Project-Based Learning, Surface Energy Balance, and Establishment of a New Undergraduate Weather Station

R. David Baker
Austin College, 900 North Grand Avenue, Suite 61627, Sherman, Texas 75090, dbaker@austincollege.edu

ABSTRACT

Through collaborative and individual projects in two upper level courses, undergraduate students established a new surface environmental observation station (Austin College Weather Station). In addition to standard meteorological observations, the Austin College Weather Station detects radiation and soil measurements. These additional measurements are used to calculate the local surface energy balance, an important indicator of local climate system interactions.

The weather station projects provided excellent opportunities for students to participate actively in the scientific process. The first phase involved establishment of the weather station. In this semester-long collaborative project, students engaged in all aspects of scientific field research, including planning, testing, implementation, data collection, analysis, and evaluation. They became experts on two weather station instruments. The second phase involved calibration and validation of the Austin College Weather Station. These 7-week individual projects required student research proposals, research papers, and peer review.

Student learning outcomes included both scientific content and scientific process. Many innovative assessment tools were utilized, including proposal writing, peer review, group meetings, research presentations, research papers, and a faculty review panel. These courses both received strong marks from students for promoting critical thinking and teaching effectiveness. Perhaps most importantly, students had fun participating in these research projects with real-world applications.

INTRODUCTION

Finding authentic ways to engage students actively in the learning process poses one of the greatest challenges in Earth system science education. Traditional lectures and laboratory exercises provide necessary foundations of knowledge, but they often limit students' participation in the scientific process. Indeed, the *National Science Education Standards* identify inquiry-based learning as the preferred method for teaching science. With inquiry-based learning, students engage in many of the same activities and thinking processes as scientists (National Research Council, 2000).

Project-based learning provides an ideal conduit for such inquiry. Student projects shift the emphasis away from teacher-centered instruction to student-centered inquiry. Depending on the scope of the course, project duration can range from a few days to a semester or more. With project-based learning, students may conduct background research, collect data, compare observations with theory, and draw conclusions based on their research. Students often learn from their mistakes and must modify their approaches to obtain better results. They may collaborate with peers and build on strengths provided by group members. Because of the interdisciplinary nature of project-based learning, projects have been successfully implemented in many geoscience courses (e.g., Woltemade and Stanitski-Martin, 2002; George and Becker, 2003).

This paper describes project-based student research activities that established and calibrated a new undergraduate environmental observation station, the Austin College Weather Station (ACWX). The Austin College Weather Station project consisted of two major phases: 1) a semester-long collaborative course project in spring 2001 to establish the weather station, and 2) individual seven-week course projects in fall 2001 to calibrate and validate ACWX measurements. Although this environmental station measures both atmospheric and soil quantities, we adopted the name "weather station" due to widespread public understanding of the term. From ACWX atmospheric and soil measurements, the local surface energy balance can be calculated. Although surface energy balance provides important clues about land-atmosphere interaction and local climate conditions, these difficult measurements are not recorded at typical weather stations. Austin College is the only liberal arts college in the United States to make such measurements.

Investigation of surface energy balance provides an easy pathway for exploring Earth as an interacting system. In simple terms, systems thinking involves reservoirs and exchanges among these reservoirs. For the Earth system, these reservoirs include the atmosphere, geosphere, hydrosphere, and biosphere. Fluxes among these reservoirs occur through energy and/or mass exchange. Surface energy balance studies primarily explore the exchange of energy between the atmosphere and geosphere. The presence of water (hydrosphere) and vegetation (biosphere) also can dramatically influence this energy exchange. Thus, surface energy balance involves interactions among all four "spheres" of the Earth system. Since the Austin College Weather Station measures the surface energy balance, the weather station projects provided unique opportunities for students to learn Earth system science.

SURFACE ENERGY BALANCE THEORY

Energy balance at the Earth's surface largely controls the local climate. In the long term, the amount of energy reaching the surface must equal the amount of energy leaving the surface. If more energy reaches the surface than leaves the surface, the surface temperature will increase until energy input and output once again balance. Likewise, the surface temperature will decrease if more energy leaves than arrives at the surface (Oke, 1987; Arya, 2001).

Energy balance measurements are relatively uncommon due to the necessity for extremely sensitive temperature and vapor pressure measurements. Currently, National Weather Service weather sites do not make routine surface energy flux measurements. Such measurements are usually confined to special field projects with a duration of only a few months (e.g., Beringer and Tapper, 2002), or to highly maintained meso-networks such as the Oklahoma Mesonet (Brock et al., 1995) or the Southern Great Plains Atmospheric

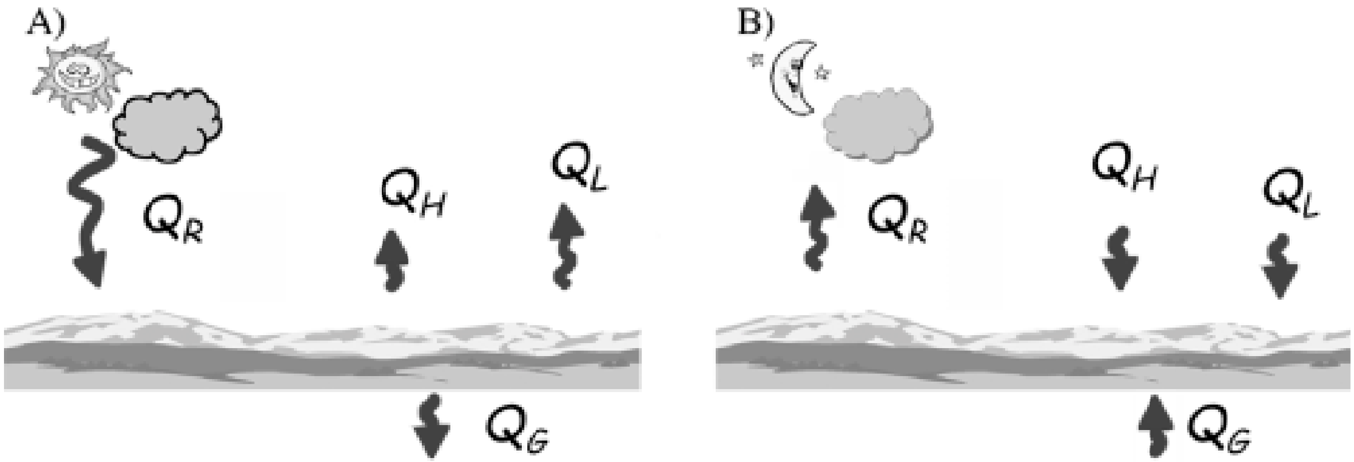

Figure 1. Typical surface energy balance during A) daytime, and B) nighttime. Arrows indicate typical direction of energy fluxes. Magnitudes vary throughout the day.

Radiation Measurement Program Cloud and Radiation Testbed (SGP ARM-CART; Stokes and Schwartz, 1994).

The Austin College Weather Station measures energy balance at the surface using an Energy Balance/Bowen Ratio (EBBR) technique (Campbell Scientific, 1998). The Bowen ratio β is the ratio of sensible heat flux Q_H to latent heat flux Q_L:

$$\beta = \frac{Q_H}{Q_L} = \frac{pc_p \Delta T}{L_v \varepsilon \Delta e} \quad (1)$$

where p is atmospheric pressure, c_p is specific heat of air at constant pressure, ΔT is the air temperature difference between two heights, L_v is the latent heat of vaporization, ε is the ratio of the molecular weight of water to the molecular weight of dry air, and Δe is the vapor pressure difference between two heights. Sensible and latent heat fluxes are not directly measured. Instead, the ratio of the two fluxes is calculated from pressure measurements, air temperature measurements at two levels, and vapor pressure measurements at two levels. This approach for calculating the Bowen ratio assumes similar transport of moisture and heat by turbulent eddies (Oke, 1987), a reasonable assumption considering the 1-m height difference between two measurements at the Austin College Weather Station.

The EBBR technique assumes that energy is locally balanced at the surface at all times:

$$Q_R + Q_G + Q_H + Q_L = 0 \quad (2)$$

where Q_R is net radiation (solar + infrared radiation) and Q_G is ground heat flux. Characteristic surface energy balance during day and night is shown in Figure 1. Positive values of energy flux indicate energy reaching the surface while negative values of energy flux indicate energy leaving the surface. At the Austin College Weather Station, Q_R is directly measured and Q_G is calculated from soil temperature, soil moisture, and heat flux measurements at 8-cm depth (Baker, 2003). The 8-cm soil measurement depth is typical for Campbell Scientific EBBR systems, so ACWX ground heat flux measurements represent heat transfer and storage in a shallow soil layer near the surface. Latent heat flux Q_L is calculated from net radiation, ground heat flux, and the measured Bowen ratio:

$$Q_L = \frac{-(Q_R + Q_G)}{(1+\beta)} \quad (3)$$

Sensible heat flux Q_H is then calculated from equation (2).

The EBBR technique for measuring surface heat fluxes does not require expensive vertical wind-speed measurements as does the eddy correlation method, another common technique for estimating energy fluxes (Oke, 1987). The necessary equipment for the EBBR method is relatively inexpensive. However, EBBR instrumentation must be maintained and frequently adjusted since very accurate measurements of air temperature and vapor pressure at two levels are required (Tindall and Kunkell, 1999).

Partitioning of energy into its various forms reveals much about local climate conditions. For example, strong sensible heat fluxes (large Bowen ratios) may indicate warm, dry surface conditions. Significant latent heat fluxes (small Bowen ratios) may indicate wet soils and strong evapotranspiration. Negative values of net radiation suggest radiative cooling at the surface under clear night skies. Rapid fluctuations in solar radiation may be caused by partly cloudy skies.

AUSTIN COLLEGE WEATHER STATION

Austin College, located 100 km north of Dallas in Sherman, Texas, is a highly selective liberal arts college with an enrollment of approximately 1300 undergraduates. The Austin College Weather Station is located on Austin College's Sneed Environmental Research Area approximately 16 km west of campus. Once farmland, the 100-acre Sneed property is currently undergoing restoration to native prairie vegetation. Hagerman National Wildlife Refuge is located directly west of the Sneed prairie. Thus, the Austin College Weather Station resides in a natural rural setting with minimal disturbance from encroaching Dallas-Ft. Worth urban sprawl.

The main objectives of the weather station are

- To provide reliable weather information for the Austin College and local communities,
- To measure the surface energy balance for land-atmosphere interaction research, and
- To involve undergraduates in high quality scientific research.

Measurement	Instrument	Height	Range	Accuracy
Meteorological Measurements				
Air Temperature	Campbell Scientific CS500 PRT detector	2.3 m	-40 to 60 °C	0.6 °C
Relative Humidity (Dew-point Temperature)	Campbell Scientific CS500 Intercap sensor	2.3 m	0 to 100% (0 to 60 °C)	3% (3.0 °C)
Barometric Pressure	Campbell Scientific CS105 Barocap sensor	2.0 m	600 to 1060 mb	2 mb
Precipitation	Texas Electronics TE525 Tipping Bucket Rain Gauge	1.0 m	025 mm/tip	3%
Wind Speed	RM Young 03001-5 Wind Sentry Set	3.0 m	0 to 50 m/s	2%
Wind Direction	RM Young 03001-5 Wind Sentry Set	3.0 m	0 to 360°	5°
Soil Measurements				
Soil Temperature	Campbell Scientific TCAV Averaging Thermocouple (2 sets)	-2.0 cm -6.0 cm	-30 to 50 °C	1.7 °C
Volumetric Soil Moisture	Cample Scientific CS615 Water Content Reflectometer	-4.0 cm	0.0 to 0.45	10%
Soil Heat Flux	Hukseflux HFPO15C Heat Flux Plate (2 plates)	-8.0 cm	-200 to 100 W/m^2	3%
Radiation Measurements				
Solar Radiation	Li-Cor LI200X Pyranometer	3.0 m	0 to 1800 W/m^2	5%
Net Radiation	REBS Q-7.1 Net Radiometer	1.0 m	-70 to 700 W/m^2	3%
Bowen Ratio Measurements				
Air Temperature	Campbell Scientific BR Thermocouples (2 sets)	1.3 m 2.3 m	-200 to 900 °C	0.006 °C
Dew-point Temperature (Vapor Pressure)	Campbell Scientific 023A Colled Mirror Dew Point Hygrometer	1.3 m 2.3 m	-70 to 60 °C (0.20 mb)	0.003 °C (0.1 mb)

Table 1. Instrumentation at the Austin College Weather Station.

The Austin College Weather Station utilizes state-of-the-art research instrumentation similar to that used by the National Weather Service (NOAA, 2005), the Oklahoma Mesonet (Brock et al, 1995), and the Salt Lake City 2002 Olympics (Horel et al., 2002). ACWX records standard meteorological observations including air temperature, relative humidity, dew point, wind speed, wind direction, barometric pressure, and precipitation (Table 1). In addition to these standard measurements, ACWX measures surface quantities such as soil moisture, soil temperature, solar radiation, net radiation, and soil heat flux. These additional quantities are used to calculate energy balance at the Earth's surface using the EBBR method. Purchased from Campbell Scientific, ACWX equipment (including sensors in Table 1, tripod, datalogger, modem, enclosure, solar panel, and PC software) costs approximately $14,000. A personal computer for downloading weather data added another $1,000 to the final cost. This project was funded through an Austin College faculty start-up grant.

A web site (http://weather.austincollege.edu) provides current surface and weather information for local communities. The web site contains an overview of the Austin College Weather Station, current weather conditions (including local radar and satellite images from the National Weather Service), instrumentation and measurement information, an introduction to surface energy balance theory, and a list of student research projects. In addition, links to the local weather forecast, regional sources for Earth system science data, and national laboratories and agencies are included. The Austin College Weather Station web site has a direct link from the Austin College home page. This link increases exposure of Earth system science to the casual visitor and provides a useful shortcut for the frequent user of ACWX information.

STUDENT LEARNING OUTCOMES

Undergraduate students established the Austin College Weather Station through collaborative and individual research projects in two upper-level special topics physics courses. In the spring 2001 *Establishment of the Austin College Station* course, students conducted a semester-long group research project to plan, install, and test the weather station. In fall 2001, students calibrated

Figure 2. Participants after final installation of the weather station (from upper left): David Baker (instructor), Colin Lindsay, Colby Dykes, Chris Perez, Ismael Avila, Phil Hayes (technician), Dilini Pinnaduwage, and Michael Entzminger.

and validated ACWX instruments in individual 7-week projects as part of an *Atmospheric Physics and Fluid Dynamics* course.

The following student learning outcomes apply to one or both phases of the Austin College Weather Station study. Because of the focus on inquiry and student-centered learning, students were given learning opportunities that span all six levels of Bloom's taxonomy: knowledge, comprehension, application, analysis, synthesis, and evaluation (Bloom, 1956). After participating in this project, a student should

Content

- Recognize basic meteorology principles, including relationships among wind, temperature, pressure, and water
- Understand basic soil properties, including soil texture, soil conductivity, and soil porosity
- Apply thermodynamics and heat transfer concepts, including phase changes, conduction, convection, and radiation
- Understand theoretical foundations and application of electronics
- Explain physical processes measured by specific instruments
- Recognize system interactions between land and atmosphere through energy and water exchange

Scientific Process

- Participate in collaborative research project from beginning stages to completion
- Utilize state-of-the-art research equipment
- Formulate scientific and technical questions and determine the best approach to address these issues
- Analyze scientific data in a real-world setting
- Integrate information from different instrument teams to guarantee proper functioning of the weather station
- Evaluate weather station measurements to assess uncertainties and to ensure proper accuracy
- Communicate research findings in oral and written formats
- Critique student proposals and research through peer-review process

ESTABLISHMENT OF THE AUSTIN COLLEGE WEATHER STATION (PHASE I)

The spring 2001 course consisted of two main components: American Meteorological Society *Online Weather Studies* modules (Moran, 2002) and a semester-long collaborative research project to establish the weather station. The class met twice per week. Once a week, we would have a standard lecture or discussion based on *Online Weather Studies* to obtain a solid foundation on basic meteorological and land surface concepts. Project team meetings occurred during the other class meeting time. The course contained three seniors and three juniors; each student would become an expert on two instruments on the weather station. The research project comprised 70% of the total course grade.

During project meetings, students would make important decisions regarding the weather station. Students posed essential questions (e.g., what are National Weather Service and Environmental Protection Agency measurement requirements?) and discussed potential solutions for the project (e.g., ways to meet these requirements). The instructor would facilitate the meetings and occasionally redirect the conversation, but students had significant input on the decision-making process. Together, we established project timelines and milestones. The optimum weather station site was chosen with assistance from a module developed by Desert Research Institute (1998). Students assessed power requirements of each instrument to ensure adequate power from the solar panel. We discussed data collection and storage options (data are downloaded every 20 minutes to a personal computer on campus). Students also debated telecommunications options, ultimately choosing a dedicated landline to communicate remotely with the weather station instead of cellular service due to poor cellular quality during heavy thunderstorms.

Prior to field setup, students needed to gain expertise on their instruments. They searched primary literature to identify strengths and weaknesses of our devices. Laboratory exercises on anemometer electronics and rain gauge accuracy were adapted from undergraduate laboratories developed at the University of Oklahoma (AMS, 2001). Perhaps most importantly, students visited the Oklahoma Mesonet site in Norman to observe a weather station with many of the same instruments as the Austin College Weather Station. They asked critical questions of the Mesonet meteorologist, and implemented changes to the ACWX process as a result of this meeting. Finally, students tested their instruments and conducted a mock setup in the laboratory before locating them in the field.

The final few weeks of the course were devoted to construction of the weather station. Students raised the tripod, mounted their instruments, and wired instruments to the datalogger (Figure 2). On April 27, 2001, the Austin College Weather Station recorded its first measurements.

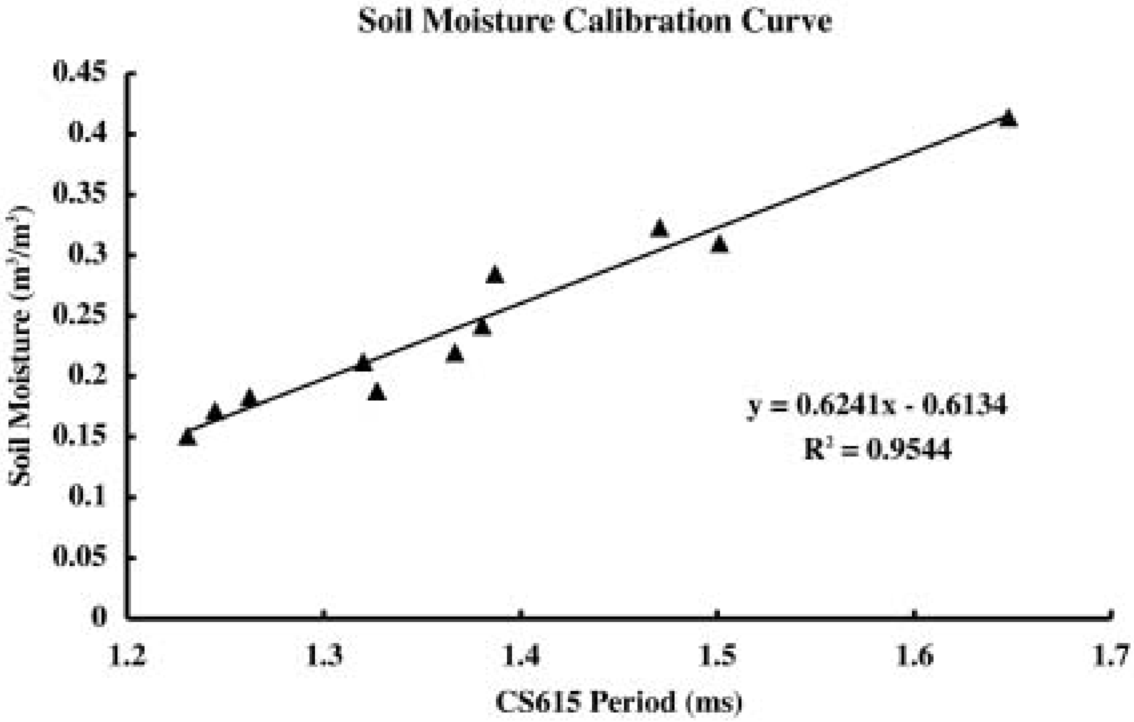

Figure 3. Soil moisture calibration curve for high clay content soil at the Austin College Weather Station.

Students communicated their research results through research papers and an oral presentation. Students wrote ten-page research papers on each of their instruments (two per student). Each paper described background on the physical process measured by the instrument, technical specifications of an instrument, and special considerations for ACWX-specific measurements. For example, the student paper on the net radiometer that measures Q_R describes surface energy balance, solar radiation, and infrared radiation. It then discusses technical aspects of the radiometer, including how the instrument measures radiation and how the radiometer voltage reading is converted to energy flux units of W m^{-2}. ACWX data collection, mounting height, maintenance requirements, and sample measurements are also presented. As a capstone, students gave a joint hour-long presentation on the project to the Austin College campus.

CALIBRATION AND VALIDATION (PHASE II)

In fall 2001, five student projects in an upper-level *Atmospheric Physics and Fluid Dynamics* course involved calibration and validation of ACWX instruments. Unlike the semester-long project that established ACWX, these projects took seven weeks to complete. Students wrote research proposals, peer-reviewed these proposals, conducted the proposed research, wrote a ten-page research paper, and peer-reviewed another student's paper. The projects provided valuable insight for students on the scientific process and communication of scientific ideas. These projects comprised 35% of the total course grade (the remaining 65% included homework, participation in class activities, and a fluid dynamics laboratory project).

One crucial calibration that resulted from these projects involved soil moisture measurements. Due to the high clay soil content in north Texas, the default laboratory calibration of the water content reflectometer was inadequate. Since soil moisture affects soil heat capacity (Campbell Scientific, 1998), soil moisture content can alter ground heat flux. Thus, accurate soil moisture measurements are necessary to properly calculate the surface energy balance. Soil moisture calibration utilized gravimetric techniques in which soil cores were sampled, weighed, baked to remove all moisture, and re-weighed. Water content values calculated from mass differences between original and dried soil samples were then correlated to raw reflectometer signals (Figure 3). The CS615 reflectometer raw signal is the time period (ms) for a high frequency pulse to travel the length of the reflectometer and back. Soil moisture affects the soil dielectric constant, which affects the travel time of the pulse. Volumetric soil moisture is the ratio of water volume to total volume of wet soil. This calibration reduced measurement errors from over 100% to 10%.

Another student research project resulted in purchase of a second temperature/relative humidity sensor. ACWX dew-point temperatures are measured using a chilled mirror hygrometer. Chilled mirror measurements are extremely accurate when properly maintained, but are also sensitive to contamination by particulates (Brock and Richardson, 2001). Validation studies showed that our dew-point temperature measurements occasionally disagreed, especially in the morning, with nearby dew-point measurements at the Grayson County airport. A new sensor (CS500; see Table 1) was installed to check the chilled mirror measurements. We now verify sensitive chilled mirror measurements with more stable (but less accurate) observations from the new sensor.

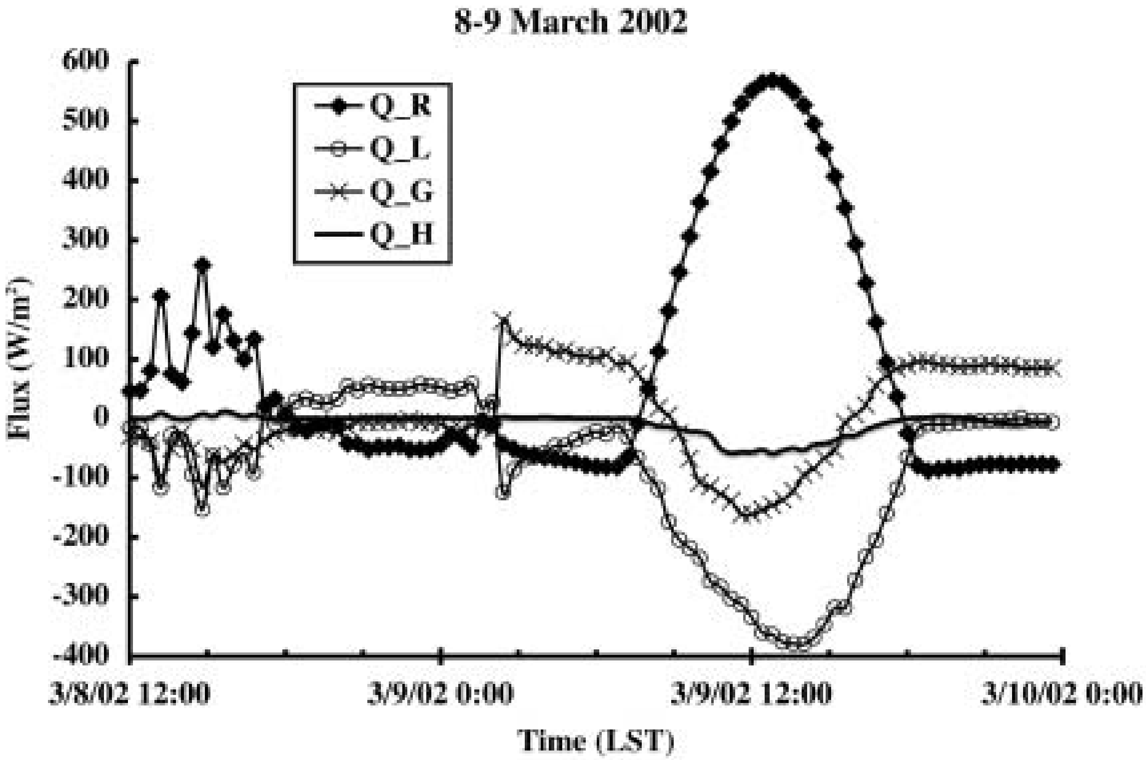

Figure 4. Surface energy balance at the Austin College Weather Station over a 36-hour period on 8-9 March 2002. Positive values indicate energy reaching the surface, and negative values indicate energy leaving the surface.

AUSTIN COLLEGE ENERGY BALANCE MEASUREMENTS

Figure 4 shows surface energy balance measurements from the Austin College Weather Station over a 36-hour period. Although these measurements occurred after student projects were completed in 2001 (calibrations were fully implemented in February 2002), they represent the culmination of months of student research. Cloudy conditions in the afternoon of 8 March 2002 produce fluctuations in net radiation Q_R. Latent heat flux Q_L and ground heat flux Q_G largely balance net radiation. Sensible heat flux Q_H is practically negligible during this time. At night, negative values of Q_R indicate radiative cooling and positive values of Q_L suggest condensation at the surface (relative humidity values of over 90% and 0.51 mm of rainfall were recorded).

In the early morning, a cold front passes through and alters the surface energy balance. Both Q_L and Q_G change sign rapidly. Dry, cold air at the surface allows for rapid evaporation (negative Q_L) and transfer of heat from deeper soil (positive Q_G). As the sun rises, energy fluxes assume classic features of clear day energy balance. Strong solar radiation input occurs during the day, driving large latent and ground heat fluxes. Again, very little energy is transported by sensible heat. Volumetric soil moisture measurements show large values of 0.32 m^3/m^3 (saturation occurs at 0.42 m^3/m^3). Partitioning of energy on this day is characteristic of grasslands with abundant soil moisture (Oke, 1987).

ASSESSMENT

Student learning outcomes were assessed in a variety of ways. Traditional evaluation instruments such as exams, homework assignments, and laboratory exercises were used to evaluate most content-oriented outcomes. For example, the AMS *Online Weather Studies* modules were utilized as graded homework assignments to assess recognition of basic meteorological principles. Two content outcomes (explain physical processes measured by specific instruments and recognize systems interactions) were assessed specifically through final project papers and presentations.

Scientific process learning outcomes were largely assessed through implementation evaluation, informal evaluation, final presentations, and project papers. These courses implemented a hands-on scientific method approach. Students participated in collaborative research using state-of-the-art equipment. In group meetings, students formulated scientific questions and determined the best approach. These opportunities are normally absent in standard courses. Throughout this process, the instructor informally assessed individual (and group) progress and provided appropriate feedback. Final presentations were formally evaluated on the quality of content and communication delivery. Students reviewed other students' proposals and papers using a standardized peer-review form. They were graded on the quality of their reviews of another student's work.

Questions from Course Evaluation	The professor encouraged me to ask questions and think critically.	In comparison with other courses, how much have you learned in this course?	How does the professor's overall teaching effectiveness compare to that of other professors you have had?
Establishment of the Weather Station (Spring 2001; semester-long collaborative project)	Class Mean: 7.0 College Mean: 6.0	Class Mean: 7.0 College Mean: 5.2	Class Mean: 6.8 College Mean: 5.2
Atmospheric Physics and Fluid Dynamics (Fall 2001; 7-week individual projects)	Class Mean: 6.8 College Mean: 5.9	Class Mean: 5.2 College Mean: 5.2	Class Mean: 5.6 College Mean: 5.1

Summative assessment of individual student learning occurred through final project papers and through a faculty review panel. The final project paper synthesized content-oriented outcomes with process-oriented outcomes. For example, basic meteorological content, electronic foundations, analysis of scientific data, and evaluation of measurements were all addressed in the final paper. Papers were graded with student learning outcomes in mind. Furthermore, a panel of three faculty members (including the instructor) assessed student research presentations. The faculty members attended the presentations as regular audience members but met afterward to discuss the presentations. In particular, the panel reflected on basic content knowledge (expertise) of each student, quality of analysis and uncertainty, and ability to communicate scientific ideas (delivery, confidence, and appropriate detail). Panel feedback was used to assign presentation grades.

Although a formal assessment comparing project-based learning with more traditional approaches was not performed, student course evaluations provide some insight on the effectiveness of these projects. At Austin College, student course evaluations consist of two components: an objective Likert scale (1-7) section with specific questions and an unprompted written comment section (i.e., students can offer written feedback on any aspect of the course). The overall learning experience in both courses was positive (Table 2). The first course recorded exceptional scores for critical thinking, quantity learned, and teaching effectiveness. While still positive, lower evaluations on the second course were most likely caused by an overzealous professor requiring too much work. Individual weather station projects in the second course should have been a larger percentage of the final grade (70% instead of 35%). In addition, establishing a new weather station is considerably more fun for most students than calibrating it. Specific student written comments related to the projects include:

Spring 2001

> "This was a great class and a great experience for me. It was the first time I have had a chance to participate in research. It was really nice to be able to participate actively in all aspects concerning the weather station."

> "The project design of this course was unique and challenging…ultimately, I'm glad I didn't miss out on this. It was worth it."

> "It was hard work, but it was really fun. I would recommend this class to anybody."

Fall 2001

> "I know that I will be pursuing research in the future, so this experience was very beneficial."

> "The projects were difficult and extremely time consuming."

> "I appreciate the experience I gained in scientific writing…that will be one of the main things I will take away from the class."

DISCUSSION

To inspire the next generation of Earth system scientists, educators must provide opportunities for undergraduate students to do science rather than merely to hear about it. Students need to observe, question, hypothesize, analyze, and evaluate. Instead of only doing simple "recipe" laboratory activities, students need to explore more complex problems with interacting components. They need to be given opportunities to explore real-world problems in which the answers are currently unknown or uncertain. Students need to be granted ownership of their learning. They need to be able to communicate their scientific ideas in written and oral forms.

The weather station project described here accomplished these goals. Through investigation of surface energy balance, students explored complex interactions of the Earth system. In the first phase (establishment), students made important decisions on project design and implementation. They assessed and re-assessed the plan throughout the project. They became experts on two instruments, and were able to effectively present their results to a faculty audience. In the second phase (calibration and validation), students participated in the complete scientific process of proposal writing, research manuscript writing, and peer-review. Each individual project had a direct, real-world application. Results from these projects confirmed the accuracy of existing sensors, produced new calibrations, or resulted in the purchase of new instruments.

Student learning outcomes for both content and scientific process were assessed in a variety of ways. In addition to traditional evaluation instruments such as exams, homework, and laboratory activities, less traditional evaluation tools such as proposal writing and peer review were used for formative assessment. However, interactions during student meetings provided the most useful feedback for students. During these times, the instructor could recognize students' level of understanding and offer suggestions in a low-risk (ungraded) situation. Learning occurred naturally in this setting, with open questioning, a free exchange of ideas, and informal yet authentic assessments.

A faculty review panel of student presentations offered essential feedback for summative assessment of student learning. In addition to the instructor, two faculty members served as external reviewers on the panel. External faculty members provided useful perspectives on student expertise levels, quality of analysis, and presentation style. In addition to helping with grade assignment, panel feedback was communicated to students through the instructor. Given the added value of external assessments, the Austin College physics department continues to use faculty panels to review student presentations.

Overall, the weather station projects were quite effective in meeting student learning outcomes. Importantly, the weather station was successfully established and students could use measurements to learn about Earth system interactions. Although students would have still learned about the scientific process, failure to create a working weather station would have diminished the learning experience. Student course evaluations suggest that project-based learning promotes critical thinking, quantity learned, and teaching effectiveness. Although the projects were time-consuming and challenging, students enjoyed the opportunity to participate in research. Students had fun in these courses, which may be the most important element for a positive and influential learning experience.

Although the weather station projects were very productive, the learning experiences could be improved even further. First, individual projects in Phase II (calibration and validation) would encompass the entire semester rather than only seven weeks. Undergraduate students need more time to assimilate information, collect data, make mistakes, and synthesize results. This ambitious requirement in a short time frame likely diminished the learning experience. Second, individual projects could have been collaborative projects instead. There are significant benefits to collaborative work: informal communication of scientific ideas, stronger interdisciplinary focus, group research that builds on individual strengths, responsibility to peers, etc. Conversely, the peer review process may have become weaker with collaborative projects given the small number of students in the class. Finally, it would be useful to contact students now to assess the long-term impact of these projects. Informal conversations with former students have yielded comments like "easily my favorite course" and "a much richer experience integrating concepts and applications". A more systematic survey could provide useful data on the long-term effectiveness of project-based learning.

Based on the Austin College experience, there are a few key elements required for successful project-based learning of this scale. First, adequate funding must be in place at least six months prior to the course. Because of substantial upfront costs, faculty start-up funds or external funding is necessary. Second, equipment must be purchased prior to the beginning of the course. Although it would be a useful exercise for students to be involved in sensor selection, the purchasing process takes about two months. Third, the number of students involved in the project should be limited in size to allow for adequate participation and feedback. In our case, six students participated in the first course and five students participated in the second course. Finally, students should be self-starters and should work well with others. Initiative and collaboration are crucial for a successful experience.

Benefits of the undergraduate weather station go well beyond the original classroom experience. The Austin College Weather Station has three main objectives: to provide reliable surface and weather data, to measure surface energy balance, and to provide students with unique research opportunities. These objectives have been largely met. The Austin College community uses ACWX measurements to obtain current weather conditions. The web site has been used frequently in other regularly offered Earth system science courses at both the introductory and advanced levels. Hagerman National Wildlife Refuge has used ACWX measurements to monitor surface conditions during preventive fire burns. Twelve student research projects, including two senior honors theses and a summer undergraduate research experience, have utilized ACWX measurements.

In spring 2006, a new course entitled *Earth, Atmospheric, and Environmental Physics* will be offered. Supported by NASA and Universities Space Research Association's Earth System Science Education for the 21st Century (ESSE 21) program, this course will utilize the semester-long collaborative research project approach. Replacement sensors (at a cost of approximately $4000) will be installed on the weather station, and students will use energy balance measurements to understand land-atmosphere interaction during dry and wet conditions. As part of the course, students will design and participate in a two-week intensive field measurement campaign. This student learning experience promises to be as rewarding as the original Austin College Weather Station projects.

ACKNOWLEDGMENTS

I would like to acknowledge the following students for their dedication and hard work on the weather station projects: Ismael Avila, Kelly Dobson, Colby Dykes, Mark Eichenberger, Michael Entzminger, Jonathan Laib, Colin Lindsay, Chris Perez, Dilini Pinnaduwage, and Tru Robertson. Philip Hayes and Doug Hotalen have provided valuable instrumentation support for the Austin College Weather Station. This work has been funded by Austin College Faculty Research and Austin College Cullen grants.

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