Bringing the Sun Down to Earth

Designing Inexpensive Instruments for Monitoring the Atmosphere

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Cover photo: Sunset over Manama, Bahrain, December 2004. The orange-red sky over the capital city of this small island nation in the Arabian Gulf (the name preferred in the Middle East for this body of water) is due to scattering of sunlight caused by urban pollution and wind-blown sand and marine spray.

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Preface

In 1998, my colleague, Forrest Mims, and I began a project to develop inexpensive handheld atmosphere monitoring instruments for the GLOBE Program, an international environmental science and education program that began its operations on Earth Day, 1995. GLOBE's goal was to involve students, teachers, and scientists around the world in authentic partnerships in which scientists would develop instrumentation and experimental protocols suitable for student use. In return, data collected by students and their teachers would be used by scientists in their research. This kind of collaboration represented a grand vision for science education which had never before been attempted on such a scale, and we embraced this vision with great enthusiasm.

Between 1998 and 2006, Forrest Mims and I collaborated on the development of several instruments based on Mims' original concept of using light emitting diodes as spectrally selective detectors of sunlight, which was first published in the peer-reviewed literature in 1992. These instruments have evolved into a set of tools and procedures for monitoring the transmission of sunlight through the atmosphere, and they can be used to learn a great deal about the composition of the atmosphere and the dynamics of the Earth/atmosphere/sun system. If measurements with these instruments are made properly, they have significant scientific value, as well.

For most GLOBE Program protocols, the original vision of scientists, teachers, and students collaborating in published research was never realized, but atmospheric science was an exception that led to several peer-reviewed publications about the instruments we developed and their science applications. These kinds of activities require patience because they can take years to bear fruit, even for "professionals." For example, when a completed paper that may represent several years of work is submitted to a peer-reviewed journal, it may not appear in print for yet another year or more.

Sadly, the GLOBE Program and its sponsors lost patience with this process, and GLOBE has now abandoned its original vision of engaging students and teachers around the world in authentic science. Nothing would please me more than for the readers of this book to resurrect this vision in their own schools, homes, and communities.

My experience in working with students and teachers around the world has demonstrated that it is very rare to find individuals with the skills required to design and build their own instruments. In my view, this is a problem within science education that seriously limits students' abilities to understand the world around them. Today's students have grown up in a world dominated by digital technology. However, the world is a fundamentally analog place and must be understood on those terms.

Atmospheric and Earth sciences rely heavily on observation, and only by immersing ourselves in observations and measurements can we understand the atmosphere and the dynamic processes that drive weather and climate.

These kinds of activities are not just for an academic elite. Our nation is struggling to retain and educate a competitive world-class science and engineering workforce, but this workforce must also include a technical support infrastructure that requires practical as well as academic skills. A great deal of attention is being paid to the academic side of this equation, but at least in my perception, very little to the practical side.

Although this book is based in large part on what I have learned by working with K-12 students and their teachers around the world, I know that the audience extends into colleges and universities. I am often contacted by professors who have discovered that their students, even those who are candidates for advanced degrees in science and engineering, have no idea about how to design, build, calibrate, maintain, and use the instruments that are essential to their careers. (A few years ago I had a student assistant who was a sophomore mechanical engineering major at Drexel University and who had never seen an analog panel meter.) For that audience, this book should provide an valuable introduction to essential skills. After all, the process of designing instruments and experiments remains fundamentally the same regardless of whether an instrument costs \$20 or \$20,000. It certainly makes sense to develop and practice new skills with \$20 instruments rather than with their more expensive counterparts!

This book is not intended for use just in formal education settings. It provides a great deal of material for science projects that can be conducted by anyone interested in their environment. Traditionally, "environmental science" projects have not fared as well in science fairs as projects in other areas. Perhaps this is due to a lack of information about making authentic quantitative measurements. If so, this book, in which I have tried to strike a balance between science and practical design matters, should help!

There are several places in this book in which I have discussed prices of instruments and components, in order to give readers a better idea of my definition of "expensive" and "inexpensive." Although the relative price comparisons should hold in the future, the absolute prices are in 2008 US dollars and, of course, may not be directly applicable in the future.

Although it is fair to describe these instruments as relatively inexpensive compared to their commercial counterparts, it may not be inexpensive or easy to build just one or two. There are almost always cost advantages to buying components in quantity.

It is inevitable that there are some practical construction details that I should have included but did not—the book was conceived more as an "idea manual" than a "construction manual." Building these instruments may require specialized hardware and tools. In my own shop I have all the equipment I need for the required mechanical and electronic work. I have designed and had manufactured custom enclosures and printed circuit boards for some of these instruments, but these undertakings are practical only when ordering items in quantity.

In some cases, kits of parts and detailed construction instructions may be available through *Institute for Earth Science Research and Education.* However, I cannot predict what kinds of assistance will be available when you read this book. I invite you to search for me and *IESRE* on the Web and contact me to find out about current activities.

There are many facts about the sun and the Earth/atmosphere system presented in this book, especially in Chapter 2, and I have not attempted to provide specific references for all of them. If there are errors, I take full responsibility for them. There are, of course, many online sources that can be used to check facts and obtain more information about specific topics.

Unless noted otherwise, all figures and tables represent my own work. All figures in the text are printed in black and white. However, in a few cases where I believed that color versions were necessary to render the figures understandable, figures are reproduced in color plates at the end of the book, with the same chapter-specific figure numbers.

Finally, note that although the URLs for online sources given occasionally in this book were valid at the time the manuscript was written, there is no guarantee that they will be available in the future.

Acknowledgements

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Anyone who is interested in the kinds of measurements and instruments described in this book is deeply indebted to the groundbreaking and continuing work by Forrest M. Mims III, the inventor of LED-based instruments for atmospheric measurements, and Co-Principal Investigator with me for eight years on the GLOBE Program's Aerosols and Water Vapor Monitoring Projects. Mr. Mims has been a professional inspiration, a valued colleague, and a personal friend since the beginning of our work together in 1998.

I also want to thank Wade Geery, a teacher at Arrie Goforth Elementary School in Norfork, Arkansas, USA, and Richard Roettger, a teacher at Ramey School, Ramey, Puerto Rico, for their ongoing commitment to doing real science with their students and for collecting and reporting atmospheric data over several years, some of which appear in this book.

Finally, I need once again to thank my wife, Susan, for proofreading this manuscript prior to its submission. Her patience is especially noteworthy considering that this was the third book manuscript I asked her to read within a period of less than a year and a half.

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February, 2008

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1. Introduction

For many years, the principles of inquiry-based science activities have spread throughout the science education community, and the "hands-on" mantra has gained the status of a cliché for education reform. Nevertheless, the transition from cliché to reality remains elusive, at least partly because of the gap between the worlds of working scientists, classroom educators, and students. In an educational environment increasingly driven by the use of standardized testing to assess the performance of schools, teachers, and students, and with rewards and penalties based on scores on these tests, it is difficult for even the most diligent educators to involve their students in doing real science in partnerships with scientists. Correspondingly, it is also difficult for scientists to provide full access to and participation in a research environment that can seem unapproachable to a nonscientist.

The purpose of this book is to bridge these gaps in one particular area—the science associated with interactions between solar radiation and the Earth/atmosphere system. Although this topic may seem esoteric, in fact it is very approachable by teachers, students, and others spanning a wide range of ages and interests, and is a necessary component of any curriculum that meets national science education standards [National Research Council, 1996].

This topic is important to all of us because sunlight is the ultimate fuel source driving the Earth/atmosphere "engine." Most obviously, solar energy and its daily and seasonal variability provide the driving force for weather and climate. Even the youngest students are taught to make simple weather observations and to answer questions such as, "Has it been raining?" "How cloudy is it this morning?" "How hot will it be today?" Basic qualitative observations can lead to quantitative measurements and more sophisticated questions: "How much rain have we had this month, and is that more or less than average?"; "What is the percentage of cloud cover and what kinds of clouds are present?"; "Is it getting warmer where we live?"; "Why does the atmosphere appear hazy and what does this have to do with weather and climate?"

These kinds of questions are interesting to students and others because they are so closely bound to our daily experiences and relate to issues of climate change that will dominate Earth science in the 21st century. Activities that help answer these questions serve as essential starting points for building a scientifically literate society that understands, for example, the potential for and consequences of human-induced climate change, and which values the investments required to lead students to pursue professional careers in the "STEM" disciplines—science, technology, engineering, and mathematics. However, these activities must be chosen with care to make sure that they provide reliable results and that those results are used appropriately.

As a first step toward studying sun/Earth/atmosphere interactions, this book addresses how these interactions maintain Earth and its atmosphere in a radiative balance that supports life as we understand it, and how to measure the effects of those interactions. These processes are illustrated conceptually in Figure 1.1. Some version of this image is invariably found in the Earth science texts often used in 8th and 9th grade courses [*e.g.*, Allison *et al.*, 2006]. There is a great deal of science embedded in such images, most of which no doubt remains a mystery to non-specialists, including students *and* their teachers.

Earth and its surprisingly thin and fragile blanket of atmosphere (with a thickness equal to about 1/100 of Earth's radius) form a dynamic, interconnected system. Incoming sunlight is reflected, scattered, and absorbed by Earth's atmosphere and its surface. Different surfaces, including cloud top "surfaces," reflect and absorb sunlight in different ways. Oceans absorb almost all the radiation that falls on them. New snow reflects nearly all radiation. Whatever the surface, absorbed radiation is ultimately re-emitted as longwave thermal radiation, as indicated by the red arrow in Figure 1.1.

Earth's yearly journey around the sun and its daily rotation about an axis that is tilted relative to its orbital plane keeps Earth and its atmosphere in a constant state of flux that is driven by diurnal and seasonal cooling and heating. On average, this ongoing process of absorption and re-emission keeps the Earth/atmosphere system in the radiative balance that is required by basic physical laws.

The details of the processes summarized in Figure 1.1, are what fascinate atmospheric and Earth scientists. Although the explanations can sometimes be complicated, atmospheric and Earth sciences still rely heavily on observation. Many observations and quantitative measurements of the atmosphere are not difficult to understand and are well within the capabilities of students, teachers, and anyone else who is curious about their environment.

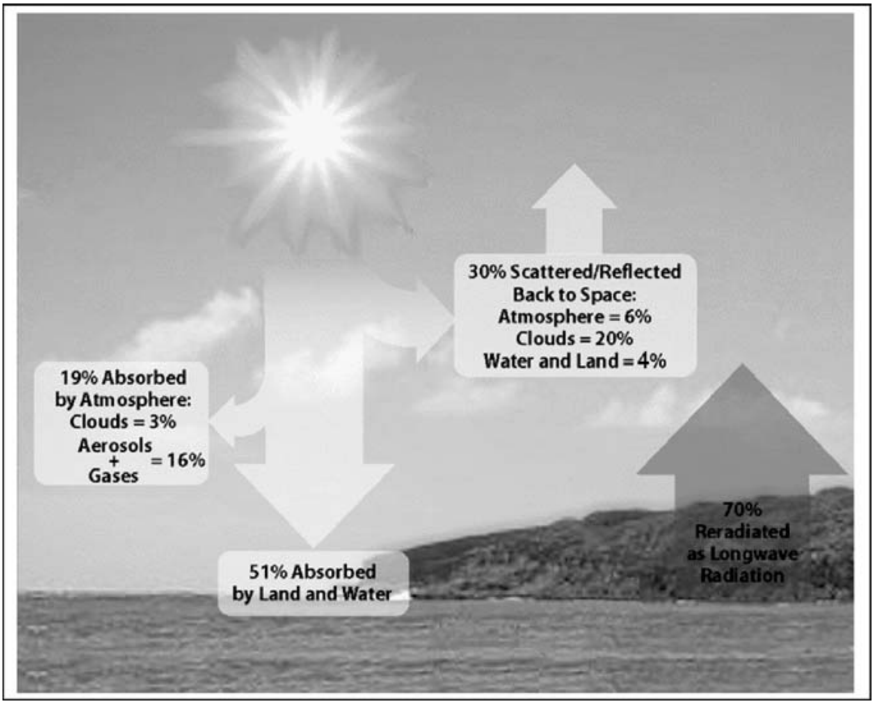

Figure 1.1 (see color plates). Schematic representation of Earth's radiative balance [Graphic by Vivek Dwivedi, NASA Goddard Space Flight Center].

Even the simplest measurements require an understanding of the principles of scientific research and of how measuring instruments work. The principles and challenges of designing and building scientific instruments, including dealing with their calibration, interpretation, stability, and reliability, are the same regardless of whether those instruments cost $20 or $20,000 and should be applied to all activities in appropriate ways.

Although it may be tempting to conclude that the accuracy of observations and measurements made "just" for educational purposes is not particularly important, this is a mistake! Without observations and measurements that make sense relative to accepted scientific standards, it is easy for students to become discouraged. Without reasonable data quality standards, scientists will not be motivated to participate in the learning process. But, when scientists, teachers, and students collaborate to design experiments, including building their own instruments as described in this book, participants are engaged in an authentic science experience that confers true ownership of the data and benefits all stakeholders.

In this context, examining sunlight and its interaction with Earth's atmosphere offers many opportunities for "hands on" activities that meet all the requirements of state-of-the-art science education. In addition, all the measurements described in this book have genuine scientific value when they are made carefully and, ideally, are used as part of a research plan developed in partnership with scientists.

Although it is important to present science in an age-appropriate way, this book is not directed at a specific student age group, and it is not intended to provide thoroughly developed curriculum material that is suitable for use "as is" by teachers in their classrooms. The level of the presentation may be more appropriate for science educators and other adults than for younger students. It assumes some science and mathematics background at the secondary school level, but not a specialized knowledge of the topics discussed. The material is certainly accessible to older secondary school students and should be an excellent source of science projects and other student research through secondary school and beyond. Hopefully, this book will encourage educators, especially, to develop their own science interests, to build some of their own instruments for monitoring the atmosphere, and to transmit their enthusiasm to their students. The book could easily serve as a source for undergraduate and even graduate courses in environmental or atmospheric science or environmental engineering.

The approach taken in this book has been developed specifically because it is so easy simply to buy equipment for collecting science data and use it without giving much thought to the underlying design principles. This may seem reasonable and expedient in some circumstances, but it removes an important layer of understanding from the science process. Because of our society's increasing dependence on digital technology, this book (in spite of its embracing technology as appropriate) will hopefully serve as a reminder that the physical world is an analog place. Anyone who understands this fact and has the skills to deal with it will continue to be in great demand in science and many other careers!

The book is divided into three basic sections. It begins with an introduction to the sun, Earth's atmosphere, and some of its constituents. The second section presents a discussion of the principles behind full-sky and direct sun measurements and the science that is reasonably accessible with relatively inexpensive instruments.

The third section, starting with Chapter 4, describes how to design and use atmospheric monitoring instruments that are both inexpensive and reliable. Supplementary materials in appendices delve more deeply into some of the mathematical and technical issues, but they are not essential for understanding and applying the material in the book.

2. Earth's Sun and Atmosphere

Chapter 2 provides some facts about the sun and Earth's atmosphere. Equations are presented that show how the Earth/atmosphere system is maintained in equilibrium with the radiation arriving from the sun, and how greenhouse gases in the atmosphere affect that balance.

2.1 Earth's Sun

Stars generate huge amounts of energy through the process of nuclear fusion, in which hydrogen atoms are converted into helium atoms. Earth's sun, an unremarkable medium-sized star, produces a total power P of about 3.9×10^{26} watts (W).[1] This power is radiated into space uniformly in all directions. At planetary ditances, the sun looks like a point source of radiation and fundamental physical laws tell us that the intensity of a point source of radiation decreases as the inverse square of the distance from the source. The solar constant S_o is defined as the power per unit area of solar radiation falling on the surface of an imaginary sphere of radius R around the sun:

$$S_o = P/(4\pi R^2) = P/(4\pi\cdot 150{,}000{,}000{,}000^2) \approx 1370 \text{ W/m}^2 \qquad (2.1)$$

where R is the average Earth/sun distance (1 astronomical unit or 1 AU), about 1.5×10^{11} m. The solar output actually fluctuates a little as a result of disturbances on the sun's surface. More importantly, the solar "constant" varies by about ±3.4% during a year because Earth is in a slightly non-circular orbit around the sun. The maximum and minimum values occur at perihelion and aphelion—the minimum and maximum Earth/sun distances:

$$S_{max} = S_o/(1 - e)^2 = S_o/(0.983)^2 = 1417 \text{ W/m}^2 \text{ (at perihelion)} \qquad (2.2a)$$
$$S_{min} = S_o/(1 + e)^2 = S_o/(1.017)^2 = 1324 \text{ W/m}^2 \text{ (at aphelion)} \qquad (2.2b)$$

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[1] A list of symbols, organized by chapter, is given in Appendix 1.

where e is the eccentricity—a dimensionless measure of the departure of an orbit from a circle with a value between 0 and approaching 1. Earth's eccentricity varies slowly, with a period of about 100,000 years. The current value is about 0.0167. Earth is closest to the sun, at perihelion, in early January, so this is when maximum solar radiation reaches Earth.[2] The minimum amount of radiation is received at aphelion, 6 months later.

Light and heat are the obvious perceptible components of solar radiation, but the energy distribution of solar radiation is much more complex than that. The sun's energy, like that generated by other stars, is distributed over a broad range of the electromagnetic spectrum, following well-known physical laws. It behaves approximately like a "blackbody," a perfect radiator and absorber, at a temperature of about 5,800 K—"approximately" because of electromagnetic activity and other processes constantly taking place within the sun's interior and on its surface. Its maximum output is in the green-yellow part of the visible spectrum, around 500 nm. Not surprisingly, this is near the maximum sensitivity of the human eye.[3]

Astronomers classify stars using a series of letters based on their equivalent blackbody temperatures, as shown in Table 2.1. Earth's sun has an absolute temperature of about 5,800 kelvins (K), which places it near the upper end of type G stars, near the middle of the range of star temperatures.

The radiation leaving the sun on its journey through the solar system is not a completely smooth function of wavelength. Figure 2.1 shows the extraterrestrial solar radiation—what an observer would see from a vantage point just above Earth's atmosphere—obtained from the SMARTS2 model. For reference, the distribution of blackbody radiation at 5,800 K as a function of wavelength is also shown. Appendix 2 provides more details about the equation for Planck's law, one of the most famous in the history of physics, needed to generate the blackbody radiation curve.

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[2] Although many people living in the northern hemisphere believe the sun must be closer to Earth during the northern hemisphere summer, this is not true!

[3] It is reasonable to conclude that the human eye has evolved to respond optimally to solar radiation. The fact that other animals respond differently, for example, by being able to "see" ultraviolet or thermal radiation, suggests many fascinating questions that are beyond the scope of this book.

Table 2.1. Star type classifications by temperature [Cannon and Pickering, 1912].

Spectral letter	**Temperature range (K)**	**Stellar color**
O	>30,000	Blue
B	10,000–30,000	Blue
A	7,500–10,000	Blue-white
F	6,000–7,500	White
G	5,000–6,000	Yellow-white
K	3,500–5,000	Orange
M	<3,500	Red

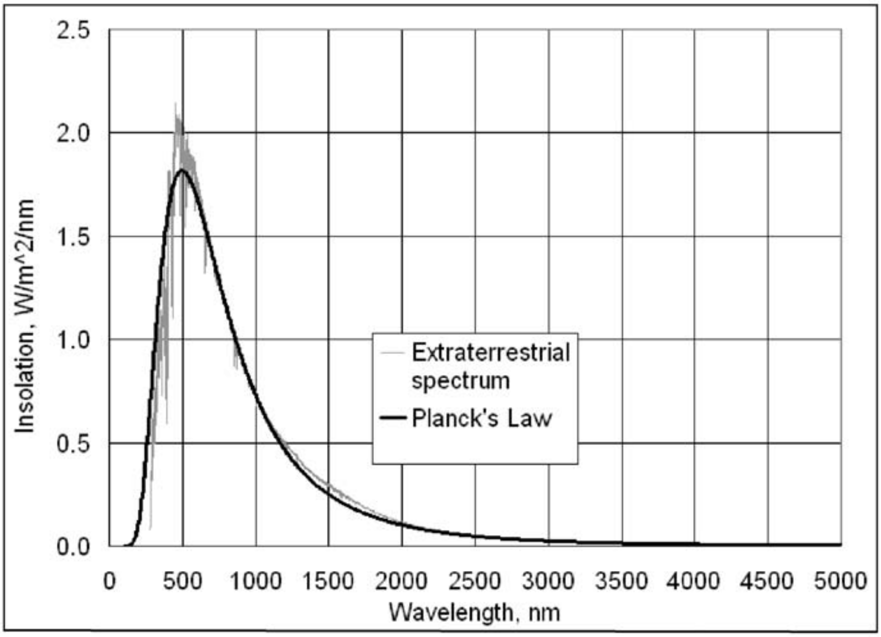

Figure 2.1. The extraterrestrial spectrum [from SMARTS2 model, Gueymard, 1995] with Planck's law blackbody radiation for a temperature of 5,800 K superimposed.

2.2 Earth's Atmosphere

Earth's size, density, and distance from the sun in a nearly circular orbit have produced a fortuitous set of circumstances for supporting life as we understand it. Gravity keeps in place an oxygen-rich atmosphere. The average surface temperature (about 16°C), as controlled by the solar constant and the atmosphere, allows water to exist naturally in all its three