

An International Haze-Monitoring Network for Students

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ABSTRACT

The Global Learning and Observations to Benefit the Environment (GLOBE) Program is an international network of schools in 71 countries that monitors up to 20 environmental parameters. Recently GLOBE added a haze-monitoring program to its measurement protocols. This network has the potential of providing important data about changes in the aerosol optical depth of the atmosphere caused by weather fronts, industrial and automobile pollution, and smoke from forest and brush fires and volcanic eruptions. Initially, monitoring will be conducted with an inexpensive, single-channel (520 nm) sun photometer. Unlike conventional sun photometers that use interference filters that are subject to unpredictable and rapid degradation, the GLOBE instrument uses a common light-emitting diode (LED) as a spectrally selective detector. Annual calibrations of two LED sun photometers at Mauna Loa Observatory since 1992 show that these instruments have insignificant degradation when compared to filter sun photometers. Some 175 prototype versions of a kit LED sun photometer have been assembled and tested by students from 16 countries at the University of the Nations and by more than 130 high school teachers in various pilot studies. These studies have demonstrated that even inexperienced students and teachers can quickly assemble a sun photometer from a kit of parts and perform a reliable Langley calibration. The pilot studies have also demonstrated that sun photometry provides a convenient means for allowing students to perform hands-on science while they learn about various topics in history, electronics, algebra, statistics, graphing, and meteorology.

1. Introduction

The transparency of the atmosphere is modulated by aerosols that absorb and scatter sunlight. Natural and anthropogenic processes can increase the abundance of aerosols and appreciably reduce the atmosphere's transparency by increasing its optical depth. Optical depth is a dimensionless measure of the attenuation experienced by a direct beam of sunlight during its passage through the atmosphere. Increased optical depth reduces visibility and photosynthetic radiation and alters the radiation balance. While optical depth is a key variable in climate models, there are few long-term measurements of optical depth.

Optical depth can be measured with a sun photometer, an instrument that measures the intensity of a direct beam of sunlight. A new kind of inexpensive, hand-held sun photometer has been developed that exhibits much better long-term stability than instruments that use interference filters (Mims 1992, 1993a, 1995). More than 100 prototype versions of this instrument (Fig. 1) have been assembled and tested by students and teachers in various pilot studies. Recently, the technology behind this new instrument was selected by the Global Learning and Observations to Benefit the Environment (GLOBE) Program for use in haze monitoring by an international network of students. The goal of the proposed network is to provide optical depth data at local solar noon for hundreds of sites in dozens of countries.

This paper discusses the educational and scientific goals of the proposed GLOBE sun photometer network. Also discussed are results of pilot studies with the new sun photometer and the reliability of scientific data collected by students. Professional meteorologists

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rologists are invited to assist public, private, and home schools in becoming part of GLOBE's haze-monitoring network.

2. Sun photometry 101

The proposed GLOBE sun photometer haze network is as much an educational program as it is an observational science project. Students will learn why sun photometry measurements are important for satellite ground truth studies and climate models. They will learn how to make sun photometer observations, how to analyze data, and how to compare their results with those from other students and professional instruments. They will also learn how to recognize thin clouds, cloud haze, and diffuse contrails that can interfere with their observations. These learning goals are interdisciplinary, as they cover such topics as meteorology, atmospheric chemistry, astronomy, algebra, statistics, computerized spreadsheets, electronics, and history. The following sections summarize some of the key topics students will learn about.

a. The roots of sun photometry

Nearly a century ago the Astrophysical Observatory (APO) of the Smithsonian Institution began a

long-term program to measure the mean intensity of solar radiation at the top of Earth's atmosphere (the solar constant I_0) (Abbot and Fowle 1908). This research took APO observers and scientists to some of the most remote and desolate places on Earth and made for faraway adventure stories in *National Geographic* magazine (Abbot 1926a,b). The APO showed that relatively simple instruments, at least by today's standards, can measure direct sunlight at Earth's surface (I) with sufficient accuracy to quantify reductions in the transparency of the atmosphere caused by aerosols, ozone, and water vapor.

The APO instruments were the predecessors of today's sun photometers. During the 1960s, Frederick Volz developed a simple hand-held sun photometer (Volz 1959). The Volz instrument served as the model for contemporary sun photometers (Shaw 1983), including the student instrument described here.

b. Atmospheric transmission

The presentation of the history of the APO is a convenient place to introduce students to some basic sun photometry vocabulary and definitions. The APO defined the transmission of a direct beam of sunlight through the atmosphere (T) as the ratio I/I_0 and reported its measurements in terms of the percent transmission ($T \times 100$). Astronomers who monitor variable stars are also interested in the extinction of the light from their targets. They prefer to express transmission (T) in terms of logarithmic extinction or aerosol optical depth ($AOD = -\ln T$), also known as aerosol optical thickness (AOT; $AOD = AOT$). Extinction has become the preferred method for expressing optical depth within the scientific community. But since transmission is more intuitively obvious than extinction, both percent transmission and the optical depth will be used in the proposed student network.

c. The Langley calibration method

The measurement of optical depth requires a knowledge of I_0 at the spectral response band(s) of the sun photometer. The Langley method perfected by the APO early in this century remains the most common method for determining I_0 . All students in the network will learn how a Langley calibration is performed, and selected students will actually perform such calibrations on weekends and holidays.

A Langley calibration is performed by using a sun photometer to measure the intensity of a narrow spectrum of direct sunlight as the sun rises (or falls) over the course of a clear morning (or afternoon). The thick-

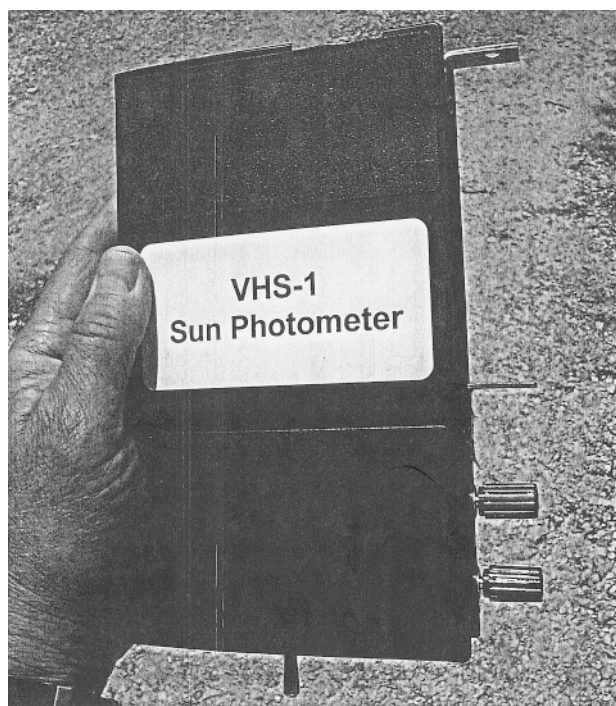


FIG. 1. The inexpensive VHS-1 sun photometer uses a light-emitting diode as a spectrally selective detector.

ness of the atmosphere or air mass (m) between the instrument and the sun when each measurement is made relative to the thickness of the zenith sky ($m = 1$) is then plotted against the natural log of each measurement. If the atmosphere and its constituents have remained relatively stable over the course of the measurement period, the points will fall along a straight line, as shown in Fig. 2. Extrapolation of this line to the intercept ($m = 0$) yields I_o . Careful measurements with a stable instrument on clear days yield values of I_o that are repeatable to within $< 1\%$. The sun photometer training materials for students include a typical Langley plot. Also included will be a pictorial representation of the air mass for different sun angles.

d. Computing aerosol optical depth

It is important for students to understand how AOD is calculated from the raw voltage measured by their instruments. Full details will be given in a protocol now being developed. Briefly, knowing I_o , subtracting losses caused by Rayleigh scattering, and assuming near-monochromatic light, the optical depth caused by aerosols is given by

$$\text{AOD} = [\ln I_o - \ln I - (\tau_R \tau_o m p/p_o)] m^{-1}, \quad (1)$$

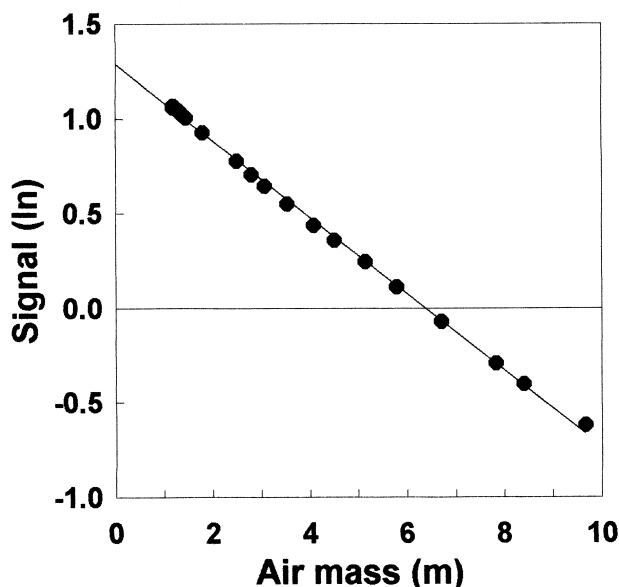


FIG. 2. Clear-sky Langley calibration plot for a prototype student LED sun photometer. The correlation coefficient (r^2) of the least squares linear regression line through the points is 0.999. Although measurements over an airmass (m) range of about 2–6 are normally used in such plots, measurements outside this range are included here to demonstrate that very linear Langley plots can be obtained even when the interference filter of the traditional sun photometer is replaced by an LED.

where I_o is the extraterrestrial constant at the mean Earth–sun distance, I is the measured solar radiation corrected to the mean Earth–sun distance, τ_R is the AOD ($m = 1$) due to Rayleigh scattering at the measured wavelength, τ_o is the AOD ($m = 1$) due to ozone absorption at the measured wavelength, m is the optical air mass corrected for the earth’s curvature, and p/p_o is the ratio of the measured pressure to the pressure at sea level.

Some students and nonspecialists might at first be somewhat intimidated by Eq. (1). But derivation of Eq. (1) is straightforward, and GLOBE curricula will discuss the equation in simple language. This approach has been quite successful in tests with humanities majors from 16 countries at the University of the Nations. The curricula will be supplemented by a user-friendly computer spreadsheet that computes AOD after the student enters the raw voltage from the sun photometer, the coordinates of the observation site, and the time and date of the observation. A preliminary version of the spreadsheet has been successfully used by high school and college students.

3. A student sun photometer

GLOBE’s decision to add haze monitoring to its 20 existing student monitoring protocols was based in large part on the development of a new kind of very inexpensive, hand-held sun photometer that provides a longer operating lifetime than instruments that use expensive interference filters. Conventional sun photometers are either hand-held or mounted on automatic sun trackers. Most use interference filters and silicon photodiodes that detect two or more discrete spectral bands of sunlight. Their cost ranges from a few thousand dollars to about \$25,000.

The most critical and expensive components of these sun photometers are the interference filters. Quality filters cost more than \$100 in quantity. Their major limitation is gradual change in transmission. As degradation of an interference filter is unpredictable, the spectral transmission of filters must be periodically checked or periodic Langley tests must be performed with the complete instrument.

The spectral bandpass of the interference filters used in most sun photometers is typically 10 nm full width at half maximum (FWHM). If a wider bandpass is acceptable, there is a very inexpensive and more reliable alternative to using interference filters in sun photometers. Light-emitting diodes (LEDs) emit

quasi-monochromatic visible or near-infrared radiation having a spectral width ranging from about 20 to 150 nm. A little-known feature of LEDs is that they can also function as quasi-monochromatic photodetectors (Mims 1973) with a spectral bandpass of about 16 to 100 nm (FWHM).

a. The LED sun photometer

LED sun photometers are inexpensive and can be made very small and rugged. They provide highly repeatable Langley calibrations. And the first reports describing the use of LEDs for sun photometry (Mims 1992, 1993a) have been independently validated (Acharya et al. 1995). Therefore, the LED sun photometer is being carefully evaluated for use in a proposed international student haze-monitoring network.

LED sun photometers have been used alongside filter sun photometers during a variety of research expeditions. For example, two kinds of LED sun photometers, one of which is microprocessor controlled, have been used to measure the optical depth of severe air pollution during burning season in Brazil (F. Mims 1995, unpublished report; Mims and White 1997) and at major forest fires in the western United States (F. Mims 1996, unpublished report). A microprocessor-controlled

five-channel LED sun photometer was used to measure the attenuation of sunlight caused by aircraft contrails over Alaska and Switzerland (Mims and Travis 1997) and by juniper pollen in Texas (Mims 1998a). LED sun photometers are now being tested during long-term, ongoing pilot studies, two of which are described next.

b. LED sun photometer AOD time series

The first sun photometer with LEDs as spectrally selective photodetectors was assembled in 1990 (Mims 1993a). Figure 3 shows the AOD (820 nm) measured with this instrument near Seguin in south Texas (29.6°N, 97.9°W) at solar noon since February 1990. Besides recording the seasonal aerosol cycle, this 9-yr time series shows increased AOD caused by various natural and anthropogenic aerosol events, including a major Sahara dust event (May 1991), the eruption of Mount Pinatubo (June 1991), and significant smoke from Mexico and Central America (May 1998).

c. LED sun photometer long-term stability

An ongoing study has shown that LED sun photometers are considerably more stable over time than instruments that use conventional interference filters.

One such instrument, which uses six LEDs mounted on a single substrate (Mims 1993a), has been calibrated using the Langley method at Mauna Loa Observatory (MLO), Hawaii, each year since 1992. These calibrations have shown that the I_0 of the visible channels of this instrument has remained within $\pm 1.9\%$ of their initial values. Much better results have been obtained from a microprocessor-controlled sun photometer with five separate LEDs and a better means of alignment. Annual Langley calibrations of this instrument since 1996 show negligible changes in the calibration of all channels. The coefficient of variations [I_0 (std dev)/ I_0 (mean)] for the 376-, 520-, and 680-nm channels are, respectively, 0.0027, 0.0004, and 0.0011. The calibration of some filter instruments varies considerably more. For example, as shown in Fig. 4, the I_0 of a filter sun photometer used during a research study from 1986 to 1990 declined to only 12.7% of its initial value (Pinker 1994).

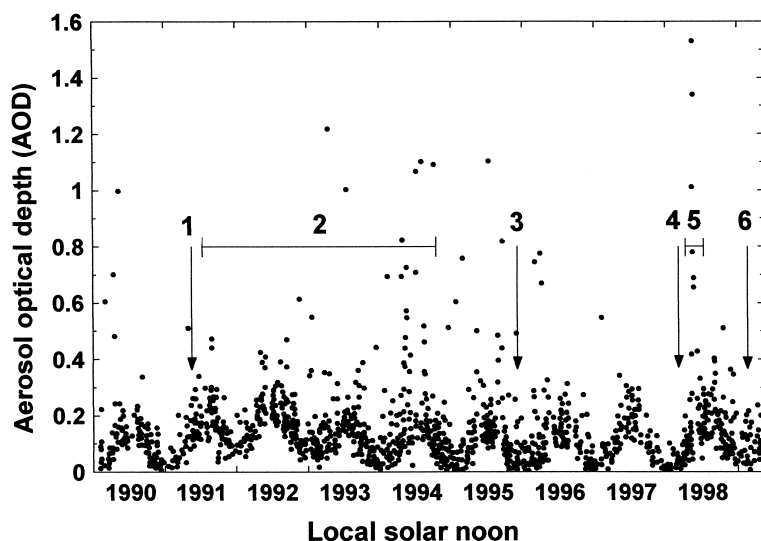


FIG. 3. Time series of 1738 AOD observations at 820 nm made by the author using an LED sun photometer in south Texas (29.6°N, 97.9°W) at solar noon from 4 Feb 1990 to 28 Apr 1999. The plot shows the annual cycle and the effect of numerous aerosol events, including Sahara dust in May 1991 (1), increased AOD caused by the eruption of Mount Pinatubo on 15 Jun 1991 (2), poleward migration of optically dense stratospheric aerosol clouds of tropical origin (3), Asian dust on 28–29 April 1998 (4), significant smoke from fires in Mexico in May 1998 (5), and smoke from regional burning of debris from the record floods in south Texas of 17–18 Oct 1998 (6).

4. Student sun photometer pilot studies

In 1996, the Technology Education Resource Center (TERC), with support from the National Science Foundation, sponsored the development of a single-channel LED sun photometer called the Visual Haze Sensor (VHS-1). This simple instrument, which is shown in Fig. 1, requires only three electronic components (a resistor, operational amplifier, and LED), all of which are installed on a solderless breadboard as shown in Fig. 5. The breadboard and the associated hardware (switch, battery clips, and sun alignment brackets) can be assembled in a few hours, without soldering, inside a VHS videocassette case (Mims 1996). The total cost of components, which are available from neighborhood electronics and hardware stores, is about \$21. An inexpensive digital voltmeter serves as a readout device.

Following initial development and tests of two prototype VHS-1s, three additional instruments were assembled during a pilot study at the Kailua-Kona, Hawaii, campus of the University of the Nations, an international Christian institution. Students C. Sigamoney and B. Maxwell, and Dean of Science J. Kuhne, assembled the instruments based only on a circuit diagram and pictorial view scheduled to be included in a then-unpublished instruction manual. No kit of components or other information was provided, and all three of the assembled instruments worked properly. Figure 6 shows students with their instruments at Mauna Loa observatory. Also shown is Dr. Kuhne. A comparison of simultaneous, unsupervised Langley tests conducted by Sigamoney and Maxwell near sea level on a clear afternoon yielded a correlation (r^2) of 0.998 (Fig. 7).

The success of the initial pilot study at the University of the Nations led to the inclusion of the VHS-1 in the science curriculum required for the university's humanities majors. Some 75 students from 16 countries have since built VHS-1s, many of which were operated by students during field trips to the Mauna Loa Observatory (Fig. 8). During the May

1998 field trip, the MLO Web site showed near-real-time images (updated every 10 min) of students measuring the AOD at MLO.

Some inquisitive students at the University of the Nations have used the VHS-1 for applications other than sun photometry. Figure 9, for example, shows student Mia Spengler during a science project poster session as she explains how the VHS-1 can be used to measure the transmission of various leaves to sunlight at 520 nm.

More than 100 secondary school science teachers have assembled VHS-1s at three workshops in Texas and Massachusetts. These trials have demonstrated

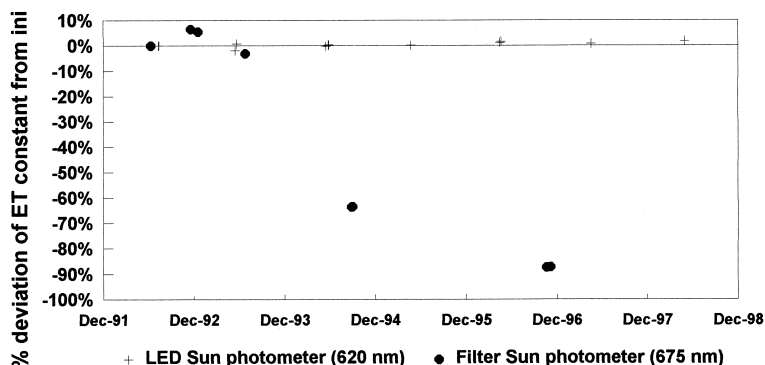


FIG. 4. Comparison of the significant I_0 (extraterrestrial constant calibration) drift of a filter sun photometer (Pinker et al. 1994) with that of an LED sun photometer (F. Mims 1999, unpublished manuscripts). The measurement dates of the filter instrument have been advanced six years (1986 becomes 1992).

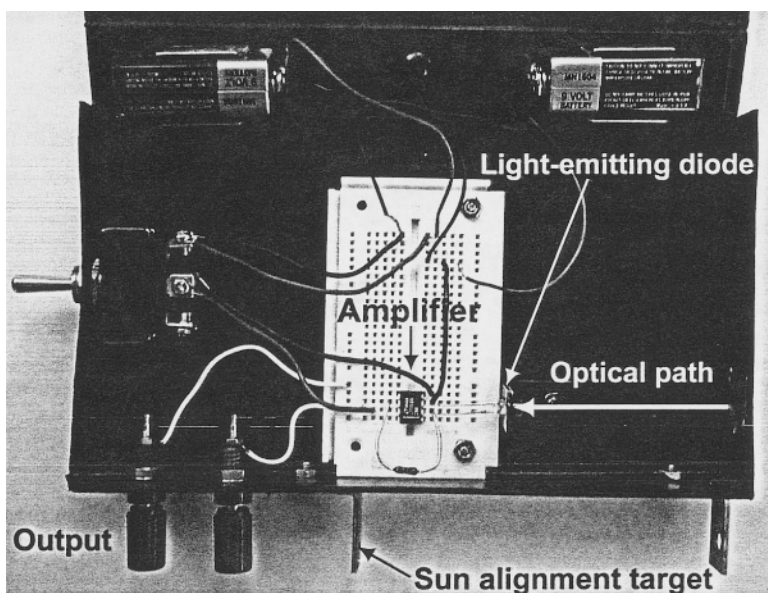


FIG. 5. Interior view of a VHS-1 sun photometer showing the optical path of sunlight, light-emitting diode that serves as a photodiode, circuit breadboard, and sun alignment brackets.



FIG. 6. Dr. J. Kuhne and students C. Sigamoney and B. Maxwell (left to right) of the University of the Nations at Kailua-Kona, HI, were the first to assemble and calibrate postprototype VHS-1 student LED sun photometers. The instruments held by the students provided the data in Fig. 7.

that nontechnical students and teachers can quickly learn to assemble, operate, and calibrate the VHS-1. One science teacher with no prior electronics training assembled the instrument in only 35 minutes. In all of these classes and workshops, students and teachers assembled the VHS-1 from a kit of parts. This exercise is especially helpful for students and teachers who have no prior experience assembling electronic circuits. Besides demystifying the simple circuitry of the instrument and teaching some fundamentals about operational amplifiers and photodetectors, the exercise gives participants a sense of accomplishment. These sessions and various short courses on sun photometry at the University of the Nations have demonstrated that sun photometry provides a convenient means for allowing students to perform hands-on science while they learn about various topics in history, electronics, algebra, statistics, graphing, and meteorology.

Assembly details for the VHS-1 were published in "The Amateur Scientist" column in *Scientific American* (Carlson 1997). The Concord Consortium supports the VHS-1 with an interactive site on the World Wide Web (<http://concord.org/haze/>), and the *Scientific American* article is also available on the web (<http://www.scientificamerican.com/0597issue/0597amsci.html>). Instructions for assembling a basic LED sun photometer were also published in an inexpensive book (Mims 1995) and a comic book (Mims

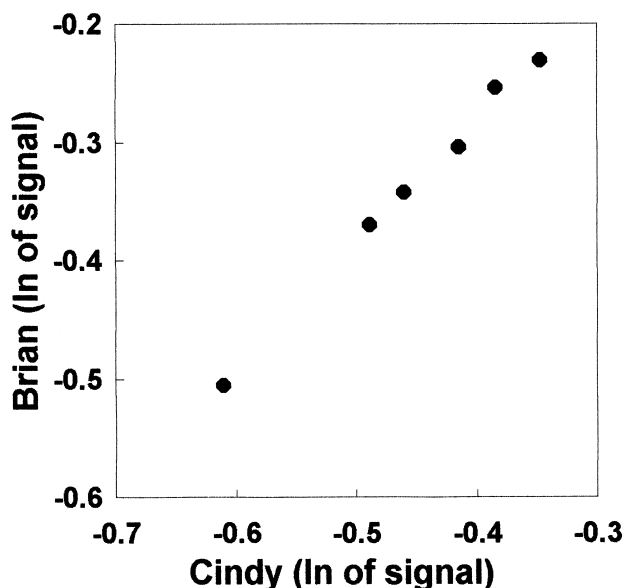


FIG. 7. The x-y scattergraph comparing simultaneous Langley calibrations of the first student-assembled VHS-1 LED sun photometers. The correlation (r^2) is 0.998. The instruments were assembled and calibrated by University of the Nations students Cindy Sigamoney and Brian Maxwell.

1993b) that was distributed by a chain of some 7500 electronics stores. These widely available resources have led to the construction of similar sun photometers by additional students and even professional scientists. For example, Darold Ward and his colleagues at the U.S. Forest Service assembled 20 two-channel versions of the VHS-1 sun photometer. African science teachers used these instruments for two months during the 1997 burning season in Zambia in what was possibly the largest temporary sun photometer network ever attempted (ZIBBEE Field Campaign Summary 1997).

An improved version of the prototype instrument is now being designed for the GLOBE program with the expectation that it can be used to establish a geographically broad network of reliable ground-based sun photometers. Besides providing climate modelers with data about seasonal aerosol variability, the proposed GLOBE sun photometer network will provide new information about the occurrence, magnitude, and transport of natural and anthropogenic aerosol events, including desert dust storms, volcanic eruptions, and forest fires. Student participants will learn how to use and calibrate a sun photometer and how to process and evaluate its data. They will also gain experience in remote sensing, graphing, regression analysis, and observational meteorology.



FIG. 8. Humanities students from the Kailua-Kona, HI, campus of University of the Nations watch as fellow student B. Maxwell uses a VHS-1 student sun photometer to measure the aerosol optical depth at MLO.



FIG. 9. University of the Nations student M. Spengler (right) explains to staff member Y. Olson how she used the VHS-1 to measure the optical transmission (520 nm) of various leaves.

5. The GLOBE Program

David Brooks of Drexel University and I are the principle investigators for the GLOBE program's new haze-monitoring project. The GLOBE Program (<http://www.globe.gov/>) is an international network of primary and secondary school students, teachers, and scientists that monitors and studies various environmental parameters. GLOBE is administered by an interagency team of the U.S. government that includes personnel from the National Oceanic and Atmospheric Administration, the National Science Foundation (NSF), the Environmental Protection Agency (EPA), and the Departments of Education and State. GLOBE works closely with more than 50 state and local partner organizations.

As implied by the nature of the science agencies that manage the program, GLOBE is a serious effort to use students to collect scientifically useful data while simultaneously enhancing their scientific experience and knowledge. To this end, GLOBE employs a chief scientist and various curriculum specialists. GLOBE also contracts with an array of specialists in various earth science disciplines to design and coordinate the measurements program and to recommend instruments and calibration methods. GLOBE students presently monitor up to 20 features of the atmosphere, precipitation, bodies of water, land cover, and soil. The measured parameters are selected only after peer review, and monitoring is performed according to protocols developed by scientists. Learning activities for each area of investigation help

students analyze their data and better understand their significance.

The GLOBE Program is best implemented by schools with Internet access, since detailed information for teachers, data collected by students, and conversations among students, teachers, and GLOBE scientists are posted on the World Wide Web. By August 1997, some 4000 U.S. teachers and 1000 international teachers had received GLOBE training. During the 1996–97 school year, over 800 GLOBE schools submitted data each month, and in 1998 the number of participating countries reached 71. Meteorologists will be pleased to know that each of the atmospheric measurement protocols is implemented by at least 75% of active GLOBE schools. GLOBE takes seriously its stated goal of having students collect accurate data that professional scientists will find of significance, and it is likely that publications resulting from this student–scientist partnership will begin to appear over the next few years.

In recent years controversies have arisen over errors and misleading information in some environmental textbooks and curricula. The GLOBE Program strongly emphasizes and advocates both accuracy and objectivity. For example, the student learning goals for the atmospheric measurements program directed by Susan Postawko begin with the following statement: “Within GLOBE, students can enhance their education through involvement in hands-on, scientifically valid research. Student learning goals for this module are: To observe and measure weather and climate-related phenomena accurately and objectively . . .”

[[http://globe.ngdc.noaa.gov/sda-bin/wt/ghp/tg+L\(en\)+P\(atmosphere/sciletter\)](http://globe.ngdc.noaa.gov/sda-bin/wt/ghp/tg+L(en)+P(atmosphere/sciletter))].

Can doing science enhance academic performance?

Some educators have asked if involving students in hands-on science genuinely enhances learning or is merely another educational fad. This concern is especially appropriate in view of the dismal performance of U.S. students during the 1995 Third International Mathematics and Science Study (TIMSS), the most comprehensive and rigorous international comparison to date of mathematics and science achievement. As in previous international comparisons going back to the 1960s, the results of U.S. students were significantly below the average of students from the 40 other participating countries. The U.S. Department of Education concluded that "U.S. students' performance was among the lowest of the participating countries in mathematics and science general knowledge, physics, and advanced mathematics" (Takahira et al. 1998). Neal Lane, former director of NSF, has observed that the TIMSS results for U.S. students "suggest that students appear to disengage from learning critical mathematics and science content as they progress through the school system. The sources of disengagement may include the classroom environment, the quality of instruction, and [lack of] parental and community support for the value of science and mathematics to our children's future" (Takahira et al. 1998).

GLOBE has contracted with SRI International to evaluate various aspects of the program, including the relative performance of GLOBE and non-GLOBE students. A detailed evaluation by SRI of 44 GLOBE classes and 27 classes whose teachers had applied for GLOBE training but had not yet formally entered the program showed that GLOBE students consistently outperform non-GLOBE students in their conception of what scientists do and in their understanding of sampling, measurement principles, and data interpretation (Means 1997). The study did not compare the academic achievement scores of the two groups of classes.

Whether or not GLOBE boosts academic performance, the SRI study demonstrates that students who make scientific measurements learn more about the methods of science than can be taught in a text or quantified by an examination. GLOBE's proposed new haze-monitoring program will provide many opportunities for students and scientists to perform research. Publication of assembly details of the VHS-1 sun photometer in *Scientific American* (Carlson 1997) stimulated the interest of several students, who constructed

and calibrated the instrument and then used it in various research projects.

C. Beicker, a high school student from Seguin, Texas, built a VHS-1 without supervision using parts he purchased locally. He used the instrument to monitor AOD during transects around a large coal-fired thermal power plant. Beicker's measurements clearly showed the presence of a prominent haze plume downwind from the plant. For his senior project, Beicker measured variations in the optical depth along transects downwind from San Antonio, work that was recognized in the form of major awards at several science fairs. C. Gorish, a seventh-grade student in California, used a VHS-1 to study increased optical depth caused by blowing dust from Owens Lake. V. Carr, a high school freshman from Lexington, Massachusetts, also monitored haze using a VHS-1. Like Beicker, these and other students received various science fair awards for their VHS-1 research projects.

6. Is there a scientific need for a student sun photometer network?

An international student sun photometer network has the potential of becoming the largest and most geographically diverse of such networks. Students will generally be unable to provide more than 1–3 observations per day. But their observations can fill major gaps in existing sun photometer networks.

It is important for both students and professional scientists to understand that the most accurate AOD measurements are made from the ground and not from satellites. They should also understand that the major gap in AOD data is due to the failure of an international sun photometer network (see section 6b below) and that new networks are now in development.

a. Are student data reliable?

Some scientists have questioned the ability of students to perform scientific measurements and the reliability of their observations. Previous studies have demonstrated that properly trained and equipped students can indeed conduct reliable scientific measurements. Students and their teachers must understand that scientists will treat their data seriously only if the data are collected with appropriate supervision using carefully designed protocols and properly calibrated instruments. They must also understand that the quality of their data is often related to the students' experience with the instruments used to collect it.

Scientists should realize that objections they raise about the quality of student observations might also be raised by students about the quality of observations by trained professionals. A few years ago a major government meteorological laboratory invited me to give a seminar about measurements of solar ultraviolet radiation by amateur scientists and students. Afterward a prominent scientist jokingly asked how students could be kept from getting peanut butter on their UV instruments. First, I described the care with which mature students treat scientific instruments. Then I suggested that the seminar adjourn to the roof of the building to inspect the laboratory's expensive array of UV instruments, which are sometimes coated with a water mist from a large air conditioning unit. Although I was prepared to cite other such examples, the one provided was sufficient to end criticisms of students.

Anecdotal evidence clearly demonstrates that students can be taught to make careful environmental measurements. Indeed, some scientists rely on networks of students and amateur scientists to provide data about variable stars, meteors, bird surveys, and meteorology. A classic example is the Massachusetts Acid Rain Monitoring Project (ARM). During the early 1980s, some 1000 volunteer collectors provided water samples to 73 professional test laboratories each month for more than one year. This and subsequent surveys provided information about the acidity of 85% of all named lakes and streams in Massachusetts. P. Godfrey, director of ARM, has described the considerable attention devoted to ensuring that the quality of samples and data collected by ARM non-professionals meets the standards of the EPA (Godfrey 1991).

While the documented experience of the Massachusetts Acid Rain Monitoring Project is encouraging, whether students can provide scientifically valid optical depth observations remains to be seen. GLOBE will develop protocols for evaluating the quality of such data. One suggested protocol is to enlist the participation of schools located very near robotic sun photometers such as the Cimel instruments of the AERONET network. This will permit the student data to be quickly compared with that from a well-calibrated professional instrument.

b. Failure of the first international sun photometer network

The Volz sun photometer was used in various networks, including 95 stations of the international

Background Air Pollution Monitoring Network (BAPMON) of the Global Atmospheric Watch program. Begun in 1968, BAPMON was sponsored by the World Meteorological Organization and the Global Environmental Monitoring System in cooperation with NOAA and the EPA. Significant problems due to degradation of the filters used in BAPMON sun photometers were eventually recognized. NOAA's Atmospheric Research Laboratory, which led the expert review of the BAPMON sun photometer network, reported that "the sunphotometer network has been shut down. In brief, the instruments employed filters that drifted with time, and calibration requirements were therefore too much for the network to handle" (ARL 1998).

The new kind of sun photometer developed for use by students has no interference filters. Students will learn about the stability of this new instrument and that properly conducted haze measurements can help fill the void left by the failure of the BAPMON network.

c. New sun photometer networks

Recently, two kinds of very expensive, automated instruments have been used in new aerosol networks, including AERONET (<http://spamer.gsfc.nasa.gov/>), the U.S. Department of Agriculture UVB Monitoring Program (http://nadp.nrel.colostate.edu/UVB/home_page.html), and the Atmospheric Radiation Measurement Program created by the Department of Energy. These new instruments have experienced the filter degradation problems that plagued earlier sun photometers. A concise account of how the filter problem has affected the Cimel automated sun photometers of the AERONET network is given by Holben et al. (1998): "With respect to the long-term stability of the calibration coefficients, the optical interference filters are the limiting factors. The results are typical for interference filters. On average, there has been a decrease from 1 to 5% per year and, after 2 years, there has been a rapid decay in some filters." Holben is now evaluating a new kind of filter that may provide much better stability.

Students will be kept advised about results from these new networks. Comparisons of student LED sun photometers with calibrated Cimels at MLO will be performed periodically, and results will be provided to students and professional scientists. If the student instruments remain stable, both students and the scientific community will have confidence in the student measurements.

7. Conclusions

Although GLOBE schools must pay for their own instruments, computers, and internet links, management of the GLOBE Program is dependent on federal funds and is therefore subject to the same uncertainties that affect most federally funded science programs. Thus the future of GLOBE will be determined as much by budgetary and political considerations as by the program's success in enhancing science education and providing valid data to scientists.

Meanwhile, GLOBE offers by far the world's largest and most geographically diverse student network. This network provides an unprecedented opportunity for widely dispersed measurements of the atmosphere's optical depth using an inexpensive, stable sun photometer. Currently, David Brooks and I are studying various technical aspects of the GLOBE student sun photometer (Brooks et al. 1998; Mims 1998b). We are particularly interested in comparing the performance of sun photometers that use broadband LED detectors (70 nm) with those that use narrowband (10 nm) filters. To this end a microprocessor-controlled sun photometer has been assembled with the following channels: 520-nm LED (70-nm FWHM); 500-nm filter (80-nm FWHM); and 500-, 520-, and 540-nm filters (10 FWHM). This instrument will be calibrated using the Langley method and compared with the 500-nm channel of a Cimel sun photometer at Mauna Loa Observatory. Brooks and I are also studying the effect of various fields of view in hazy and clear-sky conditions. We will soon begin a GLOBE pilot study by distributing prototype instruments to selected teachers.

Besides providing daily AOD measurements for the GLOBE network, student sun photometers are well suited for use in many kinds of science fair projects. Professional meteorologists are encouraged to visit GLOBE's Web site and to mentor local students in haze monitoring and other areas of atmospheric research.

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