An inexpensive and stable LED Sun photometer for measuring the water vapor column over South Texas from 1990 to 2001

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[1] A Sun photometer that uses near-infrared light-emitting diodes (LEDs) as spectrally-selective photodetectors has measured total column water vapor in South Texas since February 1990. The 12 years of solar noon observations to date are correlated with upper air soundings at Del Rio, Texas (r^2 = 0.75), and highly correlated with measurements by a Microtops II filter Sun photometer (r^2 = 0.94). LEDs are inexpensive and have far better long term stability than the interference filters in conventional Sun photometers. The LED Sun photometer therefore provides an inexpensive, stable and portable means for measuring column water vapor. *INDEX TERMS:* 0394 Atmospheric Composition and Structure: Instruments and techniques; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 1694 Global Change: Instruments and techniques; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 9805 General or Miscellaneous: Instruments useful in three or more fields

1. Introduction

[2] Water vapor is the key ingredient of tropospheric weather and the atmosphere's principal greenhouse gas. Besides its role in cloud formation, water vapor condensed on sulfate, nitrate and other hygroscopic aerosols significantly increases the optical thickness of the cloud-free atmosphere. Any one of these factors provides ample justification to supplement measurements of ambient water vapor at the surface with long-term monitoring of changes and trends in the total column abundance of atmospheric water vapor.

[3] This paper describes an inexpensive Sun photometer [*Mims*, 1992] that has measured column water since February 1990. The Sun photometer provides long-term stability by replacing the drift-prone interference filters of conventional instruments with light-emitting diodes operated as very stable, near-infrared (near-IR) photodetectors [*Mims*, 1999]. The development of very similar LED Sun photometers that accurately measure aerosol optical thickness (AOT) has been described elsewhere [*Brooks and Mims*, 2001].

2. Column Water Vapor

[4] Total column water vapor, or precipitable water (PW), is the thickness of the vertical water vapor column condensed as a liquid at standard temperature and pressure. *Fowle* [1912] exploited water vapor's absorbing bands at 1,130 and 1,470 nm and nearby non-absorbing bands to measure PW. The accuracy is affected by the detector's spectral response and temperature.

[5] Fowle observed the direct Sun with a prism spectrometer. Many subsequent instruments have used interference filters. *Volz* [1974] developed a handheld Sun photometer with filters at the water absorption band at 940 nm and a nearby window at about 880 nm or 1020 nm. Interference filters are expensive and subject to unpredictable drift. While the peak spectral transmission of a filter may remain stable, the transmissivity can degrade over time.

[6] Today PW is widely measured by instrumented sounding balloons and by satellite and ground-based instruments. Upper air soundings provide vertical distribution of water vapor and PW. Accuracy is affected by the quality of the temperature and humidity sensors and the wake effect of the ascending balloon. Various satellite instruments measure PW. The MODIS instrument aboard the TERRA satellite does so by measuring the ratio of backscattered pairs of near-IR wavelengths [*Kaufman and Gao*, 1992].

[7] Since microwaves are attenuated by water molecules, PW can be inferred from Global Positioning System (GPS) signals [*Bevis et al.*, 1992]. Accuracy is affected by ground reflected signals and azimuthal differences. Precipitable water can also be measured by a microwave radiometer tuned to frequencies emitted by liquid and gaseous water molecules [*Liljegren*, 1994]. Accuracy is affected by temperature sensitivity of the instrument, reflected sunlight and liquid water on the instrument's window.

3. LED Column Water Vapor Sun Photometer

[8] Although light-emitting diodes (LEDs) are designed to emit quasi-monochromatic light, they can also detect a relatively narrow spectrum of wavelengths [*Mims*, 1973]. This principle has been applied in a novel PW instrument in which a pair of near-IR LEDs serve as spectrally selective photodetectors [*Mims*, 1992]. LEDs are very rugged, stable, and inexpensive. Thus they are ideally suited for use as photodetectors in Sun photometers.

[9] The first of a series of LED Sun photometers that measure PW and aerosol optical thickness (AOT) was placed in service at Geronimo Creek Observatory (GCO) in South-Central Texas (29.61 N, 97.93 W; 244 m msl) on 4 February 1990. Measurements are made at or near solar noon each day the investigator is present and the Sun is not obscured by clouds. Thus far observations have been

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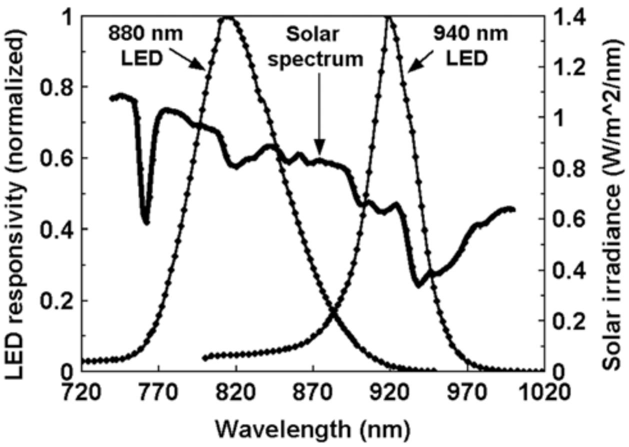

Figure 1. Spectral response of near-IR LEDs in the photodiode mode superimposed over the solar spectrum. The latter is a copyright of Analytical Spectral Devices (2001) and is used with permission.

made on 2,271 of 4,364 days (52%) during the past 12 years.

3.1. Led Sun Photometer Design Considerations

[10] The basic electronic circuitry of the LED Sun photometer has been described elsewhere [*Mims*, 1990]. Here several important design consideration are discussed.

3.1.1. Electronic and optical design

[11] The Sun photometer uses an operational amplifier to amplify the photocurrent from the LEDs and to transform the photocurrent to a voltage that can be displayed on a digital readout. The instrument uses a pair of commercially available LEDs hermetically sealed in TO-18 headers with flat glass windows. The leads from each LED are soldered to 2-conductor miniature phone plugs. The phone plug covers restrict the field of view (FOV) of the LEDs to about 20 degrees. While this is ~10X greater than the FOV of subsequent LED Sun photometers, the sky radiance in the near IR is very low and has little effect on measured PW. The cost of components for the instrument was about $15 plus a digital volt meter.

3.1.2. Led selection

[12] In principal, water vapor can be detected with only a single detector that responds at an absorption band. In practice, the unpredictable nature of scattering and absorption by aerosols requires two detectors, one of which responds outside the absorption band. The ratio of the signal from each detector divided by the air mass is proportional to PW.

[13] The LED instrument detects PW within the 900 to 980 nm absorption continuum with a GaAs LED having an emission peak at 940 nm and a response peak at 920 nm with a full-width, half-maximum (FWHM) bandpass of 40 nm (part number 1N6265 or similar). The reference LED is an AlGaAs LED having a peak emission wavelength of 880 nm and a response peak at 815 nm with a bandpass of 65 nm FWHM (part number F5E3 or similar).

[14] Figure 1 superimposes the spectral response of the two LEDs over the solar spectrum. The sharp absorption spike at 762 nm is an oxygen absorption band. The 940 nm LED responds across much of the 900 to 980 nm water vapor continuum. Note that the peak of the 880 nm reference LED response falls directly over the 820 nm water vapor absorption feature. Figure 2 This does not affect PW measurements, because this band has much less absorption than the 900–980 nm continuum.

3.1.3. Led temperature bias

[15] As with conventional photodiodes, LEDs operated as photodiodes have a temperature bias. As temperature rises, the responsivity of an LED falls. The error is compounded by a simultaneous shift in peak spectral response. The temperature error was investigated empirically by comparing column water retrievals from a Microtops II filter Sun photometer and a Sun photometer equipped with near-IR LEDs. A temperature sensor was mounted between the two LEDs, and the instrument was cooled to 10.6° C and then warmed with hot air to 33.9° C. Over this range the water column measured by the LED instrument increased nearly linearly with temperature from PW = 23.74 mm to 24.73 mm. Since the actual PW remained constant during the brief test, this yields an acceptably low temperature coefficient of 0.042 mm/°C for the instrument.

3.2. Instrument Calibration

[16] Although the measurement of PW by solar absorption has a long history, there are unexplained differences in instrument calibrations based solely on radiative transfer models. For example, a recent robust comparison of 4 solar radiometers yielded a spread of 8% in retrieved PW [*Schmid et al.*, 2001]. Models require that the extraterrestrial constants of the detectors be accurately measured. Since the Langley method can be confounded by changes in the water vapor column during the measurement session, various LED Sun photometers have been operated from aircraft at an altitude >11 km and from the summit of Mauna Kea, Hawaii, when the PW was < 1 mm. These measurements will be used to refine the calibrations of these instruments. Meanwhile the original LED Sun photometer has been calibrated by various empirical methods that are easily implemented in the field. Two methods are discussed here.

3.2.1. Dewpoint calibration

[17] The surface dew point is related to PW, and this formed the basis for the initial calibration of the LED Sun photometer. Because the vertical water vapor profile is not

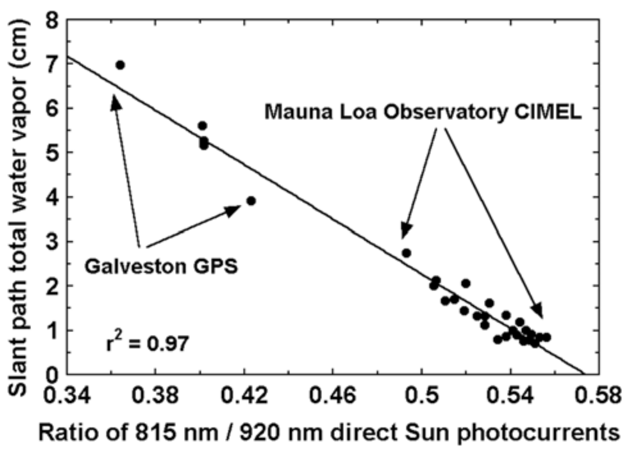

Figure 2. Transfer calibration of LED Sun photometer.

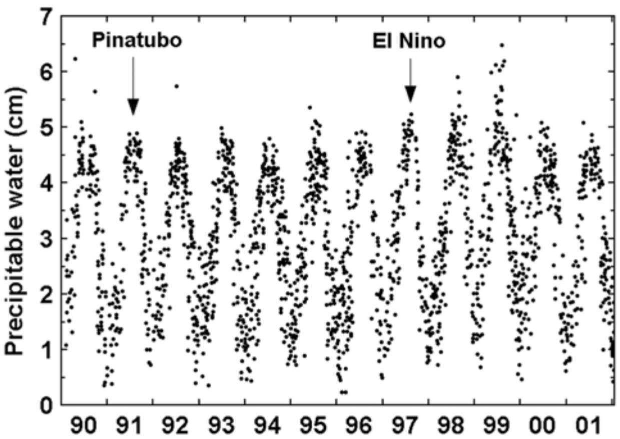

Figure 3. Column water vapor (PW) over Geronimo Creek Observatory from Feb 1990 to Jan 2002.

constant and varies with weather, however, this method should be used only for test purposes until a proper calibration can be achieved.

[18] *Reitan* [1963] derived from radiosonde soundings an algorithm for estimating column water vapor from the monthly mean values of the surface dew point for the continental U.S.:

$$\ln PW = -0.981 + 0.0341\,td \quad (1)$$

where PW is the column water vapor in cm and td is the dewpoint temperature in degrees F. Reitan reported that the standard error of this algorithm was generally within 10% of the mean. *Linacre* [1992] surveyed many empirical algorithms that estimate PW from the surface dew point and found that the Reitan algorithm has a higher correlation ($r^2 = 0.98$) than any of 16 models ($r^2 \$ 0.49 \# 0.96$). Over a wide range of dew points, the LED Sun photometer yielded an empirical regression algorithm for estimating column water vapor:

$$PW \cdot (((I_{815\ nm}/I_{920\ nm})/m) - 1.155)/0.286 \quad (2)$$

where m is the air mass and $I_{815\ nm}$ and $I_{920\ nm}$ are the direct Sun photocurrents provided by, respectively, AlGaAs and GaAs:Si LEDs with peak spectral responses at 815 nm and 920 nm.

3.2.2. Transfer calibration

[19] While the dew point algorithm clearly shows the annual cycle in PW, much better results have been obtained by a transfer calibration against a CIMEL Sun photometer at Mauna Loa Observatory (MLO), Hawaii (June 2001) and a GPS Meteorology Demonstration Network site at Galveston, Texas (August 2001). The CIMEL is calibrated using the modified Langley method [*Holben et al.*, 1998]. The Mauna Loa comparison covered a slant path water vapor column of 0.70 to 2.73 cm. The Galveston phase covered 3.91 to 6.98 cm. The linear regression of the total slant water vapor for these sites and the respective ratios of the photocurrents from the LEDs yields a correlation coefficient (r^2) of 0.97. The resulting empirical algorithm is,

$$PW = (17.627 + (-30.719) * I_{920\ nm}/I_{815\ nm})/m \quad (3)$$

Because a Cimel calibrated at MLO was used in the robust instrument comparison described by *Schmid et al.* [2001], it is reasonable to assume that the application of equation 3 to the LED Sun photometer yields PW within the 8% range found for the instruments in that comparison.

4. Experimental Results

[20] Figure 3 shows the column water vapor over Geronimo Creek Observatory given by applying equation 3 to observations at or near local solar noon from 4 Feb 1990 to 13 Jan 2002. Equation 3 can be reliably applied to the entire 12-year time series because of the very low drift of LEDs operated as detectors [*Mims*, 1999]. The data in Figure 3 follow the seasonal trends of temperature and dewpoint, and there is qualitative agreement in the winter minimums of PW and dew point. Reduced PW during the 2 summers following the Pinatubo eruption [of 1991] is associated with a 1–2 C° reduction in temperature at GCO. Reduced PW and temperature after Pinatubo was a global phenomenon, and the temperature reduction associated with the El Niño of 1991–3 was brief and much smaller than that caused by Pinatubo [*Soden et al.*, 2002]. Reduced PW did not accompany a Pinatubo-like temperature reduction during the El Niño of 1997, which was accompanied by large-scale changes in atmospheric circulation and precipitation.

4.1. Microtops II Comparison

[21] Equation 3 was tested in a comparison with PW retrievals from a Microtops II Sun photometer. This instrument, which is described more fully by *Morys et al.* [2001], measures total column ozone and water vapor with a mean difference of 5% from PW measured by a microwave radiometer [*DeFelice*, 2001]. The Microtops II water vapor algorithm is based on a radiative transfer model [*Morys et al.*, 2001]. The instruments were compared for 169 days in 2001 when measurements were made by both instruments at or near solar noon (Figure 4). This comparison yields a correlation of $r^2 = 0.94$, an excellent result in view of the independent calibration of the two instruments.

[22] The LED instrument has a very wide FOV of about 20°, while the FOV of Microtops II is about 2°. PW

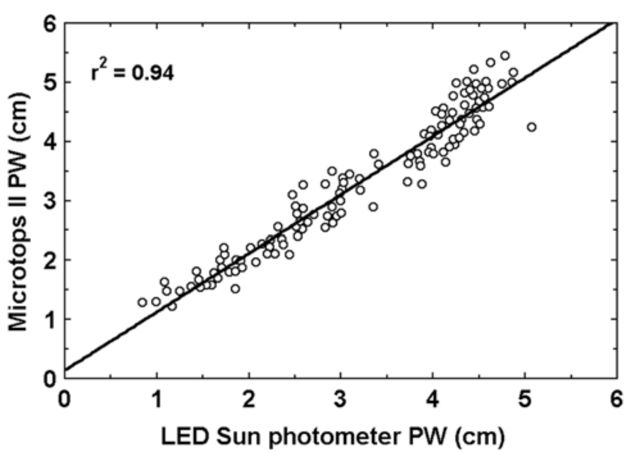

Figure 4. PW retrievals during 169 days in 2001 from LED instrument and Microtops II.

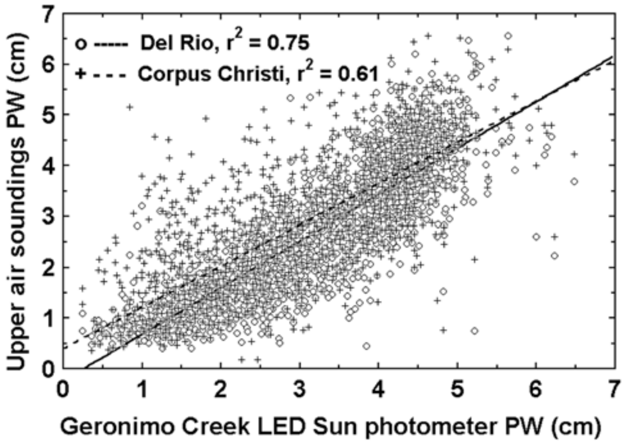

Figure 5. Scatter plot of PW measured from Feb 1990 to Jan 2002 by the LED Sun photometer and the upper air sounding sites closest to Geronimo Creek Observatory.

observations by both instruments on 26 clear days in 2001 were compared to look for FOV-induced error. The correlation of the measurements on clear days is $r^2 = 0.98$, which is slightly better than the correlation for all days, where $r^2 = 0.94$. It therefore appears that the wide FOV of the LED instrument contributes some error when clouds are near the Sun and when the size of the solar aureole is increased during turbid conditions. Subsequent LED Sun photometers have narrower FOVs (2–3°), but the long measurement history of the original instrument is worth preserving in spite of its wider FOV.

4.2. Upper Air Sounding Comparison

[23] Figure 5 compares the 12-year time series of PW measured by the original LED Sun photometer at GCO with that measured by the daily 1200 UTC upper air soundings from Del Rio and Corpus Christi, Texas. Del Rio (29.36 N, 100.91 W; 313 m msl) is 287 km west of GCO, and its air is generally drier. Corpus Christi (27.76N 97.50W; 13 m msl) is on the Gulf of Mexico 210 km SE of GCO, and its air is wetter. The comparison yields correlation coefficients (r^2) of 0.75 for Del Rio and 0.61 for Corpus Christi. These results are reasonable in light of the intermediate location of GCO between the two upper air sites and the fact the correlation of PW measured at Del Rio and Corpus Christi is 0.65.

5. Conclusion

[24] The original goal of this work [*Mims*, 1992] was to develop a family of inexpensive, accurate LED Sun photometers for the measurement of aerosol optical thickness (AOT) and total column water vapor. The success of the AOT instruments has been described elsewhere [*Mims*, 1999; *Brooks and Mims*, 2001]. The results presented here demonstrate that the water vapor goal has also been achieved. The LED Sun photometer provides results similar to those of a much more costly instrument that uses interference filters. It is also much more robust and is not subject to unpredictable drift. It is much more portable and less costly than other total water vapor instruments. It is reasonable to conclude that the LED method is appropriate for measuring both diurnal changes and long-term trends in PW.

[25] Future work will improve the PW algorithm with a more rigorous transfer calibration and inclusion of a temperature correction factor. A radiative transfer model will also be developed. PW sensing LEDs are being installed in a Yankee MFR-7 temperature-regulated shadowband radiometer for a long-term test at Geronimo Creek Observatory.

[26] **Acknowledgments.** Donald Heath measured the spectral response of the LEDs. Vicki R. Mercer compiled the National Weather Service PW data archived by the University of Wyoming. Brent Holben provided CIMEL data from MLO. NOAA's GPS Meteorology Demonstration Network provided GPS data. Analytical Spectral Devices, Inc. provided the solar spectrum in Figure 1. I very much appreciate suggestions by David R. Brooks and two anonymous reviewers that improved the paper. I also appreciate helpful discussions with John DeLuisi, John Barnes, Robert Roosen, James Slusser, Brent Holben and Sanjay Lamaye. Preparation of this paper was assisted by the GLOBE program.

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