Teaching Graduate Atmospheric Measurement

BY STEPHEN A. COHN, JOHN HALLETT, AND JOHN M. LEWIS

With the atmosphere as our laboratory, progress in atmospheric science depends crucially on observational scientists and instruments. Instruction in the use of these instruments is fundamental to our university curriculum. How can this instruction be best meshed with the theoretical basis of atmospheric science? We address this question, with specific emphasis on connections between universities and national facilities. There is a need to continuously train the next generation in observational skills and to closely link such skills to the design and use of instruments with new capabilities. The 1991 Study on Observational Systems sponsored by UCAR and the AMS reviewed education in observational techniques and discussed these needs.

One of the principal conclusions was

> . . . very few universities are able to produce the specialists who will be responsible for designing, developing, implementing, and exploiting the next generation of observing systems.

Further,

> Universities see a need for an increased role for national centers and laboratories in the formal educational enterprise itself. Possible contributions go beyond adjunct faculty appointments for laboratory scientists and student appointments at laboratories and include assistance and participation in developing instructional materials and conducting segments of courses using laboratory platforms and premises.

AFFILIATIONS: COHN—National Center for Atmospheric Research, Boulder, Colorado; HALLETT—Desert Research Institute and University of Nevada, Reno, Nevada; LEWIS—National Severe Storms Laboratory, Norman, Oklahoma, and Desert Research Institute, Reno, Nevada
CORRESPONDING AUTHOR: Stephen A. Cohn, NCAR Earth Observing Laboratory, P.O. Box 3000, Boulder, CO 80303
E-mail: cohn@ucar.edu

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The discussions leading to the creation of the 1991 study also led the University of Nevada at Reno (UNR) to first seek national facilities. This paper presents our viewpoint and experiences from conducting ATMS 748: Measurement in the Atmosphere, a course on the principles and practice of atmospheric measurements, which has applied national facilities from NCAR and the Colorado State University (CSU)'s CHILL radar to training in observations.

Since the 1970s, this course has been required for Ph.D. students in the atmospheric science program at the University of Nevada, Reno, and has been taught approximately every three years. On several occasions beginning in 1989, it received the support of National Science Foundation (Lower Atmospheric Observing Facilities; www.nsf.gov/geo/atm/ulafos/laof), whose scientists also participated in teaching the course. Here we discuss lessons learned related to instrumentation and its place in the atmospheric science curriculum. Our hope is that university departments will be motivated by our experience to initiate or rejuvenate similar instrumentation courses, and that national facilities will be made available for such courses.

COURSE DEVELOPMENT. In addition to being required for Ph.D. students, ATMS 748 is open to M.S. students who have sufficient skills in mathematics, physics, and computing. Thus, every graduate of the UNR Atmospheric Science Ph.D. program has this training, and every qualified graduate student in the university has the option of learning about atmospheric measurement.

The first use of national facilities for this course was in 1989, when the NCAR *Electra* devoted four flights to a teaching program in aircraft measurement techniques. Ten graduate students participated in this program. Lectures both in Reno and during the 2-week field trip to the *Electra*'s base in Colorado provided context for in-flight measurements collected by the students. In 1991, 10 more ATMS 748 students spent two weeks at the CSU CHILL radar facility. These students applied theory gained from lectures to the analysis and interpretation of observations. Observations included not only convective storm development and clear-air boundary

INSTRUMENTATION IN EDUCATION: AN HISTORICAL BACKDROP

In view of the limited number of academic programs in meteorology in the late nineteenth century, nearly all instruction in the use of meteorological instruments took place at national meteorological centers (for more on the situation in that period, see Gisela Kutzbach's historical research). Most instrumentation during this period was associated with surface observations of the weather. However, by the end of the first decade of the twentieth century, upper-air observations began to be collected from instrumented kites, then from pilot balloons, and subsequently radiosondes in 1936. The innovative use of anemometers to study atmospheric turbulence was introduced by G. I. Taylor early in the second decade of the century (a development he recounts in a 1970 paper in the *Journal of Fluid Mechanics*).

The impetus for large-scale practical instruction with meteorological instruments came with forecaster/observer training at the onset of World War II. Nearly 6,000 forecasters were trained in the United States alone, and the nine-month instruction took place at five civilian universities [California Institute of Technology; University of Chicago; New York University; University of California, Los Angeles; and Massachusetts Institute of Technology (MIT)] and at the U. S. Army Air Corps school at Grand Rapids, Michigan. A principal component of the instruction at these schools was training in upper-air observation using pilot balloons and radiosondes. MIT was noteworthy for its course in weather surveillance radar. Subsequently, programs in meteorology began to expand well beyond the five civilian institutions mentioned above.

We examined the course titles at many institutions to provide some historical measure of courses in instrumentation. While many courses may include discussion of how instruments function in a changing atmosphere, the subtleties of how well, for example, a net radiometer works when coated with frost, or the best way to redesign an instrument for higher frequency response are often not covered. Table 1, a summary of universities offering meteorological instrumentation courses, is based on information on curricula compiled by AMS. As Table 1 shows, over the years many institutions have not offered any atmospheric instrumentation course. There was a significant decline from 1964 (the first year this information was compiled) to 1980 in the percentage of schools with any course in meteorological instrumentation, a trend continuing through 2000. Similarly, a survey and analysis by E. S. Takle (in the June 2000 *Bulletin*) indicated some recent progress, but also a decline in university investment in meteorological equipment for teaching. This trend may be related to increased sophistication of the instruments, which makes it difficult to teach with them at a university. It may also be related to an increased focus on the numerical and computational aspects of meteorology at the expense of observational subject matter. We especially worry that there is a low percentage of graduate programs with an instrumentation course. Thus, many U.S. students, both undergraduate and graduate, may only learn about instrumentation indirectly from other topical course work.

layer flows, but also ground clutter and instrument noise. In 1994, students operated an NCAR Integrated Sounding System (ISS) in the Reno basin, measuring characteristics of inversions, fronts, and precipitation with a wind profiler and supporting sensors. Lectures covered the theory and operation of wind profilers and their diverse uses, and the course required term papers with analysis of the instruments and measurements. The ISS was used again in 2002, this time with a second ISS located in the Washoe basin south of Reno. Eighteen students participated, approaching a practical upper limit, and a strong forecast component was added. The class collected serendipitous observations of a severe dust storm and of pulsed nocturnal flows into the Reno basin from the Virginia Range. Again, the focus included properties of the instruments as well as of the atmospheric phenomena. During the most recent class, in 2005, the latest GPS rawinsonde technology was brought to Reno for demonstration and evaluation. This was a short, two-day interaction with the instrument, but the same sequence of lectures, field experience, data analysis, and term papers was followed.

There have been other similar activities. In 1993, the University of Wyoming King Air research aircraft toured seven universities (Lyndon State College, McGill University, Millersville State University, The Pennsylvania State University, State University of New York at Albany, University of Maryland, and University of Wyoming), giving students at each institution two weeks of experience in all aspects of field project planning and execution. Also, in 2002 and 2003 students from a CSU class on cloud dynamics and a University of Colorado class on instrumentation participated in science projects as part of the IDEAS (Instrument Development and Education in Airborne Science) project.

In each of the ATMS 748 classes, but most notably in the classes of 1994, 2000, and 2005, there was an increasing and productive interaction between the students and the scientists from NCAR. Time in the field, during events forecast by meteorology students supporting the projects, included informal group discussions of sensor limitations (what does "bad" data look like?), alternative technologies (how might a lidar make this measurement in place of a radar?), the compromises of creating and packaging each sensor (size, weight, mobility, power use, etc.), and principles of design as brought up by the students. These discussions naturally filled time as we waited for a midmorning inversion breakup or for an approaching front. During several courses, the NCAR scientist's involvement continued remotely as the class worked on term papers in the weeks following the field exercise. When a misunderstanding was evident in the draft papers, further interpretation and clarification were given to individual students or to the entire class. The term papers revealed strengths and weaknesses of the course, and allowed iterative adjustments from one class to the next in an effort to improve the presentation. The final papers and participation in the grading process let us evaluate how much was learned and what should be kept or changed in a future class.

Table 1. A summary of universities offering instrumentation courses, drawn from three of the series of educational compendia published by the AMS: *Curricula in the Atmospheric Sciences, academic year 1963–64; Curricula in the Atmospheric and Oceanic Sciences 1980;* and *2000 Curricula in the Atmospheric, Hydrologic, and Oceanic Sciences.*

Year	1964	1980	2000
Total included	45 (U.S. only)	103 (U.S. + CAN)	97 (U.S. + CAN)
Number with course	24 (53%)	44 (43%)	37 (38%)
Undergraduate course only	16 (36%)	25 (24%)	21 (22%)
Graduate course only	6 (13%)	16 (16%)	13 (13%)
Graduate and undergraduate course	2 (5%) Texas A&M University; University of Washington	3 (3%) University of Oklahoma; Texas A&M University; University of Wisconsin—Madison	3 (3%) University of North Dakota; Purdue University; State University of New York at Albany

CRITICAL TOPICS IN INSTRUMENTATION TRAINING.

Although ATMS 748 has evolved over three decades, the cornerstone has always been an understanding of the atmosphere through measurement. Assessing the quality and limitations of observations is valuable for forecasters who base their predictions on data, for numerical modelers who rely on observations for assimilation and verification, and for those scientists who study the atmosphere through detailed interpretation of measurements. This is why the course is required for all UNR atmospheric science Ph.D. candidates. We emphasize development of an intuitive view for measurement of basic physical processes, but we do not ignore the instrument and algorithmic considerations, such as the tendency of a wind vane to overshoot, compared with a thermometer, which does not. Assignments consider the response of instruments when wet or iced, in direct sunlight or shade, and under clear or cloudy sky at night. Lectures, small demonstrations, and field experience are merged throughout the course.

We find that the field component, with the instructor and instrument specialist present and with both simple and complex sensors, is central to success in the course. Time in the field drives home classroom lessons and for many students has led to a deeper understanding of measurements they encounter elsewhere. In addition, the "incidental chatter" during field work effectively conveys practical issues.

The more recent classes especially have covered practical aspects of both measurement principles and instrument design (see Table 2). The challenge lies in being able to design and deploy new instruments for new measurements, and to understand their response. There is also a challenge for users of observations to understand the accuracy, limitations, and failure modes of measurements.

While Table 2 appears to include technical detail, in practice there has been a strong focus on the atmosphere, with emphasis on the following:

- Students are taught or reminded that the basic properties of the atmosphere cover a range of parameters and scales. They understand Reynolds numbers as a ratio of inertial to viscous forces that range from less than 10^{-2} to greater than 10^{8}; that kinematic viscosity varies with density (altitude); that eddies less than 0.01 m decay to rest after half a revolution; and that particles and obstacles coexist within the gases. They are also reminded that the atmosphere has periodicities and boundaries, which might be moving or porous. Instruments used to observe the atmosphere may be required to distinguish motions and properties from planetary dimensions down to scales of turbulent dissipation.

- They are exposed to both simple and complex instruments. Students can learn through simple experiments with simple instruments that yield interpretable results. A demonstration with a thermometer to show that it responds more quickly in water compared with air, and that it responds more quickly if things are ventilated or stirred, drives home many theoretical concepts. Other concepts are best learned with complex sensors. A meteorologist interpreting radar or wind profiler data should have some idea of how these instruments work and how they can fail. A researcher studying aerosol characteristics and making use of lidar measurements should know something about lidar principles. In both of these cases, the energy propagation and interaction with atmospheric constituents (whether refractive index gradients or aerosols) must be understood. But also, beam overlap, system noise, etc. must be understood to properly interpret the atmosphere. While no course can cover all aspects of all sensors, exposure to some complex ones lets the researcher know what questions to ask to understand (and ultimately invent!) a new sensor.
- In teaching the class, both individual instruments and instrument systems are considered. An individual instrument may respond to different scales, frequencies, or concentrations; it has modes of failure (such as snow covering a radiometer) and sources of error (such as direct solar radiation on a thermometer). We define an instrument system as a combination of instruments used together to specify properties of a given volume of the atmosphere—for example, a radiosonde, surface weather station, or instrumented aircraft. Determining a flux, for example, where both a velocity and concentration are measured and then correlated, requires an instrument system. Thus, the interaction of characteristics of all instruments in the system must be considered.
- Discussion of effects of an instrument site is important, especially in the context of long-term observations. The roof of a building on campus, a city square, or a rural farm can change dramatically over the years, influencing the measurement and the interpretation of its long-term trends. The current emphasis on observing global changes highlights how important it is to understand changes in instrument design and sites. The example of the "standard" radiosonde illustrates this, with a variety of vendors, updated technology for both temperature and humidity, and shifting launch sites over time.
- A topic discussed more in recent years is the design and production of instruments for wide application rather than solely for research. Similarly, we discuss commercially available instruments, in particular

Table 2. ATMS 748 course topics.

Introductory concepts of measurement in a turbulent atmosphere and scale dependence (e.g., from boundary layer scales to synoptic scales)
Fundamental limits of measurements; practical sensor limitations (e.g., Brownian motion, electrical noise)
Principles of data acquisition and transmission; bandwidth considerations, signal to noise ratios; analog and digital transfer; signal averaging
Measurement concepts for a turbulent medium (e.g., energy cascade and the −5/3 power law, dimensional arguments)
First- and second-order response systems (e.g., a thermometer with exponential approach to equilibrium or a wind vane with a damped sinusoidal approach); transfer functions with different functional inputs
Measurement of longwave and shortwave radiative emission and flux; gas and particle absorption, scatter, and detection
Considerations for the mechanical, thermal, and electrical design of sensors
Principles for measurement of particle characteristics and mass flux (e.g., aerosol, cloud, precipitation)
Considerations for instrument production; manufacturing and patents

those where the processing algorithms are proprietary and not available to the users. This is true, for example, of most rawinsondes used today. Users do not know the response of sensor elements, or what correction and smoothing may be done to measured signals. The instrument is like a "black box" that provides output meeting specifications published by the manufacturer (including useful quantities like resolution, accuracy, and bias), but the details are not available. Students are reminded that data from black-box sensors should probably be examined more closely than any other instrument, especially for unrealistic smoothing or realistic-looking data where one would expect a measurement to be difficult or impossible. Operational and commercial instruments have a broad exposure and, in fact, can be quite reliable, with many failure modes already identified, understood, and corrected, or filtered from the instrument output.

- Discussion of algorithms is also essential. The hardware and principles of many research sensors are well described in journal articles. With advances in computer power, algorithms associated with these research instruments have become much more complex (e.g., using neural network training or fuzzy logic algorithms). In the past, ATMS 748 has briefly discussed these techniques. The need to understand these algorithms is increasing, especially to ensure that the sensor and algorithm are operated within their range of skill and validity.

STUDENT COMMENTS—THE PERSONAL VIEW. To explore the long-term impact of the instrument course, we asked the opinions of 22 former students—some well into their careers and some recent graduates—and nine replied. All students found value in the course. A common theme in the replies was that the philosophy of the course and the topics taught stayed with them over the years. However, none appeared to make career choices based on the course.

Several students show a lasting appreciation of data quality. Marc Pitchford (Ph.D. 1992, now at NOAA Air Resources Laboratory) replied, "I know that I am a more thoughtful designer of air-quality monitoring programs because of what I learned in both of the measurements classes that I took. I'm also a more skeptical user of other scientists' data." Paul Frisbie (M.S. 1992, now at the NWS Grand Junction Forecast Office) writes, "I believe that anyone in the field of atmospheric sciences needs to understand that instruments have limitations and may be prone to errors in certain environments. As a NWS meteorologist that provides forecasts, I rely on accurate information. Unfortunately, the data I receive from remote instrumentation isn't always correct. I need to recognize this, and sometimes quickly because I make decisions based on the data I have."

Belay Demoz (Ph.D. 1992, now at NASA Goddard Space Flight Center) has applied the teaching methods to his own course, "I remember a lot of what I learned in ATMS 748 (liquid water probes, instrument designs, thermometers, and radars). I believe that the hands-on experience of seeing things firsthand has a lot to do with my retaining what I learned. I have also used the philosophy of the course a lot. In collaboration with Howard University, I helped start something similar: summer hands-on workshops on instrumentation."

Other students describe a lasting awareness of measurement strategy. For example, Yangang Liu (Ph.D. 1998, now at Brookhaven National Laboratory) writes, "The course has influenced me most on the issue of instrument resolution and its relationship with the problem of scale-mismatch when comparing measurements against modeling/theoretical results or comparing measurements taken by sensors of different scale resolutions. In my view, in an environment as turbulent as the atmosphere, the issue of scale and hence the issue of instrument resolution is critically important for further advances of the atmospheric sciences."

Finally, more recent students who replied expressed their enthusiasm for the exposure the course provided. Claudio Massoleni (Ph.D. 2003, now at Los Alamos National Laboratory) writes, "I found it especially exciting being able to use top-class research instrumentation. I'm convinced I will be influenced by the class philosophy for very long during my future career." None of the students have emphasized instrument design in their subsequent career, but the course appears to have had a broad influence—affecting the thinking of professionals in their modeling, forecasting, and teaching efforts.

CONCLUSIONS. Atmospheric science ideally blends theory with experiment and observation, including laboratory work, field work, and numerical simulation. A challenge for programs in atmospheric science (and indeed any geophysical science) is to complement the theory with observation. This includes knowledge of the instruments we devise to measure the variables in the atmosphere and, ideally, also includes field work that allows the student to become acquainted with the essentials of making meaningful and accurate measurements. Trends toward increasingly sophisticated instruments, and toward university curricula more focused on courses in numerical experimentation and data assimilation rather than on instrumentation and field work, have increased this challenge. Our students need to think about the validity and applicability of the data they collect or see in their computer plots. Is the instrument accurate enough and suitable for the intended purpose? From the instructor's viewpoint, have the students learned to assess data thoroughly enough to justify their use supporting conclusions that may influence human behavior and government policy?

We have presented our experience in teaching an instrumentation course. Our aim is to train not only those whose career is to follow instrument design, use, and deployment, but also (and perhaps more so!) those who analyze climatological or synoptic records. The content of our course applies to the use of data in many atmospheric science career paths. Our field needs scientists trained in observational principles and observational techniques. It also needs inventors—people who create and use new instruments for new purposes.

As we review our experience and consider the comments of our former students, we are convinced that interaction with complex instruments and scientists who specialize in them is a valuable form of mentorship, which increases a student's understanding well beyond the immediate problem. These experiences prepare students for the realistic world of scientific measurement. Institutions operating national facilities (NCAR, CSU, University of Wyoming) support greater use of these facilities for education. The cost and effort of using a major facility for education is nontrivial, but small compared with a major field project. The skills developed by a student who uses such facilities effectively even once in their career, in our opinion, more than justifies this expense and effort.

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