

BRIDGING THE GAP BETWEEN THEORY AND APPLICATIONS

AN INQUIRY INTO ATMOSPHERIC SCIENCE TEACHING

BY PAUL J. ROEBBER

An exploration of the role of mismatches between student learning styles and that implicit in curricular design was conducted with the objective of identifying methods for improving student learning and retention.

THE PROBLEM. It is widely understood that the atmosphere exhibits chaotic dynamics, a characteristic that imposes finite limits on predictability, regardless of the adequacy of the prediction model (Lorenz 1963; Leith 1974). In practice, imperfections in the weather prediction models themselves, as well as errors in observations, contribute to the growth of the instabilities that ultimately limit forecast accuracy (e.g., Houtekamer et al. 1996).

As noted by Shulman (1999), a teacher can teach in the same manner to three classes in a row and experience different results each time. This lack of predictability in teaching outcomes is likewise the

result of combined uncertainties—those of the initial state of the students (such as prior knowledge, learning style, innate ability, and motivation) and the teaching model that is employed. As with weather forecasting, interactions between uncertainties in the student state and the imperfect teaching model ultimately limit learning.

Again, as in weather forecasting, there is a certain degree of inevitability to this consequence, so one might reasonably ask whether it is a cause for concern. It is worth noting, however, that the number of bachelor's degrees awarded in the physical sciences declined by 20% from 1981 to 1995 (NCES 1998), despite growth in the overall population of undergraduates in all fields. Vali et al. (2002) document declines in the number of undergraduate and M.S. degrees awarded in the atmospheric sciences from 1995 to 2000 and a substantial decrease in the number of applications to graduate departments in the field during this period. This corresponds to difficulties worldwide in recruiting students to the environmental sciences (Brasseur 2000). While there are many reasons for such difficulties, and legitimate concerns regarding current and future demand for graduates in the atmospheric sciences (e.g., Mass 1996; Pielke

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2003), it is clear that under no circumstances should the community tolerate practices that diminish learning in our programs.

Despite this, there is the perception (since no comprehensive data exist) that attrition rates in undergraduate meteorology programs are high. For example, in the quantitatively oriented atmospheric science program within the Department of Mathematical Sciences at the University of Wisconsin—Milwaukee (UWM),¹ the undergraduate attrition rates for the period 1998–2001 was 52%. This rate is consistent with those found throughout the United States in the sciences, mathematics, and engineering (National Research Council 1995; Felder et al. 1998; Center for Institutional Data Exchange and Analysis 2000). Are these attrition rates then simply the price of doing business in a demanding discipline or do they in part reflect teaching practice? To put it another way, can we expect to improve this situation by improving our teaching or are we already operating at the practical limits to achievable learning?

To answer this question, we must understand the student initial state and its interactions with prevailing teaching models. As noted above, the student state is composed of the following several factors: prior knowledge, learning style, innate ability, and motivation. Simply put, students are not empty vessels waiting patiently to be filled with knowledge; new learning must connect with what students already know (Shulman 1999). To connect, it is important to employ teaching strategies that account for the range of student learning styles (see below) present in a given classroom (Knox 1986; Felder 1993; Felder et al. 1998). Finally, innate ability and motivation can do much to overcome limitations in the other factors,

while conversely, the lack of skill or drive can incapacitate even the best learning environment.

At many universities, the research culture exerts a powerful influence on the classroom experience. The primary model for postsecondary education is the professor as scholar rather than teacher (Stenberg and Lee 2002). Positive effects include enhanced knowledge currency, credibility, and competence in supervision. In teaching, this model assumes that understanding is equivalent to mastery (Bass 1999). Undergraduates, however, lack the broader disciplinary perspective that comes about only when true understanding is achieved, and as a result, their grasp of the connections between theory and practice often remains weak. This lack of connection is not an obstacle to students who value the acquisition of knowledge for its own sake and are thus willing to defer application until much later. But is this an accurate description of our students?

Felder and Silverman (1988) and Schroeder (1993) have collected considerable information on the learning styles of students and faculty. Learning styles are multidimensional [i.e., there are many facets to learning (e.g., Felder and Silverman 1988)] but can be broadly categorized into a relatively few “types.” Nonetheless, in a given class, an instructor will be confronted with the full array of student learning styles. Data from a variety of sources indicate that a substantial discrepancy in learning styles exists between current students and faculty. Students tend to be goal oriented, preferring direct, concrete experiences in a practice-to-theory route, while faculty tend to be abstract, conceptual learners who focus on the world of ideas, preferring traditional theory-to-practice. Schroeder (1993) suggests that curricular design reflects the preferred learning styles of faculty. This lack of congruence between instruction and the aptitudes of the students can lead to suboptimal learning (Cronbach and Snow 1977; Snow 1989).

This is not equivalent to suggesting that faculty abandon their leadership role in the classroom. Felder and Silverman (1988) note that for technical disciplines, the addition of a fairly small number of teaching techniques to the traditional approaches is sufficient to accommodate the breadth of learning styles. For example, Knowles’ (1984a,b) theory of andragogy emphasizes that adult learners need to understand the motivation for learning something, need to learn experientially, and learn best when the topic has some immediacy and is approached as problem solving. Felder (1989, 1993) has shown that learners who exhibit these traits are more prone to being weeded out by a curricular design that does not ad-

¹ UWM is an urban university with a student population of approximately 25 000 (78% undergraduate; 56% female; average age 25). The student body is racially diverse, with a 17% minority population. The National Survey of Student Engagement (NSSE; Kuh 2001) seeks to survey undergraduate students on issues related to effective educational practice (e.g., Chickering and Gamson 1987). The survey is intended to provide information on the extent to which students at universities are participating in educational practices that are strongly associated with high levels of student learning and hence provide information to institutions seeking to improve the quality of undergraduate education. The results from 2000–02 indicate that students at UWM are engaging as much as would be predicted, based upon institutional and student characteristics. Hence, the attrition rates reported here are not likely to deviate substantially from those at other institutions.

dress these requirements, even though they are just as likely as other learners to succeed in scientific careers if they persist. Concrete suggestions for overcoming these limitations by “teaching around the learning cycle” (i.e., providing learning opportunities geared toward a range of learning cycles at different times throughout a course) are provided at the end of this article (see examples in the discussion section).

What about innate ability? Although it is difficult to quantify, ability is clearly a critical element in determining student success. Hence, a reasonable (and perhaps, convenient) explanation for high attrition rates is to dismiss the academic abilities of those who leave the discipline. A skeptic might argue that one can correlate the number of students in a major with the average grade given in that field of study. It has been shown in engineering and mathematics, however, that there is little difference in academic

status between those who stay in the field and those who leave it (Hewitt and Seymour 1991; Seymour and Hewitt 1994; Besterfeld-Sacre et al. 1997). The explanation for the dissatisfaction instead appears to be tied to a complex set of factors that relate directly to student classroom experience, such as self confidence, and the quality of interactions with instructors and peers both in and out of class (Boshier 1973; Cross 1981; Seymour and Hewitt 1994; Felder et al. 1998).

These notions return us to the connections between theory and practice in atmospheric science. Rossby (1934), one of the founders of modern meteorology, wrote, “The principal task of any meteorological institution of education and research must be to bridge the gap between the mathematician and the practical man, that is to make the weather man realize the value of a modest theoretical education

TABLE 1. Three dimensions of learning styles (active/reflective, sensing/intuitive, and sequential/global), based on the results of the Felder learning-style questionnaire for UWM students, former students, and faculty. Preferences within each of the eight resulting learning styles are listed.

	Active		Reflective	
	Sequential	Global	Sequential	Global
Sensing	Preferred information is external, in the form of sights, sounds, and physical sensations. Information is processed through engagement in applications or discussion. Progress toward understanding is achieved in logical steps.	Preferred information is external, in the form of sights, sounds, and physical sensations. Information is processed through engagement in applications or discussion. Progress toward understanding is holistic, occurring in jumps.	Preferred information is external, in the form of sights, sounds, and physical sensations. Information is processed through introspection. Progress toward understanding is achieved in logical steps.	Preferred information is external, in the form of sights, sounds, and physical sensations. Information is processed through introspection. Progress toward understanding is holistic, occurring in jumps.
Intuitive	Preferred information is internal, in the form of possibilities, insights, and hunches. Information is processed through engagement in applications or discussion. Progress toward understanding achieved in logical steps.	Preferred information is internal, in the form of possibilities, insights, and hunches. Information is processed through engagement in applications or discussion. Progress toward understanding is holistic, occurring in jumps.	Preferred information is internal, in the form of possibilities, insights, and hunches. Information is processed through introspection. Progress toward understanding is achieved in logical steps.	Preferred information is internal, in the form of possibilities, insights, and hunches. Information is processed through introspection. Progress toward understanding is holistic, occurring in jumps.

and to induce the theoretical man to take an occasional glance at the weather map.” As is apparent from the previous discussion, we continue to struggle with this issue many decades later, and the failure to address the problem may have direct and serious consequences for the profession. The following sections present a local analysis of this issue and general recommendations for improvements.

METHODS. As a means of organizing the inquiry, the following propositions are formulated and tested:

- P1) Students and faculty can be broadly classified as either goal seeking or knowledge seeking. Most meteorology students, as in the general population, qualify as the former. Most faculty fall into the latter category.
- P2) Goal seekers are more likely to be confronted with and challenged by an apparent disconnect between theory and practice.
- P3) Faculty views tend to reinforce existing modes of operation, reflecting the lack of rewards for exceptional effort expended in the teaching arena. Students advocate the need for teaching reforms that emphasize the relevance of coursework to real-world applications. Responses from both groups reflect individual learning styles.

Open-ended interviews elicited the opinions of past and present students and faculty. Interviewees included students enrolled in the early stages of the program (juniors, the first year in which substantial core discipline learning can take place at UWM), seniors, graduate students, and recent graduates now employed in the field (National Weather Service). The interviews of faculty showed where student and faculty perceptions agree and where they diverge.

The interviews commenced with administration of the Felder Index of Learning Styles Questionnaire. This consists of a series of 44 questions that allow the measurement of particular learning skills and competencies on the following scales: active/reflective; sensing/intuitive; sequential/global; visual/verbal (Felder and Silverman 1988; Felder 1993, 1996). Analysis of the data reveals that all respondents in the survey possess a visual preference; hence, the Felder learning style matrix is collapsed to the first three dimensions, representing eight possible learning styles (Table 1). The reflective–intuitive–sequential mode describes the predominant learning style emphasized in most lecture-based science courses (e.g., Felder 1993). In contrast, laboratory courses, decidedly a minority of the curricular choices (e.g., laboratory-based credit hours represent approximately 13% of the total credit load in preparatory, elective, and core courses for UWM atmospheric science majors), favor active–sensing–sequential modes of learning.

Following the survey, a set of eight questions (see appendix) guided the interview through assessment of professional background, to expectations and experiences in atmospheric science education, to probing of a knowledge-seeking vision. Transcripts of the interviews were made and were coded independently by two individuals for analysis using qualitative research techniques.

RESULTS. The results of the learning style survey (Table 2) demonstrate that most students (faculty) lie within the sensing (intuitive) learning style. Given the description of sensing versus intuitive learning styles (Table 1), this

TABLE 2. Results of the Felder learning-style questionnaire for UWM undergraduates (U), graduate and postgraduate students (G), and faculty (F). Also shown are the learning styles for the sample, stratified according to students and postgraduate students (S) and faculty (F). Total sample size is 17.

	Active		Reflective	
	Sequential	Global	Sequential	Global
Sensing	U 44%	U 11%	U 0%	U 11%
	G 25%	G 0%	G 50%	G 25%
	F 0%	F 0%	F 0%	F 25%
Intuitive	U 0%	U 0%	U 22%	U 11%
	G 0%	G 0%	G 0%	G 0%
	F 0%	F 0%	F 25%	F 50%
Sensing	S 39%	S 8%	S 15%	S 15%
	F 0%	F 0%	F 0%	F 25%
Intuitive	S 0%	S 0%	S 15%	S 8%
	F 0%	F 0%	F 25%	F 50%

finding is consistent with the proposition (P1) that students and faculty represent two solitudes—goal seeking in the former case, knowledge seeking in the latter case. Notable differences in active/reflective and sequential/global learning styles are also apparent, with faculty biased toward reflective and global learning relative to students. Hence, the curricular design seems to reflect the learning style of faculty rather than students, as suggested by Schroeder (1993).

The interviews are also analyzed. The coding of statements in the interviews is based on the following nine themes that emerged from the conversations (opposites in parentheses): disconnect (connect), goal (knowledge), satisfaction (dissatisfaction), change (status quo), and gaining experience. The theme of disconnect (connect) is subdivided into occasions related to expectations prior to and during actual involvement in meteorological education. For example, the surprise of a student upon entry into a meteorology program concerning the extent of the mathematics requirement would be a “pre” disconnect. These nine themes relate directly to the issue at hand: Can we improve satisfaction in our program by removing barriers to understanding imposed by our methods of teaching the science?

A quantitative assessment of the importance of these themes to the several interview categories (faculty, etc.) is obtained by counting the percentage of the total number of sentences from each interview subject devoted to each of the themes (this method

allows for some measure of the emphasis that an individual might place upon a particular topic, while protecting against biasing the data with the observations of someone who is particularly verbose). The three key negative themes of disconnect, dissatisfaction, and change are plotted (Figs. 1 and 2). Undergraduates, who tend to be goal oriented, show the largest disconnect, the largest dissatisfaction, and the largest interest in change (Fig. 1). Graduate and postgraduate students also tend toward goal orientation, but have lower negatives than undergraduates, suggesting that a transition associated with maturation and/or educational experience may be occurring (an alternate explanation, however, that increased distance from the difficulties of undergraduate coursework may be leading to a form of selective amnesia in this group, cannot be discounted). The sizeable faculty negatives (the themes of dissatisfaction and change are the largest of all groups) indicate recognition of a problem and interest in solutions (but see below). A split of undergraduates into goal- versus knowledge-oriented cohorts (Fig. 2) shows that the former are more disconnected and dissatisfied, but that support for change is large in both groups.

These results support the proposition (P2) that goal seekers tend to be confronted with and are challenged by an apparent disconnect between theory and

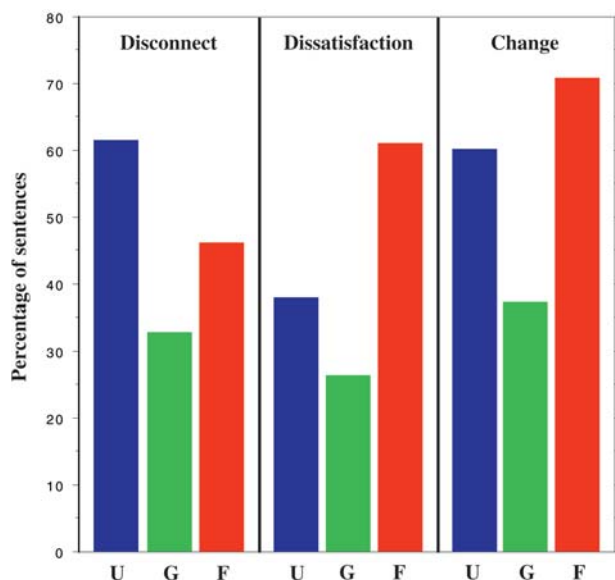


FIG. 1. The percentage of interview sentences devoted to the themes of disconnect, dissatisfaction, and change by undergraduates (blue), graduate and postgraduate students (green), and faculty (red).

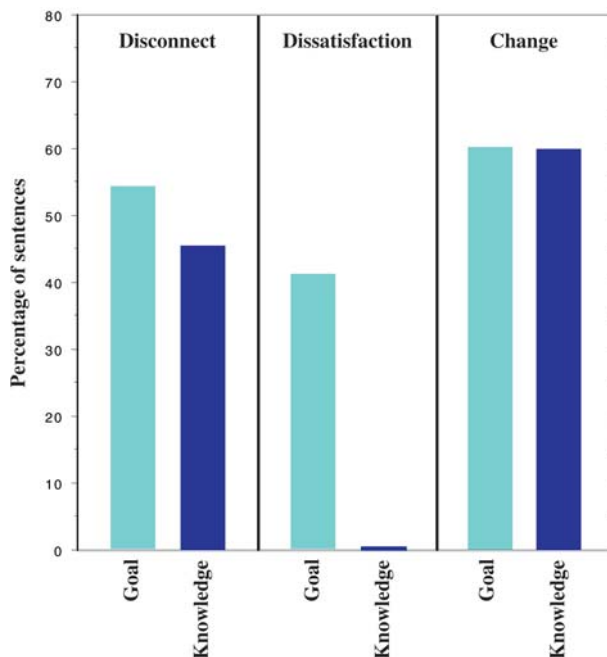


FIG. 2. The percentage of interview sentences devoted to the themes of disconnect, dissatisfaction, and change by goal-oriented undergraduates (light blue) and knowledge-oriented undergraduates (dark blue).

practice, but this notion is modified by the finding that some of the disconnect may be alleviated with student advancement, *regardless of specific learning styles*. Given that this finding may be interpreted less favorably as noted above, however, it would be unwise to focus all efforts on undergraduate curricular modification. The proposition (P3) that faculty views will tend to reinforce existing modes of operation is not supported by the data. Faculty are evidently *less satisfied than students* with the current state of atmospheric science education and open to change. Their reasons, however, may depart significantly from those of the students, as suggested below.

An exploration of specific student and faculty comments helps to illustrate these issues and evaluate possible solutions. A faculty member remarked:

Some students are just unable to make the leap from abstract simple systems to complicated. They just don't get the initial step of why we are interested in an abstract system. So it might not work for everyone, but then again, science is not supposed to work for everyone.

For this faculty member, the problem is posed in terms of the capabilities of the students (student state—innate ability). Yet, as noted previously, this disconnect may also reflect a learning style issue. Students, who tend to be active-sensing rather than reflective-intuitive, may need to be motivated to overcome their tendency to avoid abstraction. Practical examples where the relationship of the simplified systems to the complexities of the real world could be emphasized. A second faculty member expressed a related frustration:

When we derive something on the blackboard, they will understand the steps. When the professor does it, they understand. But when they try to do it themselves, they don't. It is easy when the professor does it on the blackboard, but when they try to do it themselves, there is a problem, and that indicates that their background is not very strong.

Here, the problem is viewed as one of insufficient preparation (student state—prior knowledge) and hence shifts the issue to outside of the discipline. Again, however, a learning style issue may play a role. The abstraction of mathematical symbols can be rendered less daunting by demonstrating the connection of these manipulations to physical meaning. Within faculty ranks, there was a divergence of opinion as to the relevance of the theory, as presented:

The theory is sometimes too simple and is inadequate to explain all the complexity of the observations and that makes it difficult to bridge that gap even for practicing researchers . . . there are theories that are gross simplifications and so are hard to show that it has any direct application at all.

In this instance, it is arguable as to whether such a gross simplification is worthy of study. Certainly, no researchers would publish a paper that could not be shown to have some relevance to the field. A former student, now professionally employed, expressed a continuing confusion that is tied directly to this failing:

I found myself not understanding parts of equations because I couldn't relate them to anything in the real world. It was explained with symbols and such but I tried to visualize it with a weather map or with an upper air chart. That is where I would get stuck.

Teaching style contributes a great deal to this disconnect. One faculty member expressed a view of how connections can be made:

We are looking at the math because everything starts with the equations and then we end up with the final stability criterion. But we go through this so that everything is understood, not just from the mathematical point of view but also from the physical point of view. For example, the equation of motion. We derive a stability criterion. And then, what will be the first entry in this equation of motion. From that, we will derive the criterion. So there is physics and math, together.

This idea, in which mathematics is the language to express physical reality, is straightforward to reflective-intuitive thinkers. To the active-sensing student, however, the absence of specific physical examples is a barrier to understanding, as noted by this former student:

We did equations all the time, derivations constantly, so we would think about why we were doing this. Spent five days doing a derivation, all math all the time, and wondering why were we doing that?

An evidently goal-seeking undergraduate elaborated further:

We're taught equation one and then equation two... we're just told this is equation one and this is equation two, derived from one. Do you understand?

And that's it. Some teachers directly relate theory and general application and some absolutely don't and from my perspective, that makes it very difficult. But this is meteorology: it always has a direct application to the weather. Our field is obvious, visual, everyday scenarios, and for that reason, I think that every single thing you talk about has a direct connection.

Another faculty member summarized the situation this way:

Application without theory has no direction. But theory without application is pointless. So, it is important for theoreticians to be exposed to real data, just as those working with data need to have a solid understanding of the theory. Our program has no guidance on how to blend these features. This view is not shared by all atmospheric science faculty, and consequently, the blend of theory and practice is uneven across the curriculum.

Despite these divergent views, a possible solution to the disconnect emerged from the discussion. Support for a change to the existing teaching mode, involving a radical reorganization of the curriculum (see question 8 in the appendix) is weakest among students and strongest among practitioners and faculty (27%, 50%, and 63% in favor, respectively). The support, however, grows dramatically when less radical forms of reorganization are considered, such as a capstone or graduate-only course offering with a case-study emphasis (63%, 100%, and 100% in favor, respectively). Undergraduates are less supportive of such changes than graduate students (56% versus 100%), suggesting that students may need to gain comfort with the material before showing willingness to experiment. This is consistent with the modes of learning theory proposed by Rumelhart and Norman (1978, 1981), which specifies three modes of learning: accretion (the addition of new knowledge to existing memory), structuring (the formation of new conceptual structures for organizing knowledge), and tuning (adjustment of knowledge to a specific task, such as in expert performance). In the context of atmospheric science education, accretion constitutes the initial learning of meteorological terminology and basic equations. Learning the physical basis of the equations represents structuring, while the ability to apply those mathematical-physical models in a realistic setting represents tuning. Students, particularly undergraduates, who are still in the accretion mode of learning, are not prepared for the structuring and

tuning that would be required in a curriculum centered on case studies.

Learning style was also highly relevant, with knowledge seekers generally more supportive of a case-study-driven learning process (67% versus 55%). These responses make it clear that a radical reorganization of the curriculum is not warranted, but that a careful introduction of physical examples and case-study methods into existing undergraduate courses would be helpful. Further, it is clear that such methods should be used widely at the graduate level as well.

DISCUSSION. A study designed to explore methods to improve atmospheric science instruction was conducted. A series of learning-style surveys and open-ended interviews were administered to past and present students and faculty. Analysis of the data in the light of existing research on learning reveals the following salient points:

- attrition rates in the UWM program (52%) are consistent with published rates across the United States in the technical disciplines;
- as noted in the literature for other places and fields, the predominant learning styles of students and faculty diverge substantially;
- curricular design is consistent with faculty rather than student learning styles;
- available research suggests that a mismatch between teaching style and the learning styles of students negatively affects student success;
- among students, undergraduates showed the largest negative responses to existing modes of operation and the most interest in change;
- faculty also showed considerable discomfort with existing modes and substantial support for change, although their rationale for this support may depart from those of students;
- support for a radical reorganization of the curriculum toward a case-study-driven learning process is weak, particularly among undergraduates; increased emphasis of physical examples and case studies within the existing curricular framework is supported, both for upper-level undergraduates and graduate students.

Is it possible to overcome this mismatch between the learning styles of students and that assumed by the curricular design, given Dutton's (1986, p. 7) admonition that "Pedagogy in the atmospheric sciences must somehow combine motivation, development of intuitive understanding of the atmosphere in motion, and

progress toward the mathematical maturity required for the effective use of the laws of atmospheric motion?” Felder (1993) suggests an approach, arguing that it is not necessary to ascertain the learning styles of students in a specific class and then teach to that style, but rather to address the full range of learning styles that might exist. This balanced approach would ensure that students are sometimes taught in a manner that matches their learning styles and are sometimes compelled to strengthen their less developed abilities. Furthermore, since the intuitive, reflective, and sequential learning-style dimensions are adequately addressed in traditional science teaching, the systematic use of a small number of additional teaching methods will address the sensing, active, and global categories. These methods include the following:

- motivating the presentation of theory with examples of real problems that the theory can be used to understand;
- providing concrete information (such as descriptions of atmospheric phenomena, graphical illustrations of experimental or simulation results, numerical examples, and demonstrations) to balance the theories and mathematical models that will be presented;
- providing time in class for active student participation;
- encouraging students to work in teams on assignments;
- pointing out the connections between current material and previously presented material in the same course, in other courses in the major, in the other physical sciences, and in everyday experience.

How might this be achieved, in practice? Consider potential and equivalent potential temperature, variables that would certainly arise in a discussion of thermodynamics. Before writing down Poisson’s equation (*theory*), one might set the stage for the discussion by first considering the problem of height as a vertical coordinate. Although natural, the use of height as a vertical coordinate suffers from the fact that it does not behave as a material surface (*motivation*). This can be amply demonstrated by showing examples of transport of readily identifiable quantities such as moisture or pollutants, noting the sudden appearance of these quantities at a specific level owing to vertical motions (*concrete information, connections*). This shows the usefulness of a coordinate upon which material, given the absence of heating or cooling, is only rearranged by the horizontal wind (*motivation*).

The derivation of Poisson’s equation (*theory*) would then follow from this discussion. A further demonstration of the conservation of potential temperature could be made through reference to pseudoadiabatic charts, for example, by showing a dry parcel ascent and descent across a mountain range. Such transits can be found in the observations, when relatively dry air masses pass across the Rocky Mountains (*concrete information, connections*), and could be conducted as in-class assignments (*active student participation, student teams*).

Since latent heat release is a primary physical mechanism for nonconservation of parcel potential temperature, it is useful at this point to introduce equivalent potential temperature as a conservative quantity for pseudomoist adiabatic processes (*theory*). Conservation under such conditions (*motivation*) could be presented, for example, through reference to air parcel trajectories from numerical model simulations under conditions of saturated ascent (*concrete information, connections*). A further demonstration could be made with reference to saturated ascent on pseudoadiabatic charts, perhaps by following moist parcels ascending and descending across a very high mountain range such as the Himalayas (*concrete information, connections*). Such analyses could again be conducted as in-class assignments (*active student participation, student teams*).

A key challenge in teaching dynamic meteorology is helping students develop the physical intuition that is necessary to connect the incredible complexity of the real atmosphere to simplified models that nonetheless retain the essential physics. These models start with assumptions about what is physically important, and the models follow from logical inference expressed in the form of mathematics. For example, the equations of motion in spherical form, the first law of thermodynamics, the continuity equation, the equation of state, and a water substance equation, subject to the approximations imposed on their derivation, represent a complete model of the atmosphere. These equations can then be modified using a variety of simplifying approximations, based upon the problem to be considered. Scale analysis of these equations for large-scale atmospheric motion in midlatitudes will yield the hydrostatic set of equations (e.g., Dutton 1986, 234–235). Curvature of the earth can be incorporated (beta plane, periodic in x), but how does one convince a class of undergraduates that the neglect of friction, vertical accelerations, and water substance does not invalidate this model?

We might start by an examination of the salient properties of a midlatitude cyclone (*motivation*), then

conduct the scale analysis with these parameters in mind (*theory*). Once the model is derived, we would return to the properties of the cyclone (*motivation, concrete information, connections*), noting where the model description works, and where there are deviations (frictional turning of boundary layer winds, the presence of clouds and precipitation). These demonstrations might be augmented with numerical solutions of the simplified equations. In particular, a numerical model where moisture or friction could be switched on or off could be used by students in a group exercise (*active student participation, student teams*) to explore the effects of the neglect of these processes on the dynamics (*concrete information*). Clearly, as the material becomes more complicated, the sophistication of the tools needed for exploration increases. Such exercises must be constructed with care, and collaboration among instructors, perhaps coordinated through the American Meteorological Society, would be beneficial. Clearly, such activities will necessitate that less material be covered in a given class. As instructors, we must remind ourselves to seek a balance between the amount of material that is presented and the quality of the learning that takes place.

While the emphasis of this study is on changes at the classroom level, it should be remembered that there are institutional obstacles to educational reform. In the United States and Canada, there are 65 institutions that offer both undergraduate and doctoral degrees in the atmospheric sciences, compared to 30 organizations that offer undergraduate training but whose programs do not extend to the Ph.D. level (see AMS/UCAR 2004). Clearly, meteorological education is occurring primarily at research universities and this necessarily drives teaching practice. In such settings, professional development is grounded in mastery of the discipline, with limited accountability or assessment of teaching processes and few incentives for pedagogical scholarship. In a world marked by time constraints, excellence in research is often the primary criteria used to evaluate faculty tenure and merit. Yet, Lindsay et al. (2002) found that undergraduates respond more negatively as the amount of research activity increases within a department. Without broad-based institutional support, reforms are likely to remain idiosyncratic and at the whim of individual faculty, ensuring the continuation of less effective teaching.

Owing to the small size of the program at UWM, it was possible to conduct only a limited number of interviews. Although the small sample does not permit rigorous statistical analysis, the findings

are consistent with the available literature and the cumulative experiences of the faculty. It would be of interest to record attrition rates, learning styles, and the level of disconnectedness of students across a wide range of programs in the atmospheric sciences, as has been done in other technical disciplines. It is worth noting that the findings reported here were obtained based on interviews with “persisters,” that is, students who have not (yet) given up on their pursuit of an education in the atmospheric sciences. Hence, it is likely that the issues documented here are ubiquitous in atmospheric science education. Failure to assess the extent of the problem, and to take active steps to find remedies, risks the loss of our students to other disciplines and interests, and calls into question the relevance of our educational structure. As has been noted, there is a dichotomy between theory and observations, and a related chasm between research and operations (National Research Council 2000). Addressing this gap is of more than academic interest.

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APPENDIX: THE INTERVIEW QUESTIONS.

- 1) Please outline your professional background in the atmospheric sciences (education, work experience).
- 2) As a student, what were your expectations of the atmospheric science field prior to enrollment in a program? Have your expectations changed any? How?
- 3) What do you consider to be the most useful things to know in the field of meteorology? How does your program help you/your students to learn these things?
- 4) Do you feel that experience in an atmospheric science program readily prepared you for a career in this field? Why or why not?
- 5) Carl Gustav Rossby, one of the founding fathers of modern meteorology, wrote the following in 1945: “The principal task of any meteorological institution of education and research must be to bridge the gap between the mathematician and the practical man, that is to make the weather

man realize the value of a modest theoretical education and to induce the theoretical man to take an occasional glance at the weather map.”

In reaction to Rossby’s statement, do you feel that theory and application are related clearly in the educational system of the atmospheric sciences? If yes, how have you experienced this being accomplished? If no, how does it fail to be related?

- 6) How might you best be able to learn, understand, and relate to the theory underlying real-life weather observations? What techniques could best accomplish this goal?
- 7) Do you feel that teachers in the atmospheric sciences assume students make the connection between theory and practice instantaneously? Can you give an example from your experience? Does this assumption present learning difficulties? If yes, from your experience, how might this be handled more effectively? If no, why is this not a problem?
- 8) Consider the following restructuring of atmospheric science teaching. Knowledge seeking is driven by case studies, such that the relevance of the extensive and oftentimes difficult technical material is made readily apparent. Since no individual faculty is an expert in all areas, the teaching is accomplished in a collaborative way, where faculty are brought in as their particular expertise is needed. This sharing of expertise also extends to campus visits by practitioners in the field, further underlining the relevance of the teaching. Concepts are introduced as dictated by the case studies, and the learning is “cycled” several times (e.g., the concept of stability as it relates to the production of vertical motions in the atmosphere will depend on the details of the case under consideration).

Do you believe that a restructuring of this kind would help relate atmospheric theory to real-life scenarios in a more effective manner than is presently achieved? If yes, why? If no, why not?

Would the knowledge that such a teaching method was being used have affected your eagerness to enroll in a program? If yes, why? If no, why not?

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