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Conceptions of Tornado Wind Speed and Land Surface Interactions Among Undergraduate Students in Nebraska

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ABSTRACT

To ascertain novice conceptions of tornado wind speed and the influence of surface characteristics on tornado occurrence, 613 undergraduate students enrolled in introductory science courses at a large state university in Nebraska were surveyed. Our findings show that students lack understanding of the fundamental concepts that (1) tornadoes are primarily atmospheric phenomena, and (2) they are only weakly influenced by the underlying land surface. A common alternate conception was that land surface features offer protection from tornadoes. For example, many students thought that (1) tornadoes generally cannot occur over snow cover or in mountainous terrain, (2) locally lower areas and hills provide protection from tornadoes, and (3) cities are not as susceptible to tornadoes as surrounding areas. Students also lacked an accurate conception of the wind speed in strong tornadoes. © *2015 National Association of Geoscience Teachers*. [DOI: 10.5408/14-029.1]

Key words: meteorology, alternate conceptions, misconceptions, tornado, severe weather, concept inventory, undergraduate student, atmospheric science

INTRODUCTION AND BACKGROUND

Study Overview and Goals

We conducted an exploratory study with the goal to discover undergraduate conceptions of the relative importance of the atmosphere and land surface in determining tornado behavior and local risk. Knowledge of these conceptions is helpful to further inform how the subject of tornadoes is taught in the college classroom. The study was conducted in Nebraska, a region of the U.S. with a high tornado frequency. To achieve the study's goals, we had three primary objectives: (1) Identify alternate conceptions held by Nebraska undergraduates about where tornadoes occur and risks associated with tornadoes over varying land surfaces; (2) quantify the prevalence of these alternate conceptions; and (3) discuss the implications of our findings. It is important to stress that this study was not aimed at understanding students' ideas about how tornadoes form (tornadogenesis), as tornadogenesis currently is incompletely understood by the scientific community. Instead, our focus of inquiry was on student conceptions about tornadoes after they have formed and, in particular, about the plausibility of tornado occurrence given particular surface conditions. The findings of this study could be used as a first step toward development of a concept inventory to assess student understanding of tornado behavior, although developing such an inventory is beyond the scope of the present study.

Alternate Conceptions and Mental Models

Cognitive science, science education, and developmental psychology research shows that "children and adults construct an. . .understanding of the world which is based on their everyday experience" (Vosniadou and Brewer, 1992, 536). This understanding or knowledge about the world provides explanations of natural phenomena that often differ from currently accepted scientific explanations held by experts with substantial training in a particular domain (Vosniadou and Brewer, 1992; Petcovic and Libarkin, 2007). This is the kind of prior knowledge that students bring with them to the classroom learning environment, and it may help, hinder, or have no impact on their learning (Bransford et al., 2000).

This prior knowledge has been referred to by others in a variety of ways, such as naïve ideas (Novak, 1977; Clement, 1993), children's science (Gilbert et al., 1982; Duit and Treagust, 1995), misconceptions (Helm, 1980), and alternate frameworks (Driver, 1981; Dal, 2007). Though there exists congruent but inconsistent and sometimes ambiguous use of these terms from one literature source to another, there is a general consensus that the formation of conceptions results from experiences that learners have with the world around them (Stokes, 2011). Thus, personal experience and conceptions are intimately tied. As such, for the purposes of this study, we define an alternate conception as "an idea or thought held by a student at any point in time relative to the instructional period of interest, formed by direct or inferred experience, and one that is more/less scientifically accurate and complete" (Arthurs, 2011, 137).

Given that alternate conceptions reside in the mind and "the mind is the agent of learning" (Jonassen, 1991, 6), studying alternate conceptions from the perspective of mental models is appropriate (Jonassen, 1991). Mental models are "what people really have in their heads and what guides their use of things" (Norman, 1983, 12). They are "personal, internal representations of external reality that people use to interact with the world around them . . . [that] are used to. . .make decisions. . .[and] provide the basis through which new information is filtered and stored" (Jones et al., 2011, 1).

Barquero (1995, 12) argues that a mental model is a "type of knowledge representation which is implicit, incomplete, imprecise, incoherent with normative knowledge in various domains, but it is a useful one, since it results in a powerful explicative and predictive tool for the

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interaction of subjects with the world, and a dependable source of knowledge, for it comes from the subjects' own perceptive and manipulative experience with this world." Greca and Moreira (2000, 4) say that, for Johnson-Laird (1983), mental models are "working models of situations and events in/of the world, and that through their mental manipulation we are capable of understanding and explaining phenomena and are able to act accordingly to the resulting predictions." Furthermore, they state that these models are dynamic, recursive in nature, never complete, and continually "enlarged and improved as new information is incorporated into it" (Greca and Moreira, 2000, 4).

Misconceptions Research in Atmospheric Science

Substantial misconceptions research has been conducted in areas related to climate science and atmospheric science. These include, for example, novice conceptions of cloud and fog formation (Rappaport, 2009), climate science (Keller, 2006), global climate change (e.g., Lombardi and Sinatra, 2010; Lambert et al., 2012; Bleicher and Lambert, 2013), the greenhouse effect (Shepardson et al., 2011), and radiation (Libarkin et al., 2011).

Alternate conceptions research can be applied to the construction of multiple-choice items for formative and summative assessments, such as concept inventories. With validation, such items may be incorporated into concept inventories such as those used in chemistry (e.g., Mulford and Robinson, 2002), physics (e.g., Hestenes et al., 1992), and geoscience (e.g., Keller, 2006; Libarkin and Anderson, 2007). Although a greenhouse concept inventory has been developed (Keller, 2006), a more general concept inventory has not yet been developed specifically for atmospheric science, representing a significant gap among the physical sciences. The purpose of this study is to identify students' alternate conceptions dealing with tornadoes, and, although developing a concept inventory is beyond the scope of the current study, the findings of this study may be used in the development of a future concept inventory for atmospheric science.

SETTING AND SAMPLED POPULATION

Study Location

This study was conducted at a Carnegie doctoral-research university in Nebraska, U.S.A. This institution is a state university with a total undergraduate enrollment of approximately 24,000 at the time data were collected. The study location lies within "Tornado Alley," a region of central North America with climatologically high tornado occurrence.

Sample Population

All participants ($n = 613$) were enrolled in introductory-level science courses during the fall 2012 semester. Courses from which participants were drawn included general biology ($n = 236$), general chemistry ($n = 127$), oceanography ($n = 115$), introductory geology ($n = 104$), weather and climate ($n = 85$), severe and unusual weather ($n = 80$), and environmental geology ($n = 59$). These courses are designed for nonscience majors satisfying their general science education requirement or for students first entering a major, and thus a large majority of students surveyed had not received prior college-level instruction about tornadoes. Results are expected to be reasonably representative of the general university student population, but they may be slightly biased toward responses from students with greater-than-average science interest and/or background. Gender, ethnicity, and year in college were not primary factors of interest at the onset of this study, and therefore these data were not collected. In this study, 75.4% of respondents were originally from Nebraska, and 2.6% were international students representing 13 countries. Most respondents reported being either in Nebraska for 5 or more years (79.1%), or being in Nebraska for less than a year (11.7%). As the survey was administered in introductory-level science courses during a fall semester, the latter group likely represents out-of-state freshmen or transfer participants.

METHODS

Survey Development

A 24 item survey was developed based on misconceptions and themes that appear in the literature about the relative roles of the atmosphere and land surface on tornado behavior and on the tornado risk of particular locations (e.g., Klockow et al., 2014). Prior to survey administration, the survey was reviewed by five meteorology–climatology students and one professional meteorologist at the institution where this study was conducted to obtain expert and novice input regarding validity considerations. These reviewers indicated that survey items were clearly understood, did not need further clarification, and were relevant to course instruction about tornadoes. Eight of the 24 items were applicable to the goals of the present study and were included in the analysis. Each of these questions was designed to gather background information about participants, or to assess their understanding of a particular aspect of the fundamental concepts that tornadoes are (1) primarily atmospheric phenomena and (2) only weakly affected by the underlying land surface (see the supplemental material, which can be found online at http://dx.doi.org/10.5408/14-029s1). Background items (#1–3) included home region and length of time in Nebraska, while an open-ended background item asked participants for their primary tornado knowledge source. One open-ended factual knowledge item (#8) was included, which tested knowledge of a fact that could be memorized. Conceptual understanding items (#4–7) were free-response and solicited participant reasoning using basic science concepts (see the supplemental material, which can be found online at http://dx.doi.org/10.5408/14-029s1).

Survey Administration

The primary author and a research assistant administered the survey in seven introductory-level science courses (listed in the Sample Population section). The researchers for this study were not instructors of the surveyed courses. The subject of tornadoes was not taught at all in these courses, except for the "Weather and Climate" and "Severe and Unusual Weather" courses, and the survey was administered prior to formal instruction about tornadoes in these courses in order to not bias responses with course instruction. Since the survey was administered near the beginning of the semester, it served as a pre-instruction assessment of prior knowledge on this topic. Students were not aware a survey would be given before coming to class, and it was administered to all students who came to class on the

TABLE I: Percentage of respondents who gained their tornado-related knowledge from each potential source.

Knowledge Source	% of Respondents
Primary school (K–8)	63.2%
Secondary school (9–12)	55.1%
Parents/guardians or relatives	32.1%
Television/documentaries	26.8%
Other[1]	18.6%

[1] "Other" includes self-study, personal experience, individuals besides relatives, the internet or other computer/mobile sources, "common knowledge," the movies or other popular culture, government sources, radio other than weather radio, and missing/unclear responses (1.8%).

survey day. Students received no compensation or incentive (e.g., class points) for participating, and they could choose not to participate. Collected responses were completely anonymous, and student identifiers, majors, and course identifiers were not collected.

Data Analysis

Responses to background items (#1–3) were categorized and counted, and the factual item (#8) was scored based on a predetermined rubric (see the supplemental material, which can be found online at http://dx.doi.org/10.5408/14-029s2). Two researchers independently categorized, counted, and scored all 613 responses to these items, compared their results, and eventually reached 100% agreement. Responses to conceptual items (#4–7) were coded using rubrics (see the supplemental material, which can be found online at http://dx.doi.org/10.5408/14-029s2) developed by the primary author and a research assistant. All 613 responses to conceptual items were coded by the primary author, and a subset of 100 randomly selected responses for each conceptual item was independently coded by the research assistant, with eventual 100% agreement.

RESULTS AND DISCUSSION

Knowledge Sources of Participants

More than half of respondents indicated their primary knowledge source about tornadoes was formal education, though numerous other responses were also provided (see Table I). This finding indicates that formal education, starting from the earliest grades, may represent an important source through which students could be influenced by scientifically accurate tornado information. Other important knowledge sources about tornadoes were respondents' families (32.1%) and television (26.8%), which could also be influential in providing young people with scientifically accurate information. Less common sources of tornado knowledge included self-study or personal experience (5.9%), another nonfamily individual (3.8%), and the internet or mobile sources (3.1%). A small percentage of respondents cited movies such as *Twister* or other popular culture (1.1%).

Conceptions of Tornado Occurrence Relative to Land Cover and Topography

To assess alternate conceptions and fundamental concept application about the *relative roles* of land cover and topography (which generally have a miniscule role) and atmospheric conditions (the predominant influence) on tornado occurrence, participants were asked whether tornadoes could occur over snow-covered ground or in mountainous terrain, about the effects of rivers and hills, and about the tornado susceptibility of the city in which participants were surveyed and residing in or near. Knowledge of alternate conceptions in these areas can inform instructors about their students' perceptions of how tornadoes (primarily a phenomenon driven by atmospheric conditions) interact with land surface characteristics.

Participants were asked whether a tornado could occur with snow on the ground (circle yes or no), and to explain their reasoning. The established expert conception is that tornadoes can occur with snow on the ground, as this has been observed numerous times. For example, Nebraska's first recorded February tornado occurred the same year the survey was administered, with snow on the ground. This item assesses participants' alternate conceptions regarding the role of surface temperature on tornado occurrence. Valid responses ($n = 569$) were divided into two groups, either a tornado can or cannot happen with snow on the ground. Approximately 56% of these responses indicated the expert conception that a tornado could occur with snow on the ground. Although the value of 56% could be attributed to guessing on the yes/no option of this item, the associated free responses provided further insight into student reasoning. Among those indicating a tornado could occur with snow on the ground, four types of responses each accounted for >5% of the total responses to this item:

1. Yes was circled, but with no reasoning provided (20.1% of responses; Code 10; see the supplemental material).
2. An expert-like response, which we summarize as "atmospheric conditions, not surface conditions, are the key" (13.3%; Code 1).
3. A generic response, which we summarize as "tornadoes can occur anytime," or "I assume this could happen" (8.8%; Code 8). No reasoning is provided other than the respondents' conception of what should be able to occur.
4. A response close to the expert view, which we summarize as "this could happen if warm air moved in or was in place" (6.9%; Code 2). Though correctly focusing on the atmospheric component, warm air is not essential to tornado occurrence.

Other alternate conceptions present among a small percentage of respondents included that tornadoes may occur over snow as long as the surface is still flat, because the weather can be unpredictable, and because of the high moisture content; 1.6% of respondents ($n = 9$) indicated this could happen because they had seen or experienced such an event.

A more varied set of classifications emerged among respondents who incorrectly indicated that a tornado cannot occur with snow on the ground (44%); 11.5% indicated this but did not provide any reasoning. Most of the remaining types of responses are summarized below:

1. Tornadoes cannot occur over snow due to a lack of warm and/or moist air (22.1%; Code 13; see the supplemental material). This was the single most common response on this item. It is incorrect since

tornadoes do not require warm air, and even if they did, warm air may reside over a snowpack.

2. A generic response we summarize as "weather conditions aren't right" (3.0%; Code 17). Respondents in this category were likely thinking of temperature or moisture, though this cannot be verified.
3. Tornadoes do not occur during the time of year when snow is on the ground, or this is not tornado season (1.5%; Code 16).
4. A response focused on the lack of known historical precedent (1.5%; Code 14).
5. Too much moisture is present for tornadoes (1.3%; Code 17a). A moist lower atmosphere generally favors tornadoes by producing greater instability and low cloud bases, so this response is not consistent with fundamental atmospheric science concepts.

Other responses indicated that tornadoes do not occur because the atmosphere is too stable over snow, because they avoid snow, or because others told the respondent this could not happen.

Participants were also asked whether a tornado could occur in a mountainous area and to explain their reasoning. Until 1899, it was thought that north-central Nebraska was too near the mountains to be affected by a tornado (Gale, 1899). The current expert conception is that tornadoes can occur in mountainous areas, as has been demonstrated in the literature (e.g., Bluestein, 2000). This item assesses alternate conceptions of how significant terrain features influence the low-level wind field in a tornado. The valid responses ($n = 565$) were again coded into two broad groups (a tornado can or cannot occur in mountains) with codes assigned in each representative of responses received. Only 31.7% of these responses, consistent with the expert conception, indicated that a tornado could occur in a mountainous region. Reasoning on this item was highly varied. Among responses indicating a tornado could occur in a mountainous region, three types of responses each accounted for >4% of the total responses to this item:

1. Yes was circled with no reasoning (16.1%; Code 9; see the supplemental material).
2. The generic response we summarize as "tornadoes can occur anytime" or "I assume this could happen" (6.1%; Code 8).
3. The most expert response, that a tornado could occur in mountains if atmospheric conditions were correct (4.4%; Code 1).

Additional reasoning on surveys noting that a tornado could occur in mountains included that the underlying topography does not matter (1.7%; Code 7), that a historical precedent indicates this could happen (1.4%; Code 4), and that the higher elevation would make a tornado more likely (0.5%; Code 2).

Though 23.6% of respondents gave no reasoning, several alternate conceptions for why tornadoes should not happen in mountains were revealed in students' free responses. Among responses providing reasoning, these were the four most common alternate conceptions:

1. Wind patterns are disrupted by terrain features (14.9%; Code 11). While weak tornadoes may be disrupted by significant topography, stronger tornadoes are not affected by underlying terrain. For instance, tornadoes have been known to cross the Continental Divide (e.g., Fujita, 1989). This was the most common reasoning on this item.
2. Closely related, tornadoes cannot occur in mountains because there is surface friction or because the terrain is not flat (11.7%; Code 15). This response is different from the above, since it does not focus on the obstruction or disruption of the wind field by terrain features, but rather on the perceived need of flat terrain.
3. Tornadoes cannot occur due to the high elevation in mountainous areas (4.8%; Code 10). Given the large proportion of participants who indicated areas of lower terrain were safer from tornadoes, this response was unexpected but may be related to the belief that flat land is the least safe, since most tornadoes occur in flat, open regions.
4. Atmospheric conditions are not correct in mountains (3.7%; Code 12). A complex grouping of responses fit this classification, including the lack of ability to get temperature contrasts or enough moisture, and the changing pressure with elevation.

Less-frequent alternate conceptions included lack of known precedent (2.2%; Code 14), the low pressure or cold air in mountains (4.8%: Codes 13 and 16), and the perception that clouds or rain cannot cross mountains (0.8%; Code 17), including the idea that the "rain shadow" prevents storms in mountains. The rain shadow describes a local rainfall minimum typically extending downstream from large topographic barriers (e.g., Ward, 1920), not a reduction of precipitation over mountains.

Participant understanding of the fundamental concept that land surface features are relatively unimportant to tornadoes compared to atmospheric conditions was also tested by asking participants how likely the local city (where surveys were administered) is to be affected by a tornado relative to the surrounding region. Another item presented students with a map including a city next to a river, a city next to a hill along the same river, and a city away from any terrain features, and asked the relative risk of being affected by a tornado in each city (see the supplemental material, which can be found online at http://dx.doi.org/10.5408/14-029s1). Reasoning on these items indicated a generally poor application of the fundamental concept that land features are of minor importance, and a strong false sense of protection by terrain features. A large number of respondents thought both hills and rivers provide protection from tornadoes, but students were not able to give a mechanism for why this may be the case.

A "hill misconception" was defined as the idea that a hill would either increase or decrease the likelihood of being affected by a tornado. Though some instances of topography influencing tornado behavior have been documented (e.g., Lyza et al., 2013), the general consensus among scientists continues to be that tornadoes are not much affected by underlying terrain (e.g., Kellner and Niyogi, 2014). Among 447 valid responses, only 15.0% correctly indicated that a hill should have no effect on a tornado, and 10.1% of respondents were not sure of an answer; 42.7% of responses indicated that a hill would make a tornado less likely, and 6.3% indicated a hill would make a tornado more likely but did not provide reasoning. These were the most common alternate conceptions about how tornadoes interact with hills:

1. Hills make tornadoes less likely by changing or blocking the path (12.8%; Code 5; see the supplemental material). This category included obstruction or disruption of the tornado by a hill.
2. Hills make tornadoes more likely due to the higher elevation (7.6%; Code 11).
3. Tornadoes are less likely in hills due to the lower elevation (3.1%; Code 6). Clearly, this and the prior response depend on whether the respondent interpreted the city to be at low elevation next to the hill, or at high elevation on top of the hill. Regardless, both categories show a perception that elevation changes are important to local tornado risk.

Similarly, a "river misconception" was defined as the idea that a river would increase or decrease the nearby tornado risk; this is scientifically inaccurate since tornadoes are not known to be affected by rivers (e.g., NWS–Norman Forecast Office, 2013). Only 436 participants responded meaningfully to this item. Among these, only 17.4% correctly indicated that a river should have no effect on a tornado, 12.2% were unsure of an answer, 42.7% indicated a river would make a tornado less likely, and 6.9% indicated a river would make a tornado more likely but did not provide reasoning. These were the most common alternate conceptions about how tornadoes interact with rivers (see the supplemental material):

1. A river would obstruct or block a tornado (5.3%; Code 23), making it less likely.
2. A river makes a tornado less likely due to the lower elevation (5.0%; Code 17).
3. Tornadoes are less likely near rivers because tornadoes do not occur near water (3.9%; Code 22), a response seen in prior studies (e.g., Donner et al., 2012). This response contrasted with a small group who felt tornadoes were more likely near rivers because tornadoes are "attracted to water" (1.4%; Code 26), a response also seen in prior studies (e.g., Klockow et al., 2014). The prevalence of this alternate conception might be relatively low among these respondents since the city where the survey was administered is not along a large river; however, without a larger and more geographically distributed sample population, this idea remains untested.

Less-common alternate conceptions included rivers cooling the air or adding moisture, making a tornado less likely, extra moisture making a tornado more likely, the stable climate near a river reducing tornado likelihood, and the flat land near a river making a tornado more likely there.

Perceived vulnerability of the local region was also investigated (item #4) because these perceptions are (1) related to perceptions of the regional land surface and (2) may influence safety actions. Among respondents, most thought the local city was less susceptible to tornadoes compared to the surrounding area. Though meteorological research suggests weak tornadoes may be less common near the center of large cities (e.g., Elsom and Meaden, 1982), this is a dangerous perception since stronger tornadoes are less affected by the urban land surface. A strong tornado in an urban area would present a high risk of many fatalities, so it is especially important to understand and counter alternate conceptions about tornado likelihood within cities.

Among 559 valid responses to this question, 13.6% of participants indicated they were unsure of an answer, 8.4% stated the local city was more susceptible to a tornado, and 55.5% stated the local city was less susceptible to a tornado. Only 25.0% of respondents correctly indicated that the local city is just as susceptible as its surroundings. Among participants correctly indicating equal susceptibility, some indicated that the entire local region has high tornado risk (5.9%; Code 1), gave a generic response that we summarize as "tornadoes can occur anywhere" (5.7%; Code 3), or simply noted that the entire region should have the same relative risk (4.7%; Code 4). A need for correct atmospheric conditions, knowledge of a historical precedent, similar terrain around the local region, and the unsettled nature of Nebraska weather were also cited. A small percentage of participants indicated the local area was more likely to be affected by a tornado. Reasons given for this response included the large amount of infrastructure present (2.0%; Code 21), the perceived flatter nature of the local land surface (2.0%; Code 24), and proximity to where tornadoes are common (1.4%; Code 22).

The most common alternate conception, and most dangerous from a safety perspective, is that tornadoes are locally less likely (55%). The most common reasons for this alternate conception are listed here in order of prevalence:

1. The city is at locally lower elevation (21.3%; Code 9). This was more than twice as common as any other reason provided for this item. Though portions of the city are in a slight depression, it is a minor feature and would have no noticeable effect on a tornado.
2. Due to lack of a known historical precedent, tornadoes are locally less likely (8.8%; Code 12). While true that a large tornado has not recently affected the city, this does not indicate lesser local risk; historic regional tornado tracks show a random distribution (not shown).
3. Tornadoes normally affect rural areas (5.2%; Code 15). Though numerically more tornadoes occur in rural areas since these areas account for more total surface area, tornado occurrence per square mile is not significantly lower in urban areas.
4. Tornadoes do not occur where there are buildings and other structures (4.1%; Code 11). Respondents here specified that buildings, structures, or trees afford protection.

Other alternate conceptions included that tornadoes are less likely because the city is not in a tornado-prone region, that the terrain is too flat or too hilly, that the city produces too much heat, and that tornadoes normally go around the city. In all items assessing understanding of tornado–land surface interactions, participants strongly overestimated the importance of the land surface and tended to substantially

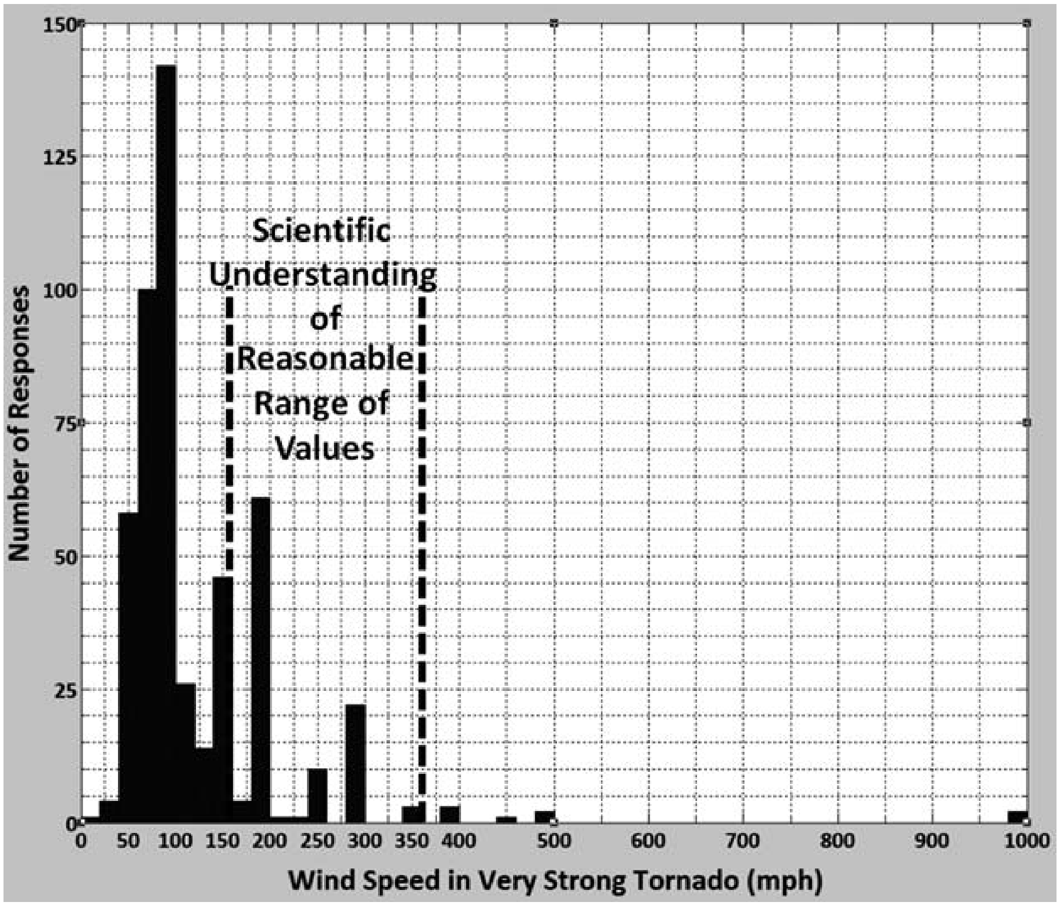

FIGURE 1: Histogram of wind speeds expected in a very strong tornado by study participants. Dashed bars indicate the current scientific understanding of a reasonable range of values.

overemphasize any protection offered by land surface features.

Conceptions of Tornado Wind Speed

Actual tornado wind speeds are determined by observations and are estimated by posttornado damage surveys. Based on this information, a reasonable range of values for a "very strong tornado" is defined as any 3 s gust speeds associated with a tornado rated EF-4 or EF-5 on the Enhanced Fujita scale (Edwards et al., 2013). Thus, when scoring student responses to item #8, winds from 166 mph to 350 mph were considered reasonable. The upper threshold was chosen to be reasonably close to the maximum wind speed measured in a tornado thus far—318 mph in the 1999 Moore, Oklahoma, tornado (NWS, 2011). Factual knowledge of tornado wind speed in a "very strong tornado" is potentially a useful measure of the realism with which students perceive these phenomena.

Compared to the range of actual wind speeds exhibited in strong tornadoes, the vast majority of participants significantly underestimated the wind speed in strong tornadoes (see Fig. 1). Meaningful responses to this item showed that a large percentage of students (39.1%) indicated that very strong tornadoes have wind speeds of 100 mph or less (see Fig. 1). Only 20.4% of respondents with meaningful responses indicated values in the reasonable range (166–350 mph), and few participants (1.6%) indicated values exceeding the reasonable range; 8.2% of participants indicated they were unsure of a reasonable answer, and 10.1% left the item blank, wrote a nonsensical answer, or provided an answer without units.

Wind speeds of 60 mph or less were indicated by 12.6% of respondents. This finding suggests that (1) a large proportion of college students may not realize that strong tornadoes have stronger winds than other phenomena in their experience (e.g., driving down the interstate), (2) students are completely unaware of the wind speeds associated with tornadoes, and/or (3) they have poorly developed skills for estimating wind speeds. The findings bring into question whether typical undergraduates in Tornado Alley would take shelter if a tornado was approaching, especially if perceived not to be strong.

Response Variation Among Participants from Different Regions

It was not a primary objective to ascertain differences in alternate conceptions held by respondents from different geographic regions, and the sample size of non–Great Plains students was relatively small. Nevertheless, significant geographical differences may exist in undergraduate perceptions of atmospheric phenomena. This is especially true of tornadoes, which, though they can occur anywhere, have a distinct geographical bias (separate from the distribution of snow and mountains). The Great Plains, including Nebras-

TABLE II: Comparison of perceptions held by non–Great Plains (NP) and Great Plains (P) respondents, derived from application of coding rubric. Italicized and bolded cells indicate comparisons with statistical significance at $p < 0.05$.

	NP, *n*	P, *n*	NP, %	P, %
Perceptions of Hill Influence on Tornadoes				
Hills have no effect	9	58	11.1%	16.1%
Hills increase risk	9	55	11.1%	15.3%
Hills decrease risk	53	214	65.4%	59.4%
Perceptions of River Influence on Tornadoes				
Rivers have no effect	11	64	15.7%	20.5%
Rivers increase risk	10	37	14.3%	11.9%
Rivers decrease risk	49	211	70.0%	67.6%
Perceptions of Local Tornado Susceptibility				
Local city equally at risk	***17***	***118***	***16.7%***	***26.0%***
Local city more at risk	7	37	6.9%	8.2%
Local city less at risk	46	240	45.1%	53.0%
Not sure about local risk	***32***	***58***	***31.4%***	***12.8%***

ka, have a high tornado occurrence, so students who grow up there might have more accurate tornado perceptions. From an education perspective, it would be valuable to know how alternate conceptions vary between students from the Great Plains and students from other regions. Here, we present some preliminary findings of geographical differences that could be explored in future studies. Such variations may be as much cultural as experience-based. For example, populations in different regions might perceive threat differently (e.g., Fothergill et al., 1999).

Survey participants were divided into those from the Great Plains states, which have high tornado prevalence ($n = 491$), and those not from this region ($n = 110$). "Plains undergraduates" are defined here as students who reported they were from Great Plains states with high climatological tornado occurrence, including Nebraska, Kansas, Oklahoma, Texas, and Iowa. Students from other locations, including international students, were classified as "non-Plains undergraduates." The two-tailed probability resulting from a z-test was used to compare the proportion of respondents in Great Plains and non–Great Plains populations with particular alternate conceptions (see Table II).

Great Plains and non–Great Plains students held virtually identical perceptions about the wind speed in a very strong tornado (128 mph and 127.2 mph, respectively). The two populations appeared to hold slightly different views of the effects of local terrain features on tornadoes. The misconception that hills offer tornado protection was held by 65.4% of non–Great Plains participants and 59.4% of Great Plains participants (see Table II), but this was not a statistically significant difference. Percentage of respondents holding a river misconception was also slightly decreased among Great Plains respondents (see Table II). Consistently, when asked about the effects of hills and rivers, fewer Great Plains respondents appeared to think that local terrain features could influence a tornado. Confirmation of this finding could be sought in future research. More Great Plains respondents thought the city where they were surveyed was equally at risk compared to its surroundings (statistically significant; $p = 0.046$), and that this city was less tornado-susceptible than its surroundings. This is because non–Great Plains residents were significantly more likely to be unsure about the local city's relative susceptibility (see Table II).

Limitations in Understanding Student Mental Models of Tornadoes

For the purposes of this study, the concept of mental models of a phenomenon is thought to encompass both factual knowledge (e.g., something a survey participant could have memorized, such as the wind speed typically associated with a strong tornado) and conceptual understanding that can be demonstrated through appropriate application of factual knowledge (e.g., given a new land-cover scenario, how do survey participants reason through how a tornado would be affected?). A complete, coherent mental model of tornadoes has not yet been developed, even by experts (e.g., Markowski and Richardson, 2014). Nevertheless, researchers can attempt to measure the completeness, coherence, and expertness of student mental models of tornadoes. In this study, we focused primarily on factual understanding of tornado behavior, including perceived effects of varying land cover on tornadoes, and perceived wind speed in a strong tornado. These foci represent a relatively narrow portion of the factual knowledge that could be associated with tornadoes (e.g., their typical life cycle, climatology, and favorable atmospheric conditions), and they do not explore in detail participants' understanding of how tornadoes form. As such, the results presented herein do not represent a complete picture of the mental model possessed by students regarding tornadoes, but they do represent a partial assessment of the factual component of student mental models. Some survey items also prompted students to reason through what should happen to a tornado over varying land cover. As these items require the application of fundamental science principles, they represent a partial assessment of student mastery of why tornadoes behave the way they do. Complete assessment of the mastery of related knowledge, however, is beyond the scope of this study and would require the development of detailed questions requiring participants to apply their knowledge to new situations in which tornadoes were occurring or might occur. Thus, the results presented herein are not meant to represent a complete assessment of the tornado mental models of participants, but make a contribution in that direction.

CONCLUSIONS AND FUTURE WORK

Survey participants learned about tornadoes through three primary sources, including formal schooling, their families, and television. Alternate and nonexpert conceptions were prevalent about the interactions between a tornado and the land surface, and the expert conception was relatively uncommon. Respondents collectively overestimated the protective influence of terrain features and substantially overestimated the degree to which land surface characteristics influence a tornado. Many respondents who felt land surface features provided protection from tornadoes could not provide reasoning to describe the mechanism of that protection. Collectively, participants did not have an accurate conception of how strong the wind typically is in very strong tornadoes.

This study shows that students hold notable misconceptions about tornado occurrence and relative risk. Most notably, this study reveals that many participants thought the underlying land surface significantly influences a tornado. The expert conception is, rather, that atmospheric processes are largely responsible for maintenance of a tornado; furthermore, land surface features such as hills, mountains, rivers, cities, and snow should not in most cases significantly diminish or increase tornado intensity. Student responses also revealed a lack of familiarity with historic tornado events—many significant events have affected mountainous areas, large cities, cities downwind from hills, and cities in river valleys. Many respondents did not properly distinguish number of tornadoes and tornado density. For instance, though most tornadoes do occur in rural areas, this is because rural areas account for much more area than cities, not because tornadoes avoid urban areas. Wind speed was vastly underestimated by many participants, who thought wind speeds in "very strong tornadoes" were not even as fast as they could drive on a highway, indicating a serious lack of ability to estimate a reasonable wind speed value for a tornado. A lack of consistency in the application of fundamental concepts was observed in the reasoning of some respondents. For example, among students who correctly specified that hills do not affect tornadoes, 33% said the local city was protected because it is at lower elevation, and among those specifying that rivers do not affect tornadoes, 27% thought that the local city was likewise protected.

Many respondents cited school as their primary source of tornado knowledge, so it appears that the current state of school instruction (which often happens during severe weather drills) is not sufficient for students to develop a complete mental model for thinking about tornadoes. Such a complete mental model would include both accurate factual knowledge and appropriate application of tornado-related concepts. While the results presented here focus primarily on factual knowledge within a relatively narrow domain of information related to tornado behavior, they indicate that most students lack a coherent mental model of tornadoes within that factual domain, even without having asked for additional information about tornadogenesis perceptions. Given the large geographical extent of the tornado threat in the U.S., students should be provided a more scientifically founded understanding of tornadoes. The current state of school instruction also may be insufficient in terms of providing students with experience using the two targeted fundamental concepts to explain tornadoes. Especially in tornado-prone regions, these learning experiences should begin early and continue through the undergraduate level as students become more familiar with the targeted concepts.

This exploratory study helps pave the way for future research. In particular, the survey that was developed for this study can be further developed for the purpose of more general and widespread use by applying accepted psychometric methods of instrument design to demonstrate its validity and reliability. In this study, nonexpert responses were often not accompanied by reasoning—future studies could use methods such as think-aloud interviews to better ascertain participant understanding. Additional items could be developed to explore participants' understanding of other aspects of tornadoes, including tornadogenesis, in order to develop a more complete measure of student mental models of tornadoes. Finally, novice conceptions about tornadoes revealed through this and future studies could be used to inform the development of formative and summative classroom assessments, possibly including a concept inventory for atmospheric science.

In addition, the same or similar questions that were asked of students enrolled in introductory-level science courses in this study could be asked of differently targeted populations to investigate possible correlations between tornado conceptions and gender, ethnicity, and/or year in college. In a similar vein, the general public could also be the focus of such future work. Particularly worthy of exploration may be the implications of regionally different tornado perceptions for those who grow up in low-risk areas and move to higher-risk areas. One purpose of such research should be to identify how tornado alternate conceptions are related to safety actions taken, with the goal of improving education and outreach efforts.

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