Inexpensive Near-IR Sun Photometer for Measuring Total Column Water Vapor

DAVID R. BROOKS

Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, Pennsylvania

FORREST M. MIMS III

Geronimo Creek Observatory, Seguin, Texas

RICHARD ROETTGER

Ramey School, Aguadila, Puerto Rico

(Manuscript received 20 January 2006, in final form 14 November 2006)

ABSTRACT

An inexpensive two-channel near-IR sun photometer for measuring total atmospheric column water vapor (precipitable water) has been developed for use by the Global Learning and Observations to Benefit the Environment (GLOBE) environmental science and education program and other nonspecialists. This instrument detects sunlight in the 940-nm water vapor absorption band with a filtered photodiode and at 825 nm with a near-IR light-emitting diode (LED). The ratio of outputs of these two detectors is related to total column water vapor in the atmosphere. Reference instruments can be calibrated against column atmospheric water vapor data derived from delays in radio signals received at global positioning satellite (GPS) receiver sites and other independent sources. For additional instruments that are optically and physically identical to reference instruments, a single-parameter calibration can be determined by making simultaneous measurements with a reference instrument and forcing the derived precipitable water values to agree. Although the concept of near-IR detection of precipitable water is not new, this paper describes a first attempt at developing a protocol for calibrating large numbers of inexpensive instruments suitable for use by teachers, students, and other nonspecialists.

1. Introduction

Of all the earth's greenhouse gases, both anthropogenic and natural, water vapor is the most important. However, the global distribution and variability of total precipitable atmospheric water vapor (PW) is still significantly uncertain. A summary of current knowledge of PW and techniques used to measure it can be found in a report published by the American Geophysical Union (Mockler 1995).

Space-based measurements are critical for global monitoring of PW. However, as with other remote sensing measurements, ground validation is important for calibrating and monitoring the performance of space-based instruments and their data analysis algorithms. PW is only approximately related to meteorological parameters available on the ground. Reitan (1963) and Smith (1966) published empirically derived globally or seasonally/latitudinally averaged relationships between PW and dewpoint temperature (derivable from air temperature and relative humidity, but such relationships are insufficiently accurate to replace direct atmospheric measurements).

Traditional techniques for directly measuring local PW with varying degrees of accuracy and vertical resolution include balloons (radiosondes), lidar, and aircraft. Within the last decade, the delay in transmission through the atmosphere of radio signals to global positioning satellite (GPS) receivers has been used to determine vertically integrated PW (Bevis et al. 1992; Gutman and Holub 2000; Birkenheuer and Gutman 2005). There are a few hundred GPS-based sites around the United States whose data are available online in nearly real time.

Corresponding author address: David Brooks, Dept. of Mechanical Engineering and Mechanics, Drexel University, 3141 Chesnut St., Philadelphia, PA 19104.
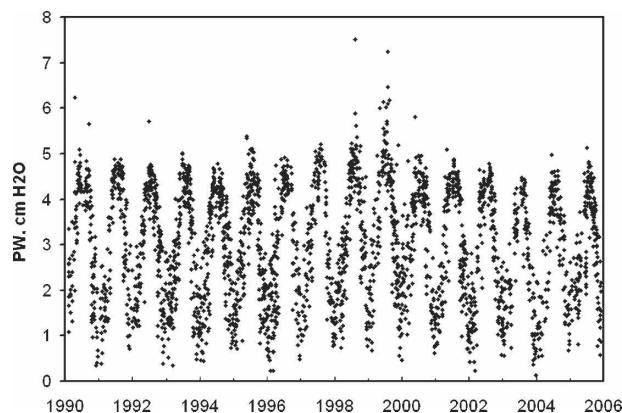E-mail: brooksdr@drexel.edu

FIG. 1. Total column water vapor measured by an LED sun photometer at Geronimo Creek Observatory, TX, 1990–2005.

It is well known that sun photometers can be used to measure vertically integrated PW from observing sites on the earth's surface by measuring the ratio of direct sunlight transmission through the atmosphere in and near water vapor absorption bands in the near IR (see, e.g., Reagan et al. 1995; Ichoku et al. 2002). This method is routinely applied to data from robotic CIMEL sun photometers in the global Aerosol Robotic Network (AERONET) (Holben et al. 1998). This paper addresses the question of whether much less expensive handheld sun photometers (with a parts cost of less than U.S. $100) can also be used to measure PW reliably when they are calibrated against independent standards.

Traditionally, sun photometers have used interference filters mounted over broadband photodetectors to measure sunlight transmission within narrow spectral intervals. Such instruments play an essential role in atmospheric and climate science. Volz (1974) proposed a handheld filter-based "economical multispectral sun photometer" for measuring PW and aerosol optical thickness more than 30 yr ago. However, interference filters can be fragile, expensive, and prone to unpredictable degradation. In the early 1990s, Mims (1992) showed that near-IR light emitting diodes (LEDs) could serve as spectrally selective detectors in handheld sun photometers for measuring PW, paving the way for a much less expensive and more reliable alternative to filter-based instruments. An LED-based water vapor sun photometer has been used by Mims (2002) continuously since 1990. Figure 1 shows a 15-yr record of PW measurements at Mims' Geronimo Creek Observatory in Seguin, Texas, based on empirical calibrations against a CIMEL robotic sun photometer at Mauna Loa Observatory (MLO) in Hawaii and a National Oceanic and Atmospheric Administration (NOAA)

GPS/MET station at Galveston, Texas. It is worth noting that the observed PW at MLO is generally so low (a few millimeters) that the AERONET data are of limited value as a calibration source for almost all observing sites (B. N. Holben 2005, personal communication). As a result, we have not used MLO data to calibrate Global Learning and Observations to Benefit the Environment (GLOBE) water vapor instruments. However, long-term stability of LED detectors, which is also a concern, has been monitored by Mims (2002) based on measurements at MLO since 1992 and will continue to be monitored in the future.

At the time Mims (1992) originally proposed his LED-based sun photometers, there was no infrastructure for implementing a widely dispersed measurement network that relied on inexpensive handheld instruments. That situation changed in 1994 with the start of the GLOBE program, an international environmental science and education program funded by the U.S. government (information online at http://www.globe.gov) and governments in other participating countries. GLOBE supports a wide range of data collection protocols that can be implemented by teachers, students, and other observers. The goal of all GLOBE protocols is to enable nonspecialists to collect reliable and scientifically useful data.

In 1998, GLOBE added support for inexpensive visible light sun photometers, leading to the development of a two-channel LED-based instrument that measures aerosol optical thickness at 505 and 625 nm (Brooks and Mims 2001). Based on the design of the GLOBE sun photometer, a water vapor instrument was developed with additional support from the National Aeronautics and Space Administration's Langley Research Center, through the now-cancelled Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) program (Brooks et al. 2003). Except for its detectors, this instrument is physically identical to the GLOBE visible light sun photometer.

Initially, it was envisioned that the GLOBE water vapor instrument would also use two LEDs, but radiative transfer modeling and testing indicated that currently available near-IR LED pairs provide lower-than-desired sensitivity to changes in PW, with significant temperature sensitivity problems appearing in the 940-nm LEDs. Advances in the manufacture of small interference filters since Mims' (1992) original paper provide a viable compromise. The current GLOBE instrument uses an LED whose output is not significantly temperature sensitive under anticipated field conditions, and one filtered photodiode. Retention of one inexpensive LED channel is justified for an instrument whose cost is an overriding consideration. For long-
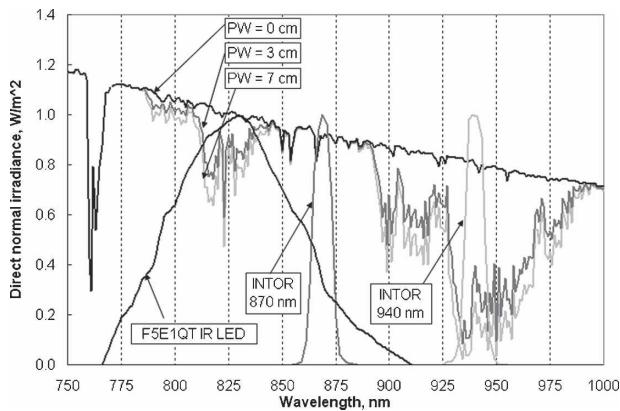
FIG. 2. Sunlight transmission through the atmosphere for overhead sun, in the near IR, with normalized detector responses.

FIG. 3. GLOBE water vapor instrument.

term comparison purposes, a few instruments have been built with two filtered photodiode detectors and, in a four-channel version, with both pairs of detectors.

2. Atmospheric transmission and detector characteristics

Figure 2 shows direct solar transmission through the *U.S. Standard Atmosphere, 1976* over the range of 750–1000 nm, based on the second Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS2) (Gueymard 1994). Direct normal irradiance at a relative air mass of 1.0 (overhead sun) is shown for no water vapor, and for 3 and 7 cm of water. The *U.S. Standard Atmosphere, 1976* PW value is 1.42 cm of H_2O, and 7 cm is near the upper limit of naturally occurring PW values. Superimposed on these data are the normalized spectral responses of a near-IR LED (Fairchild F5E1) that has a peak response at about 830 nm (compared to its peak emission at about 880 nm), as measured with a standard tungsten/halogen lamp and an Optronics Model 04 monochromator, and 870- and 940-nm filtered photodiodes from INTOR, Inc. (Part Numbers 870.0/10/45 and 940.0/10/50), as provided by the manufacturer.

The 940-nm filter/photodiode response is located directly over a water vapor band that exhibits good sensitivity to PW changes over the range of likely values. The response of the near-IR LED overlaps the weaker water vapor absorption band centered around 825 nm. Even though it is not possible to tailor the spectral response of commercially available LEDs, as can be done with interference filters, this particular LED still provides a reasonable compromise for reducing cost by eliminating one filter/photodiode detector. The calibration data presented below are for an instrument using

the 940-nm filtered photodiode and the near-IR LED. The question of whether the use of a second filtered photodiodes in place of the LED detector, as shown in Fig. 2, will provide a significant performance improvement requires additional long-term comparisons of both instrument configurations.

3. Instrument design

The GLOBE water vapor (WV) instrument, shown in Fig. 3, uses the same custom-designed printed circuit board and case as that of the GLOBE visible light sun photometer. The case measures $5.1 \times 7.6 \times 15.2$ cm. Two 5.5-mm-diameter holes at the upper end are spaced to allow sunlight to enter and strike the two detectors whose active surfaces are about 12.5 cm away near the lower end of the case. Each detector produces a small photocurrent when struck by light within its spectral response bandwidth. A 9-V battery-powered dual–operational amplifier (Linear Technology LTC1051) transimpedance amplifier converts these currents into voltages in the range of roughly 1–2 V in full sunlight.

A solid-state temperature sensor (National Semicon-

ductor LM35) that produces an output of 0.010 V °C^{-1}, with a rated accuracy of ± 0.5°C, is mounted on the front of the printed circuit board between the two detectors. It monitors air temperature inside the case, thereby giving a rough measure of the detector temperatures during measurements.

A rotary switch is used to display either of the two IR channel outputs or the voltage output from the temperature sensor. A standard DB25 connector is provided for testing, calibrating, or automating the data collection of all channels simultaneously.

4. Instrument theory and calibration

Total column water vapor is expressed in centimeters of water directly above the observing site. The value is not corrected for the site elevation, that is, it is not referenced to sea level, as is the case for barometric pressure, for example. Nearly half the water vapor in the atmosphere is found typically between sea level and a few kilometers, so there is a strong elevation effect on PW. The basic calibration strategy for the GLOBE WV instrument is to relate the ratio of outputs from its two near-IR channels to nearby independently determined values of water vapor, over as wide a range of conditions as possible.

When sunlight illuminates the detectors, the instrument electronics produce two output voltages, each of which is proportional to the amount of direct solar radiation reaching its detector:

$$\text{No water vapor: } V_1 = V_{0,1}\exp(-m\tau_{\lambda,1}), \qquad (1)$$

$$\text{Water vapor: } V_2 = V_{0,2}\exp(-m\tau_{\lambda,2})T_{\text{WV}}, \qquad (2)$$

where m is relative air mass (dimensionless), V is voltage output when illuminated by direct sunlight (V), V_0 is extraterrestrial constant (instrument output voltage when $m = 0$; V), τ is atmospheric optical thickness (wavelength dependent; dimensionless), λ is wavelength (nm), and T_{WV} is transmittance for water vapor absorption (assume $T_{\text{WV}} = 1$ for the first detector; dimensionless).

Relative air mass m is a dimensionless quantity approximately equal to $1/\cos(z)$, where z is the solar zenith angle. The extraterrestrial constant V_0 is the voltage signal the instrument would produce in the absence of an atmosphere. In full sunlight, the instrument output is on the order of 1V. The "dark voltage" produced by each channel when sunlight is not striking the detectors (no more than a few mV) is subtracted from all voltages.

The dimensionless transmittance function T describes the effect upon sunlight reaching the instrument of all gases and aerosols within the response bandwidth of the detector. In this case, it is assumed that aerosol absorption is the same at both wavelengths and that T_{WV} depends just on water vapor. Thus, T_{WV} can be expressed as a function of the total amount of water vapor between an observer and the sun, mPW, where PW is the water vapor measured directly overhead. For the first detector T_{WV} is assumed to be 1, even though this is not strictly true, as shown for the LED detector response in Fig. 1. Equation (3) gives one well-known formulation for T_{WV}, dating back to the 1960s (Gates and Harrop (1963), which has been used frequently since then (e.g., Reagan et al. 1995),

$$\ln(T_{\text{WV}}) = a - b(m\text{PW})^{\beta}. \qquad (3)$$

Gate and Harrop (1963) set $\beta = 0.5$. In the present case, with one detector overlapping a relatively weak water vapor absorption band and detectors with a spectral response bandwidth wider than is normally used in sun photometry, it is not obvious that the square root of mPW is appropriate. Instead, the value of β required to produce a linear relationship is to be determined by using a radiative transfer model and the known spectral response characteristics of the detectors to determine the response to varying PW. From Eqs. (1), (2), and (3),

$$\ln(V_2/V_1) = \ln(V_{0,2}/V_{0,1}) + m(\tau_{\lambda,1} - \tau_{\lambda,2}) + [a - b(m\text{PW})^{\beta}].$$
$$\qquad (4)$$

The atmospheric optical thickness τ at each wavelength consists of two parts—the first is due to scattering by molecules in the atmosphere (Rayleigh scattering); the other part is due to scattering and/or absorption by aerosols and gases in the atmosphere. The Rayleigh contribution can be calculated theoretically. Aerosol optical thickness varies over a wide range of values, but the range of differences between aerosol optical thicknesses at the relatively closely spaced near-IR wavelengths of the two detectors is small.

Equation (4) can be used to calculate atmospheric water vapor if all the constants are known. The extraterrestrial constants (or their ratio) are a property of the instrument itself, based on the output of the detectors and the gain of the electronics. The constants a and b are determined by the spectral response properties of the detectors and by the transmittance properties of water vapor over the spectral bandwidth. Response properties can be measured by careful laboratory measurements of the spectral response of detectors. The transmittance properties can, in principle, be calculated from atmospheric models.

Toward the end of defining a way to calibrate large numbers of these instruments quickly and easily, the
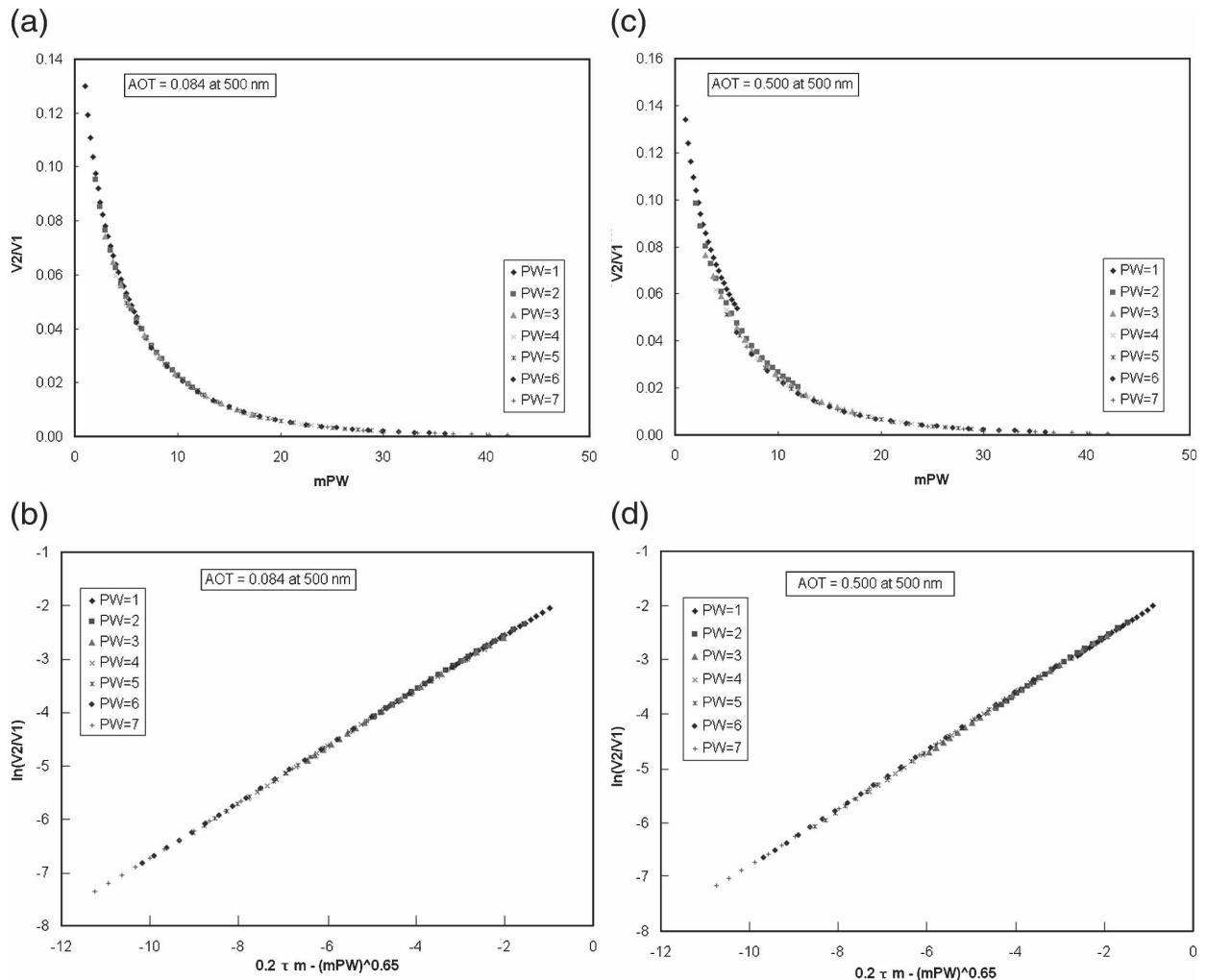
FIG. 4. The quantity V_2/V_1 vs mPW: (a) AOT = 0.084 and (c) AOT = 0.500. The quantity $\ln(V_2/V_1)$ vs $Cm\tau_{500nm} - (m\text{PW})^{\beta}$ with $C = 0.20$ and $\beta = 0.65$, that is, with AOT correction: (b) AOT = 0.084 and (d) AOT = 0.500. *U.S. Standard Atmosphere, 1976* simulations with SMARTS2.

behavior of a modified version of (4) has been examined using the SMARTS2 radiative transfer model (Gueymard 1994), along with normalized spectral response functions for the LED and filtered photodiode detectors in the GLOBE WV instrument. The "voltages" in the simulation are taken to be proportional to the integrated irradiance over the spectral response of the detectors,

$$\ln(V_2/V_1) = A + B[Cm\tau_{500nm} - (m\text{PW})^{\beta}], \qquad (5)$$

where τ_{500nm} is the aerosol optical thickness at 500 nm. The parameter C accounts for the effects of aerosol optical thickness differences between the two detector wavelengths. This simulation assumes that the entire dependence upon optical thickness at the two detector wavelengths, as given in (4), can be replaced by the

dependence upon aerosol optical thickness (AOT) at some other single wavelength.

Aerosol optical thickness at 500 nm can be specified as an input parameter in the SMARTS2 model. This wavelength is close to a GLOBE sun photometer wavelength (505 nm) and identical to a wavelength used in AERONET's CIMEL sun photometers. In principle, it should be possible to calibrate an "out-of-band" near-IR channel for calculating aerosol optical thickness. However, as shown previously in Fig. 2, the LED detector used in this instrument actually overlaps a weak water vapor band, making its output unsuitable for this purpose.

Figure 4 shows results from SMARTS2 simulations for seven values of PW, from 1- to 7-cm H_2O and relative air masses from 1 (solar zenith angle = 0°) to 6

(solar zenith angle = 80°). Figures 4a and 4c show V_2/V_1 as a function of mPW for the *U.S. Standard Atmosphere, 1976* with $\tau_{500nm} = 0.084$ (a clean atmosphere), and the same atmosphere with $\tau_{500nm} = 0.500$ (a very hazy atmosphere). Figures 4b and 4d show the same data, with $\ln(V_2/V_1)$ transformed into a linear relationship as a function of $Cm\tau_{500nm} - (m\text{PW})^\beta$, with $C = 0.20$ and $\beta = 0.65$. The relatively weak dependence on aerosol optical thickness means that good results can be achieved with only a rough estimate of AOT.

For known values of PW, Eq. (5) is the basis for calibrating GLOBE water vapor instruments. Data for three GLOBE water vapor instruments have been collected at Ramey School in Puerto Rico, which was chosen because it is an active GLOBE school and is less than 9 km from the GPS site at Isabela, Puerto Rico (see site ID PUR3; online at http://gpsmet2.fsl.noaa.gov), and within 10 m of the same elevation. The only disadvantage of this site for calibration purposes is that PW rarely falls below 2 cm of H_2O (the annual range is roughly 2–6-cm H_2O), which limits the lower end of the calibration range. GLOBE data were collected on 15 October 2004 and 23 November 2004. Figure 5 shows GPS/MET PW data from Isabela for these two dates.

Figure 6 shows $\ln(V_2/V_1)$ as a function of $Cm\tau_{500nm} - (m\text{PW})^\beta$ for the three GLOBE instruments, along with derived linear models for each instrument. The data were obtained by recording instrument output voltages V_1 and V_2 over a wide range of sun angles on each day. Calculated model parameters for each instrument are given in Table 1.

For these instruments, only the A and B coefficients are considered as variables to be determined. The B value is determined by the spectral response properties of the detectors and should be the same for all instruments in the WV2 series. (The small differences among B values in Table 1 can be considered as artifacts of the regression.) The A value is determined by the overall current output of and electronic gain applied to each detector, and therefore varies from instrument to instrument. The value for C has been chosen based on the model calculations shown previously in Fig. 4. The relatively small effect of the values of C and τ, through the term $Cm\tau$, may need to be adjusted for instruments used in areas with persistently very high or very low values of optical thickness. In circumstances where a GLOBE visible light sun photometer is also being used,
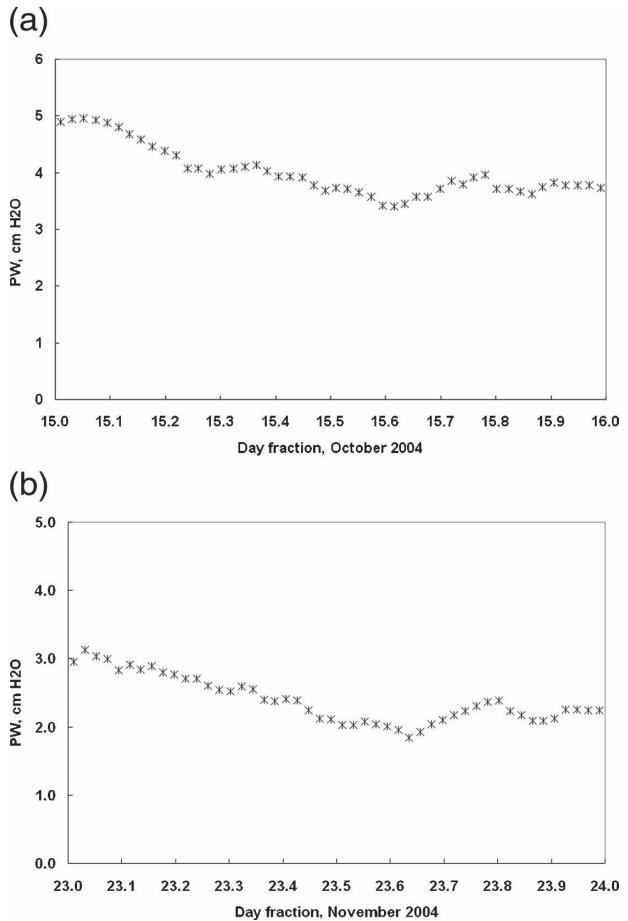

FIG. 5. The quantity PW vs day fraction for (a) 15 Oct 2004 and (b) 23 Nov 2004.

the observed value of aerosol optical thickness at 505 nm (the effective wavelength for the green light channel of this instrument) can be substituted for the assumed value of 0.10.

Of the two instrument-related coefficients A and B, B does not change significantly among instruments with the same detectors. Therefore, it is assumed to be sufficient to calculate an average value for B based on the results of representative reference calibrations and calculate a value of A for each test instrument; as previously noted, A differs from instrument to instrument because of the differences in detector current output and amplifier gain. For voltage data collected using both a reference and test instrument simultaneously, using (5),

$$\ln(V_2/V_1)_{\text{ref}} - A_{\text{ref}} = B[Cm\tau_{500nm} - (m\text{PW})^\beta] = \ln(V_2/V_1)_{\text{test}} - A_{\text{test}}$$
$$A_{\text{test}} = \ln(V_2/V_1)_{\text{test}} - \ln(V_2/V_1)_{\text{ref}} + A_{\text{ref}}. \qquad (6)$$
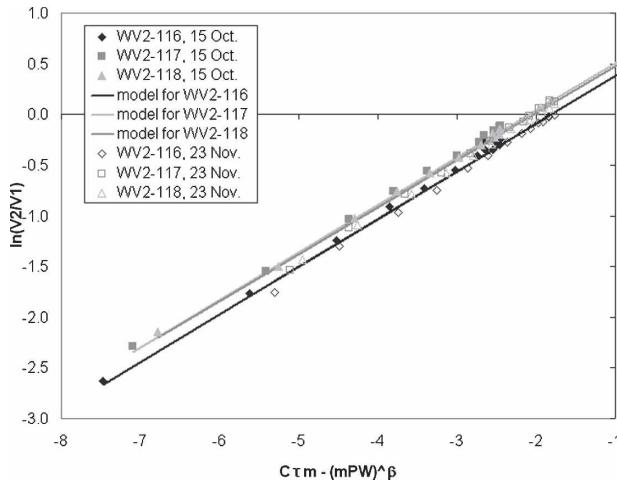
FIG. 6. Modeled fits to calibration data for three GLOBE water vapor instruments. †The quantity $\ln(V_2/V_1)$ as a function of $Cm\tau_{500nm} - (mPW)^{\beta}$ for instruments WV–116, –117, and –118 for 15 Oct and 23 Nov, along with derived linear models for each instrument.

Unpublished results with almost 100 instrument calibrations have shown that the value of A varies from roughly 0.7 to 1.2.

5. PW data from 2005

Subsequent to these calibrations, one of the instruments (WV2–116) has been used to collect data routinely at the same site in Puerto Rico. Of course, sun photometer measurements can be taken only during daylight hours when there is an unobstructed view of the sun. Students have taken measurements usually only once a day, although clearly not on all possible days. Figure 7 shows all 2005 GPS/MET data from the Isabela site along with GLOBE PW values for 2005. The Isabela site was down for a significant part of 2005.

Each GLOBE "measurement" consists of the average PW value obtained from three voltage pairs taken within roughly 2 min, as obtained from Eq. (5). During 2005, only one GLOBE measurement was discarded due to a single reported voltage value that was obviously in error. There were some questionable GPS/MET PW values too, some of which were removed

TABLE 1. Calibration parameters for three GLOBE water vapor instruments. Variables to be determined are shown in boldface.

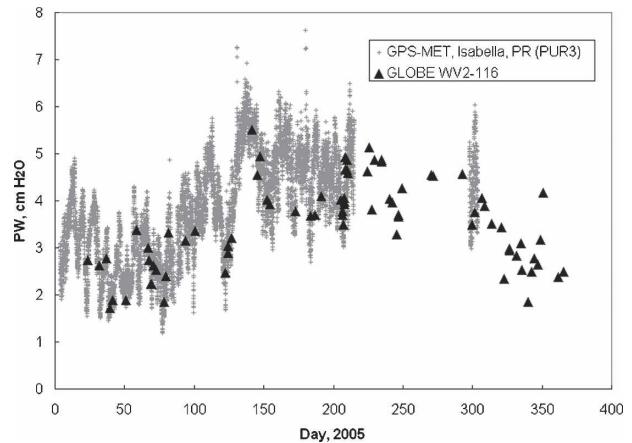| Instrument	A	B	C	β	T_{500}
WV2–116	**0.859**	**0.471**	0.20	0.65	0.10
WV2–117	**0.979**	**0.469**	0.20	0.65	0.10
WV2–118	**0.942**	**0.464**	0.20	0.65	0.10

FIG. 7. Total precipitable water vapor data, PW, from the GPS/MET site at Isabela, measured with GLOBE water vapor instrument WV2–116 at the Ramey School, Aguadila.

from Fig. 7. For example, around day 180, some questionable PW values nearly as high as 10-cm H_2O were reported. During 2005, there were 43 GLOBE measurements reported when GPS/MET data were also available. Figure 8 compares these 43 GLOBE measurements with the closest (in time) GPS/MET PW value. The root-mean-square value of ($PW_{WV2–116} - PW_{GPS/MET}$) is 0.173-cm H_2O. A least squares linear regression of GLOBE data on GPS/MET data yields a slope of 0.977 with a correlation coefficient $r^2 = 1 - s^2_{WV2–116,\ GPS/MET}/s^2_{WV2–116} = 0.974$.

6. Discussion and conclusions

Figure 8 shows that GLOBE-derived values are within a few tenths of a centimeter of H_2O of the corresponding GPS/MET values. As can be seen from the Isabela GPS/MET data, water vapor can change quickly and significantly during the day at this coastal site. Considering that the GLOBE and GPS/MET sites are in slightly different locations, that the GPS/MET values are an average of a large and unknown region of the sky over a half-hour, and that the GLOBE instrument measures water vapor only along a direct path to the sun, the agreement is remarkable. Whether there are inherent errors in the GPS/MET data is an interesting question, but irrelevant to this work, whose purpose is only to demonstrate that GLOBE water vapor instruments can be calibrated reliably against an independent and widely used source of PW data, and can then be used as independent sources of PW data. Extensive comparisons against radiosonde data (Mattioli et al. 2007; Tregoning et al. 1998) have demonstrated that GPS/MET PW retrievals are accurate to within no
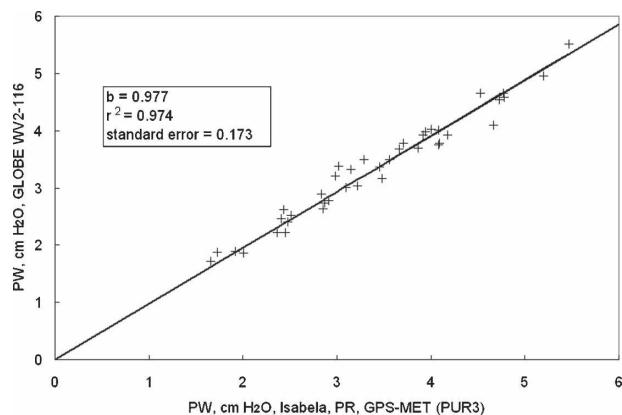
FIG. 8. Correlation of PW measurements from the GPS/MET site at Isabela with the GLOBE water vapor instrument WV2–116 at the Ramey School, Aguadila.

worse than 1–2-mm H_2O and possibly to within less than 1-mm H_2O.

It is also possible to calibrate GLOBE water vapor instruments against PW retrievals from AERONET sun photometers. In this case, the two instruments would look directly at the sun through the same air mass at the same time. The times of AERONET measurements are preprogrammed and not readily available in advance. However, if the calibration measurements are made within view of an automated AERONET instrument, an observer can watch the AERONET instrument swing into action (roughly every 15 min or so) and make measurements at the same time. These comparisons will further clarify the performance of the GLOBE instrument.

As noted above, extreme atmospheric conditions, where aerosol optical thickness and/or atmospheric turbidity are very high, can affect the model presented here. These effects can be minimized by avoiding measurements at high relative air mass ($m > 3$, e.g.). Additional work needs to be done to quantify the extent to which separate measurements of AOT at a single wavelength (as suggested above) or even qualitative observations of atmospheric turbidity (as related to horizontal visibility, e.g.) can be used to improve the accuracy of PW retrievals by providing corrections to C and τ_{500nm}. This work is also underway as part of additional calibration studies using AERONET data as the independent source. This work will also provide additional information about whether temperature corrections are needed or feasible for processing data from GLOBE water vapor instruments. (These instruments include an internal temperature sensor for monitoring air temperature inside the instrument case.)

In summary, this work demonstrates that it is possible to develop relatively inexpensive (~U.S. $150) near-IR sun photometers, which can be deployed in a water vapor monitoring network that has both pedagogical and scientific value. Reference instruments for such a project can be calibrated against a range of PW values from GPS/MET sites (as described here) or AERONET sites. "Field" instruments can then be calibrated quickly by forcing PW values derived from a test instrument to agree with a reference instrument. As noted previously, only a single constant is required to provide a "transfer calibration" for instruments that share the same detector configurations, so only a single measurement (a series of voltage pairs taken within a few minutes), is required to determine an instrument calibration.

Even though there are hundreds of GPS/MET sites in the United States and Canada and approximately 150 global AERONET sites, which are sources of PW data, global ground-based coverage of water vapor is still sparse. Although the GLOBE instrument shares the disadvantage of all sun photometers that data collection is limited to daylight hours when there is an unobstructed view of the sun, it nonetheless provides a reliable source of water vapor information wherever weather conditions permit even its sporadic use. This is of particular interest in developing countries where it is unlikely that an extensive "professional" monitoring network will be available in the foreseeable future. As is required for all GLOBE measurements, a detailed protocol has been written for users of the GLOBE WV instrument. As a supported GLOBE protocol, this guide is available online at the GLOBE Program's Web site (http://www.globe.gov), and is included in the CD-ROM version of the GLOBE teacher's guide. An annotated and updated version of the GLOBE Water Vapor Protocol, plus an expanded version of the GLOBE protocol, published as a NASA educator's guide (Brooks et al. 2003) is available online (http://www.pages.drexel.edu/~brooksdr).

tion data and with the ongoing water vapor measurements reported in Fig. 7.

REFERENCES

Bevis, B. G., S. Bussinger, T. A. Herring, C. Rocken, R. A. Anthes, and R. H. Ware, 1992: GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system. *J. Geophys. Res.,* **97,** 15 787–15 801.

Birkenheuer, D., and S. Gutman, 2005: A comparison of GOES moisture-derived product and GPS-IPW data during IHOP 2002. *J. Atmos. Oceanic Technol.,* **22,** 1840–1847.

Brooks, D. R., and F. M. Mims III, 2001: Development of an inexpensive handheld LED-based sun photometer for the GLOBE program. *J. Geophys. Res.,* **106** (D5), 4733–4740.

——, ——, A. S. Levine, and D. Hinton, 2003: The GLOBE/GIFTS water vapor monitoring project: An educator's guide with activities in earth sciences. NASA Publication EG-2003-12-06-LARC, 66 pp.

Gates, D. M., and W. J. Harrop, 1963: Infrared transmission of the atmosphere to solar radiation. *Appl. Opt.,* **2,** 887–898.

Gueymard, C. A., 1994: SMARTS2: Simple Model of the Atmospheric Radiative Transfer of Sunshine: Algorithms and performance assessment. Florida Solar Energy Center Rep. FSEC-PF-270-95, 84 pp.

Gutman, S., and K. Holub, 2000: Ground-based GPS meteorology at the NOAA Forecast Systems Laboratory. Preprints, *Fourth Symp. on Integrated Observing Systems,* Long Beach, CA, Amer. Meteor. Soc.*,* 1–5.

Holben, B. N., and Coauthors, 1998: AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sens. Environ.,* **66,** 1–16.

Ichoku, C., and Coauthors, 2002: Analysis of the performance characteristics of the five-channel Microtops II Sun photometer for measuring aerosol optical thickness and precipitable water vapor. *J. Geophys. Res.,* **107,** 4179, doi:10.1029/2001JD001302.

Mattioli, V., E. R. Westwater, D. Cimini, J. S. Liljegren, B. M. Lesht, S. I. Gutman, and F. J. Schmidlin, 2007: Analysis of radiosonde and ground-based remotely sensed PWV data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment. *J. Atmos. Oceanic Technol.,* **24,** 415–431.

Mims, F. M., III, 1992: Sun photometer with light-emitting diodes as spectrally selective detectors. *Appl. Opt.,* **31,** 6965–6967.

——, 2002: An inexpensive and stable LED Sun photometer for measuring the water vapor column over South Texas from 1990 to 2001. *Geophys. Res. Lett.,* **29,** 1642, doi:10.1029/2002GL014776.

Mockler, S. B., 1995: Water vapor in the climate system: A special report. American Geophysical Union. [Available online at http://www.agu.org/sci_soc/mockler.html.]

Reagan, J. K., J. K. Thome, and B. Herman, 1995: A comparison of columnar water vapor retrievals obtained with near-IR solar radiometer and microwave radiometer measurements. *J. Appl. Meteor.,* **34,** 1384–1391.

Reitan, C. H., 1963: Surface dew point and water vapor aloft. *J. Appl. Meteor.,* **2,** 776–779.

Smith, W. L., 1966: Note on the relationship between total precipitable water and surface dew point. *J. Appl. Meteor.,* **5,** 726–727.

Tregoning, P., R. Boers, D. O'Brien, and M. Hendy, 1998: Accuracy of absolute precipitable water vapor estimates from GPS observations. *J. Geophys. Res.,* **103,** 28 701–28 710.

Volz, F. E., 1974: Economical multispectral Sun photometer for measurements of aerosol extinction from 0.44 μm to 1.6 μm and precipitable water. *Appl. Opt.,* **13,** 1732–1733.