# 8.8 USING WORKED EXAMPLES TO TEACH ATMOSPHERIC DYNAMICS

Casey E. Davenport*
*University of North Carolina at Charlotte*

## 1. INTRODUCTION AND BACKGROUND

Atmospheric dynamics is a well-known stumbling block for many students, and can be particularly as some concepts are counter-intuitive (Persson 2010), in addition to the challenging mathematics required. A new approach for teaching atmospheric dynamics is discussed here, based on a growing consensus of research that indicates students must take an active role in constructing knowledge to maximize their learning; simply transmitting information via lecture is insufficient (e.g., Johnson et al. 1991; McDermott 1998). One way to promote student engagement is to teach concepts using real-world examples and applications; meteorology students in particular prefer learning applications first, and theory second (Roebber 2005). In fact, in the early stages of learning, novices rely on, heavily prefer, and actually learn more through examples (e.g., Pirolli and Anderson 1985; Cooper and Sweller 1987; Anderson et al. 1997). The most *effective* examples that enhance learning are those that *guide* students through self-explanations of concepts (Chi and Bassok 1989). Self-explanation is achieved through a series of questions that prompt students to critically examine the given scenario, and also target and correct common misunderstandings and misconceptions. The more self-explanation a student does, the more successful they will be (Chi and Bassok 1989).

Additional benefits of students working through examples with self-explanation prompts include explicit demonstration of domain-specific problem-solving strategies, as well as a reduction in cognitive load (e.g., Sweller and Cooper 1985; Chandler and Sweller 1991). Cognitive load refers to the extent of mental effort used in working memory; novice learners often experience a high cognitive load when presented with a problem to solve, making it more difficult to recognize patterns and identify key concepts needed to solve the problem, resulting in a lower rate of success (Sweller and Cooper 1985; Yuan et al. 2006). As summarized by Ward and Sweller (1990), "A heavy cognitive load is imposed because of the need to simultaneously consider and make decisions about the current problem state, the goal state, differences between states, and problem solving operators that can be used to reduce such differences. When non-automated operators are being used, the process becomes even more difficult."

Guided examples that are paired with self-explanation prompts are known as *worked examples*, and aim to demonstrate an expert's solution to a given problem by explicitly describing concepts and problem-solving methods. Implementing worked examples in the classroom has proven to be effective in enhancing learning and problem solving skills in a variety of scientific disciplines, including mathematics (e.g., Sweller and Cooper 1985), physics (e.g., Chi and Bassok 1989; Atkinson et al. 2000), engineering (e.g., Moreno et al. 2013), chemistry (e.g., Crippen and Brooks 2009), and statistics (e.g., Paas 1992).

Understanding the strong desire that students have to learn from examples and utilizing an abundance of real-world applications, the worked example pedagogy was implemented in the atmospheric dynamics course sequence at the University of North Carolina at Charlotte during the Spring 2017 and Fall 2017 semesters. A description of how the examples were made, used in the classroom, and their impact on student assessments will be described below.

## 2. CONSTRUCTING WORKED EXAMPLES

While the specific format of a worked example can vary, they must nevertheless be carefully constructed to ensure that their structure and composition work to reduce cognitive load and allow learning to take place. For instance, examples that require students to split their attention between different sources of information

* *Corresponding author address*: Casey E. Davenport, University of North Carolina at Charlotte, Department of Geography and Earth Sciences, Charlotte, NC 28223; email: Casey.Davenport@uncc.edu

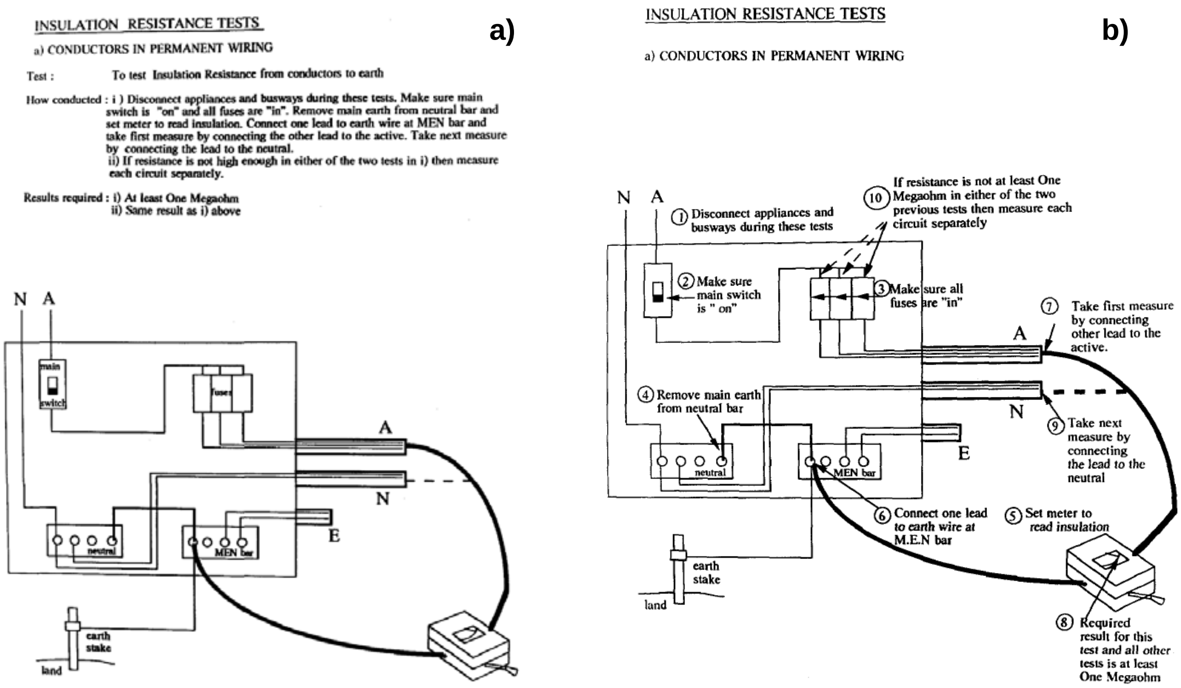



Figure 1: a) Example that separates problem statements and different sources of information versus b) an example that integrates the necessary information to solve a problem. Images taken from Chandler and Sweller (1991).

and mentally integrate them are much less effective (e.g., Tarmizi and Sweller 1988; Ward and Sweller 1990; Fig. 1a). Instead, it is recommended to visually integrate problem statements, equations, and diagrams (e.g., Ward and Sweller 1990; Sweller 1994; Atkinson et al. 2000; Fig. 1b).

Additionally, the concept(s) that are being tested in the problem should be explicitly identified to prevent inaccurate assumptions, and students should be given prompts that encourage self-explanation and target common misconceptions. It is also recommended to provide opportunities for students to complete small steps of the problem (i.e., leave example problems partially unfinished to foster additional self-explanation), as well as offer multiple examples of each concept that contain varying degrees of complexity, paired with practice problems to solve on their own (e.g., Reed and Bolstad 1991; Atkinson et al. 2000).

A sample atmospheric dynamics worked example is shown in Figs. 2-6 to illustrate the general format and flow of examples used at UNC Charlotte. Figure 2 shows the first page of the example, stating the problem related to the real-world case of the Tri-State Tornado, and also providing students with a strategy for how to solve the problem based on key equations and concepts. Here, the broad concept of natural coordinates is summarized as a single equation

**Worked Example #27—Natural Coordinates #2**

**Directions: Study the example problem below and answer the questions regarding how it is solved.**

*Problem statement*: The infamous Tri-State tornado occurred on March 18, 1925, tracking across Missouri, Illinois, and Indiana ($\phi_{ave}$ = 37.9°N). Though no formal damage surveys were completed, it is widely regarded as a devastating F5/EF5 tornado, giving estimated wind speeds within the tornado of approximately 90 $m/s$. The damage path was estimated to be 1.2 $km$ wide on average. What is the estimated central pressure of the tornado if the ambient pressure was approximately 970 $hPa$ and the temperature was 65°F?

*Strategy*: Similar to our previous Worked Example in natural coordinates, relatively little information is given about the tornado and the environment it occurred in. Yet, this is sufficient to answer the question concerning the central pressure of the tornado. Recall that the equation of motion in the natural coordinate system is given as:

$$\frac{dV}{dt}\hat{t} + \frac{V^2}{R}\hat{n} = -\left(\frac{\partial \Phi}{\partial s}\hat{t} + \frac{\partial \Phi}{\partial n}\hat{n}\right) - fV\hat{n}$$

Note that $\Phi$ can be rewritten in the natural coordinate system as $\frac{1}{\rho}p$. Thus, the equation of motion can also be written as:

$$\frac{dV}{dt}\hat{t} + \frac{V^2}{R}\hat{n} = -\left(\frac{1}{\rho}\frac{\partial p}{\partial s}\hat{t} + \frac{1}{\rho}\frac{\partial p}{\partial n}\hat{n}\right) - fV\hat{n}$$

Recall that a series of force balances can be identified from the equation of motion:

| Balance | Forces | Comments |
|---|---|---|
| Geostrophic | Coriolis + PGF | Straight flow (parallel to isobars), no curvature |
| Inertial | Coriolis + Centrifugal | An oscillation is produced; no PGF |
| Cyclostrophic | PGF + Centrifugal | Curved flow, only at a small horizontal scale |
| Gradient | Coriolis + PGF + Centrifugal | Adds curvature effects to geostrophic balance |

Figure 2: First page of a sample worked example on natural coordinates illustrating the problem statement, key equations and concepts used to solve the problem.

*Calculation*:

- Step 1: Determine the force balance at play.
  - Here are the key details provided in the problem:
    - The latitude ($\phi_{ave} = 37.9°N$)
    - Wind speeds in the tornado ($V = 90\ m/s$)
    - Width of damage path (total is 1.2 $km$, thus $R = 600\ m$)
    - Ambient pressure ($p = 970\ hPa$)
    - Central pressure ($p = ?$)
    - Ambient temperature ($T = 65°F$)
  - A big giveaway here is that we know there is a pressure gradient; we are given the ambient pressure and need to find the central pressure in the tornado. Thus, this removes inertial balance, which does not include PGF. The remaining force balances that include pressure gradient force are:
    - Geostrophic balance (PGF + Coriolis)
    - Cyclostrophic balance (PGF + Centrifugal)
    - Gradient balance (PGF + Coriolis + Centrifugal)
- A close inspection of the information provided, as well as an assessment of the scale of the situation leads to the conclusion that cyclostrophic balance is the relevant balance here.
- Question 1: Why is cyclostrophic balance at play in a tornado? Hint: Why does Coriolis not matter?

Figure 3: The first calculation steps and self-explanation prompt of the sample worked example.

- Step 2: Modify the equation of motion to be reflect the force balance at play.
  - The equation of motion is given as:

$$\frac{dV}{dt}\hat{t} + \frac{V^2}{R}\hat{n} = -\left(\frac{\partial \Phi}{\partial s}\hat{t} + \frac{\partial \Phi}{\partial n}\hat{n}\right) - fV\hat{n}$$

Or,

$$\frac{dV}{dt}\hat{t} + \frac{V^2}{R}\hat{n} = -\left(\frac{1}{\rho}\frac{\partial p}{\partial s}\hat{t} + \frac{1}{\rho}\frac{\partial p}{\partial n}\hat{n}\right) - fV\hat{n}$$

  - We know that a pressure gradient is present between the inside and outside of the tornado (i.e., *perpendicular* to the flow). Thus, this tells us that we'll only need the PGF term in the $\hat{n}$ direction:

$$-\frac{1}{\rho}\frac{\partial p}{\partial n}\hat{n}$$

The term with $p$ is utilized since we are given the actual ambient pressure.

Figure 4: Excerpt of the equation manipulation step in the sample worked example.

- Step 3: Solve for the variable of interest.
  - The problem asks us to find the central pressure of the tornado. The key will be to convert the $\partial p/\partial n$ term. First, we'll get the $\partial p/\partial n$ term by itself:

$$\frac{\partial p}{\partial n} = -\frac{\rho V^2}{R}$$

  - Next, recall that a partial derivative can be rewritten simply as a difference. First, rewrite the $\partial p$ term as a difference in pressures:

$$\frac{p_{central} - p_{outer}}{\partial n} = -\frac{\rho V^2}{R}$$

  - Question 3: Why is the pressure difference shown as $p_{central} - p_{outer}$ instead of $p_{outer} - p_{central}$?

Figure 5: Solving the equation for the variable of interest and a related self-explanation prompt.

with two forms, but can be divided into sub-concepts of different force balances that are listed in a table with brief notes on when each balance is valid. Next, Fig. 3 shows the beginning of the calculation phase, explicitly listing how different data given in the problem statement are translated to various variables. The force balance at work in the problem is also clearly stated, with the first

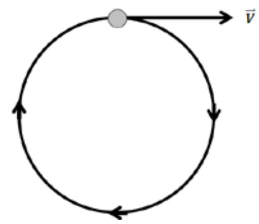
- Finally, we can combine our given values into our equation to solve for the central pressure in the tornado:

$$p_{central} = p_{outer} - \rho V^2$$

$$p_{central} = 97000\ Pa - (1.16\ kg/m^3)(90\ m/s)^2$$

$$p_{central} = 87604\ Pa \approx 876\ hPa$$

- Question 4: Would the answer change if the tornado had been a rare, anticyclonically-turning tornado? Justify your answer by re-drawing the force balance below.




**Application—Problems to Try on Your Own**

**Directions: Solve the following problem by applying the principles and steps outlined in the previous worked example.**

1. The Tornado Intercept Vehicle (TIV) intercepted a large tornado (0.8 $km$ wide) on May 27, 2013. The onboard barometer measured pressure outside the tornado of 995 $hPa$, pressure inside the tornado of 939 $hPa$, as well as an ambient temperature of 20°C. How strong were the winds within the tornado?

Figure 6: Final answer calculation, self-explanation prompt, and application problem.

self-explanation prompt given so that students can explain why that balance is valid. Manipulation of the equation identified on first page follows (Fig. 4), followed by solving the equation for the variable of interest (Fig. 5). Lastly, the variable values are plugged into the equation and a final result is calculated. Students are asked to extend their understanding in a concluding self-explanation prompt. Following completion of the worked example, students are given the opportunity to apply what they've learned in a related application problem (Fig. 6). Ideally, students would follow the same steps outlined in the worked example.

## 3. IMPLEMENTING WORKED EXAMPLES

During the Spring 2017 and Fall 2017 semesters, the atmospheric dynamics course sequence was dramatically modified to be oriented around these worked examples; previous offerings of the course sequence were oriented around lectures and detailed derivations during class. To implement the worked example pedagogy, each dynamics concept was converted into one or more worked examples, depending on its complexity or depth. For example, a more straightforward and familiar concept such as the pressure gradient force was associated with a single worked example, while a very complex concept such as quasi-geostrophic theory had several worked examples. Students were assigned to complete 1-2 worked examples *before* each class period and were also expected to read the related textbook section; the goal is for students to construct a basic understanding of concepts and how they are used. Right before the start of class, the instructor checked each student's example(s) to assign up to 10 points based on *completeness*; as long as a reasonable attempt was made to answer each question and work through the application problem, credit was given.

Each 75 minute class period consisted of 3 components. First, a *brief* (3-5 minutes) summary of the main concept is given (termed "crib notes") to lay a proper foundation for the class period and to emphasize key points that students should understand. Since there is no formal lecture during class, these brief summaries also provide something concrete that can be quickly referenced by students as a study tool. Next, the assigned worked example(s) is (are) discussed; each step is very briefly summarized and student responses from the self-explanation prompts are elicited. This component is typically very interactive, with many students offering their answers, bringing up additional questions, drawing pictures or equations on the board, and debating among one another. This continues until all students feel comfortable with the worked example, including the associated application problem, typically taking 30-45 minutes. The final component taking up the remainder of the class period consists of students working on in-class examples, designed to solidify the key concept and provide additional depth and practice (Atkinson et al. 2000). These in-class examples varied widely in terms of format and content, ranging from more application problems (exposing students to different types of problems on the same concept) to more theoretical applications, including derivations. Students are also strongly encouraged to work together on the in-class examples to support peer learning (e.g., Crouch and Mazur 2001).

## 4. QUALITATIVE & QUANTITATIVE RESULTS

The effect of implementing worked examples was quite stark. To begin, students overwhelmingly supported the approach. Several representative quotes from end of semester evaluations are listed below.

"*I think going over the Worked Examples in class was a really great idea and helped me learn the topics more effectively*."

"*I like that we don't have to sit and watch a teacher write a whole bunch of notes on the board because the class is interactive and we all work on the examples together. I find material easier to learn when we are doing examples than reading notes or the textbook*."

"*Dr. Davenport's worked examples, crib notes, and in-class examples are a really great system for reinforcing what we've learned*."

"*Worked examples are a lot…but they are pretty effective at helping you learn the material and I think it works better for this course than lecture style*."

Additionally, a cursory evaluation of the impact on student grades is fairly unambiguous. Tables 1-2 show the average grades on a variety of assessments of all students who have taken dynamics from the author as a lecture-oriented or the worked-examples oriented course. In Dynamics I, students subject to the worked examples pedagogy performed better on nearly all types of assessments, with their exception of their exams. Notably, however, their final exam scores (reflective of *all* course material covered during the semester) were nearly 10 percentage points higher than the lecture students, which is particularly remarkable given that the final exam has not changed at all from year to year. Other types of assessments do change from year to year, though not significantly so.

Similarly, in Dynamics II, worked examples students had much higher scores in each assessment category, with the exception of the final exam. While this is in contrast to the marked improvement on the Dynamics I final exam, the weaker performance could be attributable to the fact that the content covered in Dynamics II is generally more difficult and multifaceted; more complex topics (such as quasi-geostrophic theory) are more challenging to condense into well-constructed, well-explained examples. The author intends to modify and improve many examples in future iterations of the course to enhance their efficacy.

| *Dyn. I* | Homework | Quizzes | Exams | Final Exam | Final Grade |
|---|---|---|---|---|---|
| **Lecture** | 78.5 | 72.4 | 72.9 | 63.7 | 75.5 |
| **WE** | 81.8 | 76.2 | 71.0 | 73.4 | 78.0 |

Table 1: Average scores of students (lecture or worked example [WE]) on different types of assessments in the Dynamics I course.

| *Dyn. II* | Homework | Quizzes | Exams | Final Exam | Final Grade |
|---|---|---|---|---|---|
| **Lecture** | 76.8 | 69.8 | 67.7 | 69.8 | 72.1 |
| **WE** | 84.1 | 79.9 | 69.9 | 67.4 | 77.4 |

Table 2: As in Table 1, but for Dynamics II.

## 5. SUMMARY AND FUTURE WORK

The worked examples pedagogy is an instructional approach that has proven to be effective in reducing cognitive load and enhancing student learning. Worked examples were constructed for each concept addressed in the two semester atmospheric dynamics course sequence, and first implemented during the Spring 2017 and Fall 2017 semesters. Students were required to complete 1-2 examples before each class period to familiarize themselves with the applications of a particular concept. In-class time was primarily used to discuss the assigned example(s) and work on additional problems.

Preliminary assessment of the worked examples approach is promising. Student comments on course evaluations were overwhelmingly positive, and student grades were markedly improved. The extent to which these results can be generalized is not yet able to be quantified; the author intends to improve the examples and continue implementing this pedagogical approach in the coming semesters. Additionally, more detailed assessments concerning the efficacy for different student demographics (e.g., gender, math aptitude, etc.), individual concepts, and long-term understanding will also be assessed.

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