}$$

where λ indicates the spectral character of the measurements and γ is a parameter which depends on both the spectral range of the measurements and atmospheric conditions. Between the parameters γ and W exists a linear relationship that allows determining of the atmospheric water vapour content by means of these measurements of radiance in the TIR region.

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The aim of the present study is divided into two stages. The first stage is centred on a simulation study which determines a mathematical relation between W and γ in four spectral ranges in the TIR region by means of radiosoundings data obtained from the CLAR database (Galve *et al*. 2008). The last stage is focused on validating the previous relation by means of direct measurements of W (in cm) and γ.

2. Modelling a relationship between W and γ

Starting from 180 different atmospheric conditions, obtained from the CLAR radiosoundings database, a simulation of values W and γ was possible by means of introducing these 180 atmospherics profiles into a radiative transfer code (RTC). From the simulated values, a linear relationship was established that allows a calculation of atmospheric water vapour content with sky radiance measurements.

2.1 CLAR database

The Cloudless Land Atmosphere Radiosounding (CLAR) database was made up from compiled radiosoundings by Atmospheric Science Department from the University of Wyoming, anyone can obtain these radiosoundings, due that they are available through their website: http://weather.uwyo.edu/upperair/sounding.html.

CLAR contains a total of 382 radiosoundings, measured in terrestrial meteorological stations allocated uniformly for the entire world. The radiosoundings were filtered to remove all which contained clouds. A radiosounding with a layer of 90% humidity and a subsequent layer of 85% humidity is considered as cloudy and removed. A radiosounding with 80% humidity in the first two kilometres is considered as foggy and is also removed. CLAR possesses a good distribution of atmospheric water vapour content, which is uniform up to 5.5 cm, reaching 7 cm. Their distribution in absolute latitude is based in three groups: 40% of radiosoundings are in low latitudes (< 30°), 40% are in middle latitudes (30° - 60°) and the remaining 20% are in high latitudes (> 60°).

For the present study, a total of 180 radiosoundings were chosen from the CLAR database, distributed between the months of June and August during the years 2003 to 2008.

2.2. Simulated values of W and γ

Each one of the 180 radiosoundings assumes an atmospheric profile, with measured values of air temperature and relative humidity able to be introduced into a RTC to obtain simulated values of W and γ. With this quantity of values, it was possible to produce a graph of W versus γ. The present study introduced atmospheric profiles into the MODTRAN 4v3r RTC model (Berk *et al*. 1999) to obtain values for W, given in cm, and the atmospheric downwelling radiance measured at a zenithal range of 0°-90°,which is independent of azimuthal angle (Rubio, 1997).

In order to obtain γ in this study, the atmospheric downwelling radiance was filtered for eleven zenithal angles, corresponding to Gaussians angles (Wan and Dozier, 1989), concretely: 0°, 11,6°, 26,1°, 40,3°, 53,7°, 65°, 70°, 75°, 80°, 87° and 89°. The value of radiance at 0° corresponds to the parameter $L^{\downarrow}_{atm}(0°)$ in equation (1), and the parameter $L^{\downarrow}_{atm}$ at the same equation is obtained in integral form:

$$L_{atm}^{\downarrow} = 2\int_0^{\pi/2} L_{atm}^{\downarrow}(\theta) cos\theta\ sin\theta\ d\theta \quad (2)$$

With these two values it is possible to calculate γ from equation (1) by:

$$\gamma_{\lambda} = \frac{L_{atm,\lambda}^{\downarrow}}{L_{atm,\lambda}^{\downarrow}(0°)} \quad (3)$$

where γ is spectral dependent. Now we have 180 simulated values of W and other 180 corresponding of γ.

Figure 1 presents W versus γ, for the 180 different atmospheric situations, in 4 different thermal spectral bands, corresponding to the 4 spectral channels of the multispectral radiometer used in the present study (see point III). From the linear regression of the graphs in Figure 1 for each spectral band, it is possible to establish a mathematical expression which relates the atmospheric water vapour content with γ:

$$W = 36{,}4 - 25{,}3\ \gamma_{ch1} \quad (4)$$

$$W = 17{,}3 - 10{,}7\ \gamma_{ch2} \quad (5)$$

$$W = 18{,}7 - 10{,}7\ \gamma_{ch3} \quad (6)$$

$$W = 42{,}8 - 29{,}7\ \gamma_{ch4} \quad (7)$$

With these relationships obtained from Figure 1, there is a possibility of calculating W with the availability of an instrument which works in one of the four aforementioned spectral bands. The relationships from equations (4) to (7) have uncertainties for W of: ± 0.4 cm (Ch1), ± 0.3 cm (Ch2), ± 0.2 cm (Ch3) and ± 0.3 cm (Ch4).

The next step is to validate the previous relationships by means of direct measurements of W and γ, the latter calculated with measurements of atmospheric downwelling radiance using equation (3).

3. Validation of modelled relation

With the aim of validating the relationships extracted from Figure 1, it was decided to take *in situ* measurements of $L^{\downarrow}_{atm}(0°)$ and $L^{\downarrow}_{atm}$, to calculate γ using equation (3), and parallel measurements of W. These measured values were compared with the simulated values of Figure 1.

To measure the radiance $L^{\downarrow}_{atm}(0°)$, a CIMEL Electronique® multispectral thermal radiometer was used, more specifically the model CE 312 (Brogniez *et al*. 2003). This radiometer has four spectral channels working in four different spectral ranges of TIR, located at: 8 – 14 μm (channel 1), 11.5 – 12.5 μm (channel 2), 10.5 – 11.5 μm (channel 3) and 8.2 – 9.2 μm (channel 4). To measure the hemispheric radiance $L^{\downarrow}_{atm}$ we pointed the CE 312 at a diffuse reflectance panel. This diffuse reflectance panel (García-Santos *et al*. 2010) has a rough gold surface capable of reflecting the atmospheric downwelling radiance in all angular directions, as it behaves in a lambertian manner. The only correction applied to the measurements of the panel is to its spectral emissivity (Korb *et al*. 1996). The panel contributes to measurements and this radiative contribution has to be removed. From measurements of thermodynamic temperature of the panel, taken *in situ* with a contact thermometer, the contribution of emissivity of the panel can be corrected by:

$$L_{atm,\lambda}^{\downarrow} = \frac{L_{panel,\lambda} - \varepsilon_\lambda B_\lambda(T_{panel})}{(1-\varepsilon_\lambda)} \tag{8}$$

where $L_{panel,\lambda}$ is the radiance measured directly over the panel, ε_λ is the spectral emissivity of the panel and $B_\lambda(T_{panel})$ is the Planck function of the panel temperature T_{panel}.

Then we have the two needed radiances to calculate γ by means of equation (3). The uncertainties associated to γ for channels 1 to 4 of CE 312 are: ±0.03, ±0.04, ±0.06 and ±0.05, respectively.

To obtain W a CIMEL Electronique® sunphotometer was used, more specifically the model CE 318 (Holben *et al*. 1998). This instrument measures the atmospheric columnar water vapour in a channel centred at 940 nm, with an uncertainty of ± 0.2 cm (Bruegge *et al*., 1992). The full width at half maximum of this channel is around 10 nm, and the sensor head is equipped with a double collimator with a 1.2° field of view.

Figure 2 shows a comparison of validation results with simulated results from Figure 1, for the four spectral channels of CE 312. Due to the few points of validation measured, taken in the months of February, March and May, the range of measured W was limited between 0.5 and 2.5 cm. It was therefore decided to compare the validation and simulation values of W and γ in this range, with their corresponding errors.

4. Results and discussion

Results from Figure 2 show clearly that channel 2 has the only simulated values coincident with the validation values. This is not strange since the atmosphere has the most pronounced presence of W in the spectral range of 11.5-12.5 μm (Varanasi, 1988). This range is coincident with channel 2 of CE 312 and it seems evident that this channel has to be the most sensitive to changes of W in the atmosphere, and therefore the most suitable from which to obtain W from measurements of atmospheric radiance in TIR region. So by establishing interest solely in the spectral region 11.5-12.5μm, which is the region in Channel 2 of the CE 312 radiometer, and by considering the validation results as satisfactory, it is possible to establish a relationship between W and γ.

Considering equation (5) as the desired expression to obtain W, obtaining measurements of the atmospheric downwelling radiance with a TIR instrument can be estimated to have an uncertainty of ± 0.3 cm, which corresponds to the standard deviation. Furthermore, the difference between the simulated value of W from the measured value of γ by equation (5) for each of the 10 validation points, and the value of W measured directly by the CE 318, is presumed to have a BIAS of ± 0.4 cm. The RMSE is then ± 0.5 cm.

We can conclude that there exists an expression which obtains the atmospheric water vapour content, equation (5), and by using that expression there is an assumption of making an uncertainty in the determination of W of ± 0.5 cm.

The study could probably be improved with more validation points, which is desired by the authors. In any case, this is the first approximation of an alternative method to those currently in use in determining W, and with different instrumentation, as to compliment an experimenter who only has TIR radiometers available.

V. Conclusions

In the present study, an alternative method has been studied to determine the atmospheric water vapour content by means of measurements *in situ* of atmospheric radiance, in the thermal infrared range. The proposed method is to use direct measurements of atmospheric downwelling radiance related with atmospheric water vapour content by means of the factor γ, present in the diffusive approximation proposed by Rubio *et al*. (1997). After a comparison of simulated values, obtained from the CLAR radiosoundings database, with *in situ* measurements of atmospheric water vapour content and γ, for the four spectral ranges in which the thermal radiometer CE 312 works, it has come to the conclusion that it is possible to obtain W through measurements of atmospheric downwelling radiance in the TIR region of 11.5-12.5 μm, with a RMSE of ± 0.5 cm. This study has the ability to improve results by means of obtaining more validation points.

Acknowledgments: This work was made possible with the finance of the Spanish *Ministerio de Ciencia e Innovación* (grant of V. García-Santos associated to project CGL2007-64666/CLI, and project CGL2007-29819-E/CLI, cofinanced by FEDER funds), and the finance of the *Conselleria d'Educació de la Generalitat Valenciana* (project PROMETEO/2009/086). The authors want to thank the CEAM foundation for its contribution in this work, the radiosounding data (project TRANSREG (CGL2007-65359/CLI)) and to Dr. Victor Estellés, from the Solar Radiation Group in Dept. of Earth Physics and Thermodynamics (University of Valencia), by providing us atmosphere water vapour content, framed in projects CGL2007-60648 and CGL2010-07790.

REFERENCES

- Berk A., Anderson G.P., Acharya P.K., Chetwynd J.H., Bernstein L.S., Shettle E.P. *et al.* (1999): MODTRAN 4 user's manual. MA: Air Force Research Laboratory, *Space Vehicles Directorate*, Air Force Material Command, Hascom AFB. **95**.

- Brogniez G., Pietras C., Legrand M., Dubuisson P. and Haeffelin M., (2003), A high-accuracy multiwavelength radiometer for in situ measurements in the thermal infrared—Part II: Behavior in field experiments, *J. Atmos. Ocean Technol*., **20**, nr. 7, pp. 1023–1033.

- Bruegge, C. J., Conel J. E., Green R. O., Margolis J. S., Holm R. G., and Toon G. (1992), Water vapor abundance retrievals during FIFE, *Journal of Geophysical Research*, **97**(D17), nr. 18, pp. 759–18,768.

- Estellés V., Martínez-Lozano J.A., Utrillas M.P. and Campanelli M., (2007), Columnar aerosol properties in Valencia (Spain) by ground-based Sun photometry, Journal *of Geophysical Research*, **112**, D11201, pp. 9, doi: 10.1029/2006JD008167.

- Galve J.M., Coll C., Caselles V. and Valor E. (2008): An atmospheric radiosounding database for generating Land Surface Temperature algorithm. *Remote sensing of Environment*: **46**, pp. 1547-1557. Doi:10.1109/TGRS.2008.916084.

- García-Santos V., Valor E., Mira M., Coll C., Galve J.M. and Caselles V., (2010), Evaluación de distintos métodos de medida de la radiancia atmosférica descendente en el infrarrojo térmico, *Revista de Teledetección* (under review).

- Guanter L., Gómez-Chova L., Moreno J., (2008), Coupled retrieval of aerosol optical thickness, columnar water vapor and surface reflectance maps from ENVISAT/MERIS data over land, *Remote Sensing of Environment*, **112**, pp. 2898–2913, doi:10.1016/j.rse.2008.02.001.

- Holben B. N., Eck T. F, Skitsker I., Tanré D., Bziis J. P., Setzer A., Vermote E.,. Reagan J. A, Kazlfnzan Y. J., Nnknjima T., Lauemi F., Jan kozoink I. and Smi mov A., (1998), AERONET—A federated instrument network and data archive for aerosol characterization, *Remote Sensing of Environment*., **66**, pp. 1– 16.

- Korb A.R., Dybwad P., Wadsworth W. and Salisbury J.W., (1996), Portable Fourier transform 283 infrared spectroradiometer for field measurements of radiance and emissivity, *Applied Optics*, **35**, nr. 10, pp. 1679-1692.

- Milz M., Clarmann T.V., Bernath P., Boone C., Buehler S.A., Chauhan S., Deuber B., Feist D.G., Funke B., Glatthor N., Grabowski U., Griesfeller A., Haefele A., Höpfner M., Kämpfer N., Kellmann S., Linden A., Müller, S., Nakajima, H., Oelhaf, H., Remsberg E., Rohs S., Russell III J.M., Schiller C., Stiller G. P., Sugita T., Tanaka T., Vömel, H., Walker, K., Wetzel, G., Yokota, T., Yushkov, V. and Zhang, G. (2009), Validation of water vapour profiles (version 13) retrieved by the IMK/IAA scientific retrieval processor based on full resolution spectra measured by MIPAS on board Envisat, *Atmospheric Measurement Techniques,* **2**, pp. 379–399.

- Noël, S., Buchwitz, M., and Burrows, J. P., (2004), First retrieval of global water vapour column amounts from SCIAMACHY measurements, *Atmos. Chem. Phys*., **4**, pp. 111–125.

- Rubio, E., Caselles, V. and Badenas, C., (1997), Emissivity Measurements of Several Soils and Vegetation Types in the 8-14/ m Wave Band: Analysis of Two Field Methods, *Remote Sensing of Environment*, **59**, pp. 490-521.

- Rubio, E., (1997), hacia la optimización de la medida de la emisividad y la temperatura en teledetección, *Tesis Doctoral*, **2**, pp. 42-51.

- Varanasi, P., (1988), Infrared absortion by water vapor in the atmospheric window. *SPIE Modeling of the atmosphere,* **98**, pp. 213-230.

- Wan, Z. and Dozier, J., (1989), Land-surface temperature measurement from space: Physical principles and inverse modeling, *IEEE Trans. Geosci. Remote Sens.*, **27**, nr. 3, pp. 268–277.

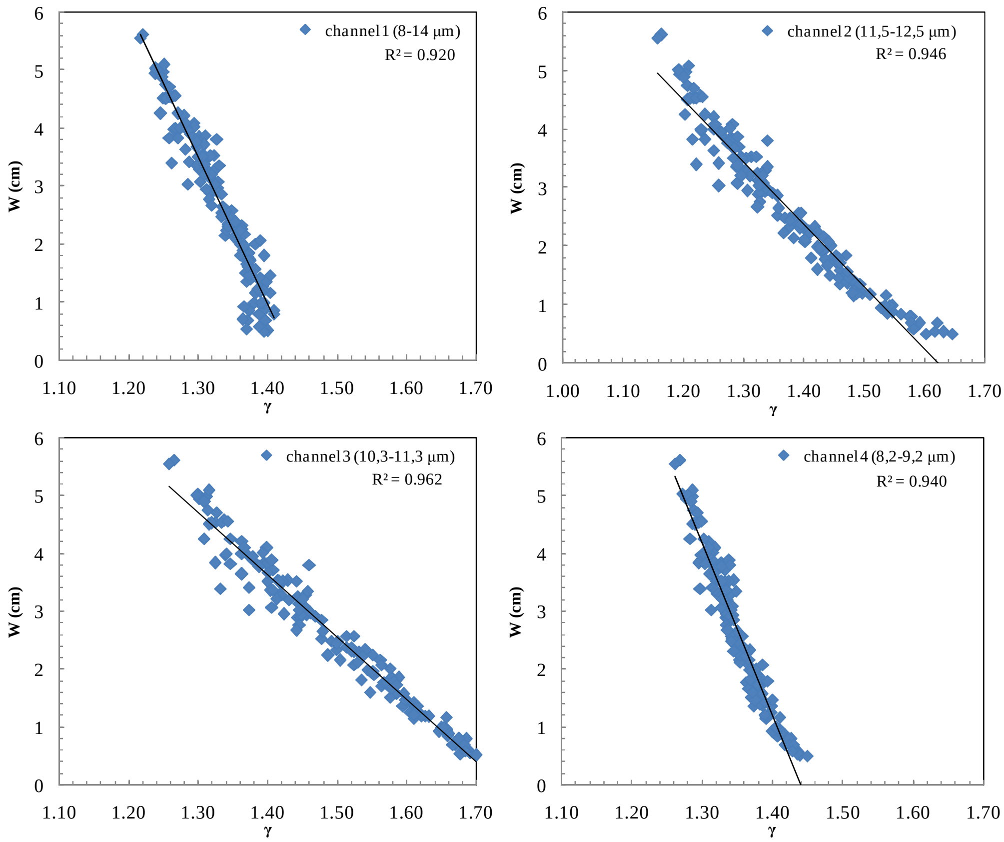

Figure 1: Representation of W versus γ obtained with the 180 atmospheric situations extracted from radiosoundings database CLAR, once were introduced in a RTC. The expressions of the linear regression represented at each spectral range correspond to equations (4) to (7), in the graphs appears the correlation coefficient (R^2).

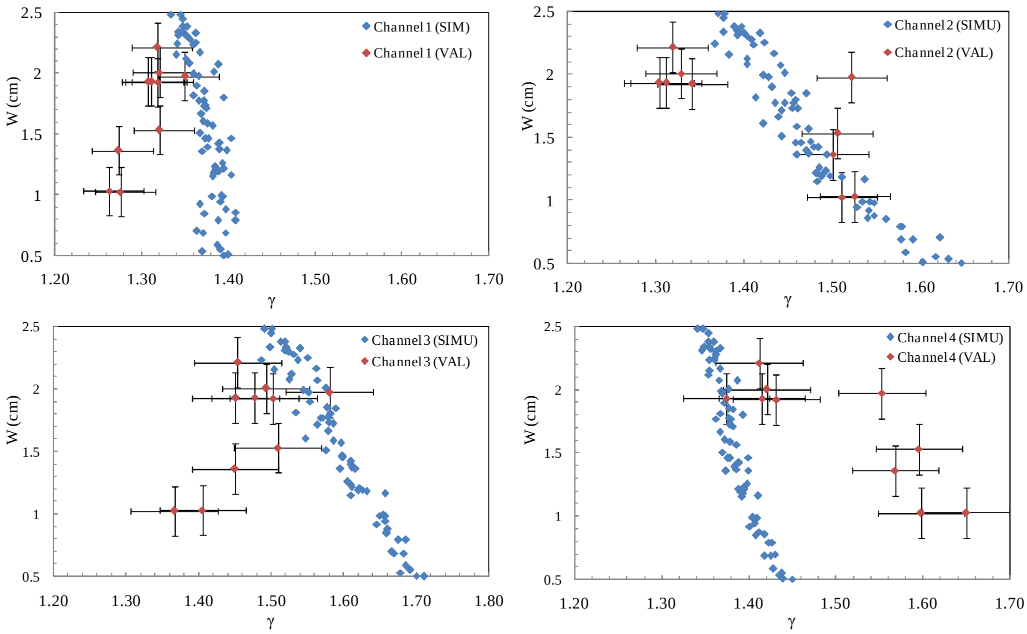

Figure 2: Comparison of validation results (VAL) and simulated values (SIMU) of W and γ in the 4 spectral channels of the CE 312. Are included the errors of γ and W in the case of the validation results.