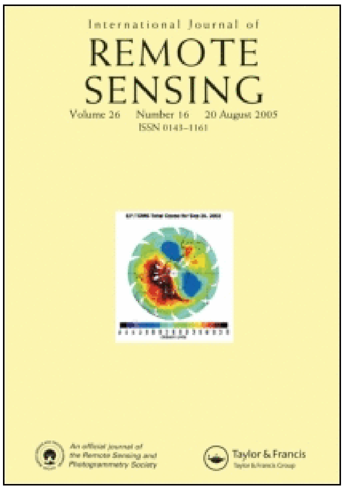

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Water-vapour retrieval from Meteosat 8/SEVIRI observations

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This paper aims to propose operational algorithms to retrieve the total atmospheric water vapour content (W) using the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on-board Meteosat 8. MODTRAN3.5 was used to obtain simulated data in the thermal infrared channels IR10.8 and IR12.0, in order to determine the numerical values of the coefficients of the algorithms. The algorithm proposed for land pixels takes into account the SEVIRI observation geometry and the radiometric temperatures obtained in the split-window channels at two different times during a day and requires a minimum difference of 10 K in terms of temperature between the two situations. Comprehensive error analyses gave rms errors lower than $0.5\,\mathrm{g\,cm^{-2}}$ when observations were taken between the nadir and 50°. The algorithm is validated with *in situ* values, i.e. radiosondes and W measurements with a CIMEL CE318 sun photometer, both obtained from a field campaign, with rms validation errors of 0.2 and $0.7\,\mathrm{g\,cm^{-2}}$, respectively. Additionally, six stations all over the SEVIRI field of view were selected to validate the algorithm from radiosondes data, providing an rms error of $0.4\,\mathrm{g\,cm^{-2}}$. Concerning sea pixels, the linear atmosphere–surface temperature relation is adapted to SEVIRI and takes into account the sea-surface temperature, the atmospheric effective temperature, and the radiometric temperature in the IR10.8 channel. The total error obtained from this methodology has a value between 0.8 and $1.1\,\mathrm{g\,cm^{-2}}$, and the validation is carried out using radiosonde data from four stations near the sea, providing rms errors lower than $0.6\,\mathrm{g\,cm^{-2}}$.

1. Introduction

Atmospheric water vapour has a great impact on the Earth's climate. It is an important parameter to understand the hydrological cycle, biosphere–atmosphere interaction, and energy budget, as well as to monitor climate change due to greenhouse gases. Moreover, knowledge of the total atmospheric water vapour content (W) is necessary to improve the precision when estimating the land surface temperature (LST) obtained from satellite data by means of split-window algorithms. In particular, an accuracy of $0.5\,\mathrm{g\,cm^{-2}}$ is required in order to obtain LST from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on-board Meteosat 8 with an error lower than 1.5 K when the viewing zenith angles are less than 50° (Sobrino and Romaguera 2004).

The W may be estimated by means of atmospheric radiosondes simultaneous with the sensor, when it overpasses the same region. However, this is not always possible,

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especially when historical satellite databases are considered. Moreover, radiosondes are not systematically carried out over many regions in the planet. In order to solve this problem, several methodologies have been proposed to obtain *W* from different sensors, such as Moderate Resolution Imaging Spectrometer (MODIS) and Advanced Very High-resolution Radiometer (AVHRR). In this respect, the inclusion of the ratio of transmittances in the split-window region between 10 and 12 μm permits the elimination of a significant quantity of error in the retrieval of LST, which was proved by Harris and Mason (1992) and Sobrino *et al.* (1993, 1994) with the AVHRR sensor. Therefore, the ratio of transmittances for AVHRR was obtained by Kleespies and McMillin (1990) from the channel brightness temperature differences, assuming that the atmosphere and surface emissivities in channels 4 and 5 are invariant. Other improved techniques use the ratio of the spatial variance of the channel brightness temperatures (Jedlovec 1990) or the split-window covariance–variance ratio (Sobrino *et al.* 1993, 1999).

Sobrino *et al.* (2002) developed a simplified method for estimating the total amount of atmospheric water vapour over sea surfaces. The method is named linear atmosphere – surface temperature relationship (LASTR).

In particular, several methodologies have been developed to obtain *W* from the recent SEVIRI sensor on-board Meteosat 8. Thus, Fernández (2004) proposes a methodology based on the ratio logarithm (Chesters *et al.* 1987) and Split-Window differences (Andersen 1996), where the coefficients of the algorithms are obtained by simulation using radiosondes and numeric models. Stengel *et al.* (2005) use the Moderate Resolution Imaging Radiometer (MODIS) water vapour products for land pixels and the ESA's microwave radiometer on Aqua for sea pixels, in order to provide *W* from SEVIRI infrared brightness temperatures.

In this context and bearing in mind the temporal resolution of SEVIRI imagery (15 min), the objective of this paper is to propose an algorithm to retrieve *W* from SEVIRI land data following the methodology given by Schroedter-Homscheidt *et al.* (2004a, b), which is based on Kleespies and McMillin (1990) and considers the split window channels at two acquisitions which differ in time. In addition, the LASTR methodology will be adapted to SEVIRI imagery in order to obtain *W* over sea pixels.

To this end, the theory associated with the *W* retrieval is described in §2. §3 explains the procedure to obtain the simulated data sets and the *in situ* data. §4 includes the formulation of the *W* algorithms and the sensitivity analysis. Finally, in §5, the validation of the algorithms is carried out, and an application is performed.

2. Theory

2.1 *Land-surface pixels*

The algorithm developed to retrieve the *W* over land surface pixels is based on the model presented by Kleespies and McMillin (1990). In general, infrared measurements are affected by air temperature, surface temperature, surface emissivity, water vapour, and absorption of other atmospheric gases. The split window channels at 10.8 and 12.0 μm are used and selected close to each other, so that equal emissivity and absorption of other gases besides water vapour can be assumed. Surface temperature is the same for both channels, as this parameter is not dependent on the observer's wavelength. This reduces the dependence of measurements in these channels to air temperature and water-vapour absorption. Two times with varying surface temperature are selected, and so two brightness temperature measurements can be exploited. With these two equations, the air-temperature dependence can be eliminated. SEVIRI offers the possibility of using this approach as it involves measurements in a 15-min temporal resolution and, therefore, can deliver two situations with varying surface temperatures during the daily temperature cycle. Equations (1) and (2) describe the functional relationship between brightness temperatures and W, according to Schroedter-Homscheidt *et al.* (2004b):

$$\frac{\tau_{11}}{\tau_{12}}=\frac{\left(T_{11}^{\mathrm{A}}-T_{11}^{\mathrm{B}}\right)}{\left(T_{12}^{\mathrm{A}}-T_{12}^{\mathrm{B}}\right)} \tag{1}$$

$$W=\mathrm{fct}\left[\frac{1}{\sec\theta}\ln\left(\frac{\tau_{11}}{\tau_{12}}\right)\right], \tag{2}$$

where T_{11} and T_{12} are brightness temperatures in channels IR10.8 and IR12.0, θ is the satellite zenith angle, A and B are two temporal different situations, and τ stands for the transmission. The boundary conditions of the methodology are a cloud-free sky and non-existence of heavy atmospheric instabilities or a high aerosol burden.

Kleespies and McMillin (1990) proposed a linear relationship between the argument in equation (2) and the water-vapour content. Schroedter-Homscheidt *et al.* (2004a) found that the results were improved when a third-order polynomial relation was used. In this case, the coefficients of the relation were obtained from simulations with MODTRAN3.7 (Abreu and Anderson 1996), by considering radiosondes from the Thermodynamic Initial Guess Retrieval (TIGR) (Scott and Chedin 1981) and setting the surface emissivity to a global average value of 0.975.

The aim of this paper is to develop the relation showed by equation (2), according to the Schroedter-Homscheidt *et al.* (2004b) methodology by considering a high variety of surface emissivity values.

2.2 *Sea-surface pixels*

The algorithm developed to retrieve the W over sea surfaces is based on the linear atmosphere–surface temperature relationship (LASTR). Starting from the radiative transfer equation for a cloud-free situation, and considering the emissivity as being equal to one for a blackbody, the transmittance through the atmosphere from the surface to the satellite in channel i can be obtained following Sobrino *et al.* (2002), as:

$$\tau_i=\frac{T_i-T_{\mathrm{a}i}}{\mathrm{SST}-T_{\mathrm{a}i}}, \tag{3}$$

where T_i is the brightness temperature measured at the satellite level in channels IR10.8 and IR12.0, SST is the corresponding sea surface temperature, and $T_{\mathrm{a}i}$ is the effective atmospheric temperature, which can be considered as the temperature at which the whole atmosphere radiates. $T_{\mathrm{a}i}$ is estimated from a correlation with SST which is obtained from Romaguera *et al.* (2005) for SEVIRI observations according to:

$$\begin{aligned}\mathrm{SST}=&\,T_{\mathrm{IR10.8}}+(0.99\cos\theta+0.21)[T_{\mathrm{IR10.8}}-T_{\mathrm{IR12.0}}]+\\&+\left(\frac{0.364}{\cos\theta}+0.15\right)[T_{\mathrm{IR10.8}}-T_{\mathrm{IR12.0}}]^2+\left(\frac{0.327}{\cos^2\theta}+0.11\right),\end{aligned} \tag{4}$$

where $T_{IR10.8}$ and $T_{IR12.0}$ are the at-sensor brightness temperatures of the IR10.8 and IR12.0 SEVIRI thermal channels (in Kelvin), and θ is the observation angle. The total error of this algorithm is 0.8 K.

Finally, a simple linear relationship is defined between the total atmospheric vapour content along the path and the atmospheric transmittance in the IR10.8 channel.

3. Data

3.1 *Simulation data*

The MODTRAN3.5 radiative transfer code was used to predict the radiances in IR10.8 and IR12.0 SEVIRI channels with the suitable channel filter functions. The simulations were made for a set of 61 radiosonde observations carefully extracted from the TIGR database on a worldwide scale and for seven different satellite zenith angles, 0°, 10°, 20°, 30°, 40°, 50°, and 60°. The first boundary layer of the radio-soundings was considered as the surface temperature (T_{sa}). Four 'surface temperatures' were considered: $T_s=T_{sa}$, $T_s=T_{sa}+5$ K, $T_s=T_{sa}+10$ K and $T_s=T_{sa}+20$. Concerning emissivity, an amount of 74 surface emissivity spectra was selected from the ASTER Spectral Library (http://speclib.jpl.nasa.gov/). Summarizing, 4514 different situations were obtained for each 'surface temperature' and satellite zenith angle (Sobrino and Romaguera 2004).

In order to select the couple of radiometric temperature data sets which will be used in equation (2) to generate the algorithm, an analysis of the inclusion of the noise equivalent delta temperature (neΔT) was carried out. Two datasets with surface temperature difference (ΔT_s) of 5 K were considered, namely $T^A=T_{sa}$ and $T^B=T_{sa}+5$ K. The deviation of the values in equation (2) is 0.24 g cm^{-2} when ideal conditions are assumed. On the other hand, they range up to 1.24 g cm^{-2} if the neΔT are considered, which are 0.25 K and 0.37 K in the IR10.8 and IR12.0 SEVIRI channels in the *end-of-life* conditions of the sensor (Aminou *et al.* 2003) (table 1).

Assuming the less favourable combination shown in table 1, an improvement in the deviation values is found when higher ΔT_s values are considered, yielding 0.33 and 0.20 g cm^{-2} with ΔT_s of values 10 and 20 K. Therefore, in the forthcoming analysis, two data sets will be used, namely $T_s=T_{sa}$ and $T_s=T_{sa}+10$ K, in order to avoid any noise effects.

In parallel with this, an additional database was generated, taking into account only the sea surface emissivity and its angular variability according to the procedure given by Masuda *et al.* (1988) (Romaguera *et al.* 2005) and three surface temperatures, namely $T_s=T_{sa}$, $T_s=T_{sa}-5$ K, and $T_s=T_{sa}+5$ K. The upwelling radiance and transmittance obtained from MODTRAN simulations was used to calculate T_{ai}

Table 1. Deviation of water vapour (g cm^{-2}) in equation (2) when $T^A=T_{sa}$ and $T^B=T_{sa}+5$ K databases are considered and different combinations of neΔT are taken into account.

	${T_{11}}^A+0.25$ K	${T_{11}}^A-0.25$ K	${T_{11}}^A+0.25$ K	${T_{11}}^A-0.25$ K	
${T_{11}}^B-0.25$ K	0.49	0.24	0.24	0.49	${T_{12}}^B-0.37$ K
${T_{11}}^B+0.25$ K	0.24	0.18	0.51	0.27	${T_{12}}^B+0.37$ K
${T_{11}}^B+0.25$ K	0.49	0.27	0.24	0.48	${T_{12}}^B-0.37$ K
${T_{11}}^B-0.25$ K	0.24	0.51	**1.24**	0.24	${T_{12}}^B+0.37$ K
	${T_{12}}^A+0.37$ K	${T_{12}}^A-0.37$ K	${T_{12}}^A-0.37$ K	${T_{12}}^A+0.37$ K	

according to Sobrino *et al.* (1996):

$$T_{ai} = B^{-1}\left(\frac{R_{\text{up } i}}{1-\tau_i}\right), \tag{5}$$

where B is the Planck function, and $R_{\text{up}i}$ and τ_i are the atmospheric upwelling radiance and transmittance in channel i.

3.2 *Validation data: Radiosondes and CIMEL data*

In order to validate the algorithms proposed in this paper, two data sets were considered. The first was extracted from the database of a field campaign over land, and the second was obtained from radiosondes launched all over the SEVIRI field of view. The validation campaign over land was developed in the Barrax field site, located in the south of Spain approximately 20 km away from Albacete (39°3′ N, 2°6′ W, 700 m elevation) observed by SEVIRI under an angle of 45°. A set of seven radiosondes launched in 2004 between 13 and 18 July in the framework of the Spectra Barrax Campaign (SPARC) was analysed. MODTRAN3.5 was used to obtain W under an observation angle of 45°. Furthermore, a CIMEL CE318 sun photometer was used to obtain W from the region of validation. This instrument has a filter situated in the water-vapour absorption band (940 nm), which allows W to be derived by means of photometric techniques (Bruegge *et al.* 1992). The measurements were taken every 15 min, with an error of 0.2 g cm^{-2} (Estellés *et al.* 2004). The W measured values were averaged during 1.5 h, 15 min before, and 1.25 h after the radiosonde launch, and were corrected by the cosine angle to obtain the W in the observation direction.

The second data set was obtained from the radiosondes launched during the period 10–24 of July 2004, in ten stations located all over the SEVIRI disk. These radiosondes were extracted from the *Atmospheric soundings* website of the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). The lack of some data in the African stations and the existence of clouds at the radiosonde launch time were the main constraints when selecting the test sites. Six stations were selected to validate the water vapour algorithm over land, namely Tamanrasset (22.8° N, 5.43° E), In Salah (27.23° N, 2.5° E), DAOF (27.7° N, 8.16° W), FBSK (24.55° S, 25.91° E), Farafra (27.05° N, 27.96° E), and Madrid (40.5° N, 3.58° W) observed by SEVIRI at angles of 27.2°, 31.8°, 33.4°, 40.7°, 44.1°, and 46.6°, respectively, and four stations for the validation over sea, namely St. Helena Is. (15.93° S, 5.66° W), Guimar-Tenerife (28.47° N, 16.38° W), FACT (33.96° S, 18.6° E), and Lajes (38.73° N, 27.06° W) at viewing zenith angles of 19.7°, 37.7°, 44.1°, and 52.8°, respectively. Radiosondes were launched in these sites at 00 UTC and/or 12 UTC. The value of precipitable water for the entire sounding given by the database is corrected by the observation angle cosine to obtain W in the SEVIRI observation direction. Figure 1 shows the location of the different test sites over land and over sea.

Additionally, data from radiosondes launched at 00 and 12 UTC in Madrid (Spain) during the year 2005 were used in order to estimate the stability or stationarity of the atmospheric water-vapour value during the day. Excluding missing data, a period of 252 days was selected to analyse the day–night variation in W. This topic is addressed in §5.

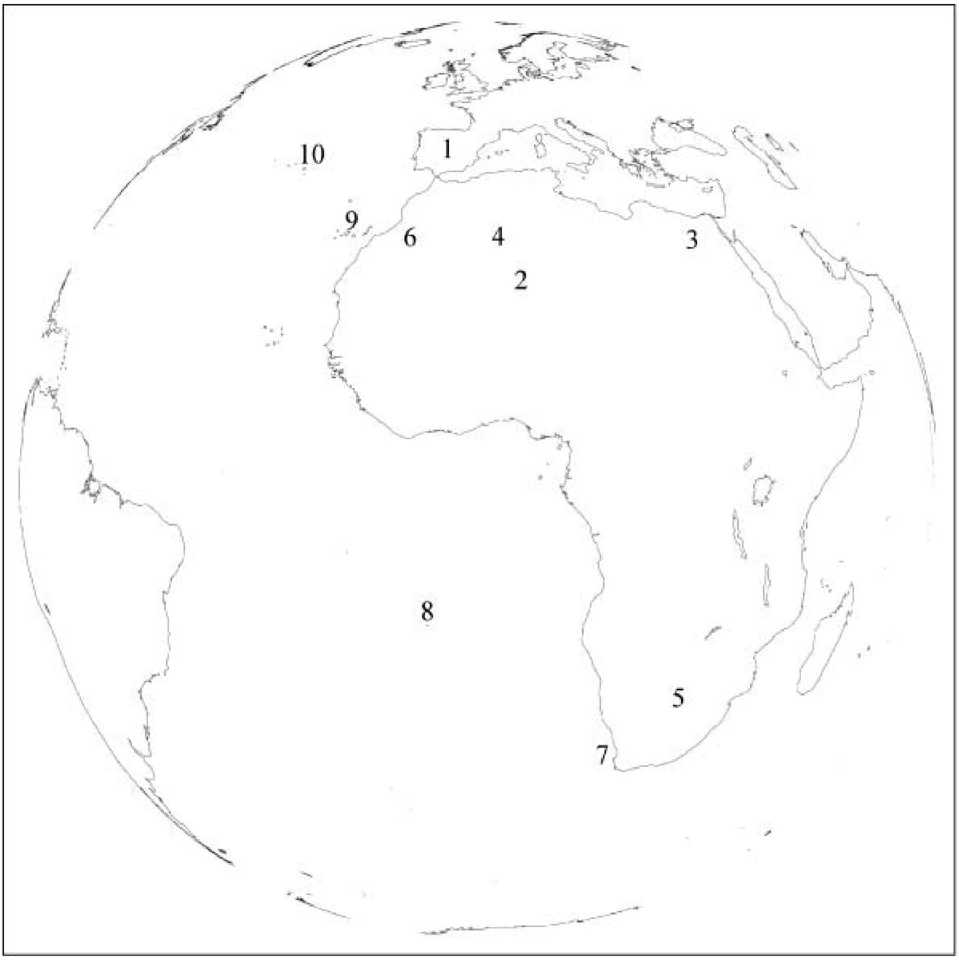

Figure 1. Location of the test stations selected for the validation of the W algorithms over land (equation (6)) and over sea (equation (8)).

4. Results

4.1 *Land-surface pixels*

4.1.1 From simulated data. In order to evaluate the relation given by equation (2), different relationships were analysed. The Levenberg–Marquardt regression was used under a nadir observation, yielding correlation coefficients with values of 0.984 for the linear relationship and 0.994 for the second- and third-order polynomial relationship. In terms of standard deviations, the results were $0.24\,\mathrm{g\,cm^{-2}}$ for the linear relation. For both the second- and third-order polynomial, these results were $0.15\,\mathrm{g\,cm^{-2}}$. Therefore, the results were not significantly improved due to a third-order polynomial, and the W was fitted for every observation angle to a second-order polynomial expression. Moreover the coefficients obtained for every angle were parameterized with the angle, so that the general formulation of the methodology is as follows:

$$\begin{aligned} W &= a \arg^2 + b \arg + c \\ a &= -15.1 \sec\theta + 5.1 \\ b &= 16.4 \sec\theta - 2.8 \\ c &= 0.336 \sec\theta - 0.117 \\ \arg &= \frac{1}{\sec\theta} \ln\left(\frac{T_{11}^{A} - T_{11}^{B}}{T_{12}^{A} - T_{12}^{B}}\right), \end{aligned} \tag{6}$$

where a minimum difference of 10 K between T_{12} in situation A and B is required to avoid noise effects.

Therefore, equation (6) represents the algorithm that is proposed to yield W from SEVIRI whose mean minimization error considering all the simulated angles is 0.19 g cm^{-2}. Figure 2 shows a comparison between the water vapour values obtained from the radiosondes (W_{rad}) and those calculated with the algorithm given by equation (6) (W_{alg}) under the nadir observation. The horizontal dispersion in W_{alg} for a given W_{rad} is related to the selection of 74 surface emissivity values to generate the database.

4.1.2 Sensitivity analysis. In order to obtain the accuracy in W retrieval, the error theory was applied to equation (6). Two situations were considered: first the *beginning of life* conditions of the sensor with neΔT(IR10.8)=0.074 K and neΔT(IR12.0)=0.11 K and second the *end of life* conditions with

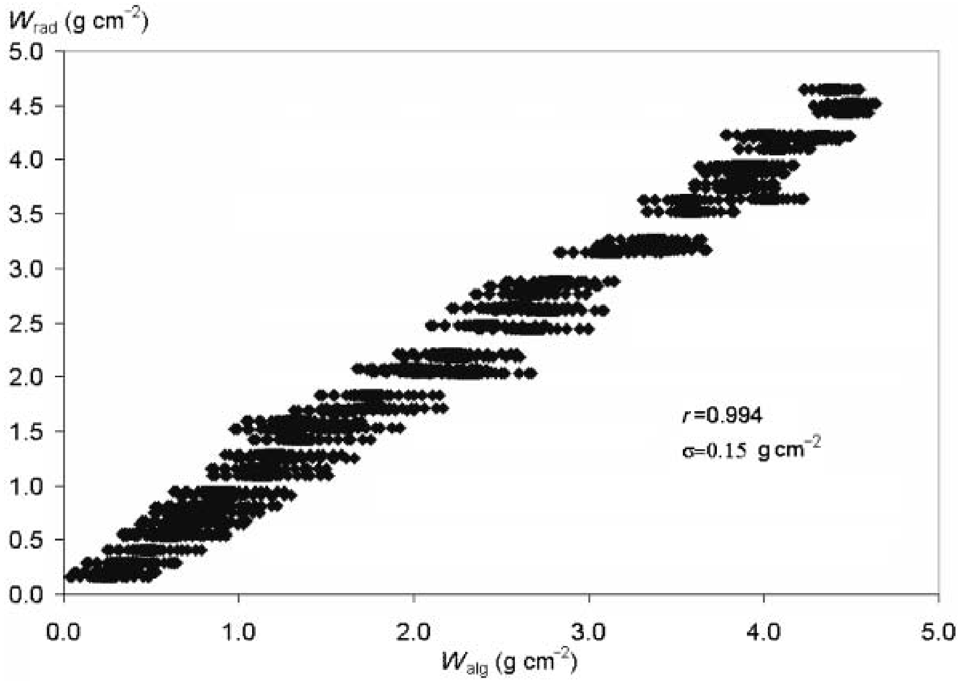

Figure 2. Total water vapour at nadir (W_{rad}) versus total water vapour modelled with equation (6) (W_{alg}), correlation coefficient, and standard deviation.

neΔT(IR10.8)=0.25K and neΔT(IR12.0)=0.37 K according to Aminou *et al.* (2003). The total error was calculated according to the expression: $\sigma^2{}_{\text{total}}=\sigma^2{}_{\text{minimization}}+\sigma^2{}_{\text{theory}}$, where $\sigma^2{}_{\text{theory}}=\sigma^2{}_{\text{ne}\Delta T}$. Considering the dataset used to generate the algorithm and assuming that the four brightness temperature terms contribute, figure 3 shows the total error obtained for every simulated observation angle.

In general, the total error in W estimation increases with observation angle, with values lower than 0.5 g cm^{-2} for the *beginning of life* conditions between the nadir and 50°.

4.2 *Sea-surface pixels*

Equation (7) shows the linear relation between $T_{\text{a}i\ (i=\text{IR10.8})}$ and SST for IR10.8 channel (the most transparent channel) with a correlation coefficient of 0.98 and an rms error of 3 K.

$$T_{\text{a IR10.8}}=\left(\frac{-0.033}{\cos\theta}+0.959\right)\text{SST}+\left(\frac{8.8}{\cos\theta}+3.5\right). \tag{7}$$

The linear fit proposed from the aforementioned simulated data to determine the water vapour over sea surfaces can be expressed by equation (8), where the coefficients of the algorithm are fitted as a function of the observation angle:

$$W_\theta=\left(\frac{-3.25}{\cos\theta}-3.36\right)\tau_{\text{IR10.8}}+\left(\frac{3.053}{\cos\theta}+3.881\right). \tag{8}$$

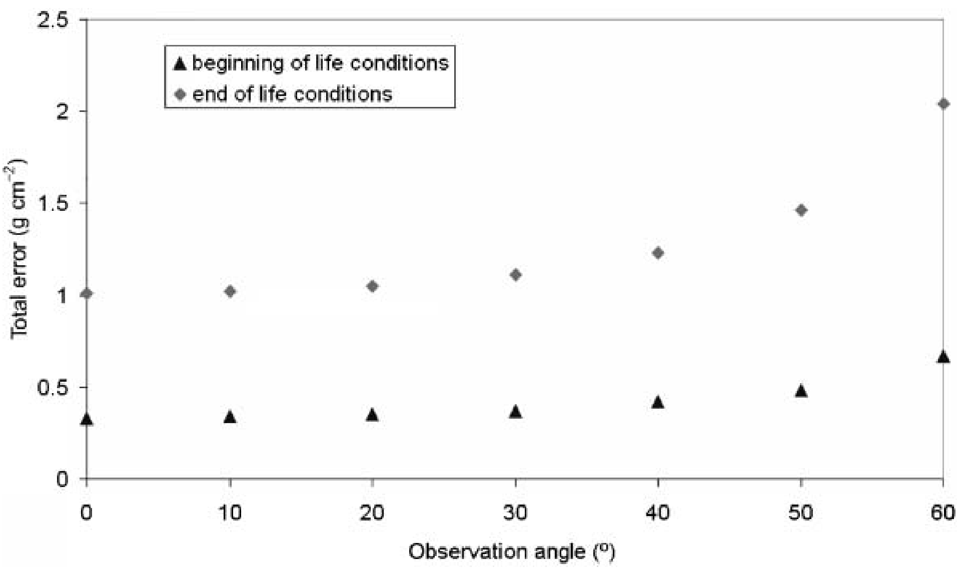

Figure 3. Total error associated with the estimation of total atmospheric water vapour content over land pixels from the proposed algorithm (equation (6)) for two situations under seven observation angles: (*a*) beginning-of-life conditions with neΔT(IR10.8)=0.074 K and neΔT(IR12.0) and (*b*) end-of-life conditions with neΔT(IR10.8)=0.25 K and neΔT(IR12.0)=0.37 K.

The sensitivity analysis of this algorithm was carried out according to the error theory and taking into account equations (3) and (8). Figure 4 shows that the proposed algorithm is not really sensitive to neΔT, and the total error varies between 0.8 and 1.1 g cm^{-2} when angles between nadir and 40° are considered. These results are comparable with those obtained by Sobrino *et al.* (2002) using the same methodology with AVHRR data.

5. *In situ* validation

5.1 *Land-surface pixels*

5.1.1 Water-vapour stationarity analysis. The W algorithm for land pixels that is proposed in this paper (equation (6)) provides a unique value per day taking into account two acquisitions along the day. This section addresses the feasibility of using this single value to validate the algorithm with *in situ* data acquired at different times along the day. Data from radiosondes launched in Madrid during the year 2005 were used to compare the day–night variability of W. Table 2 shows the analysis carried out monthly and globally. The annual rms error in the day–night difference has a value of 0.34 g cm^{-2}, which is comparable to the algorithm error (0.5 g cm^{-2}) and leads to the feasibility of using a unique W value per day. Therefore, the value obtained with the methodology proposed (equation (6)) will be compared in the forthcoming sections with data obtained from a field campaign and from radiosondes launched all over the SEVIRI field of view.

5.1.2 Validation from the field-campaign data. The algorithm proposed in this paper (equation (6)) was applied to a series of SEVIRI images acquired at the International Institute for Geo-Information Science and Earth Observation (ITC) (Gieske *et al.* 2005) during the period 10–24 July 2004. Two acquisitions per day were considered, at 05:00 and 11:00 UTC in order to ensure the 10 K difference

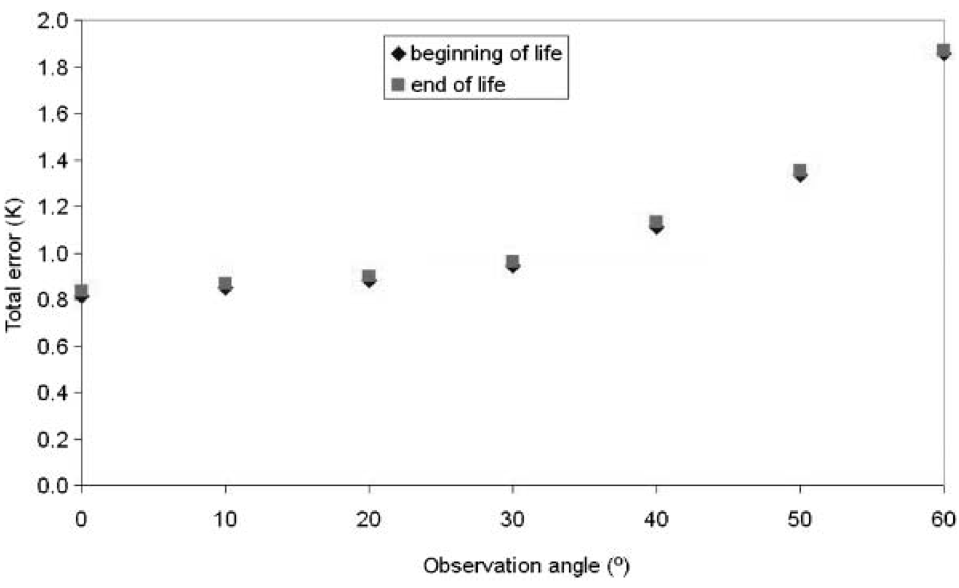

Figure 4. Total error associated with the estimation of W over sea pixels using equation (8).

Table 2. Analysis of W stationarity at Madrid station during 2005[a].

Month	Mean (W_{00}) ($\mathrm{g\,cm^{-2}}$)	σ (W_{00}) ($\mathrm{g\,cm^{-2}}$)	Mean ($W_{00}-W_{12}$) ($\mathrm{g\,cm^{-2}}$)	σ ($W_{00}-W_{12}$) ($\mathrm{g\,cm^{-2}}$)	rmse ($W_{00}-W_{12}$) ($\mathrm{g\,cm^{-2}}$)
January	0.67	0.31	0.06	0.22	0.2
February	0.71	0.28	0.003	0.22	0.2
March	0.99	0.55	0.13	0.31	0.3
April	1.14	0.44	0.016	0.35	0.4
May	1.22	0.54	0.1	0.42	0.4
June	2.19	0.65	0.43	0.65	0.8
July	1.71	353	0.34	0.6	0.7
August	1.81	0.53	0.19	0.35	0.4
September	1.65	0.74	0.53	0.77	0.9
October	1.81	0.76	0.26	0.6	0.7
November	1.43	0.47	0.31	0.61	0.7
December	0.94	0.44	0.06	0.47	0.5
Year 2005	1.3	0.7	0.18	0.5	0.5

[a]Mean value and standard deviation at 00:00 UTC, comparison of W at 00:00 and 12:00 UTC (W_{00} and W_{12}), mean value, standard deviation, and rms error of the difference.

which is required by the algorithm. Water vapour was obtained for the validation pixel and compared with the radiosonde W results and the CIMEL CE318 data, providing rms errors of 0.2 and $0.7\,\mathrm{g\,cm^{-2}}$, respectively (table 3).

5.1.3 Validation from test sites all over the disk. Six test sites were selected for the validation of the W algorithm (equation (6)), which was applied using 05:00 and 11:00 UTC acquisitions. The daily calculated W value was compared with the W available from radiosondes (two data per day as maximum). Taking into account the lack of radiosondes launching in some African stations, and excluding cloudy acquisitions, a set of validation data was generated. Table 4 shows the validation results and contains the number of validation data, average, standard deviation, and rms error. The rms validation error has a value of $0.4\,\mathrm{g\,cm^{-2}}$, which confirms the good behaviour of the algorithm developed to obtain W over land pixels. The results are comparable with others given by Sobrino *et al.* (2003), which obtain validation errors of $0.4\,\mathrm{g\,cm^{-2}}$ using the ratio technique over Moderate Resolution Imaging

Table 3. Difference between the W over land pixels obtained with the algorithm proposed in this paper (equation (6)) (W_{alg}) and that obtained from radiosondes (W_{rad}) and CIMEL CE318 measurements (W_{CIMEL}), and rms validation errors.

Date	UTC time	W_{alg} ($\mathrm{g\,cm^{-2}}$)	W_{rad} ($\mathrm{g\,cm^{-2}}$)	W_{CIMEL} ($\mathrm{g\,cm^{-2}}$)	$W_{\mathrm{alg}}-W_{\mathrm{rad}}$ ($\mathrm{g\,cm^{-2}}$)	$W_{\mathrm{alg}}-W_{\mathrm{CIMEL}}$ ($\mathrm{g\,cm^{-2}}$)
13 July 2004	16.32	1.9	1.77	Not available	0.13	Not available
14 July 2004	10.53	2.1	2.25	2.7	−0.15	−0.6
15 July 2004	8.16	2.3	2.48	3.1	−0.18	−0.8
15 July 2004	10.41	2.3	2.39	3	−0.09	−0.7
16 July 2004	11.05	2.5	2.85	3.3	−0.35	−0.8
16 July 2004	12.23	2.5	2.79	3.2	−0.29	−0.7
18 July 2004	10.13	2.8	2.51	3	0.29	−0.2
				Bias ($\mathrm{g\,cm^{-2}}$)	−0.09	−0.6
				SD ($\mathrm{g\,cm^{-2}}$)	0.2	0.2
				rmse ($\mathrm{g\,cm^{-2}}$)	0.2	0.7

Table 4. Validation of the W algorithm over land pixels (equation 6): Stations, number of validation data, *in situ* W (W_{rad}) mean value during the study period, mean and standard deviation of the comparison with algorithm outputs (W_{alg}), and rms validation error.

No.	Station	No. of data	W_{mean} ($g\,cm^{-2}$)	Mean ($W_{rad}-W_{alg}$) ($g\,cm^{-2}$)	σ ($W_{rad}-W_{alg}$) ($g\,cm^{-2}$)	Rms validation error ($g\,cm^{-2}$)
1	Madrid	12	2.6	0.5	0.4	
2	Tamanrasset	16	1.5	0.6	0.4	
3	Farafra	14	1.7	0.03	0.3	
4	In Salah	10	1.2	0.3	0.3	
5	FBSK	2	0.6	−0.4	0.2	
6	DAOF	5	1.2	0.6	0.2	
	Total	59		0.3	0.3	0.4

Spectroradiometer (MODIS) data using near-infrared radiance, and also agree with the results given by Stengel *et al.* (2005) with an accuracy of 0.3–0.6 $g\,cm^{-2}$.

5.2 *Sea-surface pixels*

Concerning sea-surface validation, four test sites were selected, and water vapour obtained from radiosondes was compared with the outputs of the algorithm proposed in this paper (equation (8)) at the time of the radiosonde launch. Taking into account the lack of radiosondes launching in some African stations, and excluding cloudy acquisitions, a set of validation data was generated. Table 5 shows the validation results and contains the number of validation data, average, standard deviation, and rms error (absolute values and relative error). The rms validation error has a value of 0.6 $g\,cm^{-2}$. These results provide confidence in the good behaviour of the algorithm over sea surfaces.

6. Application

This section includes an application of the total water-vapour content algorithm (equation (6)) to SEVIRI land data during 18 July 2004. The water-vapour content was calculated using different time acquisitions along the day. Starting from 5:00, 6:00, 7:00 UTC, and so on, and assuming a time interval of 6 h between the acquisitions A and B, ten values for W were obtained. In order to avoid any cloud effects, several regions in Africa's desert and mid-south Africa were selected. There were not sandstorms in these regions, and 91 000 pixels were computed.

Table 5. Validation of the W algorithm over sea pixels (equation (8)): Stations, number of validation data, *in situ* W (W_{rad}) mean value during the study period, mean and standard deviation of the comparison with algorithm outputs (W_{alg}), and rms validation error.

No.	Station	No. of data	W_{mean} ($g\,cm^{-2}$)	Mean ($W_{rad}-W_{alg}$) ($g\,cm^{-2}$)	σ ($W_{rad}-W_{alg}$) ($g\,cm^{-2}$)	Rms validation error ($g\,cm^{-2}$)
7	FACT	9	1.4	0.2	0.4	
8	St. Helena Is	6	1.4	−0.1	0.2	
9	Guimar-Tenerife	5	2.1	0.8	0.4	
10	Lajes	5	3.8	0.5	0.8	
	Total	25		0.4	0.5	0.6

The first calculation used the 5:00 and 11:00 UTC acquisition times (W5) and was taken as a reference to compare the rest of the combinations, named W6, W7, and so on. Figure 5 shows the water-vapour content variability using different time combinations. The W8, W9, W10, and W11 combinations are not shown in figure 5 because the radiometric temperature difference between the two acquisitions was lower than 10 K, which is a restriction in equation (6). In general, the absolute difference is less than 0.2 g cm^{-2} for more than 50% of the pixels and less than 0.4 g cm^{-2} for 90% of the pixels, which is a good result concerning the stability of the algorithm results.

7. Conclusion

In this paper, a general algorithm to retrieve W over land pixels from Meteosat 8/SEVIRI sensor data is presented. IR10.8 and IR12.0 channels are used to derive an algorithm which depends on brightness temperatures in two situations and on the observation angle. The sensitivity analysis shows that the proposed algorithm is capable of producing W with a total error lower than 0.5 g cm^{-2} for observation angles between nadir and 50°. The algorithm is validated with data from a field campaign, i.e. radiosondes and CIMEL CE318 measurements, yielding rms validation errors with values 0.2 and 0.7 g cm^{-2}, respectively. Besides, the validation of the methodology in test sites all over the SEVIRI disk provides an rmse of 0.4 g cm^{-2}. The daily stability of the method is achieved at the level of 0.4 g cm^{-2} with 90% confidence. In addition, the formulation to obtain W over sea pixels is proposed following the linear atmosphere–surface temperature relation, yielding errors of 0.8–1.1 g cm^{-2} in the sensibility analysis and rms validation errors of 0.6 g cm^{-2} obtained from radiosondes close to the sea.

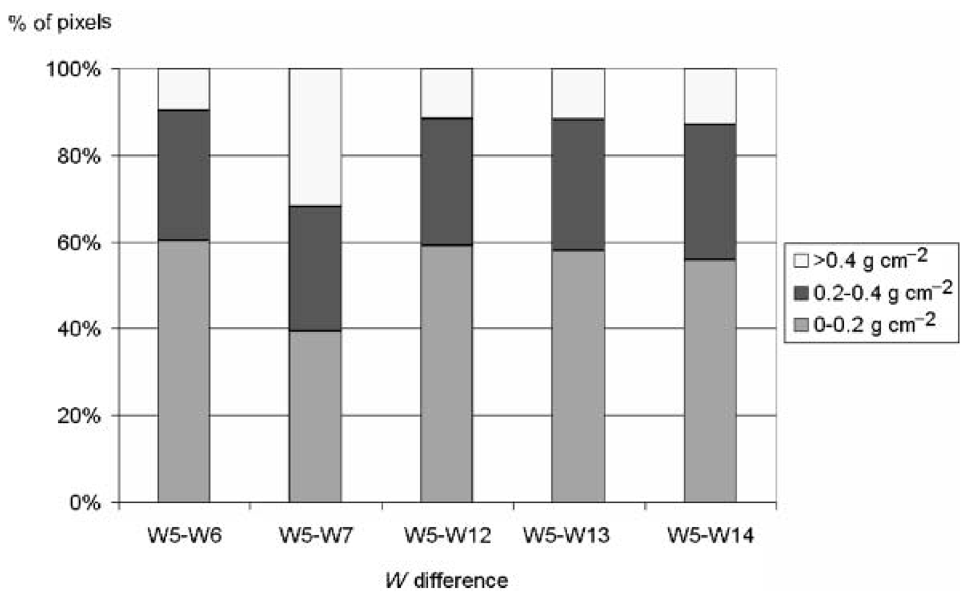

Figure 5. Difference in the estimation of W over land pixels using two time combinations along the day. The mean value of W5 in the regions of interest is 1.4 g cm^{-2}.

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