A 30-Year Climatology (1990–2020) of Aerosol Optical Depth and Total Column Water Vapor and Ozone over Texas

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ABSTRACT: A 30-yr time series (4 February 1990–4 February 2020) of aerosol optical depth (AOD) of the atmosphere, total precipitable water (TPW), and total column ozone has been conducted in central Texas using simple, highly stable instruments. All three parameters in this ongoing measurement series exhibited robust annual cycles. They also responded to many atmospheric events, including the historic volcanic eruption of Mount Pinatubo (1991), a record El Niño (1998), an unprecedented biomass smoke event (1998), and La Niña that caused the driest drought in recorded Texas history (2011). Reduced air pollution caused mean AOD to decline from 0.175 to 0.14. The AOD trend measured for 30 years by a light-emitting diode (LED) sun photometer, the first of its kind, parallels the trend from 20 years of measurements by a modified Microtops II. While TPW responded to El Niño–Southern Oscillation conditions, TPW exhibited no trend over the 30 years. The TPW data compare favorably with 4.5 years of simultaneous measurements by a nearby NOAA GPS ($r^2 = 0.78$). The 30 years of ozone measurements compare favorably with those from a series of NASA ozone satellites ($r^2 = 0.78$). In 2016, 194 comparisons of Microtops II and world standard ozone instrument Dobson 83 at the Mauna Loa Observatory agreed within 1.9% ($r^2 = 0.81$). The paper concludes by observing that students and citizen scientists can collect scientifically useful atmospheric data with simple sun photometers that use one or more LEDs as spectrally selective photodiodes.

KEYWORDS: Aerosols; Hydrometeorology; Ozone; Water vapor; Instrumentation/sensors; Remote sensing

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On 4 February 1990, I began using a handheld, homemade light-emitting diode (LED) sun photometer every day at or near solar noon when the sun was not blocked by clouds to measure the atmosphere's aerosol optical depth (AOD) and total precipitable water (TPW). Two days later, I began measuring total column ozone with Total Ozone Portable Spectrometer (TOPS), also a handheld, homemade instrument. Microtops and Microtops II later took over ozone measurements and provided redundant AOD and TPW. These ongoing measurements were made at the Geronimo Creek Atmospheric Monitoring Station (GCAMS), a 0.54-ha field adjacent to the 125-yr-old farmhouse that serves as my rural office and laboratory in central Texas (29.608°N, 97.935°W), 57 km east-northeast of San Antonio.

The 30-yr time series includes 1991–2020, which is a World Meteorological Organization (WMO) climatological mean: “the most-recent 30-year period finishing in a year ending with 0.” On 4 February 2022, the AOD and TPW time series at GCAMS will match the longest such series in the United States, the 32-yr program of the Astrophysical Observatory of the Smithsonian Institution at Table Mountain, California (1926–57).

Aerosol optical depth

The LED sun photometer (Mims 1992) is based on the ability of most LEDs to detect light at wavelengths at and slightly below their light emission wavelength. I discovered this property of LEDs in 1972 and disclosed it in my book *Light Emitting Diodes* (1973). LEDs are inexpensive and sturdy, and have a lifetime measured in decades. Conventional sun photometers employ silicon photodiodes behind expensive (>\$50), fragile optical filters with an unpredictable life.

AOD methodology. Figure 1 shows the AOD measured by the LED photometer at or near solar noon on 5,422 days from 4 February 1990 to 4 February 2020 when the sun was not obscured by clouds. The 30-yr linear regression line superimposed over the data in Fig. 1 indicates a reduction in AOD from 0.175 to 0.14.

The AOD is measured by an 880-nm GaAlAs LED (Exar XC88FD) with a peak detection wavelength of 824.6 nm. (The equivalent AOD at 500 nm is approximately 3 times higher.) This instrument has been calibrated by the Langley method (Shaw 1983) during annual visits to Hawaii's high-altitude (3,400 m) Mauna Loa Observatory (MLO) from 1992 to 2018. The extraterrestrial constant used in the standard AOD equation is the average of the three best

Fig. 1. AOD measured by the LED sun photometer declined 0.035 from 1990 to 2020. High data points denote major smoke and dust events.

Langley's during 2012 and 2015. The University of the Nations, Global Learning and Observations to Benefit the Environment (GLOBE), Rolex, and Colorado State University provided some support for many of the 25 annual MLO calibration sessions.

The time series began 17 months before the historic volcanic eruption of Mount Pinatubo on 15 June 1991, and the following 2 years exhibited some of the highest winter AODs during the 30 years. The major AOD spikes in May 1998 (Fig. 1) were caused by biomass smoke from agriculture fires in Mexico and Central America that was so dense that health emergencies were declared in Mexico and Texas. Beginning in 1999, the Navy Aerosol Analysis and Prediction System (NAAPS) model explains many other aerosol spikes in Fig. 1. For example, the major spikes in May 2003 were caused by biomass smoke from Mexico. Soon thereafter, an unusually thick blanket of sulfate pollution arrived. The NAAPS model also showed Saharan dust over much of Texas during many summer days.

The long-term stability of the 880-nm LED in the original photometer was confirmed by a comparison with an identical LED installed in TX31, a Yankee Shadowband Radiometer donated by Rio Nogales Power Project and installed atop the roof of the science building at Texas Lutheran University 6.2 km west of GCAMS in March 2004. Yankee measured the spectral response of the LEDs in TX31, which is adjacent to two shadowband radiometers that form 1 of the 36 monitoring sites of the USDA UV-B Monitoring Climatological and Research Network Program managed by Colorado State University. (I am the site manager.) A comparison of the raw signal from the 880-nm LED in TX31 (heated to a constant 40°C) and its identical companion in the LED sun photometer within 3 min of one another at or near solar noon on 789 clear days from 17 March 2004 to 30 May 2020 yielded an r^2 of 0.92. (Data from 20 August 2009 to 31 December 2010 were not used due to dust that accumulated on the LED after the zipper on its enclosure pouch failed.)

Figure 2 is a 20-yr comparison of AOD measured by the LED sun photometer within minutes of AOD measured by a modified Microtops II from 1999 to 2020. The modified Microtops II measures AOD with an unfiltered 880-nm AlGaAs photodiode (Clairex CLD340). The 20-yr comparison yielded nearly parallel regression lines that indicate both detectors possess excellent long-term agreement with one another. The LED sun photometer measured a decline in AOD of -0.018 and the modified Microtops II measured a decline of -0.017 . The displacement of the regression lines is due to the lower spectral response (824.6 nm) of the 880-nm sun photometer LED.

The scatterplot of the 20-yr time series in Fig. 3 has a correlation coefficient of 0.67, which would likely have been higher if the field of view of the original instrument (20°) were reduced to that of the Microtops II (2.5°). The slope of the regression line is influenced by the 55.4-nm difference in the spectral response of the two sensors.

Fig. 2. Trends in AOD measured by LED sun photometer at 824 nm (blue) and modified Microtops II with 880-nm filterless photodiode (red).

To determine if AOD is declining elsewhere, I contacted Brent Holben, who heads AERONET, a global network of sun photometers maintained at NASA's Goddard Space Flight Center (GSFC) (Holben et al. 1998). Holben suggested I review AOD data from a Cimel robotic sun photometer that entered service on 6 April 1994 at the CART AERONET site in Oklahoma (36.607°N, 97.486°W) 778 km north of GCAMS. This site includes 17.5 years of data, which is among the longest in AERONET. The data begin on 6 April 1994 with an AOD of 0.060 and end 31 April 2018 with an AOD of 0.0446.

The decline in AOD at both GCAMS and the CART site is likely due to cleaner air over much of the United States. According to *Monthly Energy* (U.S. Energy Information Administration, Table 6.2, May 2021), the consumption of coal for electricity production in the United States declined from 1,045,141 thousand short tons in 2007 to 436,524 thousand short tons in 2020. The U.S. EPA measured a 90% decline in SO₂ and a 62% decline in NO₂ at 104 sites across the United States from 1990 to 2019, which closely matches the length of the climatology reported here. The EPA has provided a highly detailed report on decreasing trends of various atmospheric contaminants (Jenkins 2020). For example, a trend map (their Fig. 2-15) indicates “significant reduction” in the average annual trend of PM_{2.5} concentrations from 2000 to 2017 at measurement sites near GCAMS and CART.

Declines in AOD have been reported elsewhere. A decline of 1.1% yr⁻¹ from 2000 to 2009 was measured by 20 AERONET stations across Europe (Turnock et al. 2015). Samset et al. (2018) modeled the increase in temperature across Europe that followed enhanced atmospheric transmission resulting from reduced power plant smog. Glantz et al. (2019) used MODIS and AERONET measurements across northern Europe that also confirm significant reductions in AOD. They “plan to estimate if the decrease in AOT here has contributed to the ‘extra’ warming that is observed over northern Europe.”

Total precipitable water

Figure 4 shows the TPW measured by the LED sun photometer at or near solar noon on 5,645 days from 1990 to 2020. The enhanced TPW during the historic 1997/98 El Niño is obvious, as is the low TPW during the historic 2010/11 Texas drought that accompanied La Niña.

TPW methodology. TPW was derived from the ratio of signals from a water vapor–sensitive 940-nm LED and the 880-nm LED. The 940-nm LED is a GaAs:Si diode (General Electric SSL-55C) with peak detection at 939.7 nm. The initial calibration was based on an empirical comparison of TPW measured by a NOAA GPS receiver at Galveston, Texas, in August 2001 and an AERONET Cimel robotic sun photometer at MLO in June 2001 (Mims 2002). A linear regression of the TPW measured at these two sites and the respective ratios of the photocurrents from the LED sun photometer yielded a correlation coefficient (r^2) of 0.97.

NOAA installed a GPS water vapor receiver (TXSG) 6.4 km west of GCAMS from 7 December 2011 to 29 May 2016 for a comparison with TPW measured by the LED sun photometer.

Fig. 3. Scatterplot of AOD measured by LED sun photometer at 824 nm and modified Microtops II at 880 nm (1999–2020). The offset is due to the increased AOD at the lower wavelength.

Fig. 4. TPW measured by the LED sun photometer (blue) exhibited no trend from 1990 to 2020. The photometer was compared with TPW measured by NOAA's TXSG GPS from 2012 to 2016 (red).

The 2001 GPS-derived calibration was tested against 449 daily measurements of TPW within 30-min windows at or near solar noon by the TXSG GPS. The average TPW measured by the LED photometer was 2.66 cm and that of the GPS 2.65 cm. Figure 5 is a scatterplot of this comparison ($r^2 = 0.80$).

There is no trend in the 30-yr TPW in Fig. 4. This was unexpected, for the maximum daily temperature at the closest NWS station (15.6 km northwest) increased 1.85°C from 1996 to 2020, and an increase of 1°C should allow a 7% increase in the concentration of water vapor (Myhre et al. 2013). Therefore, measurements of TPW by the Cimel robotic sun photometer at the CART AERONET site were reviewed. The intercept of the regression line through the data on 6 April 1994 was 1.9 cm, and on May 2018 the TPW had declined to 1.7 cm. This 0.2-cm decline occurred during an accompanying decline in temperature of -1.7°C , which was more of an expected finding that what occurred at GCAMS.

These findings illustrate the uncertainty of applying local data to the global system (Ho et al. 2018), especially in view of studies that also found long-term stability of TPW elsewhere, including the 32-yr time series by the Smithsonian at Table Mountain (Roosen et al. 1977; Hoyt 1979). More recently, TPW across four major regions of China declined an average of $-2.64 \text{ mm decade}^{-1}$ from 1995 to 2012 (Wang et al. 2017). A color-coded map of Global Ozone Monitoring Experiment (GOME) satellite measurements of TPW (Fig. 10 in Wagner et al. 2006) shows a slight decline in TPW over much of the central United States from 1996 to 2002. NASA's Water Vapor Project (NVAP-M) found no global trend in TPW from 1988 to 2010 (Vonder Haar et al. 2012). Chen and Liu (2016), however, found increases in TPW over global land and water.

TOTAL OZONE. Figure 6 is a time series of total ozone measured at or near solar noon during 6,486 days from 1990 to 2020 by TOPS (1990–94), Microtops (1995–97), and Microtops II (1997–2020). Ozone measured by the primary satellite instruments is also plotted in Fig. 6, including *Nimbus-7* Total Ozone

Fig. 5. Scatterplot of TPW measured by LED sun photometer and TXSG GPS (7 Dec 2011–29 May 2016).

Fig. 6. Total column ozone from 1990 to 2020. Blue: TOPS (1990–95), Microtops (1995–97), and Microtops II (1997–2020). Red: *Nimbus-7* TOMS (1990–93), Earth probe TOMS (1996–2003), OMI (2004–12), and OMPS (2012–20).

Mapping Spectrometer (TOMS) (1990–93), Earth probe TOMS (1996–2003), Ozone Monitoring Instrument (OMI) TOMS (2004–11) and Ozone Mapping and Profiler Suite (OMPS) (2012–20). The 1993–96 gap occurred when satellite data were unavailable or unreliable. Figure 7 is a scatterplot of all the data in Fig. 6 ($r^2 = 0.78$). Both the correlation and the slope of the regression line are improved after 1 September 1996 when Earth probe TOMS entered service ($r^2 = 0.82$) and after 1 October 2004 when OMI entered service ($r^2 = 0.86$).

Ozone methodology. TOPS was a homemade, handheld instrument based on a UV radiometer that I described how to make in *Scientific American's* “The Amateur Scientist” in 1990. TOPS measured ozone with a pair of radiometers fitted with UV-sensitive, solar blind GaP photodiodes and high quality 300- and 305-nm filters donated by Barr Associates. In 1991, TOPS and world secondary ozone standard (Dobson 65) at Boulder, Colorado, agreed within a few percent.

Regular calibration trips to Boulder were impractical, but NASA's TOMS aboard *Nimbus-7* was in a sun-synchronous orbit that placed it near GCAMS every day at solar noon. Therefore, the radiative transfer algorithm I was using was replaced with an empirical calibration based on a 3-month comparison of TOPS and TOMS ozone.

TOPS and TOMS agreed within 0.9% during 1991. However, from November 1991 to October 1992, average TOMS ozone was 3.4% higher than TOPS. While I was at MLO in August 1992, TOMS ozone was 1.7% higher than that measured by the world standard ozone instrument (Dobson 83). I reported this to the GSFC ozone team, and on 3 December 1992, they affirmed an aerosol error of up to 2% in TOMS data. The TOMS error supported the need for continuing the network of ground-based Dobson and Brewer ozone instruments. Therefore, this finding was submitted to *Nature*, which published it in 1993.

Fig. 7. Scatterplot of total ozone measured at GCAMS with handled instruments and by ozone satellites during overpasses (1990–2020).

Citizen science

Unknown citizen scientists with no professional training invented wheels, water pumps, sun dials, astrolabes, needles, paper, and fireworks. Some even managed to hybridize maize that feeds billions of people. While Michael Faraday had no formal training, he is widely considered one of history's most gifted amateur scientists. This ongoing 30-yr study demonstrates that today's citizen scientists and students, with little or no support and no academic training (my sole degree is a B.A. in government and English from Texas A&M University), can perform creditable science, a theme I addressed in an invited essay in *Science* (<https://science.sciencemag.org/content/284/5411/55>).

This was the goal of the GLOBE program's haze network for students, which I described in *BAMS* in 1999 ([https://doi.org/10.1175/1520-0477\(1999\)080<1421:AIHMF>2.0.CO;2](https://doi.org/10.1175/1520-0477(1999)080<1421:AIHMF>2.0.CO;2)). David R. Brooks and I developed LED sun photometers and taught the methodology and mathematics of measuring AOD and TPW

through GLOBE. Unfortunately, very few schools participated, mainly because teachers lacked the necessary time, and our protocols were not particularly simple. This 30-yr report will be sent to the National Science Teachers Association and GLOBE in an effort to cultivate renewed interest in teaching students how AOD and TPW can be measured with simple LED sun photometers and why those measurements are important. Based on the sale of 12,000 four-channel LED Sun and Sky Stations that I designed for RadioShack, the interest is clearly there.

Finally, I am hopeful that more university atmospheric science departments will supplement their courses with hands-on projects using simple instruments that measure haze, the water vapor layer, total ozone, and other important parameters. Perhaps TV meteorologists can inform their viewers about simple, handheld instruments with live demonstrations during their telecasts.

Forrest Mims on the 25th anniversary of the atmospheric measurements he performs every day at solar noon when the sun is not blocked by clouds. (Photographer: Minnie Chavez Mims)

The TOPS project received a 1993 Rolex Award, which enabled engineer Scott Hagerup to be retained to design Microtops, a microprocessor-controlled version of TOPS. Microtops had three UV channels for ozone measurements (298, 303, and 310 nm) and a pair of near-IR channels for AOD and TPW (940 and 1,000 nm). A Microtops was compared for 60 days during June–July 1995 with an EPA Brewer spectrophotometer shipped to GCAMS. The average daily ozone measurements differed by 1.44%.

A GSFC study (Labow et al. 1996) and comparisons of Microtops with Dobson 83 and Brewers 009 and 119 at MLO established that Microtops was measuring total ozone within 1% of much larger and far more expensive Dobson and Brewer spectrophotometers. The Solar Light Company acquired rights to Microtops in 1994, and Marian Morys designed Microtops II, which stores and displays up to 800 measurements of ozone, TPW, and AOD (Morys et al. 2001). (I receive a royalty on sales of Microtops II.) Today Microtops II is used by atmospheric scientists around the world.

The latest comparison of Microtops II with Dobson 83 and Brewers 009 and 119 at MLO occurred from 11 to 21 July 2016 while I was there 64 days to calibrate Dobson 83 for NOAA. The average difference in total ozone with Dobson 83 during 194 comparisons was 1.9% ($r^2 = 0.81$), which meets NOAA requirements for Dobson and Brewer instruments and is remarkable for an instrument that was calibrated to within 1% of Dobson 83 at MLO in 1997. The original calibration has never been updated, for a principal goal of this 30-yr ongoing study is to determine how long handheld instruments can be successfully employed by users without access to calibration standards (see sidebar).

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Data availability statement. All 30 years of data (1990–2020) from which the figures in this report were produced are available in an Excel file at <https://zenodo.org/record/4969147/files/Mims%2030-Years%20AOD%2C%20TPW%20%26%20total%20ozone%20over%20Texas.xlsx?download=1>. The AERONET CART site data (1994–2018) are available at https://aeronet.gsfc.nasa.gov/cgi-bin/data_display_aod_v3?site=Cart_Site&nachal=2&level=1.

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