ATMOSPHERIC TURBIDITY DETERMINATION FROM IRRADIANCE RATIOS

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ABSTRACT

A semi-physical method is proposed to evaluate turbidity from broadband irradiance measurements and other atmospheric parameters. An error analysis and various tests against measured data show that this method can predict accurate turbidities provided that the sky is perfectly cloudless and the diffuse irradiance data are very accurate. Yet, this method is insensitive to errors in input data such as precipitable water and ozone amount. Applications of this method to the quality control of radiation data are discussed. Tests with actual data from Florida and Oregon show good agreement with other methods. Evaluation of the model required a detailed discussion of the accuracy and cosine error of pyranometers, and the uncertainty in precipitable water estimates.

Keywords: Solar radiation, irradiance, turbidity, aerosols, precipitable water, calibration, radiometry.

1. INTRODUCTION

Accurate determinations of turbidity normally require clear sky spectral radiation data obtained with sunphotometers or spectroradiometers. As these instruments are expensive and scarce, turbidity is generally estimated instead from *broadband* irradiance measurements. Most investigators have been using direct beam irradiance measured with a pyrheliometer (filtered or not) to obtain turbidity [1-3]. However, this method implies that, to obtain the aerosol transmittance or optical depth, all other atmospheric extinction processes need to be known *a priori*. This may become a problem when the water vapor and ozone columns are not continuously measured onsite, as is generally the case. In particular, important short-term errors on precipitable water may result from the usual estimation method based on surface data of temperature and humidity. If precipitable water is too high or too low, a too low or too high turbidity is inevitably predicted with this direct irradiance approach [1].

At the spectral level, it has been shown [4] that the aerosol optical depth could be retrieved from the ratio of global to direct irradiance as effectively as it is from direct irradiance only. The same approach, but using different combinations of ratios of broadband global, direct, or diffuse irradiance, is investigated here. The potential advantage of this method is that it is less sensitive to the influence of ozone and water vapor, because these constituents deplete the global, direct, and diffuse spectrum almost equally. Possible drawbacks of this method, however, are that it is more sensitive to instrumental error because two radiometers are involved (instead of one) and are dependent on additional factors such as ground albedo and aerosol optical properties. This preliminary contribution is aimed at delineating the relative merits and limitations of this method compared to others, and at suggesting some useful applications.

2. METHODOLOGY

The approach used here is similar to that described previously [1] to obtain the broadband aerosol turbidity, expressed in terms of Ångström's *ß* coefficient, from direct irradiance. Again, all calculations are based on SMARTS2, a spectral radiative code described in [5]. Clear sky spectral irradiances are predicted with this code over the range of wavelengths sensed by two types of broadband radiometers: pyrheliometers used to measure direct radiation (0.28–4 μm), and pyranometers for diffuse and global radiation (0.28–2.8 μm). A preliminary series of parametric runs is performed so that the predictions of direct, diffuse and global irradiances can be re-

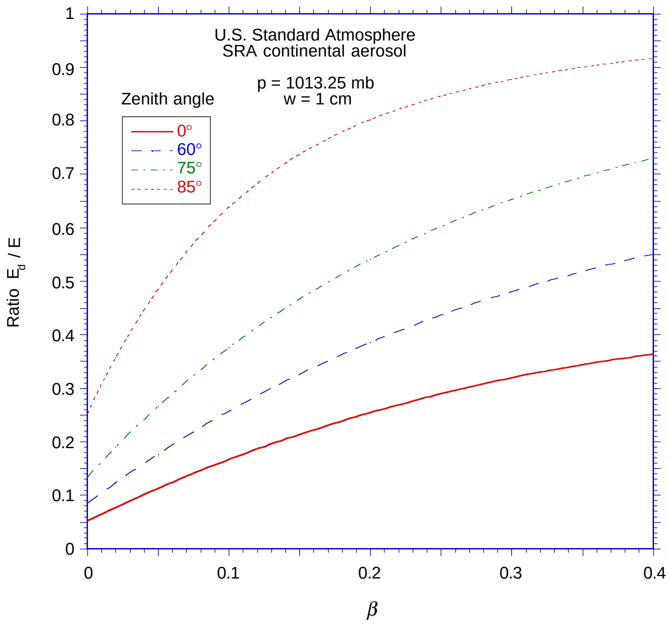

Fig. 1 Ratio $K = E_d/E$ as a function of $ß$ and Z.

lated to turbidity. It is then possible to reverse the method and obtain turbidity from irradiance data. The parametric runs cover a large range of atmospheric variables: zenith angle (Z = 0–88°), pressure (p = 600–1020 mb), precipitable water (w = 0–5 cm), ozone amount (u_o = 0–0.5 atm-cm), and aerosol turbidity ($ß$ = 0–0.4). A fixed continental aerosol model is considered here, for which the spectrally averaged wavelength exponent α is about 1.3, in conformity with the conventional Ångström model. It is stressed that, even for a given turbidity, other aerosol models would produce different diffuse irradiances. This is due to the fact that the extinction processes in an aerosol layer are governed by the latter's detailed spectral optical properties, such as optical depth, single-scattering albedo, and asymmetry factor. However, these characteristics change rapidly with time and location and are not usually known *a priori*. Therefore, some assumptions are necessary to allow generalization to the majority of cases. In the present case, the chosen continental aerosol model should be typical of locations away from any predominent influence of maritime or urban aerosols.

The fundamental relationship between the different radiation components is

$$E = E_{bn} \cos Z + E_d = E_b + E_d \qquad (1)$$

where E, E_b, and E_d are the global, direct, and diffuse irradiances on a horizontal surface, respectively, E_{bn} is the direct normal irradiance, and Z is the sun's zenith angle. According to (1), any irradiance ratio, such as E_d/E, E_d/E_{bn}, or E_b/E_d, can be expressed in terms of any other one and Z. In practice, however, the equality expressed by (1) is never perfectly achieved if E, E_{bn} and E_d are independently measured with three different instruments. In this contribution, the experimental diffuse irradiance will always be obtained from measured values of E and E_{bn} only, i.e., using (1) to obtain a *calculated* value of E_d. All irradiance calculations performed here include a correction for the circumsolar radiation that is included within the aperture cone of pyrheliometers (typically, 3° around the sun's center).

From what has been just mentioned, selecting any one of these irradiance ratios to estimate turbidity appears arbitrary because of their mathematical interdependence, although only a few such ratios have been investigated so far. A literature survey shows that only the ratios $K = E_d/E$ (e.g., [6]) and $K_{db} = E_d/E_{bn}$ [7, 8] have been purposely used as a measure of turbidity. The effect of turbidity on K and K_{db} is shown in Figs. 1 and 2, respectively. It clearly appears that K_{db} is preferable because it varies almost linearly with $ß$, and varies little with Z, especially for $Z \le 75°$. This has proven to be of considerable importance to obtain an accurate fit in $ß$ and Z. The other ratios tested, such as E_b/E_d or E/E_b, had the same kind of behavior as K and could not be fitted with sufficient accuracy. The linear behavior of K_{db} and its relative insensitivity to Z appear to be retained for a large range of atmospheric conditions. Consequently, K_{db} should be relatively constant over a day if turbidity does not vary, as has been noticed before [9].

From the large number of parametric runs performed with SMARTS2, it has been found that K_{db} can be fitted as

$$K_{db} = (a_0 + a_1\, ß + a_2\, ß^2) / (1 + a_3\, ß^2) \qquad (2)$$

where the coefficients a_i are themselves functions of Z, p, u_o, and w, but which cannot be given here due to space limitations. If an experimental value of K_{db} is obtained from measurements, (2) can be easily solved to obtain $ß$.

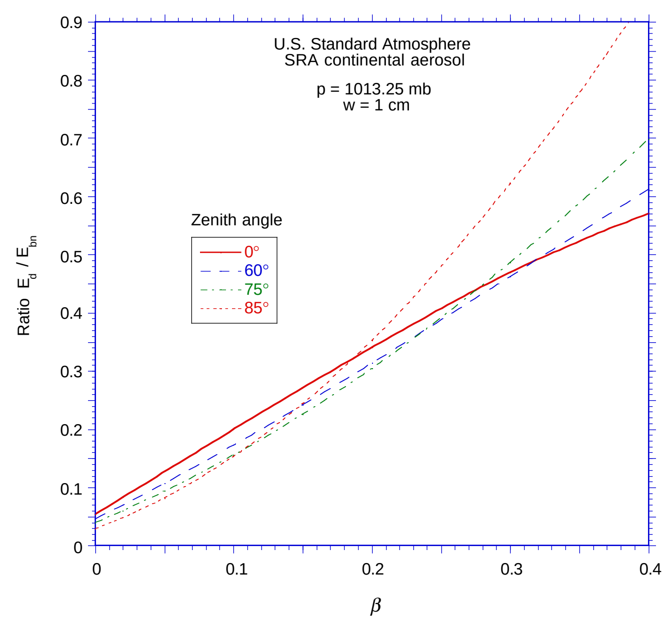

Fig. 2 Ratio $K_{db} = E_d/E_{bn}$ as a function of $ß$ and Z.

A correction needs to be applied if the average ground albedo, ρ_g, of the measurement site's area is not equal to the reference value used here, 0.15. This correction results from backscattering processes between the ground and the sky of albedo ρ_s. The latter has been fitted as a function of ß from parametric runs of SMARTS2. The rapid increase of ρ_s with ß is such that the global irradiance for both a highly reflective ground and a hazy sky can be significantly larger than the irradiance for the reference case (ρ_g = 0.15). The irradiance for the general case, $E(\rho_g)$, is related to the reference irradiance, $E(0.15)$, through

$$E(\rho_g) / E(0.15) = (1 - 0.15\ \rho_s) / (1 - \rho_g\ \rho_s). \qquad (3)$$

As ρ_s depends on ß, which is the unknown, (3) needs to be solved iteratively along with (2).

3. ERROR ANALYSIS

Comparisons between the modeled K_{db} and reference calculations [10, 11], show good to excellent agreement, with an uncertainty estimated to be ≤5%. From Fig. 2, an approximate expression for K_{db} when ß < 0.35 and $Z \leq 75°$ would be

$$K_{db} \approx 0.04 + 1.45\ ß, \qquad (4)$$

which, after differentiation, gives

$$\Delta ß/ß = (1 + 0.0276\ ß^{-1})\ \Delta K_{db} / K_{db}\ . \qquad (5)$$

Therefore, a variation of 5% for the modeled K_{db} would translate into moderate errors in ß of from 6% for a hazy sky (ß≈0.2) to 12% for a very clear sky (ß≈0.02).

However, modeling errors may be compensated or compounded by experimental errors. The error in E_{bn} may be low (typically 1–2%) if a regularly checked and calibrated pyrheliometer is used. (Egregious errors resulting from mistracking are not considered here.) The error in E_d may be far larger because diffuse radiation cannot be easily measured. In the frequent case where the monitoring station consists of a single-pyranometer/pyrheliometer combination, E_d is calculated from (1). Under very clear skies, E and E_{bn} are two large numbers resulting in a small E_d. A typical case is obtained with SMARTS2, for Z = 30°, ß = 0.02, w = 1 cm, and u_o = 0.3 cm, for which the calculated irradiances are E_{bn} = 1012 W/m^2, E = 958 W/m^2 and E_d = 81 W/m^2. Underestimating E by 5% (a typical value for field conditions, [12]) would lead to a considerable error of -60% on E_d and K_{db} in this case. If these numbers were obtained from actual measurements, the resulting ß would be *negative*. Therefore, if good quality turbidity estimates are desired with this method under very clear conditions, extremely accurate radiation measurements are needed.

An important part of the instrumental error of pyranometers comes from their cosine error; i.e., their inadequate handling of the cosine law for planar detectors exposed to hemispherical radiation. Recent laboratory measurements [13] have shown that this error is nonnegligible, and may also be compounded by azimuth errors. Each pyranometer should be individually characterized so that its cosine/azimuth error can be compensated during the quality control process. However, such a practice is very time-consuming and expensive, so that it is generally not implemented. An inexpensive alternative is to correct the pyranometric data for a generic cosine error typical of the type of instrument used. An example is given here for the Eppley PSP which is widely used in the U.S. and elsewhere. Laboratory data for the instrument response at various incidence angles (0–88°) have been used here [13]. The average *normalized cosine response*, C_b, for three instruments and two azimuths is shown in Fig. 3. By definition, this factor is the ratio of the instrument response to that of a perfect cosine receptor, normalized to 1 at normal incidence. These data points have been fitted with

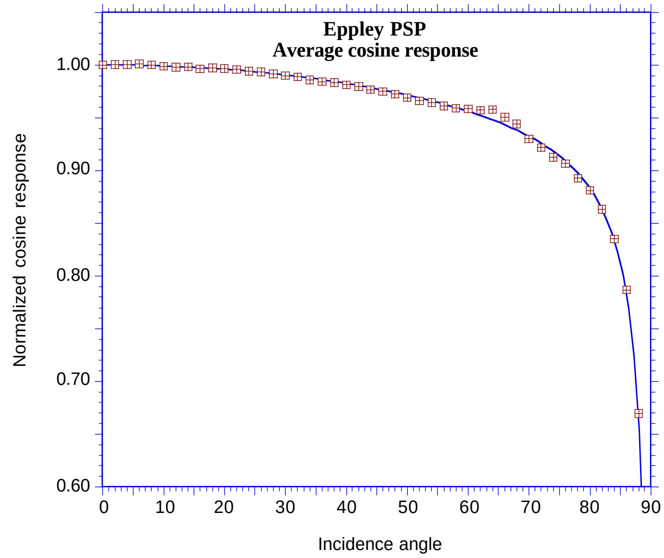

Fig. 3 Normalized cosine response of the Eppley PSP pyranometer, from laboratory data.

$$C_b = (1 - 0.010987\ \theta - 9.8179\text{E-}6\ \theta^2 + 9.6321\text{E-}8\ \theta^3) / (1 - 0.010979\ \theta) \qquad (6)$$

where θ is the incidence angle (equal to Z for an horizontal instrument). For ideally isotropic diffuse illumination, the average factor for diffuse radiation would be

$$C_d = \int_0^{90} C_b(\theta) \sin 2\theta d\theta \Big/ \int_0^{90} \sin 2\theta d\theta \qquad (7)$$

or C_d = 0.96706 after numerical integration. This value corresponds to an effective incidence angle θ_e = 51.4° in (6). The practical use of C_b and C_d depends on the calibration process for each pyranometer. For instruments calibrated with the outdoor shading/unshading method at *normal incidence*, such as practiced at the Florida Solar Energy Center (FSEC), the corrected direct and diffuse irradiances would be $E_{bn} = E_{bnx} / C_b$ and $E_d = E_{dx} / C_d$, respectively, where

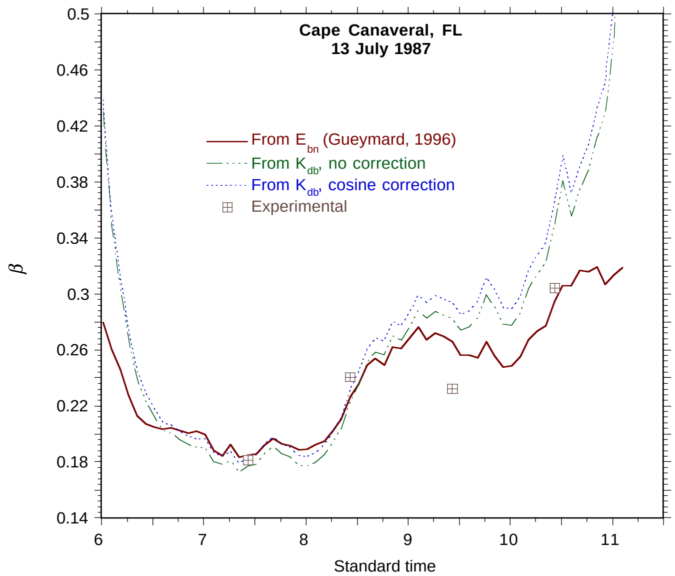

Fig. 4 Experimental comparison of the method to results obtained with [1] for a hazy summer day at FSEC.

E_{bnx} and E_{dx} are the experimental, uncorrected values. For instruments calibrated in a fixed *horizontal* position, such as practiced at the National Renewable Energy Laboratory (NREL), the calibration factor integrates the effect of C_b to a certain extent, depending on the *average* Z at which the calibration is made. For Z limited to 45–55°, as followed at NREL, the corrected irradiances would be $E_{bn} = C_b(50°)\ E_{bnx} / C_b(Z)$ and $E_d = C_b(50°)\ E_{dx} / C_d$. Finally, for an indoor calibration performed inside a white chamber under isotropic diffuse radiation, as followed by Eppley and some national networks [14], the corrected irradiances would be $E_{bn} = C_d\ E_{bnx} / C_b$ and $E_d = E_{dx}$.

This correction method is not perfect because it does not take into account the unavoidable instrument-to-instrument differences. Azimuthal errors could be modeled because some laboratory data are available, but the exact azimuthal bearing of a field pyranometer is generally not known or accessible to the data user. However, it is clear from Fig. 3 that the proposed correction is better than none, particularly at large zenith angles where large cosine errors may occur, at the risk of yielding negative turbidity estimates.

4. EXPERIMENTAL TESTS

A first test was conducted with data measured at FSEC, Cape Canaveral, Florida (lat. 28.42°N, long. 80.61°W, alt. 7 m). A hazy and humid summer day is selected here to test the performance of the present model under turbid conditions. This particular day has been previously chosen [1] to test another broadband method (where ß is derived from E_{bn} only) against an independent determination of ß derived from spectroradiometric data. Precipitable water was calculated from 5-min ground observations of air and dew-point temperature using an empirical relationship [15], and was roughly constant at about 5 cm for the day, in agreement with radiosonde data from the nearby Kennedy Space Center. Broadband observations of E_{bn} and E were available at 5-min intervals also. They were used to derive ß from E_{bn} only [1], or from K_{db} with and without cosine correction of E, according to the previous Section. Excellent agreement between the two methods, especially when the cosine correction is applied to the present one, is reached between 6:30 and 8:30 LST, when the sky was hazy but cloud-free. The rapidly decreasing turbidity between sunrise and 6:30 was caused by a dissipating fog, a frequent occurrence in this area due to the very high humidity. After 8:30, cloudiness began to build up, resulting in an obscured sun after 11:00 until sunset. For the particular conditions of this test, ignoring the cosine correction results in an underestimation of about 3–6% in ß, in accordance with the error analysis of the previous Section.

As could be expected, the present method is more sensitive to partial cloudiness than that of [1], which needs only a clear line of sight in a ≈5° cone around the sun's center. Because clouds absorb and scatter radiation more than aerosols, and thus have a profound effect on E_d, the ratio K_{db} is very sensitive to the presence of clouds in the sky, even if they do not obscure the sun. Hence the progress of the mismatch between the two broadband methods before 6:30 and after 8:30. This finding has two important consequences. First, the present method is valid only for truly cloud-free atmospheres, thus restricting its use compared to methods based on E_{bn} alone. Second, this limitation may become a strength if the present method is used not to obtain ß, as originally intended, but to detect cloud-free conditions in real-time or historic data. This may prove to be an important application because it is always very difficult to select clear conditions *a posteriori*, from radiative data alone.

A second series of tests has been conducted with data measured at Eugene (lat. 44.08° N, long. 123.12° W, alt. 150 m) and Burns (lat. 43.87° N, long. 119.03° W, alt. 1265 m), Oregon, two stations maintained by the University of Oregon (UO). Their radiometric setup is identical to that at FSEC, except that UO's pyranometers are calibrated with NREL's method instead of FSEC's. Besides the 5-min radiometric data, hourly cloud observations and meteorological data are available from each city's airport. Potentially cloud-free periods at the radiation site are assumed here if the observed cloud cover is ≤0.2 and the opaque cover is ≤0.1.

Figure 5 represents a clear summer day at Burns, using only input data from the National Solar Radiation Data Base (NSRDB) of NREL. (The Burns and Eugene radiation data in the NSRDB come from the UO Solar Radiation Monitoring Network.) This day is of particular interest because of the transition in turbidity that occurred: from the relatively low value that was prevalent during the preceding days (ß=0.02–0.06) to a relatively high value which continued for two

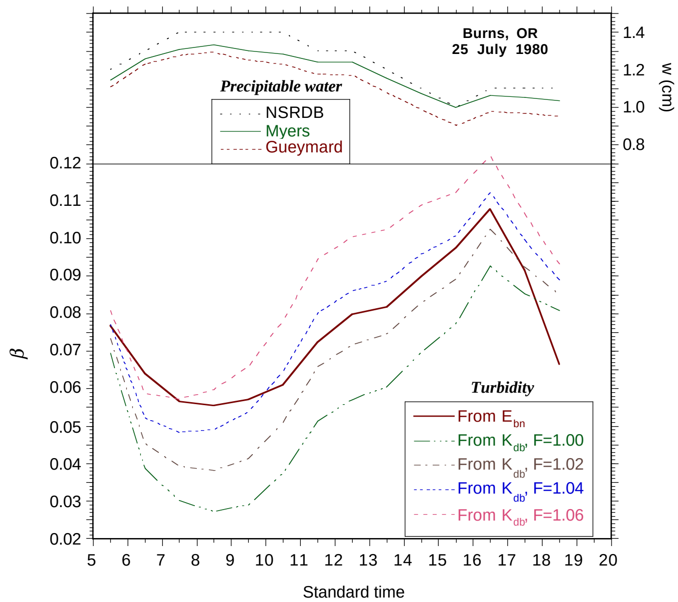

Fig. 5 Turbidity and precipitable water for a clear summer day at Burns, Oregon.

more days (ß≈0.12). The present calculations use hourly values of *w* predicted by Gueymard's method [15]. In the upper plot of Fig. 5, they are compared to the NSRDB values and to those predicted by the empirical model of Myers and Maxwell [3, 16]. Curiously, the two latter predictions do not coincide, although they should since the latter model was used to produce the NSRDB precipitable water when no radiosonde data was available, which is the case for Burns. It is possible that an undocumented change occurred so that the NSRDB calculations were made with an altered version of the Myers and Maxwell model.

This finding prompted the present authors to perform some further tests of the precipitable water calculations in the NSRDB, because of their importance in both turbidity and irradiance predictions. Precipitable water observations from radiosondes are available for Portland and Medford, Oregon and were used in the NSRDB. Radiosonde data there are available only twice a day, at 04:00 and 16:00 local time; only the latter dataset was used here. The comparison of the monthly average precipitable values obtained at Portland with Gueymard's and Myers and Maxwell's models appear in Fig. 6. Gueymard's model clearly appears to be in close agreement with the radiosonde/NSRDB data, whereas the Myers and Maxwell model underpredicts systematically. The same trend is also observed with the Medford data. Further investigations will be necessary to test how these possible systematic or location-specific inaccuracies in the NSRDB precipitable water estimates may affect its calculated irradiances.

Figure 5 also shows that no overall match is found between the value of ß predicted from E_{bn} and that predicted from K_{db}, even when considering the cosine error correction. For all the thousands of clear periods tested (using either 5-min or hourly irradiances), the only way to force a match between the two predictions of ß was by multiplying the cosine-corrected experimental value of global irradiance by a constant correction factor, *F*. A good match could then be obtained for the case of Fig. 5 with *F*≈1.035. The same pattern was prevalent throughout 1980, and a yearly average value of 1.046 was found. This problem also appeared in 1988, but with a lower average value, *F*=1.005. More thorough tests will be needed to investigate if this apparent bias is caused by modeling or experimental errors. At least, the magnitude of this correction and its abrupt change between 1980 and 1988 is consistent with the fact that NREL, during the production of its NSRDB, *a posteriori* increased the global irradiance data measured at Burns by 6% from November 1985, thus signaling a calibration problem.

Because of the uncertainty in precipitable water predictions mentioned earlier, it is important to investigate the effect it may have on ß predictions from either E_{bn} or K_{db}. A particular case is illustrated in Fig. 7 for a clear day in Eugene. (The early morning spike is due to an obstruction greatly affecting E_{bn}.) For that day, morning predictions of *w* using the airport data of temperature and relative humidity agreed relatively well with those obtained from the same type of measurement performed at UO's radiometric station. A marked drop in UO's *w* occurred after 14:00 LST, leading to values less than *half* those obtained with the airport data between 15:00 and 18:00. Such a large discrepancy in *w* is not exceptional, and it is not clear if it corresponds to a real difference due to horizontal inhomogeneities in *w* or to some instrumental problem. Predictions of ß were thus done with either UO's predicted *w* at 5-min intervals, or with twice this value. A constant correction factor, *F*=1.045, was also used. As can be seen from Fig. 7, doubling precipitable wa-

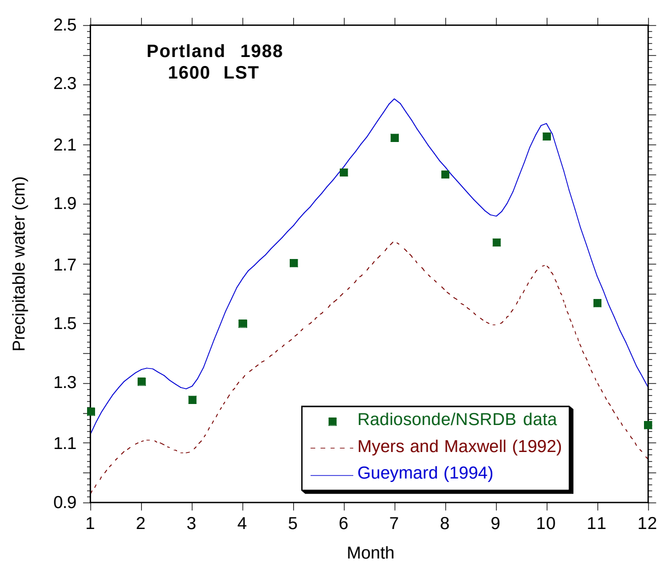

Fig. 6 Modeled vs observed precipitable water for Portland, Oregon.

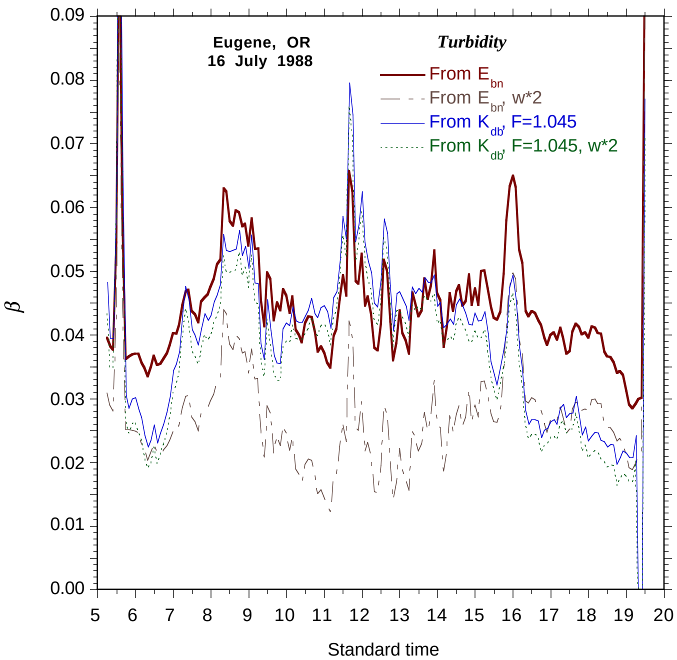

Fig. 7 Effect of doubling precipitable water on turbidity predictions for a clear summer day at Eugene, Oregon.

ter has a profound effect (a ≈50% decrease) on ß predicted from E_{bn}, but only a negligible effect (2–4% decrease) when predicted from K_{db}. This confirms that the present method may be preferable when precipitable water data are too uncertain. Also, it can be observed from Fig. 7 that a good match between the two turbidity methods is obtained until 15:30, when ß was calculated from E_{bn} with w, and from then on when a doubled w is used.

Figure 5 showed one way of using the irradiance ratio method to test the accuracy of global irradiance measurement, but this implied iterations to obtain F. A simpler way consists in using ß predicted from E_{bn}, then calculating K_{db}, from (2), and hence a predicted value of E. This value can be ratioed to its measured, cosine-corrected counterpart to obtain F. It can also provide a good estimate for E whenever global irradiance data is unavailable or questionable. Preliminary tests indicate that a very high accuracy in E is achievable with this method. The interest of using this method in quality control processes will be investigated further in a separate study.

5. CONCLUSION

A semi-physical method for turbidity determination from broadband irradiances has been presented. It requires cloudless skies and very accurate measurements of global (or diffuse) and direct radiation. These conditions appear very restrictive compared to more conventional turbidity methods based on direct irradiance only. However, one advantage of the new method is that it is less dependent on precipitable water, which can be very inaccurately estimated in some cases. Also, the new method may be applied to isolate cloudless periods in historic radiation records, as well as in quality control processes.

6. ACKNOWLEDGMENTS

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