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Estimating the Atmospheric Water Vapor Content from Sun Photometer Measurements

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ABSTRACT

The differential absorption technique for estimating columnar water vapor values from the analysis of sun-photometric measurements with wide- and narrowband interferential filters centered near $0.94 \mu\text{m}$ is discussed and adapted. Water vapor line and continuum absorption calculations are obtained through the procedures included in the radiative transfer code LOWTRAN-7. The accuracy of these calculations is assessed through comparisons with a line-by-line code associated with an updated version of the Clough–Kneizys–Davies continuum. The effects of aerosols and aging of filters on the wide-to-narrow measurements ratio is analyzed. Columnar water vapor retrievals are based upon a search inside a 4D table that contains wide-to-narrow ratios corresponding to combinations of values assumed by four independent variables: sun zenith angle, spectral dependence of aerosol extinction, turbidity level, and the columnar water vapor itself. This table is calculated by taking into account the wide and narrow filter transmission functions, as previously recorded with spectrophotometers. The overall strategy is applied by obtaining columnar water vapor estimates from sunphotometric measurements performed during two field experiments in the Sahel, one of which is the Hydrologic Atmospheric Pilot Experiment in the Sahel. The agreement between these estimates and independent evaluations resulting from radiosoundings is satisfactory, demonstrating the consistency of the authors' approach.

1. Introduction

In several fields of geophysics and atmospheric sciences, accurate and space–time-resolved information is required about the vertically integrated content of water vapor in the atmosphere (or columnar water vapor (CWV) hereafter, expressed in kg m^{-2}). This is the case for everyone interested in estimating surface reflectances as well as vegetation indices from satellite imagery in the near-infrared and evaluating components of the surface radiative budget. The achievement of such tasks may be unsatisfactory if entirely based on routine meteorological radiosoundings because the latter are usually scarce in space and time. This fact has motivated

the concept of alternate methods of remote sensing involving radiant energy observations, enabling frequent estimates of CWV with a unique radiometer located at a given point of the surface, or, alternatively, simultaneous estimates of CWV over an extensive region viewed by a single radiometer in orbit. Frouin et al. (1990) reviewed the subject at the end of the 1980s.

Two approaches devoted to retrieving CWV values have been recently developed. The first one derives CWV estimates from measurements at the top of the atmosphere of the earth microwave emission, which is performed with radiometers on board meteorological satellites, more specifically with the Special Sensor Microwave/Imager (SSM/I). This method enables reliable results over oceans only, with a root-mean-square deviation around 3.6 kg m^{-2} when compared to corresponding evaluations from radiosoundings (Liu et al. 1992). Recent studies showed that CWV estimates from SSM/I observations are more accurate than those obtained from Television Infrared Observation Satellite–N Operational Vertical Sounder observations, whose bias can reach 10 kg m^{-2} over regions characterized by large-scale subsidence drying (Stephens et al. 1994). A second approach for CWV assessment, recently improved, involves observations of the atmospheric transmittance in

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the near-infrared, by employing sun photometers or equivalent instruments. This approach, originally conceived several decades ago, enables CWV determinations with a root-mean-square deviation around 2.2 kg m^{-2} when compared to corresponding evaluations from radiosoundings (Michalsky et al. 1995). Two other approaches may be improved in the near future: The first one involves the atmospheric refraction effects on microwave signals transmitted by the global positioning system satellites (Bevis et al. 1992; Ware et al. 1996); The second one relates the CWV to the spectral features of the outgoing near-infrared radiance (Kaufman and Gao 1992; Bouffières et al. 1997).

Most groups currently working on CWV estimates from sunphotometric observations (Bruegge et al. 1992; Reagan et al. 1995; Michalsky et al. 1995; Schmid et al. 1996; Halthore et al. 1997) apply parameterizations such as

$$t_w = \exp[-a(m\text{CWV})^b], \quad (1)$$

suggested by Reagan et al. (1987) to approximate the direct transmittance of the atmosphere in the water vapor absorption bands around the wavelength of $0.94 \mu\text{m}$, where m indicates the optical air mass. The parameter a may be assessed by fitting accurate water vapor transmittance simulated data, or, alternatively, by carefully analyzing sunphotometric measurements performed in parallel with collocated independent estimates of CWV from microwave radiometry or radiosounding during very stable atmospheric conditions. The parameter b , when not assumed equal to $1/2$, is estimated together with a by fitting results obtained from measurements or from theoretical calculations. Schmid et al. (1996) recently showed that empirically and theoretically based estimates of a and b can disagree significantly.

An alternative to these procedures is offered by the differential absorption technique proposed by Frouin et al. (1990). It is based on sunphotometric observations performed with two filters centered around $0.94 \mu\text{m}$ with different bandwidths. According to the authors, the method should allow CWV estimates to be practically independent of the aerosol extinction features and of the vertical profiles of air temperature and specific humidity.

This article is devoted to improvement and analysis of the differential absorption technique, including some aspects previously neglected, such as the effect of aerosol extinction. It explores an alternative strategy to derive CWV estimates in which relationships similar to Eq. (1) are unnecessary. The basic rationale of the technique is detailed in section 2, where it is related to some additional concepts. A number of sensitivity tests are presented in section 3. Some questions recently raised by Schmid et al. (1996) about the CWV estimates from sunphotometric measurements, namely, the influence of the water vapor continuum absorption and the impact of the aging of filters, are then addressed. The strategy proposed for retrieving CWV values from sunphotometric measurements is described in section 4 and ap-

plied to two different datasets for which radiosounding results were available for comparison. The present status of the technique is summarized in section 5.

2. Adapting the differential absorption technique of Frouin et al.

The designation "differential absorption" indicates the analysis of radiative measurements differently affected by water vapor absorption, with the aim of estimating CWV. The pioneer in this subject, F. E. Fowle (1912, 1913), obtained CWV values from solar transmission observations performed under different zenith angles in different spectral regions affected by relatively strong water vapor absorption (0.93 , 1.13 , or $1.47 \mu\text{m}$). Since then, similar methods based upon photometric measurements through narrow spectral channels delimited by interferential filters have been tried. These filters can be spectrally chosen to match suitably different absorption intensities inside a water vapor band (or no absorption outside the band). Such methods have been applied to sunphotometric measurements performed at ground level, using two channels (Volz 1974) or three channels (Thome et al. 1992). They have been utilized also through measurements of the upwelling near-infrared radiance made at aircraft levels (Kaufman and Gao 1992; Bouffières et al. 1997). A particular version of these methods was proposed by Frouin et al. (1990). It is based on simultaneous observations performed through two filters with different transmission bandwidths centered around the same wavelength located in a water vapor band.

Observations performed with a sunphotometer pointing to the sun disk, in which the detector is set in a plane perpendicular to the line of sight, provide signals V that can be expressed as

$$V(\Delta\lambda) = \int_{\Delta\lambda} E(\lambda) \mathcal{R}(\lambda) d\lambda, \quad (2)$$

where $\Delta\lambda$ is the filter bandwidth transmission, defined as the wavelength domain throughout which the optical transmission function is greater than zero, and $E(\lambda)$ is the solar spectral irradiance ($\text{W m}^{-2} \mu\text{m}$) incident on the instrument aperture. In this equation, $\mathcal{R}(\lambda)$ is an instrument parameter, product of the filter transmission function, the detector responsivity, and nonspectral quantities, such as the detector-sensitive area and the conversion factor between the detector output voltage and the instrument output signal. Assuming there are no clouds in the instrument field of view, the spectral irradiance E can be written in the form of a sum of contributions E^t (directly transmitted) and E^s (resulting mainly from forward scattering of the solar beam):

$$E(\lambda) = E^t(\lambda) + E^s(\lambda). \quad (3)$$

Spectral irradiances E^t and E^s can be expressed as

$$E^i(\lambda) = (\bar{d}/d)^2 E_o(\lambda) t(\lambda) \quad (4)$$

$$E^s(\lambda) = \int_{\Delta\Omega} L(\lambda, \Omega) d\Omega, \quad (5)$$

where d is the sun–earth distance during the measurement, and \bar{d} is its mean annual value, $\Delta\Omega$ is the instrument FOV, and all other quantities are wavelength dependent; E_o is the solar spectral irradiance at the top of the atmosphere, t is the direct total atmospheric transmittance, and L is the diffuse spectral radiance incident from the direction Ω . The direct atmospheric transmittance can be interpreted, at any wavelength, in terms of the product of several components:

$$t(\lambda) = t_w(\lambda)t_g(\lambda)t_a(\lambda)t_m(\lambda), \quad (6)$$

where t_w relates to water vapor absorption, t_g to absorption by other gases, t_a to aerosol extinction, and t_m to molecular (Rayleigh) scattering. In other words, a sunphotometric measurement V may be expressed as

$$V(\Delta\lambda) = V^i(\Delta\lambda) + V^s(\Delta\lambda). \quad (7)$$

$$V(\Delta\lambda) = (\bar{d}/d)^2 \int_{\Delta\lambda} E_o(\lambda) \mathcal{R}(\lambda) t(\lambda) d\lambda + \int_{\Delta\lambda} \mathcal{R}(\lambda) \left(\int_{\Delta\Omega} L(\lambda, \Omega) d\Omega \right) d\lambda, \quad (8)$$

depending therefore on the instrument characteristics as well as on the atmospheric optical properties.

The procedure proposed by Frouin et al. (1990) to retrieve the CWV is based on the ratios of measurements performed through filters centered around $0.94 \mu\text{m}$, associated with a wide bandwidth $\Delta\lambda_w$ and to a narrow one $\Delta\lambda_N$. The authors showed the feasibility of such a principle by analyzing sunphotometric measurements at ground level as well as measurements of upwelling radiances at aircraft level, the latter resulting from solar radiation reflected by the surface–atmosphere system. We are hereafter concerned by sunphotometric measurements only.

Assuming that the relative importance of the diffuse contributions in signals $V(\Delta\lambda_w)$ and $V(\Delta\lambda_N)$ is essentially the same,

$$\frac{V^s(\Delta\lambda_w)}{V^i(\Delta\lambda_w)} \simeq \frac{V^s(\Delta\lambda_N)}{V^i(\Delta\lambda_N)}, \quad (9)$$

the ratio of measurements performed by using the wide and the narrow filters can be written as

$$\frac{V(\Delta\lambda_w)}{V(\Delta\lambda_N)} = \frac{V^i(\Delta\lambda_w) + V^s(\Delta\lambda_w)}{V^i(\Delta\lambda_N) + V^s(\Delta\lambda_N)} \simeq \frac{V^i(\Delta\lambda_w)}{V^i(\Delta\lambda_N)}. \quad (10)$$

In the case of a multichannel photometer with commutable filters on a rotating wheel in front of a single detector, the wide-to-narrow ratio of signals $V(\Delta\lambda_w)$ and $V(\Delta\lambda_N)$ can be easily analyzed. Only the spectral factors constituting $\mathcal{R}(\lambda)$ need to be considered in this ratio.

These are the transmission functions $\varphi_w(\lambda)$ and $\varphi_N(\lambda)$ associated with the wide and narrow filters, respectively, and the detector responsivity $r(\lambda)$:

$$\frac{V(\Delta\lambda_w)}{V(\Delta\lambda_N)} = \frac{\int_{\Delta\lambda_w} [E_o(\lambda)t(\lambda)\varphi_w(\lambda)r(\lambda)] d\lambda}{\int_{\Delta\lambda_N} [E_o(\lambda)t(\lambda)\varphi_N(\lambda)r(\lambda)] d\lambda}. \quad (11)$$

A particular form of such expression is hereafter employed:

$$R_{wN} = \frac{V(\Delta\lambda_w)}{V(\Delta\lambda_N)} = \frac{\int_{\Delta\lambda_w} [E_o(\lambda)t(\lambda)\varphi_w(\lambda)] d\lambda}{\int_{\Delta\lambda_N} [E_o(\lambda)t(\lambda)\varphi_N(\lambda)] d\lambda}, \quad (12)$$

once the responsivity of the detectors involved in this study is, according to the manufacturer, very flat throughout $\Delta\lambda_w$.

Equation (12) resembles but is not strictly equivalent to Eq. (1) in the article of Frouin et al. (1990),

$$\frac{V(\Delta\lambda_w)}{V(\Delta\lambda_N)} \simeq \frac{t(\Delta\lambda_w) E_o(\Delta\lambda_w)}{t(\Delta\lambda_N) E_o(\Delta\lambda_N)}, \quad (13)$$

where $t(\Delta\lambda_N)$ values are averaged values for atmospheric transmittance, weighted by instrument spectral response, whereas $E_o(\Delta\lambda_w)$ and $E_o(\Delta\lambda_N)$ are the solar irradiance at the top of the atmosphere integrated over the respective bandwidths. The authors neglected the influence of the spectral variation of the solar irradiance on mean transmittances $t(\Delta\lambda_w)$ and $t(\Delta\lambda_N)$ [see their Eq. (2)]. In point of fact, such an influence will be negligible (a) if both filter transmission functions $\varphi_w(\lambda)$ and $\varphi_N(\lambda)$ are symmetrical around the same central wavelength, and (b) if the spectral distribution $E_o(\lambda)$ is relatively constant over $\Delta\lambda_w$. The validity of these hypotheses also eliminates the influence of aerosol extinction on the wide-to-narrow ratio of sun photometer signals and therefore on the retrieved CWV values. Nevertheless, as shown in Fig. 1, it seems clear that both hypotheses cannot be accepted without restrictions. These aspects are discussed in section 3.

3. Modeling wide-to-narrow ratios

In this section we assess, theoretically, the importance of factors expected to have an influence on the wide-to-narrow ratios and therefore on the CWV values retrieved from sunphotometric observations. All the simulations employed a version of the radiative transfer code LOWTRAN-7 (Kneizys et al. 1988), modified to account for our choices about molecular scattering and aerosol extinction throughout the spectral region of interest.

The wide-to-narrow ratio of signals in Eq. (12) was

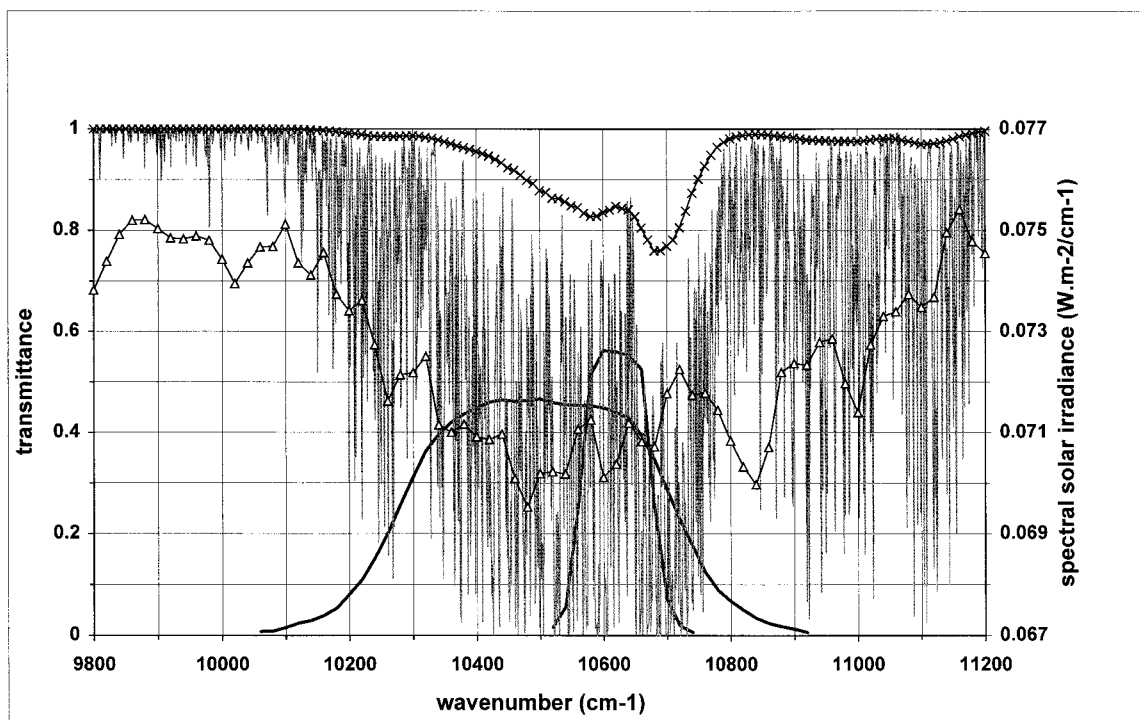


FIG. 1. Spectral distributions of the transmission functions associated with a wide and a narrow filter (black lines); the solar spectral irradiances (triangles, see scale on the right); the transmittance due to the water vapor continuum absorption obtained by running the package CKD 2.2 (crosses); and the transmittance due to the water vapor line absorption resulting from Dubuisson et al.'s (1996) line-by-line radiative transfer code (gray lines). Both water vapor transmittance spectral distributions correspond to vertical incidence through the tropical atmosphere model of McClatchey et al. (1972).

derived by performing spectral integrations from 9800 to 11 200 cm^{-1} (approximately from 0.893 to 1.020 μm), with a constant step of 20 cm^{-1} . The spectral distribution of the solar irradiance used inside LOWTRAN-7 was taken into account, although recent investigations have shown that such curves could be slightly contaminated by atmospheric absorption features near 0.94 μm (Gao and Green 1995). Filter transmittance values were interpolated at the same resolution (20 cm^{-1}) from spectrophotometric records. The components of the atmospheric transmittance in Eq. (6) were calculated at the same resolution, accounting for water vapor absorption, aerosol extinction, and molecular scattering. Absorption by molecular species other than the water vapor was neglected.

The direct transmittance due to molecular scattering was obtained from

$$t_m(\lambda) = t_m(\lambda, \zeta_o; P/P_o) \\ = \exp[-m(\zeta_o) (P/P_o) \tau_m(\lambda)], \quad (14)$$

where $m(\zeta_o)$ is the pure optical air mass (corresponding to an atmosphere without aerosol) at a sun zenith angle ζ_o , $\tau_m(\lambda)$ is the molecular scattering optical depth at wavelength λ , P is the pressure measured at the site, and $P_o = 1013.25$ hPa is the standard pressure at sea level. For the sake of simplicity, P is assumed equal to

P_o in the simulations. Optical air masses were obtained by employing the approximation formula proposed by Kasten and Young (1989). Molecular scattering optical depths were evaluated by applying the approximation formula proposed by Fröhlich and Shaw (1980), after application of the correction factor 1.031 suggested by Young (1980). Such a procedure provides $\tau_m(\lambda)$ values around 0.94 μm that are in close agreement with those obtained through more accurate calculations (e.g., Bucholtz 1995).

The direct transmittance due to aerosol extinction was expressed as

$$t_a(\lambda) = t_a(\lambda, \zeta_o; \alpha, \beta) = \exp[-m_a(\zeta_o)\beta\lambda^\alpha], \quad (15)$$

where m_a is the aerosol optical air mass and the wavelength λ is expressed in micrometers. The exponent α and the coefficient β are the Ångström turbidity parameters. The aerosol optical air masses are estimated through the same procedure as for pure optical air masses. As long as Eq. (15) is valid, the coefficient β represents the aerosol optical depth at the wavelength $\lambda = 1$ μm , indicating the turbidity level of the atmosphere.

The direct transmittance due to water vapor absorption is currently obtained by doing the product of two terms, referred to as line and continuum absorptions. The absorption due to the continuum is commonly in-

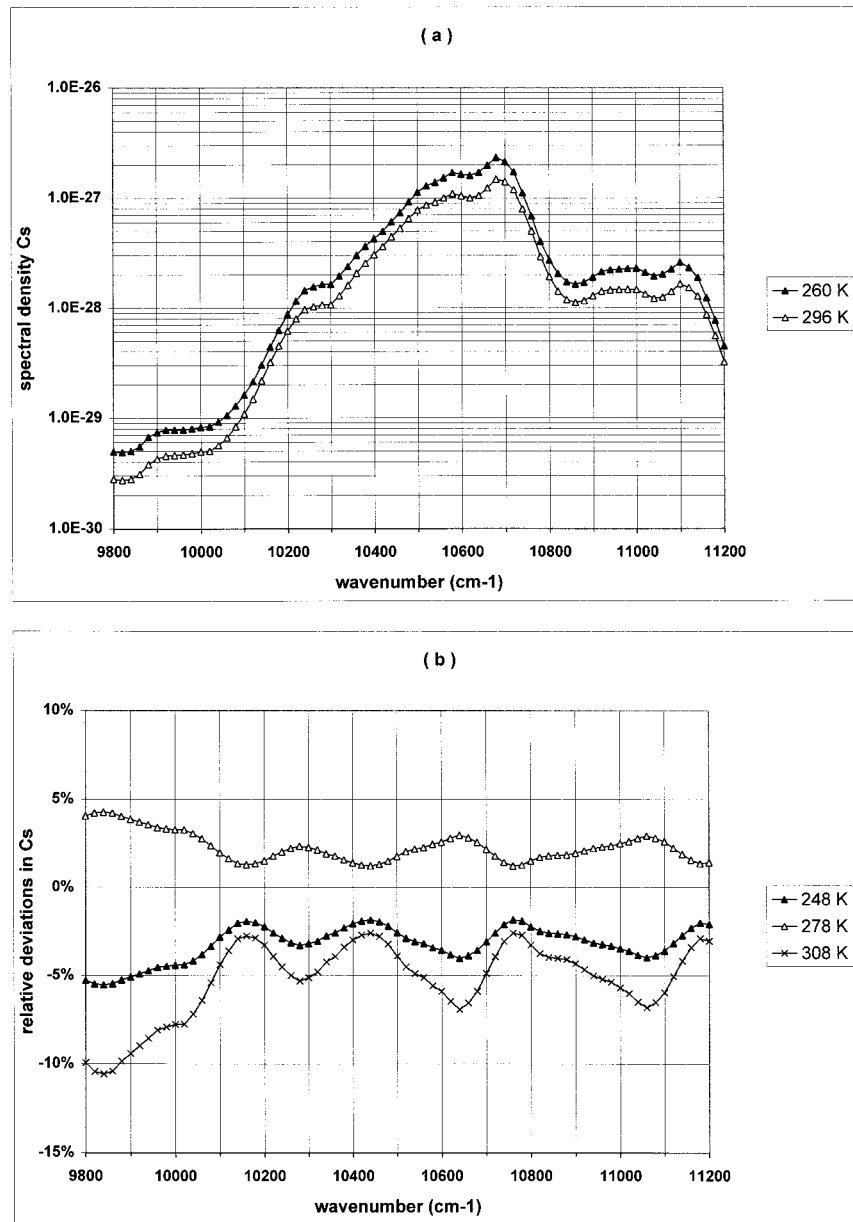


FIG. 2. Comparison between spectral densities C_s and C_f employed in the code LOWTRAN-7 and in the package CKD 2.2 for obtaining water vapor continuum absorption estimates: (a) C_s values at 260 and at 296 K for both codes; (b) relative deviations between C_s values furnished by these codes at different temperatures, measured as "LOWTRAN-7 minus CKD 2.2"; and (c) C_f values for these codes. Spectral densities are indicated in $(\text{cm}^{-1} \text{ mol cm}^{-2})^{-1}$.

terpreted as the cumulative effect of strong distant lines, which could dominate the effects of the local lines in regions of weak absorption (Ellingson et al. 1991). On the other hand, from a practical point of view, this continuum absorption can be defined primarily as the contribution to the molecular absorption that should be added to the line-by-line model contribution for providing computed results consistent with the measurements (Clough et al. 1992).

In this study, water vapor absorption estimates were

obtained by employing the framework included in the radiative transfer code LOTRAN-7 (Kneizys et al. 1988). The efficiency of the code framework ensures the fast simulation of the ratio R_{wv} under a large range of conditions. This code is well known and can facilitate the application of the developed method of CWV retrieval by other groups. Water vapor transmittances due to the line and to the continuum absorption are evaluated in this code through the procedures proposed by Pierluissi et al. (1989) and by Clough et al. (1989), respec-

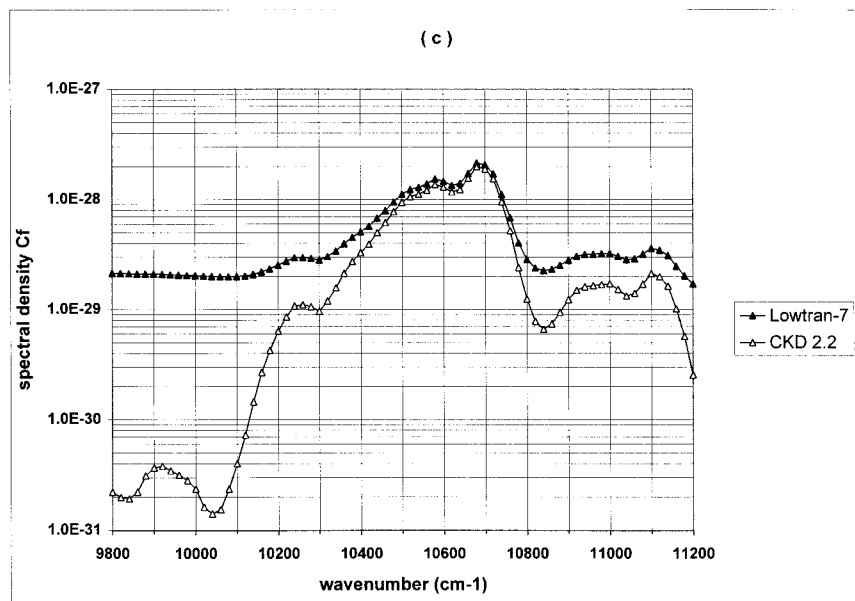


FIG. 2. (Continued)

tively. The continuum absorption mass coefficient for a given wavelength is split in two terms that are related respectively to the foreign- and to the self-broadening. Further, spectral densities C_f involved in the first term are assumed independent of the air temperature, whereas those involved in the second term (C_s) are temperature dependent and linearly interpolated between the values corresponding to 296 and 260 K. The only difference between this scheme and the one employed in the code LOWTRAN-6 (Kneizys et al. 1983) takes place around $10 \mu\text{m}$, where the C_s values were reduced by approximately 20% in order to agree with observations (Kneizys et al. 1988). In other words, the procedure included in the code LOWTRAN-7 allows estimates of water vapor continuum absorption which are, around $0.94 \mu\text{m}$, essentially the same as with the code LOWTRAN-6.

The reliability of the code LOWTRAN-7 for obtaining water vapor absorption estimates was assessed by a comparison of R_{WN} values derived from the application of its procedures and by careful benchmark calculations performed through a line-by-line radiative transfer code. This analysis is presented in section 3a for clean (no aerosol) atmospheric conditions and for a given couple of filters. The effect of aerosol extinction and the influence of the aging of filters on R_{WN} are analyzed in sections 3b and 3c, respectively.

a. Influence of water vapor transmittance calculations

The reliability of the procedures employed in the radiative transfer code LOWTRAN-7 for obtaining transmittances due to the water vapor absorption are discussed below from comparisons performed with accu-

rate calculations of R_{WN} . These comparisons include calculations performed either neglecting or accounting for the water vapor continuum absorption. Water vapor line absorption estimates were obtained through a line-by-line radiative code recently developed (Dubuisson et al. 1996). In this code, absorption coefficients are obtained by applying the STRANSAC model (Scott 1974), using spectroscopic data derived from the HITRAN 1996 version database. This model, originally developed by the Laboratoire de Météorologie Dynamique (Paris, France) for longwave calculations, was extended to the short-wave domain at the Laboratoire d'Optique Atmosphérique (Villeneuve d'Ascq, France). Water vapor continuum absorption estimates were obtained through the package Clough-Kneizys-Davies (CKD) 2.2, properly included in Dubuisson et al.'s radiative code. This package was recently released (May 1996) by S. A. Clough and his collaborators (Clough et al. 1989, 1992).

It must be noted that either the continuum absorption estimates resulting from the procedure included in the code LOWTRAN-7 or the ones obtained through the application of the package CKD 2.2 are based exactly upon the same three tables containing values of C_f and C_s . The differences between spectral densities provided by these two codes are related to the corrections applied to C_f values and to the dependence of C_s with the air temperature. In the code LOWTRAN-7, a linear dependence is assumed, whereas a more complicated relationship is taken into account in the package CKD 2.2. Considering the latter as the reference, the procedure included in the code LOWTRAN-7 overestimates C_s between 260 and 296 K and underestimates it outside this range. The same procedure overestimates C_f , mainly in spectral regions of weak absorption. The compar-

TABLE 1. Wide-to-narrow ratios associated with two ideal filter transmission functions for selected values of sun zenith angle and CWV, according to different calculations of water vapor transmittance. Molecular scattering and aerosol extinction are not considered. The figures between parentheses indicate relative deviations from the respective line-by-line (LBL) calculations, defined as "LOWTRAN-7 minus LBL."

Water vapor transmittance calculations	CWV = 10.36 kg m ⁻²			CWV = 41.44 kg m ⁻²		
	$\zeta_o = 0^\circ$	$\zeta_o = 60^\circ$	$\zeta_o = 75^\circ$	$\zeta_o = 0^\circ$	$\zeta_o = 60^\circ$	$\zeta_o = 75^\circ$
LBL without continuum	7.116	7.634	8.533	8.602	10.67	15.61
LOWTRAN-7 without continuum	7.091	7.603	8.433	8.471	10.10	13.12
	(-0.4%)	(-0.4%)	(-1.1%)	(-1.5%)	(-5.3%)	(-16%)
LBL with continuum CKD 2.2	7.279	8.015	9.463	9.576	13.57	26.24
LOWTRAN-7	7.239	7.944	9.247	9.409	12.73	21.46
	(-0.5%)	(-0.9%)	(-2.3%)	(-1.7%)	(-6.2%)	(-18%)

ison is displayed in Fig. 2 throughout the region of interest of this study.

To ensure a suitable comparison between water vapor absorption estimated through different procedures, two ideal filters were assumed, with transmission values constant over their respective bandwidths and equal to zero outside. In this study, the wide (narrow) filter is characterized by a transmission function equal to 50% between 10 200 and 10 800 cm⁻¹ (between 10 550 and 10 650 cm⁻¹). These filter transmission functions are not centered at the same wavelength, but they represent very well the ones associated with the instruments employed in our field validation (see section 4).

Table 1 displays the values assumed by the ratio of wide to narrow signals, R_{WN} , under selected conditions of CWV and sun zenith angle. All results were obtained by considering the temperature and pressure vertical profiles following the tropical atmosphere model suggested by McClatchey et al. (1972). Results labeled CWV = 41.44 kg m⁻² were based upon the original profile, whereas those labeled CWV = 10.36 kg m⁻² were obtained by using the original specific humidity profile divided by 4. According to Frouin et al. (1990), the transmittance ratios, $t(\Delta\lambda_w)/t(\Delta\lambda_n)$ in Eq. (13), would be practically independent of the atmospheric vertical profiles. The same conclusion is shown to hold for R_{WN} values.

Some aspects of the subject may be analyzed from the results displayed in Table 1, where the water vapor content integrated along the optical path—that is, the product $m(\zeta_o)CWV$ —increases from the left to the right. Although both the numerator and the denominator in Eq. (12) decrease with the water vapor integrated along the optical path, ratios R_{WN} increase with this content. This is because the denominator decreases more slowly due to a weaker overall water vapor absorption in the wide channel. On the other hand, the influence of the water vapor continuum absorption is larger on the numerator than on the denominator of this equation because both spectral densities (C_s and C_f) exhibit a relative maximum around the strongly absorbing regions (see Figs. 2a,c). Therefore, the continuum absorption in water vapor calculations results in an increase of the R_{WN} values; this effect being stronger for larger water vapor amounts.

The procedure used for obtaining water vapor line absorption estimates gives R_{WN} values that are lower with the code LOWTRAN-7 than with the line-by-line code (see results in the first lines of Table 1). The importance of such a bias increases with $m(\zeta_o)CWV$, reaching 5% or more under specific situations. It can be due to the different spectral resolutions and the scaling approaches. The last three lines of Table 1 compare R_{WN} values simulated by including both line and continuum absorption effects. The procedures included in the code LOWTRAN-7 provide biased R_{WN} values, and the magnitude of such a bias remains practically the same after the inclusion of the water vapor continuum absorption in the comparison performed. It must be noted that the contribution of the continuum absorption to the bias associated with the code LOWTRAN-7 compared to line-by-line calculations is the final result of influences with opposite signs. As displayed in Fig. 2, the effects due to the water vapor foreign-continuum absorption around 0.94 μm (around 10 650 cm⁻¹) are overestimated by the procedure included in the code LOWTRAN-7 when compared to the results obtained by applying the package CKD 2.2; in the case of the self-continuum absorption, such systematic errors may be positive or negative depending on the air temperature.

The influence of the procedure of water vapor absorption calculations on R_{WN} values may be presented also in terms of CWV biases. A reliable relation between R_{WN} and CWV can be established from the results obtained through the line-by-line radiative transfer code with the package CKD 2.2. Its analysis shows that the procedures included in the code LOWTRAN-7 underestimate the CWV for all conditions considered in Table 1. The magnitude of the bias is shown to increase with the water vapor content integrated along the optical path; for $\zeta_o = 60^\circ$ and CWV = 41.44 kg m⁻², it reaches 4 kg m⁻². In other words, the application of the code LOWTRAN-7 can result in noticeably biased CWV estimates if extreme conditions of sun position and water vapor content are met.

b. Influence of aerosol

In previous studies, two schemes have been used to correct, or at least to minimize, the possible aerosol

TABLE 2. Wide-to-narrow ratios for selected conditions of aerosol extinction (defined according to Ångström's parameters), sun zenith angle, and columnar water vapor.

Aerosol extinction	CWV = 10.36 kg m ⁻²			CWV = 41.44 kg m ⁻²		
	$\zeta_o = 0^\circ$	$\zeta_o = 60^\circ$	$\zeta_o = 75^\circ$	$\zeta_o = 0^\circ$	$\zeta_o = 60^\circ$	$\zeta_o = 75^\circ$
$\alpha = 0.0, \beta = 0.4$	3.766	4.165	4.874	4.958	6.693	11.11
$\alpha = -1.5, \beta = 0.4$	3.800	4.245	5.077	5.010	6.856	11.72
$\alpha = -3.0, \beta = 0.4$	3.841	4.343	5.329	5.073	7.052	12.48
$\alpha = -1.5, \beta = 0.8$	3.834	4.331	5.298	5.064	7.027	12.39

influence on CWV retrieval using differential absorption techniques. The first scheme is generally attributed to Volz (1974), who proposed to estimate CWV not from the atmospheric transmittance measured around 0.94 μm only, but from the ratio of atmospheric transmittances at 0.94 μm and at 0.88 μm . Such a ratio would reduce the aerosol influence on the CWV estimates because observations performed around 0.88 μm are affected mainly by aerosol extinction. A similar technique was suggested 30 years before by Foskett and Foster (1943), who employed observations around 1.38 μm (strong water vapor absorption band) and 1.25 μm ("point of reference"). Clearly, such techniques allow accurate CWV values only with spectrally independent aerosol extinction. The second scheme, proposed by Thome et al. (1992), involves the estimation of the aerosol influence around 0.94 μm by interpreting sunphotometric observations performed at two adjacent spectral regions, around 0.87 and 1.03 μm , where there is no significant gaseous absorption. This scheme provides realistic corrections under any turbidity condition.

Frouin et al. (1990) discussed the possible aerosol influence on the results obtained from their differential absorption technique for upwelling radiance measurements made from aircraft. These authors justified the inclusion of the aerosol backscattering by the low reflectances usually verified over the ocean.

In our opinion, the aerosol influence on sunphotometric observations performed around 0.94 μm can be large enough to impact the wide-to-narrow ratios. The results discussed below were obtained by applying Eq. (12) to the filter transmission functions displayed in Fig. 1. Water vapor transmittances were evaluated through the procedures included in the code LOWTRAN-7. Molecular scattering was included as described above. Aerosol transmittances were expressed from Eq. (15), assuming different choices for parameters β (turbidity level) and α (spectral dependence). In a first-order approximation, α can be related to the slope of a Junge aerosol-size distribution (Bullrich 1964; Tomasi et al. 1983).

Table 2 displays the main features of the aerosol influence on R_{WN} values under selected conditions of CWV and of sun zenith angle. Results labeled $\alpha = 0$ in this table are exactly the same as the ones obtained under clean (no aerosol) atmospheric conditions. Hence, neutral extinction—associated with aerosols characterized by significant amounts of relatively large particles when

compared to the wavelength—has no influence on the wide-to-narrow ratios at any turbidity level. On the other hand, results labeled $\alpha = -3.0$ (that would correspond to a negligible amount of large particles) show that the aerosol influence may be very important, giving R_{WN} higher than those associated with clean atmospheric conditions. Further, a comparison between the results displayed in the last two lines of Table 2 show that very similar wide-to-narrow ratios can be obtained from quite different aerosol extinction features.

The application of the differential absorption technique to sunphotometric observations is usually performed by neglecting the aerosol extinction in the analysis of wide-to-narrow ratios (e.g., Faizoun et al. 1994). The suitability of this approximation can be assessed by comparing the results displayed in the first line of Table 2 to those shown in the others. If aerosol extinction is neglected, the CWV values may be overestimated by an amount that increases with the turbidity level, the sun zenith angle, and the spectral dependence of the aerosol extinction around 0.94 μm . This overestimate can be assessed by relating R_{WN} and the values of the CWV computed in the absence of aerosol. Following such a rationale, CWV may be overestimated by around 25% through the differential absorption for $\alpha = -1.5$, $\beta = 0.4$, and $\zeta_o = 60^\circ$.

These results can be generalized as follows. The influence of the aerosol on CWV estimates obtained from the differential absorption technique increases with its spectral dependence. In other words, such an influence increases for a decrease of the presence of large particles in the atmosphere. Thus, even with a technique based upon two observations through filters centered around the same wavelength, the results present some dependence on the surrounding aerosol. In addition, the magnitude of such an influence probably depends on the wavelength difference between the centers of the transmission functions of the selected wide and narrow channels employed.

c. Influence of the aging of filters

The wide-to-narrow ratio increases with the sun zenith angle, the CWV, the spectral dependence of aerosol extinction, and the turbidity level. Each of these variables, considered separately, more strongly affects the numerator than the respective denominator in Eq. (12). The influence of the aging of filters on R_{WN} can be very

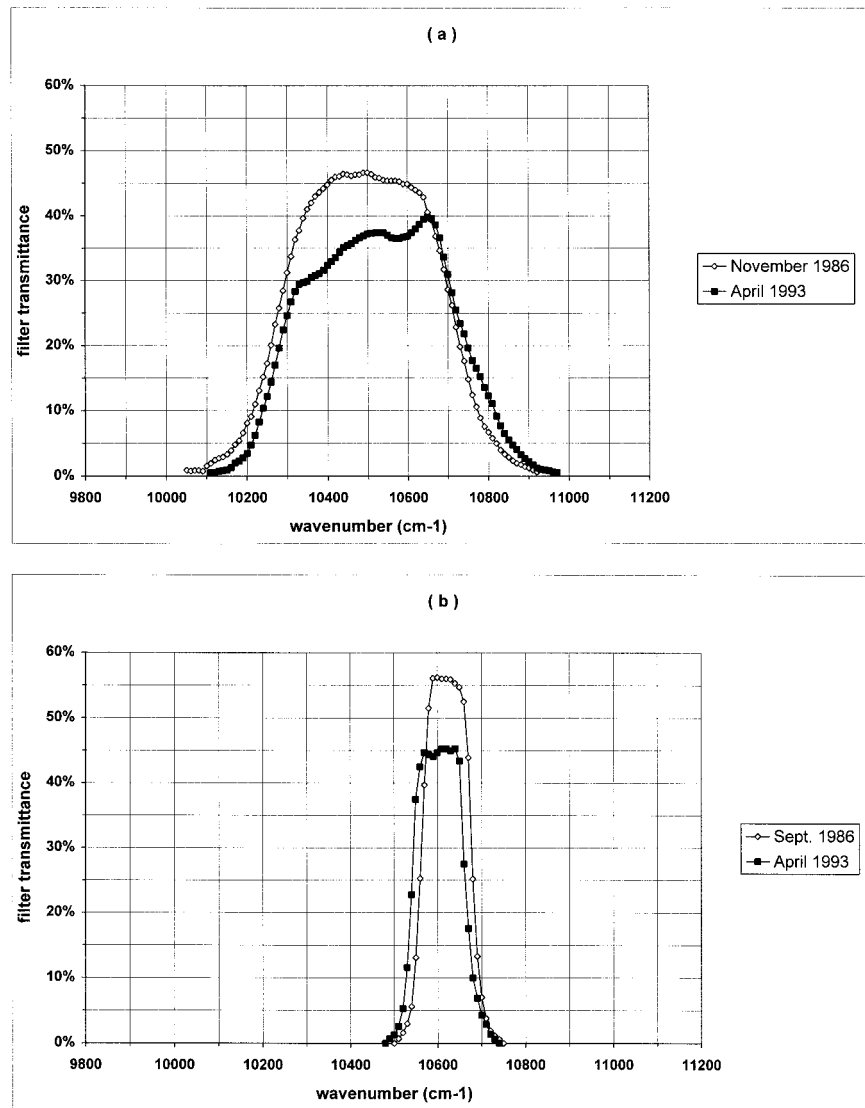


FIG. 3. Spectral distributions of the filter transmission functions associated with a wide and a narrow filter at two ages, as obtained from measurements in the laboratory.

complicated because the degradation of each filter may be different. Therefore, such aging could result either in an increase or a decrease in the wide-to-narrow ratio with time, depending on the *relative* aging impact.

Figure 3 compares the transmission functions of two filters centered around $0.94 \mu\text{m}$, measured with spectrophotometers at two stages. The plots labeled 1986 are displayed in Fig. 1. Both filters have been employed in several field experiments since the 1980s. Between September (or November) 1986 and April 1993, both filter transmission functions were significantly modified, and their transmittances have significantly decreased. The reasons for such a behavior remain undetermined. The wavelength shifts could, in principle, be attributed to the different ambient temperatures during spectrophotometric recordings in the laboratory.

The influence of the aging of filters is reported in Table 3, for selected values of CWV and sun zenith angle, under clean (no aerosol) atmospheric conditions. Wide-to-narrow ratios were evaluated by employing the procedures included in the code LOWTRAN-7. Table 3 shows, first of all, that both the numerator and the denominator in Eq. (12) decreased with time, following the decrease of the respective filter transmission functions. Since the denominator decreased to a lesser extent, the R_{wv} values decreased from 1986 to 1993. Such a relative aging would have been null if both the numerator and the denominator had presented the same rate of decrease with time. Further, the influence of the aging of filters increases with the water vapor content integrated along the optical path.

Bias can be observed in the CWV estimates if the

TABLE 3. Wide-to-narrow ratios, and their numerators and denominators, associated with two filter transmission functions, at two ages, for selected conditions of sun zenith angle and columnar water vapor. Figures between parentheses indicate relative deviations from the respective 1986 calculations, defined as "1993 minus 1986."

Ages	CWV = 10.36 kg m ⁻²			CWV = 41.44 kg m ⁻²		
	$\zeta_o = 0^\circ$	$\zeta_o = 60^\circ$	$\zeta_o = 75^\circ$	$\zeta_o = 0^\circ$	$\zeta_o = 60^\circ$	$\zeta_o = 75^\circ$
$\int_{\Delta\lambda_w} E_o(\lambda) t(\lambda) \varphi_w(\lambda) d\lambda$						
1986	10.72	8.615	6.671	6.727	4.649	2.891
1993	8.969 (-16%)	7.162 (-17%)	5.501 (-18%)	5.546 (-18%)	3.787 (-19%)	2.317 (-20%)
$\int_{\Delta\lambda_N} E_o(\lambda) t(\lambda) \varphi_N(\lambda) d\lambda$						
1986	2.846	2.068	1.369	1.357	0.6946	0.2603
1993	2.536 (-11%)	1.861 (-10%)	1.246 (-9.0%)	1.236 (-8.9%)	0.6418 (-7.6%)	0.2429 (-6.7%)
R_{WN}						
1986	3.766	4.165	4.874	4.958	6.693	11.11
1993	3.537 (-6.1%)	3.849 (-7.6%)	4.416 (-9.4%)	4.486 (-9.6%)	5.901 (-12%)	9.541 (-14%)

updated filter transmission functions are not taken into account. In the case reported in Fig. 3, the CWV values may be underestimated if the aging of filters is neglected. Such a bias can be assessed by relating R_{WN} and CWV from the results corresponding to the filter transmission functions observed in 1986. For clean atmospheric conditions (no aerosol) and $\zeta_o = 60^\circ$, the differential absorption technique may underestimate CWV by around 10% if the influence of the aging of filters is neglected.

Different results will be obtained with other pairs of filters. This is a natural issue for instruments using the same filters for several years. Section 4c is devoted to the analysis of sunphotometric observations performed with filters for which aging is reported in Fig. 3.

4. Retrieving columnar water vapor values

a. Strategy

Columnar water vapor estimates based on sunphotometric observations have been obtained so far through a two-parameter fit relating CWV to the atmospheric transmittance around 0.94 μm . An alternative strategy is proposed in this study, based on a multidimensional table, containing values of wide-to-narrow ratios corresponding to combinations of values assigned to the entry parameters, one of them being the CWV. This table is built by taking into account the transmission functions of the wide- and the narrowband filters.

Wide-to-narrow ratios R_{WN} corresponding to a given pair of filter transmission functions are assumed to de-

pend only on four variables: the columnar water vapor, the sun zenith angle (ζ_o), the Ångström exponent (α), and the turbidity level (β). It has been verified that the effect of the other variables, such as the atmospheric pressure at the site of interest (affecting the Rayleigh scattering optical depth) or the vertical humidity profile, are negligible in comparison. So, the retrieval of CWV values from sunphotometric measurements following such a strategy can be compared to the research of a point inside a 4D table. Relatively extreme values are taken into account for these four independent variables in order to encompass most of the realistic conditions (see Table 4). All the calculations are performed by adopting the temperature and pressure vertical profiles associated with the tropical atmosphere model from McClatchey et al. (1972). The specific humidity profile corresponding to that model is also employed, after multiplication by a factor ranging from 1/8 to 10/8 with a step of 1/8. The resulting CWV values are displayed in Table 4.

The CWV values are derived from sunphotometric observations as follows. Beforehand, the filter transmission functions are measured in the laboratory, and the instrument spectral response is assessed. These results are employed for computing the 4D table containing wide-to-narrow ratio values. At this step, water vapor absorption is obtained through the procedures included in the radiative transfer code LOWTRAN-7. Sunphotometric observations are performed including measurements with two filters centered around 0.94 μm and with two additional filters placed in adjacent regions

TABLE 4. Entry parameters values of the 4D table employed in CWV retrievals: sun zenith angle, Ångström exponent, Ångström coefficient, and columnar water vapor.

ζ_o	0°, 10°, 20°, 30°, 40°, 45°, 50°, 55°, 60°, 63°, 66°, 69°, 72°, and 75°
α	+1.5, 0.0, -1.5, and -3.0
β	0.0, 0.4, 0.8, and 1.2
CWV	5.18, 10.36, 15.54, 20.72, 25.90, 31.08, 36.26, 41.44, 46.62, and 51.81 kg m ⁻²

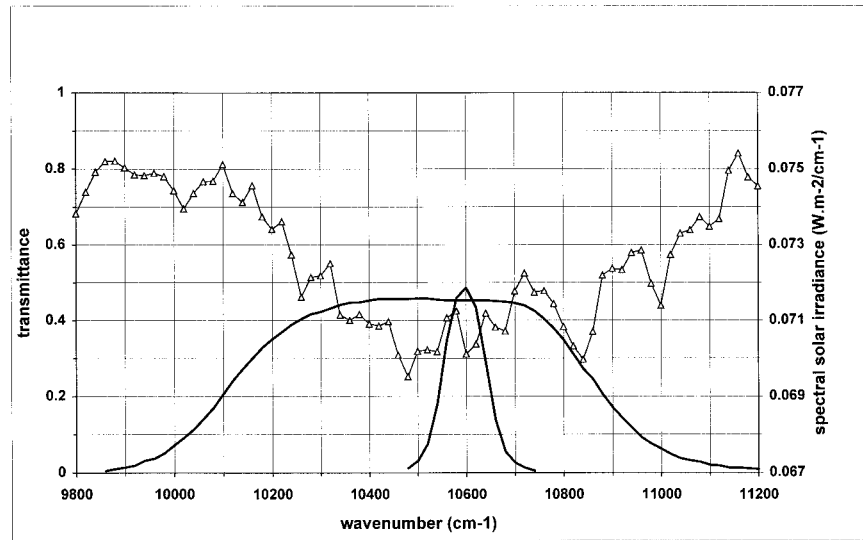


FIG. 4. Spectral distributions of the transmission functions associated with the wide and narrow filters employed for CWV retrievals during the field experiment performed at Bamako (black lines) and the solar spectral irradiances (triangles, see scale on the right).

with negligible water vapor absorption. Wide- to narrowband ratios $V(\Delta\lambda_w)/V(\Delta\lambda_n)$ of sunphotometric signals are computed from the instrument output. The sun position ζ_o is evaluated from the basic ephemeris, time, and geographical location of the measurements. The parameters α and β are derived by applying Eq. (15) into the analysis of sunphotometric observations performed in the adjacent regions. The respective values of R_{WN} , ζ_o , α , and β are then introduced in a FORTRAN algorithm specially conceived for the search, inside the 4D table, of the CWV value that would give back the measured ratio R_{WN} , respecting the specified conditions for aerosol extinction and sun position. Such an identification is performed by applying a sequence of four-point Lagrangian polynomials, centered as much as possible around the value (or the curve) of interest.

b. Measurements performed at Bamako (Mali)

Sunphotometric observations were performed during a field experiment in Bamako, Republic of Mali, at the Centre Régional d’Energie Solaire (CRES) (12.67°N,

7.98°W; altitude: 400 m MSL), from 5 November to 21 December 1991.

The measurements were carried out by employing two portable sun photometers constructed by CIMEL Electronique, Paris, France.¹ The instrument was designed for field measurements with minimal equipment and material constraints. Its aperture angle is 1.4°. In addition to the water vapor filters, it is provided with five aerosol filters in spectral regions associated with weak water vapor absorption, such as 0.87 and 1.02 μm . The filters are mounted on a wheel rotated by a stepper motor, allowing their commutation in front of the silicon cell used as a detector. The sun viewing is hand operated, while the measurements in the various channels are automated by means of a microprocessor. The data, radiometric measurements, time, and cell temperature are stored in the instrument’s memory. They can then be saved to a cartridge, allowing a large storage autonomy in the field. Figure 4 displays the transmission functions corresponding to the filters centered around 0.94 μm , measured in the laboratory by means of a spectrophotometer a few weeks after the field experiment.

The aerosol extinction parameters α and β employed for estimating CWV were derived from sunphotometric observations at 0.87 and 1.02 μm . Independent CWV estimates were obtained from radiosonde balloon soundings routinely launched from the Bamako International Airport (12.53°N, 7.95°W; altitude: 377 m).

Table 5 shows CWV estimates resulting from the

TABLE 5. Columnar water vapor values (kg m^{-2}), as retrieved from sunphotometric measurements performed in Bamako, from 4D tables constructed following different specifications, namely, the inclusion or exclusion of the continuum absorption and of aerosol extinction. Independent values obtained from radiosoundings are also displayed.

Approaches	10 Nov	21 Nov	23 Nov
	1991	1991	1991
Continuum and aerosol considered	17.3	22.7	24.7
Continuum considered, aerosol neglected	17.4	22.9	24.9
Continuum neglected, aerosol considered	22.5	30.7	33.7
Radiosoundings	15.0	20.3	21.6

¹ Mention of a manufacturer’s name does not imply endorsement of a product over those offered by other manufacturers but is merely provided for the convenience of the reader.

analysis of sunphotometric observations compared to the corresponding figures obtained from radiosoundings. Only three situations are discussed here that correspond to simultaneous balloon soundings and sunphotometric observations performed under open-sky conditions (no clouds in the line of sight of the sun disk). Results presented for each situation consist of averages performed over four or five instantaneous CWV estimates, each one obtained from a series of sunphotometric observations made during the first 60 min after the balloon launching. These three situations were very similar with respect to aerosol extinction (α around -0.4 , β ranging between 0.3 and 0.4) and sun position (zenith angle ranging between 32° and 42°).

The results presented in Table 5 can be analyzed as follows. Columnar water vapor is systematically overestimated by around 2.5 – 3.0 kg m^{-2} when obtained through the differential absorption technique. Such a bias cannot be explained by the systematic errors involved in the procedures included in the code LOWTRAN-7 for obtaining water vapor absorption estimates because the latter would provide underestimates for CWV (see Table 1). No noticeable instrument degradation was identified. Such a bias could be related to the differences existing between the microclimates associated with the sites where sunphotometer measurements and balloon launchings were performed—near the Niger River and 20 km away in a typical Sahelian environment, respectively. Thus, CWV values derived from balloon soundings would correspond to a quite drier atmosphere in its lower levels than to the column above the site of sunphotometric observations.

Columnar water vapor estimates would change very little (1%) if the influence of aerosol extinction is ignored, given its small spectral dependence. The influence of the water vapor continuum absorption is significant, contributing 30% (or more) of the CWV value. It must be noted that both aerosol and continuum influences would be present even in the case of two filters centered exactly at the same wavelength. The influence of aerosol would vanish only in the presence of a very significant amount of large particles, that is, associated with a neutral extinction, whereas the influence of water vapor continuum absorption is characterized by a small but not vanishing spectral dependence (see Fig. 1). Thus, both influences should be included in any procedures designed for CWV retrieval from solar transmission measurements in the near-infrared.

c. Measurements performed during HAPEX-Sahel (Niger)

HAPEX-Sahel (Hydrologic Atmospheric Pilot Experiment in the Sahel) was an international program focused on the soil–plant–atmosphere energy, water, and carbon balance in the West African Sahel (Goutorbe et al. 1994; Prince et al. 1995). An eight-week intensive observation period from August to October 1992 in-

cluded atmospheric radiation measurements performed by the Laboratoire d'Optique Atmosphérique (LOA) team (principal investigator: D. Tanré).

Sunphotometric observations were realized on the west central site (13.53°N , 2.50°E ; altitude: 230 m), about 80 km east of Niamey, Republic of Niger. The sun photometer employed was developed at the LOA, and it has been successfully used in several field experiments. It includes four detectors for 11 channels ranging from 0.45 to 2.2 μm . The two water vapor channels are commuted in front of a silicon detector by means of a wheel rotated by a stepper motor. The instrument sun tracking and measurements are automated. The data are transmitted for storage and processing to a personal computer. Figure 3 compares the transmission functions corresponding to the filters centered around 0.94 μm employed for the CWV estimates, available on two dates from spectrophotometric measurements made in the laboratory. The first set of transmission functions (1986) corresponds to six years before the HAPEX-Sahel field experiment, while the second one (April 1993) was obtained six months after the experiment.

The aerosol extinction parameters α and β employed for estimating CWV values were derived from observations made around 0.87 μm and 1.05 μm with the same instrument. Independent CWV estimates were obtained from radiosoundings, namely: (a) those launched at Hamdallay (13.55°N , 2.40°E ; altitude: 242 m) by the CNRM (Météorologie Nationale, France) and (b) those launched daily at the Niamey International Airport (13.29°N , 2.10°E ; altitude: 222 m).

Figure 5 compares different CWV estimates for all situations which, during the eight-week intensive observation period of HAPEX-Sahel, included simultaneous balloon soundings and sunphotometric observations performed under open-sky conditions. Crosses and gray lines indicate CWV estimates obtained from the application of the filter transmission functions available by the end of 1986 and in April 1993, respectively. The latter results agree reasonably well with CWV values resulting from balloon soundings (squares).

The results corresponding to the situations displayed in Figure 5 are summarized in Table 6. As in Table 5, CWV estimates derived from radiosoundings are compared to averages over a number of instantaneous estimates of CWV estimates, each one obtained from a series of sunphotometric observations performed during the first 60 min after the balloon launching. Different geophysical conditions are included (i.e., $8^\circ < \zeta_0 < 63^\circ$, $-0.50 < \bar{\alpha} < -0.35$, and $0.22 < \bar{\beta} < 0.76$). Deviations between CWV values resulting from sunphotometric measurements and from balloon soundings assume positive or negative values, ranging from $+2.0$ to -2.0 kg m^{-2} (from -12% to $+4\%$). The mean bias over the 11 situations is very low once it reaches only -0.1 kg m^{-2} . The latter result is consistent with the previous analysis on the reliability of the procedure employed for obtain-

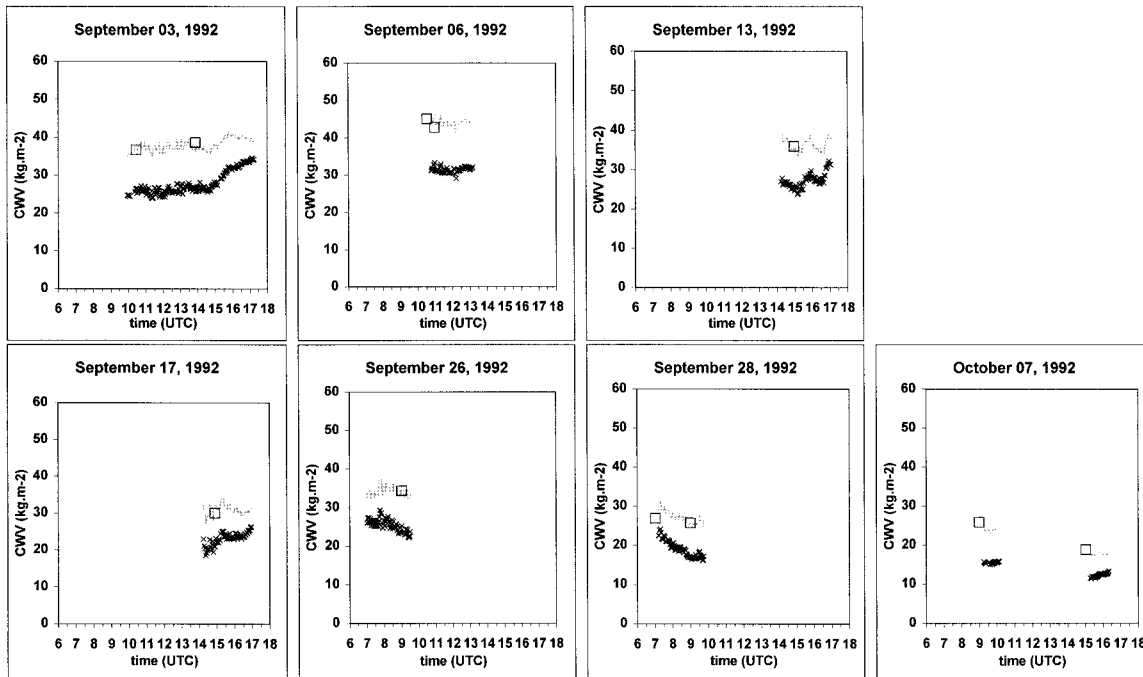


FIG. 5. Columnar water vapor values retrieved from sunphotometric measurements performed during HAPEX-Sahel, resulting from the procedure described in section 4a, by using the filter transmission functions available in April 1993 (gray lines), and from the same procedure but ignoring the aging of filters (crosses). White squares indicate the CWV values resulting from the radiosoundings.

ing water vapor line absorption estimates in the code LOWTRAN-7 (see Table 1).

5. Summary

The differential absorption technique proposed by Frouin et al. (1990) represents an alternative to the differential transmission technique successively improved

in the last years (Reagan et al. 1995; Michalsky et al. 1995; Schmid et al. 1996). Both techniques permit inclusion of nonneutral aerosol extinction by taking into account optical depths estimated on adjacent regions. Both techniques depend on instrument characteristics, such as the filter transmission functions used in the atmospheric transmittance calculations. Both techniques have been employed with the assumption of a two-parameter description of the water vapor transmittance around 0.94 μm, introducing a potential source of bias.

One major advantage may be noted in favor of the differential absorption technique, as applied in this study. The strategy proposed here was based on retaining the intrinsic nonlinearity of the subject, involving only interpolations inside a 4D table, without any two-parameter description. A second point could, in principle, be added, requiring proof in future studies: the use of wide-to-narrow ratios instead of observations performed with a single filter around 0.94 μm would allow CWV estimates less dependent on the description of the water vapor continuum absorption calculations.

Two field validations were performed, providing somewhat opposite conclusions if taken individually. In the case of Bamako, the application of the differential absorption technique furnished CWV values systematically overestimated, indicating a possible source of bias. In the case of HAPEX, the mean deviation between estimates resulting from sunphotometric measurements and from balloon soundings is practically null, being consistent with the low systematic errors associated with

TABLE 6. Columnar water vapor values retrieved during HAPEX-Sahel, and the corresponding geophysical conditions.

	<i>tb</i>	<i>N</i>	\bar{m}	$\bar{\alpha}$	$\bar{\beta}$	CWV _r	CWV _{sp}
3 Sep 1992	10.45 ^a	23	1.03	-0.40	0.22	36.7	37.1
3 Sep 1992	13.87 ^b	23	1.28	-0.37	0.22	38.6	37.0
6 Sep 1992	10.52 ^a	18	1.02	-0.50	0.31	45.1	44.1
6 Sep 1992	10.97 ^b	22	1.01	-0.49	0.32	42.7	43.8
13 Sep 1992	14.97 ^a	22	1.79	-0.35	0.38	35.9	36.0
17 Sep 1992	14.90 ^b	20	1.77	-0.36	0.38	30.0	31.9
26 Sep 1992	9.02 ^a	10	1.27	-0.43	0.64	34.3	33.4
28 Sep 1992	7.02 ^a	21	2.19	-0.43	0.76	26.9	28.9
28 Sep 1992	9.00 ^a	19	1.26	-0.45	0.62	25.7	25.7
7 Oct 1992	9.00 ^b	14	1.23	-0.41	0.33	25.8	23.8
7 Oct 1992	15.02 ^b	18	2.21	-0.42	0.32	18.8	17.6

tb: instant of balloon launching (UTC).
N: number of sunphotometric series during the first 60 min after the balloon launching.
 \bar{m} : mean value, over the *N*- series, of the optical air mass.
 $\bar{\alpha}$: mean value, over the *N*- series, of the Ångström exponent.
 $\bar{\beta}$: mean value, over the *N*- series, of the Ångström coefficient.
 CWV_r: columnar water vapor from radiosounding (kg m⁻²).
 CWV_{sp}: mean value, over the *N*- series, of the CWV estimated from sunphotometric observations (kg m⁻²).

the procedure for obtaining water vapor line absorption estimates in the code LOWTRAN-7 under low sun zenith angles. Thus, the bias verified in the first validation would be related to other sources, such as the different microclimates existing in the sites employed for sun-photometric observations and balloon launchings.

The application of the procedures included in the radiative transfer code LOWTRAN-7 for water vapor absorption enables consistent CWV retrievals through the differential absorption technique for sun zenith angles below 60°. Beyond this range, noticeable biased ratios and unsatisfactory CWV values would be obtained. Future studies in this subject should improve the reliability of wide-to-narrow ratio calculations (e.g., by employing a recent MODTRAN version or similar radiative transfer code) and span the range of sun zenith angles in the scope of field validation.

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