Teaching Upper-Atmospheric Meteorology Using Two- and Three-Dimensional Models

A Pilot Study

BY TIMOTHY W. HAWKINS, KAYLA J. KIPHART, AND JANET S. SMITH

Upper-atmosphere meteorological concepts often confound introductory meteorology students. In particular, students are challenged by the three-dimensional nature of constant-pressure surfaces. This struggle is likely due, in part, to the fact that nearly all representations of these three-dimensional surfaces are presented in two dimensions. Recent research argues that spatial visualization in three dimensions can be improved through instruction. However, several studies suggest that comprehension of a three-dimensional environment does not necessarily occur equally between males and females, or between individuals with different spatial abilities.

The purpose of this project was to begin to assess whether three- or two-dimensional models of upper-atmosphere constant-pressure surfaces were more effective as teaching and learning tools. The models were developed and tested on two groups of introductory meteorology students, and the results of the assessment were analyzed to determine which model was more effective and, secondarily, if there were differences in student performance based on sex. It was hypothesized that certain concepts would be better understood in three dimensions, while others would be better understood in two dimensions. It was also

hypothesized that males would outperform females especially when using the three-dimensional model, given some studies showing differences in spatial processing abilities between males and females (see next section). This study serves as an initial inquiry into this area of teaching research. By requiring relatively little classroom time, this study helps to establish the merit of devoting significant classroom time to future research. As the ultimate goal of any type of teaching research is to improve student learning, it must first be demonstrated that extensive classroom-based research is also beneficial to student learning.

TWO- AND THREE-DIMENSIONAL LEARNING, SPATIAL ABILITIES, AND SEX-RELATED DIFFERENCES. Although there are relatively few empirical studies investigating three-dimensional visualization and learning, two recent projects examining the use of three-dimensional models are of note. Huk (2006) found that using three-dimensional models in cell biology significantly assisted students with a preexisting strength in spatial abilities in acquiring new information, but handicapped students who were less able in their spatial thinking. Piburn et al. (2006) noted in their work with three dimensional models in geology that comprehension differences between males and females could be mitigated through instruction.

Differences in spatial abilities on the basis of sex have long been examined in psychology and, more recently, in the Earth and physical sciences. Males have consistently outperformed females in specific tasks that require rotation and visualization (e.g., the Rod and Frame Test, which measures field dependence and independence) (Voyer et al. 1995; Caplan and Caplan 1997), reading maps (Chang and Antes 1987), and interpreting contour maps (Henrie et al. 1997). In their study of sex differences in map reading and using Landsat images, Goldberg and Kirman (1990) found differences between males and females were margin-

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DOI:10.1175/2010BAMS2825.1

A supplement to this article is available online (DOI:10.1175/2010BAMS2825.2)

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FIG. 1. Surface analysis from 25 Feb 2007. Analysis prepared by the National Centers for Environmental Prediction, Hydrometeorological Prediction Center (www.hpc.ncep.noaa.gov/dailywxmap).

ally significant and recommended that future research should examine specific skill tasks.

Critically assessing teaching and learning in meteorology has received increasing amounts of attention recently. Researchers have examined undergraduate education in general with a focus on both large lecture classes and at liberal arts institutions, as well as student perceptions, goals, and interests associated with introductory meteorology classes. Specific content areas have been examined as well, including climate change and measurement techniques at the graduate level. In a 2008 *Bulletin* article, Charlevoix argues that the discipline of meteorology needs to more fully embrace the notion of the “scholarship of teaching and learning.” In other words, more meteorologists should use their scientific skills to critically test the techniques used in meteorology classrooms to assess whether teaching is effective and students are learning. As an example, Bond and Mass (in a 2009 *Weather and Forecasting* paper) evaluated students’ weather forecast skill over the course of a semester and determined that skill improves over the first six weeks of the term and then levels off. The results could be used to more effectively teach forecasting techniques. The project presented here attempts to begin a discussion regarding teaching techniques associated with upper-atmosphere meteorology.

MODEL DESCRIPTIONS. Two- and three-dimensional models of upper-atmosphere constant-pressure surfaces were created using a geographic information system (GIS) that allowed students to

interact with and customize the various features of each model. Both models were based on the upper-atmospheric features of a typical midlatitude cyclone that occurred 23–26 February 2007. Figure 1 shows the surface analysis for the storm on 25 February 2007.

Upper-atmosphere and surface pressure data were obtained from the NCEP/NCAR reanalysis project and were processed for use in the standard GIS platforms ArcMap (two-dimensional) and ArcScene (three-dimensional). Pressure surfaces were contoured for display in the two-dimensional environment and rasterized for display in the three-dimensional environment. Surfaces were created for each day of the storm and for each standard pressure level as well as the surface. Every attempt was made to ensure that the two- and three-dimensional models were identical except for the obvious difference in dimensions (e.g., layer colors, layer order, and labels). Figure 2 shows screen shots of the student view of both the two- and three-dimensional models. Note that the actual models were not static. Students were able to turn layers on and off and zoom in and out. In the case of the three-dimensional model, students were able to rotate the image to change their perspective.

FIG. 2. Screen shots showing the student view of the two- and three-dimensional models of a constant-pressure surface.

TABLE 1. Upper-atmosphere concepts that were assessed. Also shown are common misconceptions held by introductory meteorology students when they first begin learning this material. Many misconceptions are successfully clarified as the class progresses. Misconceptions are based on anecdotal experience teaching introductory meteorology students.

Concept 1	Standard maps of upper-atmosphere constant-pressure surfaces represent a height to a constant pressure. Common misconception: <i>Standard upper-atmosphere maps represent spatially varying pressure values.</i>
Concept 2	The height to constant-pressure surfaces varies spatially. Common patterns in these variations are termed ridges and troughs. Common misconception: <i>Ridges and troughs are primarily oriented in the horizontal plane with no vertical variation.</i>
Concept 3	Generally speaking, constant-pressure surfaces slope downward from the equator toward the poles due to temperature gradients. Common misconception: <i>Constant-pressure surfaces exhibit no general spatial variability.</i>
Concept 4	Surface low pressure systems generally form downstream of an upper-atmosphere trough. Common misconception: <i>Surface patterns are unrelated to upper-air patterns. Also, surface low pressure systems form below the axis of the upper-air trough.</i>
Concept 5	Atmospheric pressure decreases with height. Therefore, the lowest constant pressure levels are found at the highest altitudes. Common misconception: <i>Pressure-level values increase with height (e.g., 200 mb is closer to the surface than 700 mb).</i>

ASSESSMENT AND ANALYSIS. The five basic upper-atmosphere concepts that were assessed in this study are presented in Table 1. Based on experience teaching introductory meteorology students, these five concepts critically assist understanding the upper atmosphere and its relationship to surface weather. Additionally, Table 1 lists common misconceptions associated with each concept.

To gain insight into the quality of both the models and assessment instruments, an upper-level meteorology class consisting of 14 students (4 masters students and 10 upper-level undergraduate students) were shown both the two- and three-dimensional models and completed both of the corresponding assessments. These students were also given a series of open-ended questions soliciting suggestions for improvements. Feedback was used to improve both the models and assessment instruments. For example, a suggestion was made to limit the functionality of the software as much as possible so that students could focus more on the concepts being tested.

The actual assessment was conducted with introductory meteorology students. At the time of the assessment, the students had been introduced

to many fundamental meteorological concepts (e.g., temperature, humidity, pressure, wind, air masses, fronts, and midlatitude cyclones). However, the students' exposure to upper-atmosphere concepts was minimal and limited to brief current weather discussions at the beginning of each class. Students were divided between two computer labs in which the two- and three-dimensional assessments were administered separately. Student placement in either group was based on sex and prior ability (as determined by performance on the first exam of the semester) to ensure an equal distribution of males and females as well as to attempt to balance higher- and lower-achieving students in each assessment group. Table 2 profiles the number of students in each group. The alternative would have been to randomly assign students to a group. However, given the relatively small sample size, it is likely that students would not be equally divided in regard to prior ability, and this variable would then need to be controlled for in all resulting analyses.

Students in both the two- and three-dimensional assessment groups were given identical instructions upon entering the lab and prior to beginning the

TABLE 2. Number of students for each assessment group.

	3D model	2D model	3D model followed by 2D model	Total unique students
Males	15	11	10	26
Females	19	21	18	40
Total	34	32	28	66

assessment. Students were also given a brief tutorial about how to use the computer-based models and were instructed to read a two-page introductory statement describing basic concepts associated with the upper atmosphere. During the assessment, students were given limited access to the functionality associated with the GIS models. Students were able to zoom in and out and turn layers on and off. The only additional functionality in the three-dimensional model was the ability to rotate the model. Each group had the full 50-minute class period to complete the assessment, and no student ran out of time.

The assessment instrument consisted of 12 multiple-choice questions. The two- and three-dimensional instruments were identical with the exception of language differences necessitated by the models. Two questions addressed each of the five fundamental concepts (Table 1) resulting in 10 questions that were model-based and aimed at determining how well students understood the concepts. Additionally, students each completed a two-question demographic survey.

In addition to the two assessment groups detailed above, the students who originally participated in the three-dimensional assessment were evaluated two days later using the two-dimensional model. The purpose of this second assessment group was to determine if prior exposure to the three-dimensional model would influence performance using the two-dimensional model. Data about these students are also presented in Table 2.

A series of Mann-Whitney U-statistics were calculated using the overall scores on the assessments as well as the designation of correct/incorrect for the individual question responses. Similar to a *t*-statistic, the U-statistic assesses differences between groups. The nonparametric U-statistic, however, requires no assumption of normality and thus is useful given the relatively small sample

size for this study. The U-statistic is calculated by ranking all the observations and then comparing the ranks of one group with the other group. Due to the relatively small sample size, in addition to the significance values associated with the U-statistic, we also cal-

culated the exact significance using Fisher's Exact Test. This test does not rely on an approximation of a distribution that becomes exact as the sample size approaches infinity, and thus is not dependent on sample size. By using the U-statistic and Fisher's exact test, we provide a more conservative estimate of significance that is not dependent on sample size. We evaluated differences in performance between the three- and two-dimensional models for all students; the three- and two-dimensional models within sex groupings (e.g., did males perform better using the three- or two-dimensional model?); males and females for all models; males and females using the same model (e.g., did males or females perform better using the three-dimensional model?).

RESULTS. Table 3 summarizes the differences in overall assessment scores that were recorded as a percentage, as well as the difference in the percentage of students answering a particular question correctly for students using the three-dimensional model and students using the two-dimensional model. Note that significance for these differences is based on the more conservative U-statistic, which relies on rankings of the data and Fishers Exact Test. Differences as they are presented are more easily interpreted. Differences in rankings used for the U-statistic (not shown) mirror the presented results.

There was no significant difference in overall assessment scores between users of the three- and two-dimensional models (Table 3, left side). When broken down by sex, there was no significant difference between models for male users. Females, however, scored 13% higher using the two-dimensional model. With the exception of concept 4, each concept had significant differences in scores for some combination of questions and/or sex. Generally speaking, students performed better using the two-dimensional model on concepts 1 and 3, while

TABLE 3. Assessment differences for 3D vs. 2D models and 3D/2D vs. 2D models. For the overall score, differences are between the average assessment scores, which were recorded as a percentage. For the concepts, differences are between the percentages of students that answered correctly. Results are sorted by males, females, and all students. Individual questions are arranged according to concept. Positive values indicate that users of the 3D model or 3D/2D model outperformed users of the 2D model. Negative values indicate that users of the 2D model performed better. Green (positive) or gray (negative) shading indicates differences in mean rank were significant at the 95% confidence level. Differences in rank that were also significant at the 95% confidence level using Fisher's exact test are indicated by *.

		3D vs. 2D			3D/2D vs. 2D		
		All	Male	Female	All	Male	Female
Score		−4	9	*−13	*−12	−3	*−17
Concept 1	Q1	*−36	−1	*−60	*−30	5	*−48
	Q2	−14	4	−28	−5	14	−16
Concept 2	Q1	*33	*50	20	−9	24	−27
	Q2	21	41	5	−15	15	−31
Concept 3	Q1	0	10	−12	−8	−14	−5
	Q2	*−37	*−46	−29	−18	−23	−15
Concept 4	Q1	−1	−7	2	13	−17	30
	Q2	−5	−5	−7	−20	−35	−11
Concept 5	Q1	*19	36	9	−3	−4	−3
	Q2	−17	0	−31	*−26	0	*−40

they performed better using the three-dimensional model on concepts 2 and 5.

Students who used the three-dimensional model were assessed two days later using the two-dimensional model. The results of these so-called 3D/2D students were compared with results from students who had only used the two-dimensional model (Table 3, right side) to assess whether having seen the three-dimensional model aided student performance. Students using the two-dimensional model scored 12% higher than 3D/2D students. Male differences were not significant, while females scored 17% higher when using only the two-dimensional model. For the individual questions and concepts, five of the six significant differences favored two-dimensional students over 3D/2D students.

Table 4 summarizes the performance differences between males and females. Regardless of which model was being used, males scored 13% higher overall than females. Males scored 22% higher when using the three-dimensional model but did not perform significantly better when using the two-dimensional model or when using the 3D/2D models. In examin-

ing performance differences for individual questions and concepts, the 13 significant differences all indicated that males outperformed females. There were no significant differences where females outperformed males. Male performance was most notable when using the three-dimensional model or the 3D/2D models. There were no significant differences between sexes when using the two-dimensional model.

DISCUSSION. As hypothesized, significant differences between users of the two- and three-dimensional models did exist for specific concepts. Concept 1 related to understanding that maps of constant-pressure surfaces showed the height of these surfaces. Students performed better using the two-dimensional model. From a novice student perspective, presenting constant-pressure surface heights in three dimensions does not necessarily mean that students will understand what they are viewing. To a novice student, it is a reasonable mistake to assume that a three-dimensional pressure surface represents something other than height (e.g., pressure). Furthermore, the language necessary for

TABLE 4. Assessment differences between males and females. For the overall score, differences are between the average assessment scores, which were recorded as a percentage. For the concepts, differences are between the percentages of students that answered correctly. Results are sorted by all students, 3D model students, 2D model students, and 3D/2D model students. Individual questions are arranged according to concept. Positive values indicate that males outperformed females. Negative values indicate that females performed better. Blue (positive) or pink (negative) shading indicates differences in mean rank were significant at the 95% confidence level (note: there are no pink values). Differences in rank that were also significant at the 95% confidence level using Fisher's exact test are indicated by *.

		All	3D	2D	3D/2D
Score		*13	*22	1	14
Concept 1	Q1	15	37	-21	32
	Q2	*23	35	3	33
Concept 2	Q1	*28	29	-2	*49
	Q2	*27	34	-3	43
Concept 3	Q1	*31	*47	26	17
	Q2	-10	-15	2	-6
Concept 4	Q1	-5	4	13	-34
	Q2	5	14	12	-12
Concept 5	Q1	-10	5	-22	-23
	Q2	*26	34	3	43

the three-dimensional assessment may have been confusing to students. Three-dimensional maps were described as surfaces, a term that had not been used extensively with students, while two-dimensional maps were described as contours, a term students had used extensively when dealing with other class material such as isotherms and isobars.

For Concept 2, which related to understanding the shape of upper-atmospheric ridges and troughs, users of the three-dimensional model performed better. For the three-dimensional model, students simply needed to correctly describe what they were viewing in terms of the undulations associated with the ridges and troughs (Fig. 2). For the two-dimensional model, however, students needed to translate the two-dimensional image (i.e., closed-contour line circles in Fig. 2) into the proper three-dimensional representation (i.e., a vertical drop in the constant-pressure surface). The fact that this translation step was not necessary when using the three-dimensional model likely contributed to higher three-dimensional scores for Concept 2.

Concept 3 related to the general slope in constant-pressure surfaces from the south to the north due to the general temperature gradient. Concept 3, Question 1 asked about this slope when viewing the constant-pressure surface from either the west or east coast when the slope would be most apparent, while Concept 3, Question 2 asked about this slope when viewed from the south when the slope would be more difficult to see. The three-dimensional model from the eastern or western perspective should show much more clearly the slope of the constant-pressure surface compared to the two-dimensional model. However, the lack of difference in performance scores for this question suggests that students were again confused by the language used in the three-dimensional assessment or perhaps were unsure of ex-

actly what they were viewing in the three-dimensional model. Not surprisingly, for Concept 3, Question 2, students performed better in two dimensions. Because this view was from the south, the three-dimensional view was likely confusing because of the viewer orientation relative to the slope, while the two-dimensional model showed a series of contours labeled with decreasing values from south to north.

Concept 4 related to the relationship of surface weather features to the location of upper-atmospheric weather features. For both Concept 4 questions, regardless of model, students performed most poorly compared with other concepts. Poor performance was likely because to answer correctly, students had to first assess an upper-atmosphere concept that they were not familiar with using language they were exposed to for the first time (e.g., "trough axis") and then apply it to a surface concept. It was believed that the geographic relationship between upper-atmosphere and surface features would be better seen when the maps were overlaid in two dimensions. In the three-dimensional model, the surface and upper

atmosphere are physically separated vertically, and therefore the horizontal relationship between features is much more difficult to visualize.

Finally, Concept 5 relates to the relative vertical orientation of multiple constant-pressure surfaces. For Concept 5, Question 1, students examined four constant-pressure surfaces at the same time and were asked which surface was highest in the atmosphere. Students performed better using the three-dimensional model, which showed color-coded, separated, vertically layered surfaces, while the two-dimensional model overlaid all the surfaces in one layer and created a very complex display. Concept 5, Question 2 asked students whether the different constant-pressure surfaces intersected. Significant differences did not exist between the models. Because the two-dimensional model displays all the surfaces on one layer, students were relying on the knowledge they received from the introductory statements and likely did not use the model much to answer the question. Depending on the perspective from which a student was viewing the three-dimensional model, it is very possible that the surfaces would appear to intersect. It was necessary to significantly manipulate the model in order to see that the surfaces did not intersect. A student who had been instructed or shown how to manipulate the model in this manner would likely have been more successful in assessing whether constant-pressure surfaces intersect.

Fewer significant differences exist when comparing 3D/2D students with students who only used the two-dimensional model. With one exception, all of these significant differences favored students of only the two-dimensional model. This suggests that using the three-dimensional model or being exposed for a second time did not help performance on the two-dimensional assessment. Ideally, to control for students being exposed to the material for a second time, the original two-dimensional students would have been split for their second assessment so that half took the two-dimensional assessment for a second time and half took the three-dimensional assessment. The relatively small number of students prohibited this further subdivision.

Similarly, students who took the three-dimensional followed by the two-dimensional assessments performed 8% better on the three-dimensional assessment (not shown) despite the fact that they were essentially taking the assessment for the second time when they were using the two-dimensional model. Anecdotal discussions with students after taking

the two-dimensional assessment having already taken the three-dimensional assessment suggest that switching to the two-dimensional model was indeed confusing. Students commented that they did not feel comfortable with the material in general, and therefore to switch dimensionalities was particularly confounding. It is likely that more long-term exposure (i.e., during the course of a semester) would alleviate much of this confusion.

Not examined in this study is the role that conceptualizing three-dimensional representations plays in understanding the concept at hand (i.e., upper-atmosphere meteorology). Females consistently performed less well than males, especially when using the three-dimensional model. Given that females in the study actually had a higher grade-point average than males, it seems unlikely that intelligence differences were the cause of performance differences. Rather, it is more likely that females had greater difficulty “unpacking” what was presented to them (especially in the three-dimensional environment) and therefore were not able to answer questions as successfully because their efforts were more concentrated on understanding the

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model as opposed to understanding the concepts the model was attempting to explain.

Previous studies have shown that if provided quality instruction and adequate time, students can overcome an initial inability to grasp the purpose of a model. Given the inherent three-dimensional nature of upper-atmosphere constant-pressure surfaces, it seems reasonable to expect that all students could benefit from a three-dimensional representation of these surfaces. Particular students may require more time and effort to understand the three-dimensional model. Also, certain concepts may be better understood in two dimensions.

CONCLUSIONS. Two- and three-dimensional models were used to assess undergraduate introductory meteorology student comprehension of upper-atmosphere meteorological concepts. The main results can be summarized as follows.

There was no statistical difference in overall performance between students using the three-dimensional versus the two-dimensional model. However, statistically significant differences in performance using the two models did exist for individual concepts. Males generally outperformed females when using either model. These performance differences were significant when using the three-dimensional model. When compared within sex groups, male performance was strongest using the three-dimensional model while female performance was strongest using the two-dimensional model.

The results suggest that both two- and three-dimensional representations should be used when teaching upper-atmospheric meteorological concepts. Significant differences exist in student concept comprehension depending on which model is used. Furthermore, certain concepts are better understood using different versions of the model. Presentation of both model types could occur in a traditional classroom lecture environment as well as in a more hands-on laboratory environment. Anecdotal evidence based on discussions with students indicates that student comprehension of these concepts increases after being allowed to manipulate both the two- and three-dimensional models outside of a traditional lecture environment.

Caution must be taken when interpreting these results. Student participants in this study essentially had no prior exposure to upper-atmosphere meteorological concepts. Also, certain students likely had difficulty simply processing what the models were

showing. Consequently, overall student performance was not particularly strong. While males clearly outperformed females in the three-dimensional environment during the initial exposure, it is hypothesized that all students would improve their performance given longer-term and more in-depth exposure to both models. An interesting future direction for this research will be to assess student comprehension of these concepts after independent exposure to either two- or three-dimensional models during a teaching unit of several weeks or more.

ACKNOWLEDGMENTS. Thank you to Scott Drzyzga for assistance in developing the GIS models and Kurt Fuellhart for statistical assistance. Thank you also to Steve Ackerman and an anonymous reviewer for valuable comments.

FOR FURTHER READING

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