Multidisciplinary Analysis of an Unusual Tornado: Meteorology, Climatology, and the Communication and Interpretation of Warnings*

RUSS S. SCHUMACHER+

National Center for Atmospheric Research,# Boulder, Colorado

DANIEL T. LINDSEY

NOAA/NESDIS/STAR/RAMMB, Fort Collins, Colorado

ANDREA B. SCHUMACHER, JEFF BRAUN, AND STEVEN D. MILLER

Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado

JULIE L. DEMUTH

National Center for Atmospheric Research,# Boulder, Colorado

(Manuscript received 28 December 2009, in final form 9 April 2010)

ABSTRACT

On 22 May 2008, a strong tornado—rated EF3 on the enhanced Fujita scale, with winds estimated between 136 and 165 mi h^{-1} (61 and 74 m s^{-1})—caused extensive damage along a 55-km track through northern Colorado. The worst devastation occurred in and around the town of Windsor, and in total there was one fatality, numerous injuries, and hundreds of homes significantly damaged or destroyed. Several characteristics of this tornado were unusual for the region from a climatological perspective, including its intensity, its long track, its direction of motion, and the time of day when it formed. These unusual aspects and the high impact of this tornado also raised a number of questions about the communication and interpretation of information from National Weather Service watches and warnings by decision makers and the public. First, the study examines the meteorological circumstances responsible for producing such an outlier to the regional severe weather climatology. An analysis of the synoptic and mesoscale environmental conditions that were favorable for significant tornadoes on 22 May 2008 is presented. Then, a climatology of significant tornadoes (defined as those rated F2 or higher on the Fujita scale, or EF2 or higher on the Enhanced Fujita scale) near the Front Range is shown to put the 22 May 2008 event into climatological context. This study also examines the communication and interpretation of severe weather information in an area that experiences tornadoes regularly but is relatively unaccustomed to significant tornadoes. By conducting interviews with local decision makers, the authors have compiled and chronicled the flow of information as the event unfolded. The results of these interviews demonstrate that the initial sources of warning information varied widely. Decision makers' interpretations of the warnings also varied, which led to different perceptions on the timeliness and clarity of the warning information. The decision makers' previous knowledge of the typical local characteristics of tornadoes also affected their interpretations of the tornado threat. The interview results highlight the complex series of processes by which severe weather information is communicated after a warning is issued by the National Weather Service. The results of this study support the growing recognition that societal factors are just as important to the effectiveness of weather warnings as the timeliness of and information provided in those warnings, and that these factors should be considered in future research in addition to the investments and attention given to improving detection and warning capabilities.

---

* Supplemental information related to this paper is available at the Journals Online Web site: http://dx.doi.org/10.1175/2010WAF2222396.s1.

+ Current affiliation: Department of Atmospheric Sciences, Texas A&M University, College Station, Texas.

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Dr. Russ Schumacher, Dept. of Atmospheric Sciences, Texas A&M University, College Station, TX 77843.
E-mail: russ.schumacher@tamu.edu

DOI: 10.1175/2010WAF2222396.1

1. Introduction

On 22 May 2008, a strong tornado caused one fatality and numerous injuries, and caused an estimated \$193.5 million in damage along a 55-km track through northern Colorado (Fig. 1). It was the costliest tornado in Colorado history (Rocky Mountain Insurance Information Association 2009). Several characteristics of this tornado were unusual for the region: 1) the storm formed in the late morning hours, in contrast to the climatological late afternoon maximum; 2) the storm moved very quickly toward the north-northwest (taking it toward the densely populated urban corridor of the Front Range), as opposed to more common eastward-component storm tracks away from population centers; and 3) the tornado was surprisingly strong and long lived in such close proximity to the Front Range where weaker tornadoes are more commonly observed. Considering these characteristics, an analysis of the meteorological ingredients that led to this significant tornado is warranted, as is a consideration of this tornado in climatological context. Additionally, the unusual nature of this tornado raised questions about how warnings and other weather information were communicated to and interpreted by decision makers, and then passed on to the public.

Although some studies of warning communication during tornadoes have been conducted in the past (e.g., Legates and Biddle 1999; Hammer and Schmidlin 2002; NWS 2009; Sherman-Morris 2009), such data are limited in comparison to meteorological data (Golden and Adams 2000). Substantial efforts are being made to increase the accuracy and lead times of National Weather Service (NWS) severe weather warnings by improving detection and numerical prediction (Stensrud et al. 2009). Much less is known about what happens to warning information *after* the warning is issued.

Understanding the flow of warning information among decision makers and the public, and how warnings are interpreted, are key first steps toward maximizing the effectiveness of these warnings. It is also likely that people's interpretations of threats from severe weather are based on the local climatology and their past experiences with weather hazards. Understanding these interrelated processes requires methodologies, data, and knowledge from the social sciences in addition to those from meteorology. This study integrates meteorology, climatology, and social science methods to document warning communication and interpretation in a significant tornado event that took place in a location that experiences tornadoes regularly but is relatively unaccustomed to significant tornadoes. [Following Hales (1988) and Grazulis (1993), significant tornadoes are defined here as those rated F2 or higher on the Fujita scale, or EF2 or higher on the enhanced Fujita scale.] It also integrates information about the meteorology and climatology of tornadoes along the Front Range with how that information may have affected the interpretation of the warnings. Such integrated analyses can yield insights into meteorological situations that may not be obtained from examining weather data alone (e.g., Demuth et al. 2007). Overall, the primary questions we seek to answer are as follows:

- What were the meteorological conditions responsible for a significant tornado on 22 May 2008?
- How rare was this event, in terms of the storm's motion, the location so near the Front Range, the length of the track, and the time of day?
- How was severe weather information communicated and interpreted in an area relatively unaccustomed to significant tornadoes?

2. Overview of meteorological conditions

This section will provide a brief overview of the meteorological conditions that brought together the necessary ingredients for severe convection and significant tornadoes, namely moisture, instability, lift, and vertical wind shear (e.g., Doswell 1987). At upper levels, a deep, negatively tilted trough was located over the western United States on 22 May 2008, with several jet streaks moving through it (Fig. 2a). At 1800 UTC [1200 local time (LT), where LT = UTC − 0600], one of these jet streaks, with southerly winds exceeding 40 m s^{-1}, was located over eastern Colorado. At the surface, a 982-hPa low pressure center was located just east of Denver, with southerly winds and dry air to the south of the low, and easterly winds advecting relatively moist air around the north side of the low (Fig. 2b). In addition to the moisture gradient, a temperature gradient and wind convergence boundary was also present and was oriented from approximately west to east. The advection of moisture from the east is a common feature in severe weather environments along the Front Range (Doswell 1980), but the upper-level low on 22 May was much stronger than the typical, relatively benign, upper-level pattern shown in the composite analysis of Doswell (1980). In association with the warm, moist air being advected toward the Front Range, values of surface-based convective available potential energy (SBCAPE) were greater than 1000 J kg^{-1} in the North American Mesoscale (NAM) model analysis (Fig. 2c). There was also strong vertical wind shear in northern Colorado, with a vector wind difference of more than 40 m s^{-1} over the 0–6-km layer (Fig. 2c) and 10–20 m s^{-1} over the 0–1-km layer (Fig. 2d).

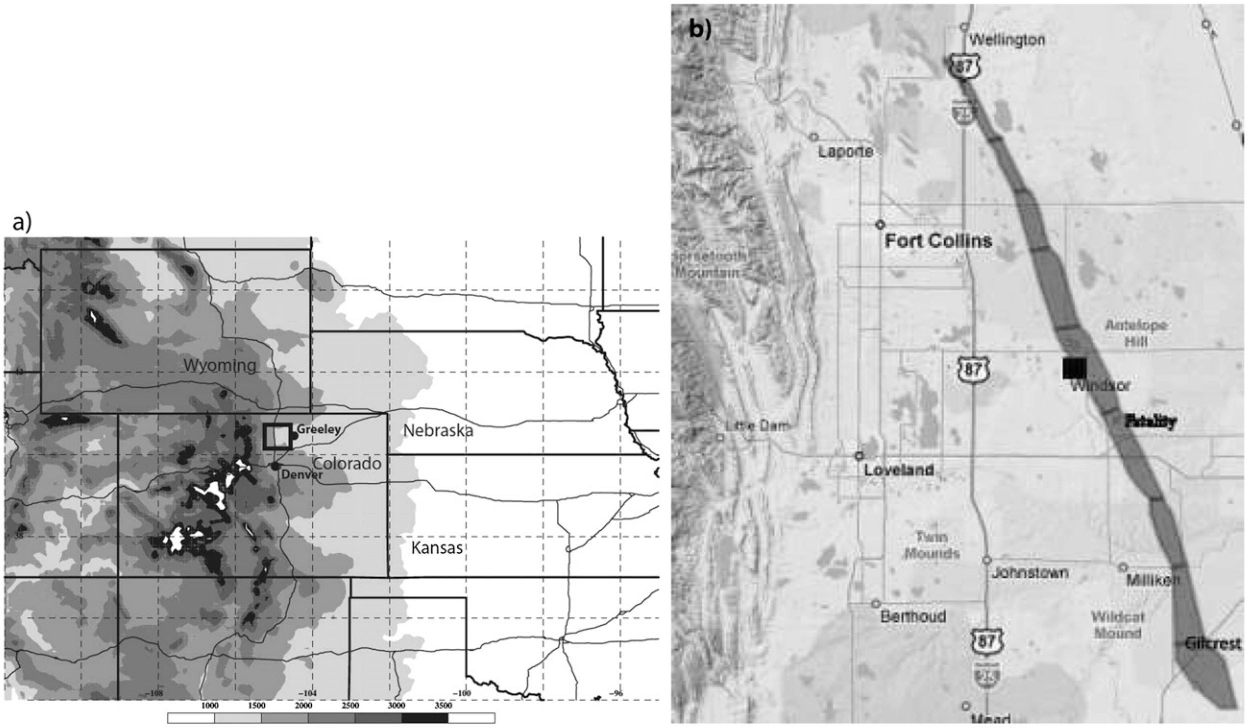

FIG. 1. (a) Map of the western Great Plains and Rocky Mountains, with elevation (m) shaded, and the approximate location of the map in (b) shown by the black rectangle. (b) Damage track of the tornado on 22 May 2008. The storm moved from the south-southeast to the north-northwest. The location of Windsor is indicated by the black square, and the location of the one fatality is shown. (Image courtesy of the NWSFO in Boulder.)

A loop of the *Geostationary Operational Environmental Satellite-12* (*GOES-12*) visible band (available online at http://rammb.cira.colostate.edu/case_studies/20080522/goes_visloop.asp) shows the boundary between cloud-free air to the south and moist, cloudy air to the north. As the moist air moved southwest around the north side of the low pressure center between 1400 and 1600 UTC, the stratus clouds just behind the boundary dissipated, allowing a narrow region to receive considerable insolation (Fig. 3). In this area of reduced cloudiness, the surface warmed and the atmosphere destabilized relative to the surrounding areas. The supercell that would produce the Weld County tornado initiated just south of this boundary around 1645 UTC, and quickly intensified at around 1700 UTC as it reached the warm, moist air.

The surface observation from Greeley, Colorado, at 1700 UTC (Fig. 4a), which was located in the narrow region of reduced cloudiness mentioned above, indicated a temperature of 21.1°C (70°F), a dewpoint of 12.8°C (55°F), and easterly winds at 15.4 m s^{-1} (30 kt) with gusts to 21 m s^{-1} (41 kt). This provides the best available estimate of the low-level air that the storm was ingesting. Modifying the special 1800 UTC sounding from Denver with the Greeley surface data (and changing the low-level temperature, moisture, and wind profiles to make them realistically match the surface observation) results in the sounding shown in Fig. 4b. This modified sounding has a 100-mb mixed-layer CAPE (MLCAPE) value of 2094 J kg^{-1} and a 0–1-km storm-relative helicity of 219 m^2 s^{-2}, which are both similar to values found in other significant tornado environments by Thompson et al. (2003). The 0–1-km vector shear magnitude in the modified sounding is 19.5 m s^{-1}, which is above the 90th percentile of significant tornado environments found by Thompson et al. (2003). Additionally, the lifting condensation level (LCL) of 1047 m AGL (see also Fig. 2d) is consistent with those in other significant tornado environments (Thompson et al. 2003) and is unusually low for Colorado. In summary, the strong upper-level trough, easterly near-surface winds advecting moisture westward, the west–east-oriented surface boundary, and the conditionally unstable atmosphere combined to provide the necessary ingredients for severe convective storms, and strong vertical wind shear at low and upper levels indicated the potential for tornadic supercells.

The Storm Prediction Center's (SPC) day 1 convective outlook, issued at 1630 UTC (1030 LT), highlighted the potential for severe convection in Colorado, stating that

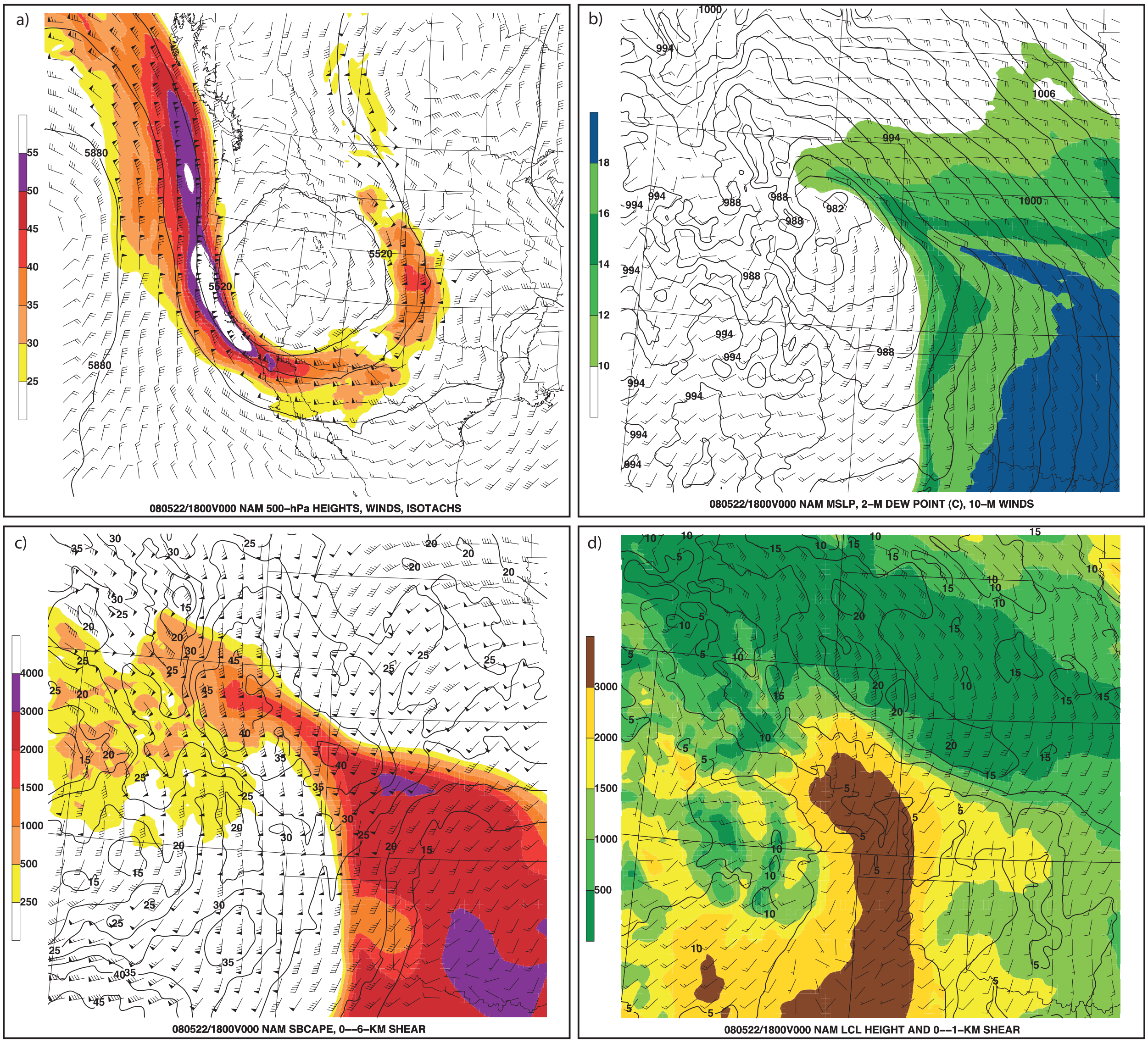

FIG. 2. NAM model analyses at 1800 UTC 22 May 2008. (a) Analysis of 500-hPa heights (black contours every 120 m), wind speed (m s^{-1}, color shading, and wind barbs, where a short barb represents 2.5 m s^{-1}, a long barb represents 5 m s^{-1}, and a pennant represents 25 m s^{-1}). (b) Pressure corrected to sea level (black contours every 2 hPa), 2-m dewpoint temperature (°C, color shading), and 10-m wind barbs; the map has been zoomed in to focus on CO. (c) Surface-based CAPE (J kg^{-1}, color shading), 0–6-km vector wind difference magnitude (black contours every 5 m s^{-1} above 15), and 0–6-km vector wind difference (wind barbs). (d) Height of the lifting condensation level (m AGL, color shading), 0–1-km vector wind difference magnitude (black contours every 5 m s^{-1} above 15), and 0–1-km vector wind difference (wind barbs).

> SURFACE BASED STORMS ARE LIKELY TO DEVELOP ACROSS NERN CO…ESPECIALLY ALONG AND NORTH OF THE PALMER RIDGE BY EARLY AFTERNOON. ONCE STORMS FORM…THE AMOUNT OF INSTABILITY AND EFFECTIVE SHEAR AT 60 KT WILL RESULT IN RAPID SUPERCELL DEVELOPMENT. THERMODYNAMIC PROFILES SUGGEST VERY LARGE HAIL WILL BE THE MAIN THREAT…THOUGH SRH VALUES FROM 200–300 M2/S2 FAVOR TORNADOES…SOME STRONG.

In this convective outlook, the northeastern corner of Colorado, along with much of Kansas and parts of Nebraska and Oklahoma, were at a moderate risk for severe weather, whereas areas near the Front Range were at a slight risk (Fig. 5a). Similarly, the northeastern corner of Colorado was assigned a greater than 15% probability of a tornado within 25 mi of a point—and a greater than 10% probability of a significant tornado—but areas near the Front Range were assigned a greater than 2% probability for tornadoes and were

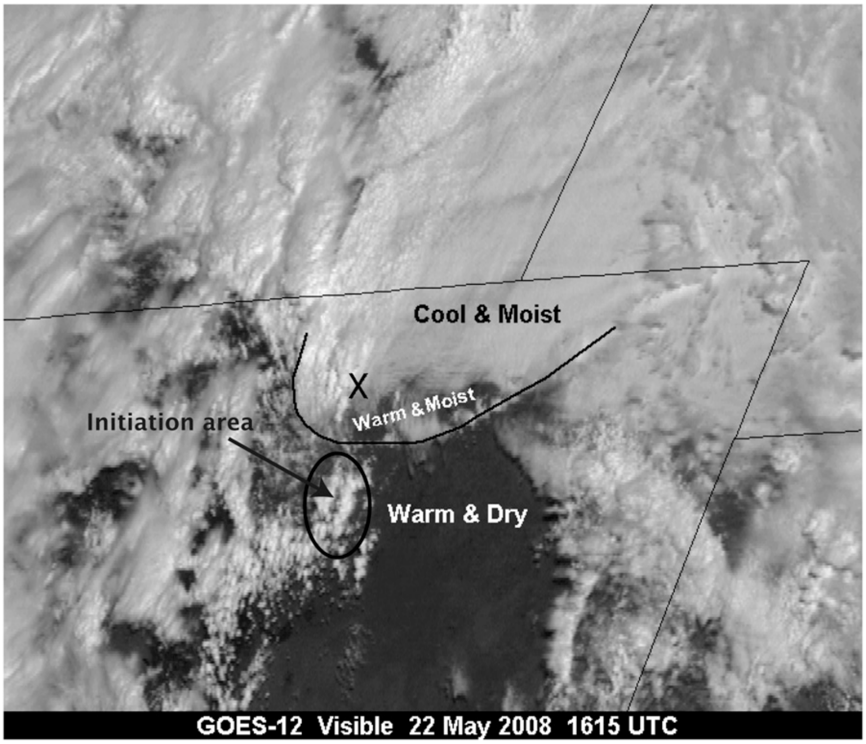

FIG. 3. *GOES-12* visible image from 1615 UTC 22 May 2008 with a frontal boundary and three air masses denoted. The image covers northeast CO, southeastern WY, and the southwestern NE panhandle. The location of Windsor is shown with an ex. The area where the thunderstorms initiated is also shown.

not highlighted for significant tornadoes (Fig. 5b). The storms formed much earlier than expected, with deep convection initiating around 1645 UTC [1045 local time (LT)]. The primary cell rapidly intensified, became supercellular, and tracked quickly toward the north-northwest (Fig. 6; animation available online at http://rammb.cira.colostate.edu/case_studies/20080522/kftg_reflloop_highres.asp). At 1106 LT, the SPC issued a

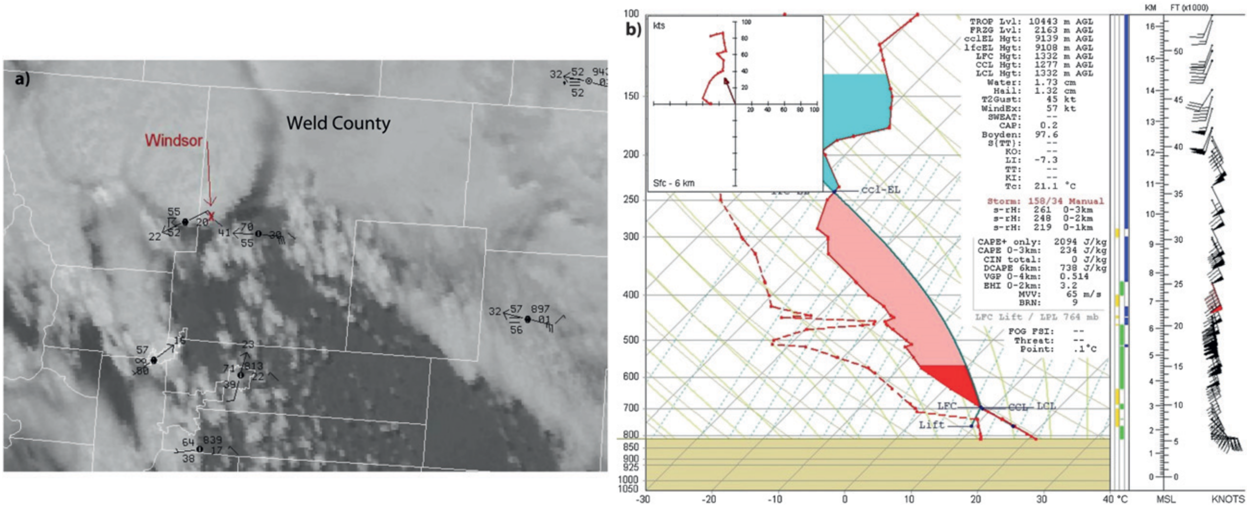

FIG. 4. (a) *GOES-12* visible image from 1745 UTC 22 May 2008 and surface observations. The location of Windsor, is shown with a red x. (b) The 1800 UTC sounding from Denver modified with the 1700 UTC Greeley surface observation.

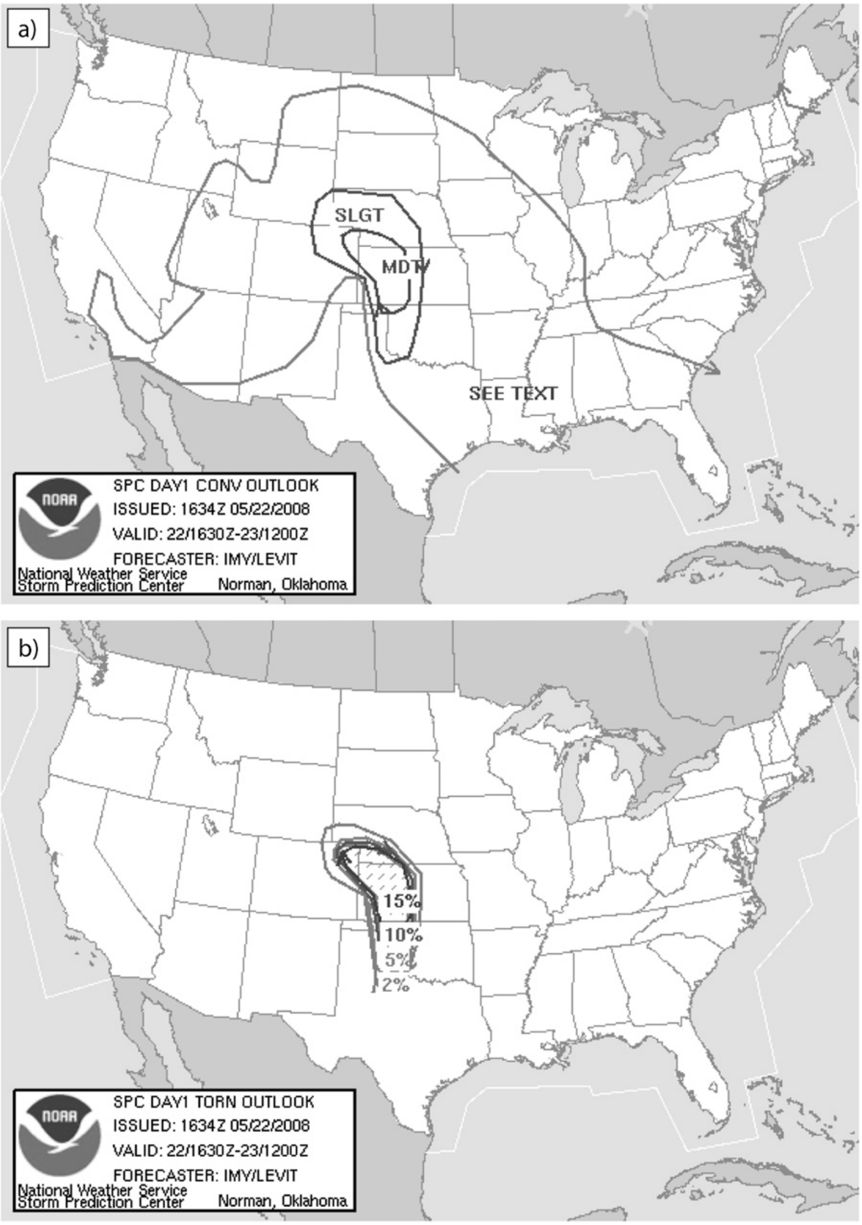

FIG. 5. SPC graphical convective outlook issued at 1630 UTC 22 May 2008. (a) Categorical graphic, with lines surrounding areas of general thunderstorms (outermost line), slight risk of severe thunderstorms, and moderate risk of severe thunderstorms. (b) Probabilistic tornado graphic, which represents the probability of a tornado within 25 mi (40 km) of a point. The hatched area represents a 10% or greater probability of EF2–EF5 tornadoes within 25 mi (40 km) of a point. Obtained from the SPC Web site (http://www.spc.noaa.gov/products/outlook/archive/2008/day1otlk_20080522_1630.html).

mesoscale discussion indicating that a tornado watch would be issued soon. The first severe thunderstorm warning was issued by the National Weather Service Forecast Office (NWSFO) in Boulder at 1109 LT (Fig. 7), and the first tornado warning was issued at 1118 LT. A tornado watch was then issued by the SPC at 1125 LT. The first tornado was reported east of the town of Gilcrest at 1126 LT (Fig. 7), and the tornado hit Windsor just before noon. The Boulder NWSFO continued issuing tornado warnings and severe weather statements throughout the period between the initial tornado report and when the storm weakened somewhat after hitting Windsor.

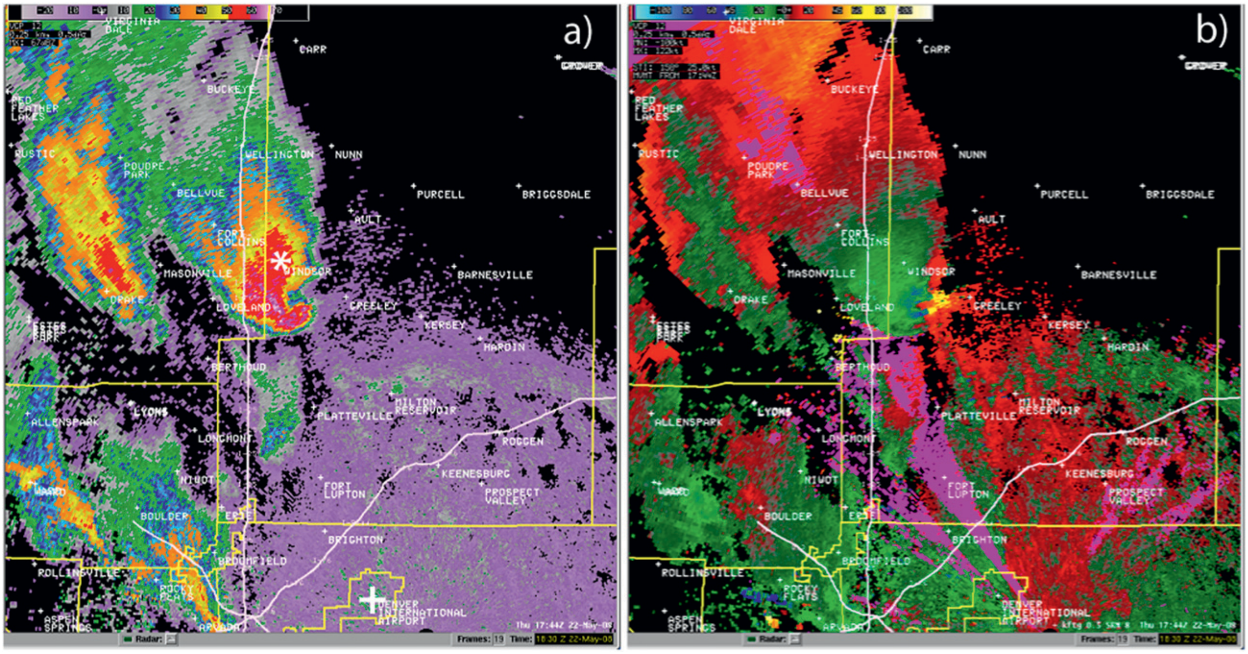

FIG. 6. (a) Base radar reflectivity (dB*Z*) and (b) storm-relative velocity (kt) data from the Front Range Airport (KFTG) radar in Aurora, CO, at 1744 UTC 22 May 2008. The location of Windsor is shown with an asterisk and the location of Denver International Airport with a plus sign in (a). (Images courtesy of the NWSFO in Boulder.)

The text of all of the NWS warnings is available in the online supplement (http://dx.doi.org/10.1175/2010WAF2222396.s1).

3. Climatological context

For experienced weather observers in Colorado, many aspects of this storm seemed unusual: the long north-northwestward track, the early time of day, and the location of such a strong tornado so close to the Front Range. With this in mind, the tornado climatology was investigated to understand how rare this event was. The following datasets were used in this analysis:

- the "SVRGIS" database from the NWS FO in Indianapolis (information online at http://www.crh.noaa.gov/ind/?n=svrgis), which includes severe weather reports from 1950 to 2006 in GIS format, including the time, location, and length of tornado tracks, and
- for information on historical tornadoes (those occurring prior to 1950), the work of Grazulis (1993) was used, which includes data about all significant tornadoes in the United States from 1680 to 1991.

Additionally, the track of the Windsor tornado of 22 May 2008 was manually added to the database, based on the damage survey provided by the Boulder NWS office.

We begin by examining the climatology of all tornadoes in Colorado and Wyoming (Fig. 8a) during the period 1950–2006, plus the 22 May 2008 tornado. Almost all tornadoes in these states occur east of the Continental Divide. There are some tornadoes that have long tracks, but most are short lived, appearing simply as points in the figures. Narrowing these data down to only significant tornadoes reveals that only a small percentage of tornadoes in Colorado and Wyoming are significant—just over 10% (Fig. 8b). Nationwide, this percentage is approximately 28%, which means that Colorado and Wyoming experience an even lower proportion of significant tornadoes than does the rest of the country. As with the total population of tornadoes, nearly all significant tornadoes are east of the divide. It is important to note that the Fujita (and now enhanced Fujita) scales rate tornadoes primarily on the damage they cause; therefore, storms affecting rural areas (where there are few structures to damage) may be biased toward lower ratings (e.g., Doswell and Burgess 1988). As such, significant tornadoes are artificially more common in populated areas. Because eastern Colorado and Wyoming are sparsely populated, it is possible that many tornadoes are underrated in these areas.

Focusing in on tornadoes near the Front Range in Colorado and Wyoming (Fig. 9a), defined here as tornadoes occurring west of 104°W (the Wyoming–Nebraska border), it is apparent that short-lived, weak tornadoes are quite common, with a few areas appearing to be preferential for formation, such as the areas just to the

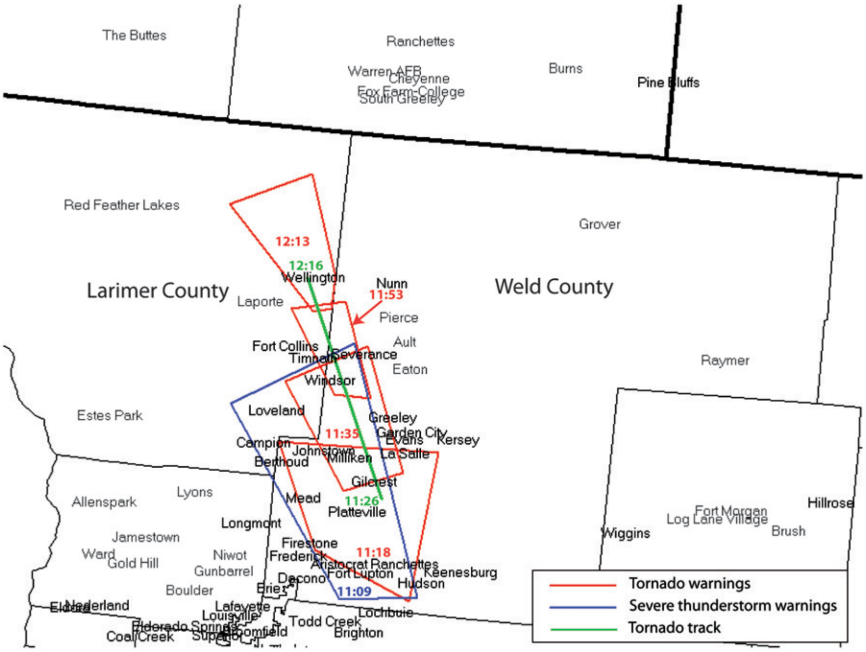

FIG. 7. Summary of the NWS warnings issued on 22 May 2008 in relation to the tornado track. The tornado track, along with its start and end times, are shown in green. Severe thunderstorm warning polygons are shown in blue, and tornado warning polygons in red. The local time each warning was issued is also shown. Only warnings associated with the tornadic storm that impacted Windsor are shown; other warnings that were issued on 22 May are not shown.

north and southeast of Denver International Airport. One reason for the large number of tornadoes in this area is the occurrence of the topographically-induced ''Denver cyclone'' (e.g., Szoke et al. 1984), which is often associated with severe weather and tornadoes. Nonsupercell tornadoes are also common in this area (e.g., Wakimoto and Wilson 1989). Weld County, with its huge size, also has a large number of tornadoes. A notable aspect of the Windsor tornado was its track toward the north-northwest. To examine this property in more detail, all of the tornadoes with a component of motion toward the west have been highlighted in green in Fig. 9a. Tracks with a westward component have happened before [including one of the tornadoes described by Zipser and Golden (1979)], but make up only a very small minority of Front Range tornadoes. The Windsor tornado stands out as the longest green line on this map: it had the longest track of any tornado with a westward component near the Front Range, and the fourth-longest track among all tornadoes near the Front Range. Narrowing the data further to look at only significant tornadoes near the Front Range, and adding historical significant tornadoes, shows that long-track, significant tornadoes have indeed occurred near the Front Range in the past (Fig. 9b). In particular, Weld County has experienced numerous significant tornadoes over the years. Also, a few significant tornadoes in the past have had a westward component (shown in green), but most move toward the east.

Finally, considering only those tornadoes in and around Weld County shows that western Weld County is not immune to strong, long-track tornadoes (Fig. 9c). This area has been hit several times in the past, though prior to the May 2008 storm the last times the Windsor area experienced a significant tornado were in May 1957 and May 1952, and the last significant tornado anywhere in Weld County occurred in 1996. In addition to these, there were some destructive tornadoes in the past that are shown on the map in blue: an F3 tornado that began near Severance in 1920, an F4 tornado that hit Johnstown and killed two people in 1928, and a pair of F2 tornadoes on the same day in May 1943 (Grazulis 1993). The May 2008 Windsor tornado still stands out on this map because of its unusual north-northwestward track, as almost all of the other tracks shown on the map were either toward the northeast or the southeast. Furthermore, it is the only recorded F3 or greater tornado near the Front Range with a westward component to its track. Demographically, much has changed about northern Colorado since these historical tornadoes took place, including major changes in the area's population from a sparsely populated rural area to developed suburban towns. These changes, in conjunction with the lack

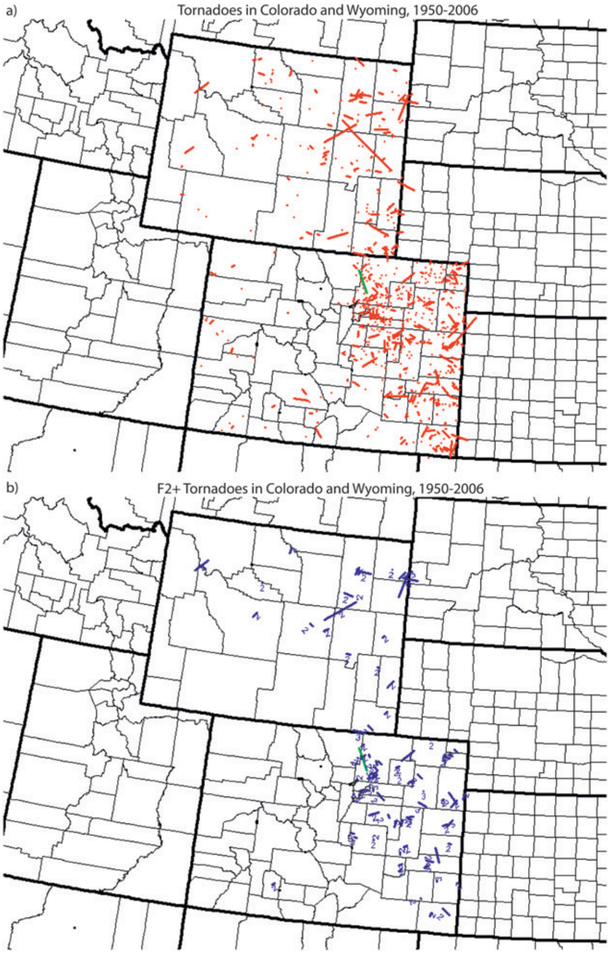

FIG. 8. (a) All tornadoes in CO and WY during 1950–2006, plus the 22 May 2008 tornado, which is shown in green. (b) As in (a), but for only significant (F2+ or EF2+) tornadoes.

of significant tornadoes in recent years, suggest that many residents of western Weld County had never experienced a significant tornado in the area prior to May 2008. The climatology shows that although such events may be rare, they are a real threat in northern Colorado.

Another seemingly unusual aspect of the May 2008 Windsor tornado was the time of day at which it formed, approximately 1126 LT. Figure 10 shows the time of day for significant tornadoes near the Front Range. The large majority of tornadoes near the Front Range occur in the afternoon and evening, between 1400 and 1900 LT. The Windsor tornado occurred on the very early side of this distribution, though there have been a few other significant tornadoes in this area that have developed before noon. In summary, this climatological analysis shows that although the individual aspects of the 22 May 2008 storm (such as its location, length of track, intensity, westward

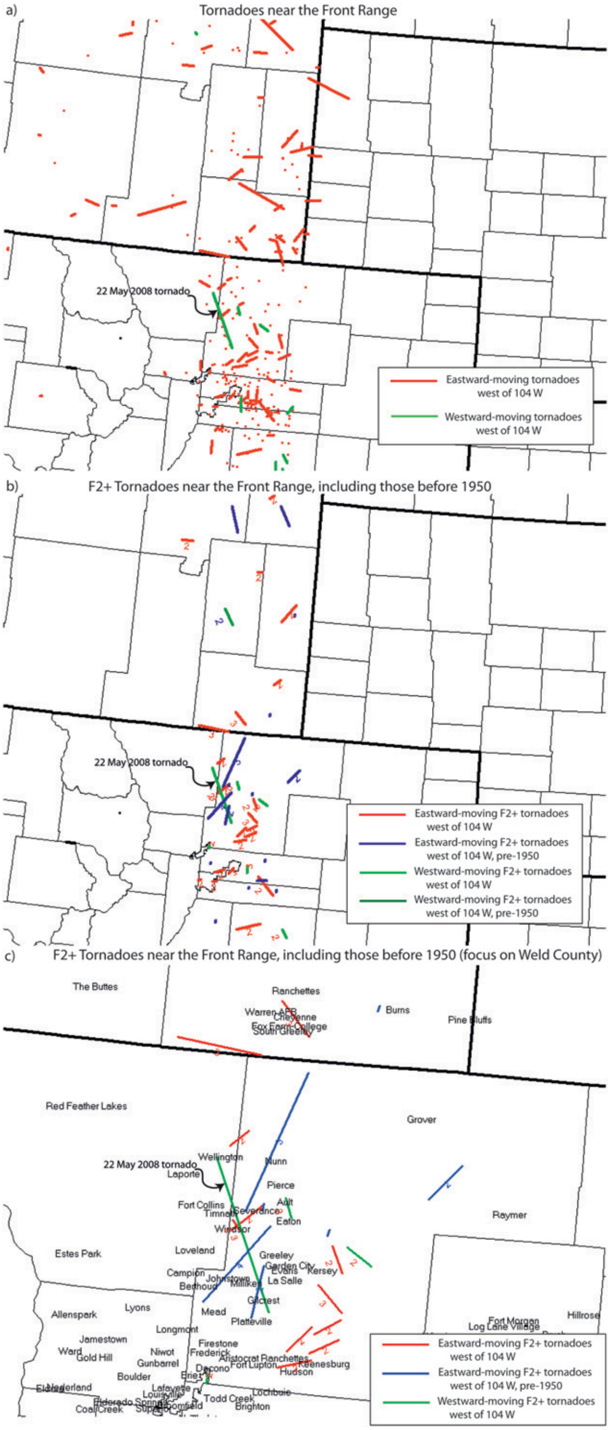

FIG. 9. (a) As in Fig. 8a, but only showing tornadoes near the Front Range (defined here as tornadoes occurring west of 104°). Tornadoes with a component of motion toward the west have been highlighted in green. (b) As in (a), but for only significant (F2+ or EF2+) tornadoes. Manually added historical tornado tracks, obtained from Grazulis (1993), are also included in (b). These historical tracks are shown in blue, with the one westward-moving tornado in dark green. (c) As in (b), but zoomed in on Weld County.

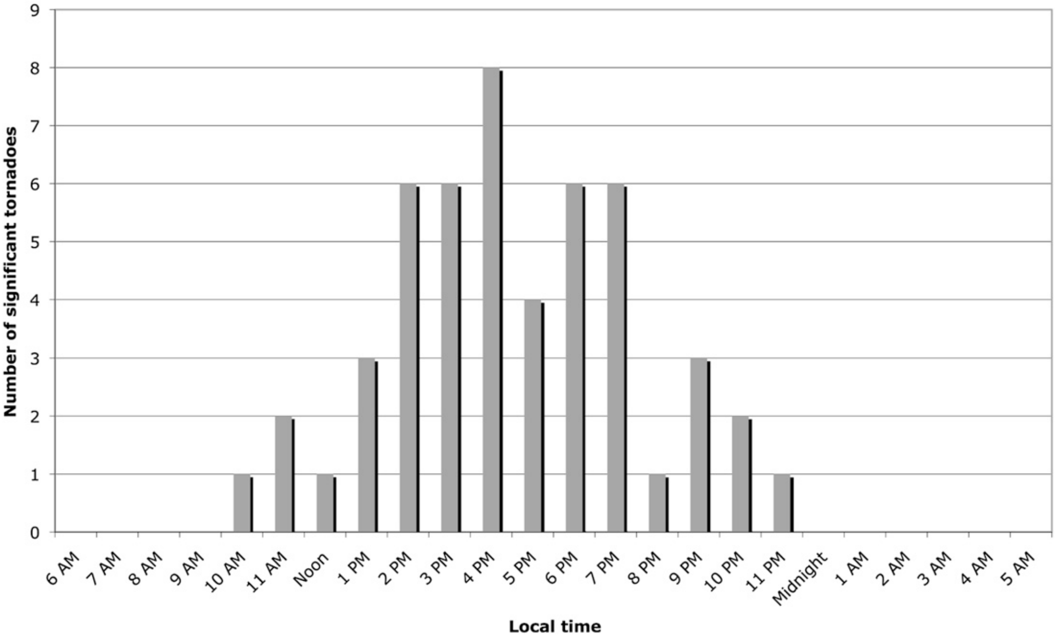

FIG. 10. Time of occurrence of significant tornadoes near the Front Range. Tornadoes included in this figure are those shown in Fig. 9b, excluding those that occurred before 1950.

motion, and time of occurrence) are somewhat rare but not unheard of, the combination of these aspects was quite unusual and perhaps unprecedented in northern Colorado.

4. Communication and interpretation of severe weather information

a. Introduction and methods

Rare, high-impact weather events provide challenging tests for meteorologists, decision makers, and emergency communication systems alike. Therefore, examining how they function during such a test can provide information that could be useful in improving the response during future events. The 22 May 2008 Weld County, Colorado, tornado provided an opportunity to examine how warnings and other weather information were communicated to and interpreted by decision makers, and then passed on to the public. Furthermore, the unusual nature of this tornado—in terms of its direction of motion, intensity, and time of day—added further complexity to an already challenging situation, which will be the focus of the analysis in this section.

During this tornado, the issuance of warnings by the NWS office in Boulder was generally consistent with typical warning lead times or longer, particularly for cases when a watch was not in effect prior to the event occurring (e.g., Keene et al. 2008). There was approximately 8 min of lead time between the first tornado warning and the first reported tornado, and approximately 20-min lead time between the issuance of the warning that included Windsor and when the tornado impacted Windsor. These data regarding the time of warning issuance are readily available from the NWS, but less is known about what happens *after* the warnings are issued. The meteorological community has traditionally focused on the detection and warning of tornado events, but official warning lead times do not tell the full story of a weather event. The story also needs to examine the societal side, including how people receive and interpret these warnings.

To begin to answer some of these questions, an exploratory study was conducted that focused on decision makers within the tornado-warned areas. The choice to use decision makers, rather than the public at large, as the subject of the study was made because these officials had some responsibility for making the public aware of the threat of severe weather, and were likely to have strong recollection of the event. Such officials are also part of the ‘‘weather warning partnership’’ (Golden and Adams 2000) that is responsible for communicating with and protecting the public. Some other recent studies (e.g., Morss and Ralph 2007; Baumgart et al. 2008) have investigated the roles that decision makers play in the weather warning and emergency management process.

To recruit potential participants, all public school districts, universities, and emergency managers within the warned areas were contacted with an invitation to be

TABLE 1. Breakdown of the positions of the 15 decision makers interviewed.

School administrators	4
Emergency managers	4
University officials	3
School teachers	2
Small business manager	1
Broadcast meteorologist	1

interviewed for this study. They need not have actually experienced damage or other direct impacts from the tornado. These populations were specifically chosen because they generally have well-defined plans of what to do in the case of severe weather, but do not need to execute those plans very often in locations near the Front Range. Not all of the decision makers that were contacted responded to our invitation, but all who did were interviewed. In addition to these groups, which make up a large majority of the participants, we were referred to a few additional participants that added further diversity of perspective on the event.

Semistructured interviews were conducted with these participants to learn about the flow of severe weather information and its interpretation on the day of the Weld County tornado. This method provides rich qualitative data and allows for flexible questioning. However, it necessitates a smaller sample size because of the time required to conduct the interviews. In total, 15 semistructured interviews were conducted in January–March 2009; 11 interviews were conducted in person, and 4 via telephone for the sake of convenience. The breakdown of the responsibilities of those interviewed is shown in Table 1. This is not intended to be a representative sample, and cannot be generalized to other events or geographic areas, but was designed to gather a diversity of points of view (similar to the approach taken in Morss and Ralph 2007). The interviews succeeded in providing a variety of perspectives, and resulted in data that offer insights into warning communication and interpretation during this event and suggest areas for future research.

The full script for conducting the interviews is provided in the online supplement. Because of the semi-structured nature of the interviews, not every sub question was asked of every interviewee, and some additional follow-up questions not on the script were asked of some interviewees based on their previous responses. Overall, the questions were grouped into the following categories:

- initial sources of information, interpretation of that information, and any barriers to receiving information;
- subsequent sources of information, interpretation, and barriers;
- past experience with tornadoes and how it related to this particular day; and
- usefulness of information that was communicated and additional information/communication methods that would have been helpful/useful.

The interview questions focused primarily on the participants' perspectives on the communication and interpretation of weather information, and did not attempt to assess their organizations' actions during the event. This distinction was made to minimize potential risks to the participants. Furthermore, as is typical with research involving human subjects, the results are reported in a way that maintains the confidentiality and anonymity of the participants and their organizations. Interviews were conducted by the first author, with a second member of the research team transcribing the participants' responses. The results are summarized herein by themes consistent with the categories of questions outlined above.

b. *Results*

1) SOURCES OF WARNING INFORMATION

Only a few interviewees said that they were aware of the possibility of severe weather that day in advance of the warnings; most were not. The early initiation of the storms and their rapid development may have played a role in this: the storms occurred earlier than forecasters were expecting, and as a result a tornado watch was not issued by the SPC until after the issuance of the first warnings.

The initial sources of warning information among the decision makers were varied, which is consistent with past research (e.g., Hammer and Schmidlin 2002; NWS 2009). In some respects, their professional position dictated the way they received the initial warnings. For example, the broadcaster first heard the warning over the alarm system in their studio (which receives data directly from the NWS), and emergency managers received information from emergency dispatchers and from the National Warning System (NAWAS). School officials reported different information sources, including the media and word of mouth—in some cases, a phone call from a parent was the first that they heard about the warning, and in one case, an emergency manager called the school directly to pass along warning information. One of the school districts reported receiving the initial warning via proprietary software that they subscribed to. The school teachers heard about the warnings when administrators made school-wide announcements over their public address system.

Two commonly considered mechanisms for disseminating warning information, National Oceanic and Atmospheric Administration (NOAA) Weather Radio (NWR) and outdoor sirens, were not used for initial information in this event by the decision makers we interviewed. None of the interviewees reported hearing the initial warnings via NWR—some reported having NWRs but that they were turned off or the batteries were dead—although several said that they used the NWR to get later information. Most of the warned areas do not have outdoor severe weather sirens, so those were not a means for communicating the warnings in this case.

The time at which the respondents received their initial information about the warnings also varied. Several received the very first warnings issued by the NWS, whereas others did not hear a warning until the storm was very close to their location. Interviewees located farther ''downstream'' (i.e., north-northwest) generally had more time to hear the previous warnings and reports and therefore had more time to respond. However, even some of the interviewees in the same general location reported widely varying times at which they heard the tornado warnings, and also varying ways in which they interpreted the information in those warnings. These interpretations will be discussed in the next subsection.

Among the variety of information sources mentioned above, there may have been multiple layers of ''filtering'' of the warning information. In other words, some of the decision makers did not receive the warning information directly, but were instead reliant on others to communicate it to them (with varying levels of completeness and accuracy). For example, the communication structure within the schools was such that teachers in classrooms relied on the school administrators to pass along the warning message. One of the teachers we interviewed recalled that a ''code'' about a possible emergency was announced over the school's intercom system; this was a general code that could be used for any type of emergency, and it did not specify that this was a weather-related threat or contain any weather information. As noted above, one school administrator reported initially hearing about the threat via a phone call from an emergency manager. When structures exist in which there is a chain of communication—that is, when some people rely on others to disseminate the information to them—a built in delay in the dissemination of that information is introduced. This is in addition to any delay that may exist in getting information to the direct receivers of that information. Furthermore, these structures can also introduce additional filters on the content of the warning: there is the possibility of misunderstanding or miscommunicating important details about the threat, or of not communicating the message at all.

In addition to the official warning information, multiple interviewees noted that visual cues were an important source of information that affected their interpretation of the threat: they stated that they had never seen the sky look so dark. A few respondents stated that they sought shelter when hail began to fall.

As the day progressed, the sources of weather information used by the decision makers were also varied. Interpersonal means of communication, such as talking in person or on the phone with other decision makers, were commonly cited (consistent with Legates and Biddle 1999 and Sorensen 2000). However, when these methods involved receiving reports from the public, they also led to some incorrect or unclear information being communicated. For instance, there were false reports of tornadoes where none actually occurred, and also conflicting information about whether a warning was still in effect. The Internet, NWR, and broadcast media were also used as information sources later in the day. However, decision makers in and near the area hit by the tornado reported difficulties in communication because both electrical power and cell phone signal were lost for much of the day, as a result of the tornado damaging towers and transmission lines. For example, school officials and emergency managers struggled to communicate within their organizations, because some of their usual methods of communication were unavailable. In some situations, this made communicating an ''all clear'' message difficult after the warnings had been cancelled. This emphasizes that although it is certainly desirable to continue advancing warnings and their communication through new technologies, they cannot entirely replace existing methods of communication, such as broadcast media and NWR. A few respondents stated that they used NWR extensively later in the day, because their other sources of information (such as the Internet) were unavailable. These results also emphasize the importance of multiple, redundant modes of communication so that the warning message can be disseminated as widely as possible, and also that educating the public and decision makers about NWR and encouraging its use as an initial information source could help to reduce some of the widely differing lead times reported here.

2) INTERPRETATION OF WARNING INFORMATION

Past studies have identified a sequence of processes that describe people's responses to warnings (e.g., Mileti and Sorensen 1990; Sorensen 2000), including the following:

- hearing the warning,
- understanding the contents of the warning,
- believing the warning is credible and accurate,
- personalizing the warning to oneself,
- confirming the warning is true and others are taking heed, and
- responding by taking a protective action.

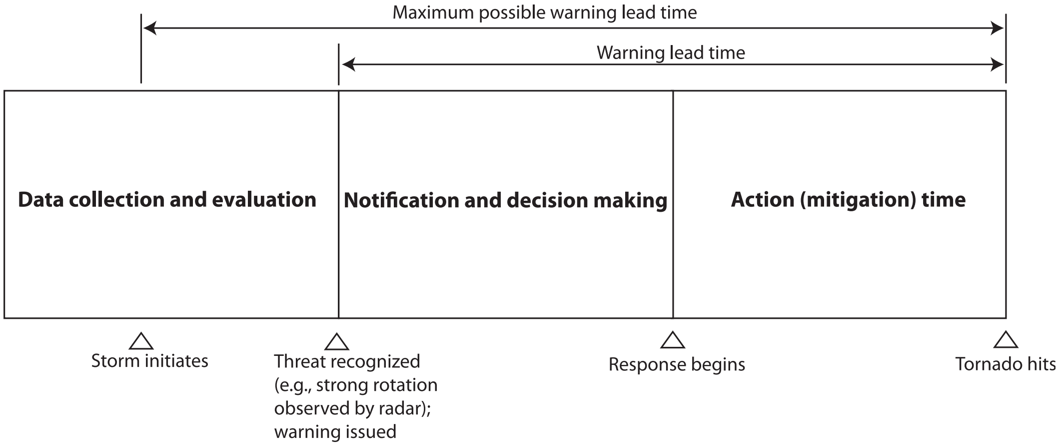

FIG. 11. Tornado warning timeline, adapted from Fig. 1 of Pingel et al. (2005). The original figure in Pingel et al. (2005) considered long-fuse flood warnings; this version is modified to consider short-fuse tornado warnings, for which the length of time available in each of the boxes is generally much shorter. The right-hand side of the diagram denotes the time the tornado hits the location of a specific decision maker or user, which is not necessarily the time of the initial tornado touchdown.

Within the context of flood warnings, though also generally applicable to the process of tornado warnings, Pingel et al. (2005) divide the warning timeline into three categories: data collection and evaluation, notification and decision making, and action (mitigation) time (Fig. 11). Compared to longer-fuse warning situations, such as floods, the entire timeline shown in Fig. 11 is compressed for tornadoes, sometimes only spanning an hour or less. The warning lead time consists of the second and third steps of the process, and can be thought to begin at the time the NWS issues a tornado warning. The length of the second box in Fig. 11 (which is inversely related to the length of the third box) is therefore dictated by the time spent on the first five steps of the Mileti and Sorensen (1990) sequence.

Overall, the interviewees' perceptions of the clarity of the warning messages varied, ranging from a response of ''crystal clear'' to responses indicating confusion about what was happening. One theme that emerged from the interviews is that hearing actual reports about the tornado was a key to the decision makers' interpretation of the threat; almost all of the interviewees stated that when they heard specific information such as ''a tornado is on the ground in Gilcrest,'' or ''damage has been reported in Greeley,'' they took the threat much more seriously. This indicates that ground-truth reports are important to the ''believing,'' ''personalizing,'' and ''confirming'' steps of the sequence, and supports the recommendations in NWS (2009) that clear wording about the presence of an actual tornado should be used in warnings. Strong wording was indeed used in NWS warnings on 22 May 2008, including statements such as ''NWS Doppler Radar was tracking a large and extremely dangerous tornado'' and ''This is an extremely dangerous and life-threatening situation.''

The complex set of processes involved in warning interpretation, and in the personalizing step, can be illustrated by the contrasting stories of two decision makers in similar locations in the path of the storm who received similar information at a similar time. Both of these officials specifically reported hearing that there was a tornado on the ground near Gilcrest (approximately 30 km southeast of Windsor); the warning with this information was issued at 1135 LT (Fig. 7). One of these interviewees also heard specifically that the storm was moving north and immediately recognized that this direction of motion was toward their area. This decision maker then began seeking additional information about the threat, passing the message along, contacting others in their organization, and so forth. In contrast, the second official either did not hear or disregarded the information about the northward motion of the storm; this person thought that since tornadoes generally move toward the east, that there was not an immediate threat to their area of responsibility. This person did not hear another warning until just a few minutes before the tornado hit, even though warnings and severe weather statements were being issued throughout this time.

Within the context of the timeline in Fig. 11, the first interviewee had a relatively short period of notification and decision making and a longer time for action and mitigation. This official's action–mitigation time was similar to the warning's actual lead-time. On the other hand, the second official was delayed by the ''understanding the

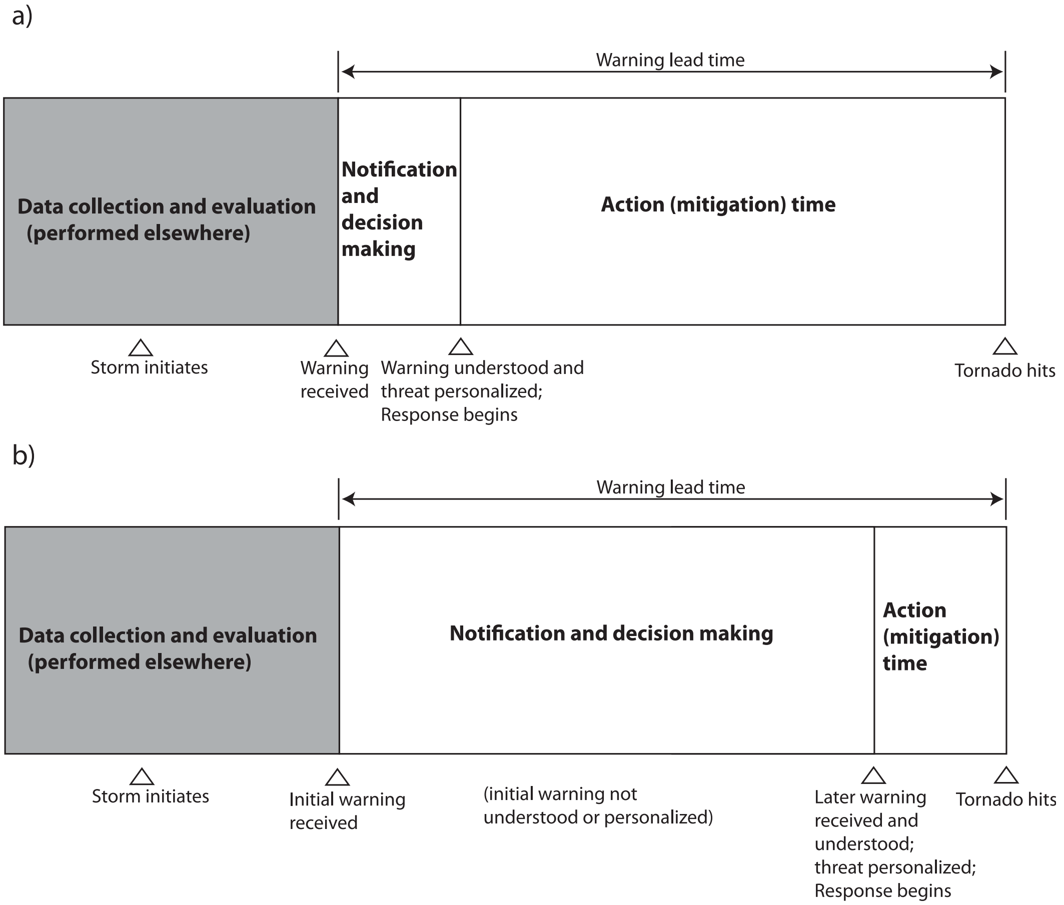

FIG. 12. As in Fig. 11, but changed to schematically depict the change in the relative lengths of the "notification and decision making" and "action (mitigation) time" sections for different interpretations of warning information. Shown are situations where (a) a person receives the warning, and understands and personalizes it quickly and (b) the initial warning information is not understood and/or personalized and the time for action is reduced. The first box is grayed out because it is assumed to be the same for both situations; the data collection and evaluation are generally not performed by the end user of the warning.

contents of the warning" and "personalizing the warning to oneself" steps of the sequence such that their action–mitigation time was only a few minutes, even though the initial information was received at approximately the same time as the first official. The contrasting warning timelines for these two officials are depicted schematically in Fig. 12. An additional interviewee also reported hearing the initial report of a tornado in Gilcrest and disregarding it because they thought that tornadoes move east, suggesting that the reaction of the second official described above was not an isolated reaction.

Almost every decision maker interviewed made a statement similar to "strong tornadoes don't happen here"; many of these interviewees have lived in the area for many years. The climatology discussed in the previous section shows that significant tornadoes do indeed happen (with some frequency) in that area, but that none had occurred in that immediate area in over 50 yr. Therefore, even those who had lived and worked in the area for 10+ yr had not encountered a situation similar to this in the past. Furthermore, the decision makers who thought that tornadoes move to the east were also generally correct in their understanding of the climatology; tornado tracks with a westward component of motion are indeed a small minority in the area (Fig. 9). Thus, an important factor in warning communication is people's experiential knowledge, namely their knowledge about tornado frequency and the distinction between the typical tornado motion (toward the east) and the unusual motion of this tornado.

These findings illustrate parts of the complex set of factors that determine the understanding and personalizing steps of the sequence, and they also emphasize the compressed warning timeline for short-fuse warning situations such as tornadoes. Small variations in the relative lengths of time shown in Fig. 11 can lead to large differences in the way that decision makers interpret the lead time and, ultimately, in the time available for protective action. These results also demonstrate that the Mileti and Sorensen (1990) sequence of processes applies to people in decision-making capacities just as it does to the public as a whole. Thus, while meteorologists may find it desirable for decision makers to act immediately upon receipt of an NWS warning, it is more likely that the decision makers will follow these steps—understanding, believing, personalizing, confirming, and then responding—as is determined by the scope of their responsibility. Communication between meteorologists and decision makers, both in warning situations and in times of nonthreatening weather, may help to foster mutual understanding of the two groups' needs and awareness that decision makers go through a process of believing, personalizing, and confirming a threat. New technologies, such as NWSChat (information online at https://nwschat.weather.gov/), as well as interactions such as those described in Baumgart et al. (2008), may be ways for this communication to take place.

3) LOCAL DECISION MAKERS' REDISSEMINATION OF WARNING INFORMATION

An additional item of discussion that was raised by a few interviewees was the use of electronic mechanisms for delivering warning messages, such as Reverse 911 and mobile phone text messages. The emergency managers that were interviewed generally felt that Reverse 911 was not an appropriate mechanism for disseminating warnings for short-fuse hazards such as tornadoes. They mentioned that the information about the timing and location of the actual tornado threat was not sufficiently specific to activate Reverse 911, although one of the emergency managers (EMs) did send Reverse 911 calls to a small area within his region of responsibility. The EMs generally noted that although their Reverse 911 system is capable of generating and making calls within a few minutes, they do not feel comfortable sending these calls during tornado warnings, because the threat may be over shortly after, or even before, the message is received. They cited both the rapidly evolving nature of tornadoes, as well as the potential for transmission delays, as reasons for their reluctance to use Reverse 911. The small-business owner that was interviewed specifically stated that he wished he would have received a Reverse 911 call in this situation, but it is unclear whether the possibility of transmission delays would have affected his opinion about Reverse 911 technology. Given the previous discussion about the already-compressed timeline for people's decision making and action during tornado events, these few minutes of possible delay can be precious and need to be fully understood by users.

One of the universities whose officials were interviewed had recently established a text message alert system, which was activated on 22 May. They noted that the system had been tested several times, but that this was the first activation in an actual emergency setting. They recounted numerous issues surrounding their issuance of text messages on 22 May. First, there were several university departments that had some responsibility for the activation of the text message system, and there was some miscommunication between these departments as well as unforeseen circumstances (such as one of the responsible officials being off campus at a meeting that day). They also reported that there was confusion over whether the campus area was under a tornado warning, or just a tornado watch, and how serious the threat to the campus was as a result. They ended up sending numerous text messages to members of the university community on 22 May, and they stated that they thought they may have sent more messages than was desirable, partly because of internal miscommunication and partly because of the rapid evolution of the weather situation. They reported receiving both positive and negative feedback about the text message alerts: some students and staff who were not on campus at the time responded negatively to receiving numerous text messages about a situation that did not directly affect them, but several people also responded and said that they would not have known about the tornado threat without the text message alerts. They also noted that although the large majority of messages were delivered shortly after they were sent, some were not delivered until many hours later, presumably as a result of cell-phone tower damage or outages. In light of recent efforts by many universities to establish campus-wide text message systems for emergency notification, these results provide some information about the actual capabilities and limitations of such a system in a short-fuse severe weather situation, especially when used for the first time. For another analysis of communication methods by a university in a tornado event, see Sherman-Morris (2009).

Some of the decision makers who were concerned about passing along detailed information—particularly the EMs and the broadcast meteorologist—would have preferred even more specific information about the location of the storm. For the broadcaster, the temporal frequency of the reports in the NWS warnings and severe weather statements, which was generally 15–20 min, was insufficient for updating the public in a live, on-air setting. This broadcaster would have preferred more frequent updates from NWS, especially prior to getting their own news crews in place to cover the storm. The

EMs desired more precise details on the location of the tornado.

4) WARNING COMMUNICATION AND INTERPRETATION ON 23 MAY

In addition to the list of questions asked of all interviewees, some interviewees were asked similar questions about tornado warnings that were issued on the following day (23 May 2008). These questions were asked only of the interviewees located within the areas that were warned on 23 May.

The results obtained from these questions were somewhat complicated because for some of the school districts, Thursday, 22 May, was the last day of school. Therefore, some of the officials and teachers were not at their schools or had different responsibilities between the two days. Perhaps the most relevant finding from asking questions about warnings on the second day was that some of the areas directly affected by tornadoes on 22 May were still without power on 23 May, so some means of communication (broadcast media, the Internet, etc.) were unavailable to decision makers in those areas when the warnings were issued on 23 May. While emergency managers had emergency operations centers active with backup power from generators, other organizations in the community did not have this capability and some who were within the warned area did not hear the warnings on 23 May. Since it is not unusual in ''Tornado Alley'' for there to be a threat of tornadoes on consecutive days, this result suggests that officials may need to consider the possibility that extended power outages may hinder warning communication for a day or two after a damaging tornado strikes.

c. Discussion

It is important to reiterate that the data from this exploratory study come from a limited sample, and they cannot necessarily be generalized to other geographic areas or other weather situations. However, these data contribute to an understanding of how decision makers receive and interpret tornado warning information, and reemphasize several ongoing questions about warning communication and interpretation. For example, once the warning is issued, what are the most effective methods for delivering that information to decision makers and individuals? How can we bridge the divide between the scientific information and knowledge that meteorologists have and how it is used? How can the research and operational meteorology community use the knowledge that most people do not respond immediately and directly to tornado warnings—instead, they go through a sequence of thought processes—to encourage the desired response to a warning?

Does the information provided in NWS warnings have sufficient detail for the decision makers that use it? Is it feasible to give more detail with the current science/technology, and are there better ways to provide key details in ways that are more useful or easier to understand? What is the best way to educate decision makers and the public about the threat for tornadoes and their overall climatology, without causing them to minimize threats that are outliers? Recall that in the story above, the second decision maker's response to the threat was based on a generally sound knowledge of tornadoes: that they move toward the east. Similar results were found in NWS (2009); in their case, some people minimized the tornado threat because it occurred outside of the typical season for tornadoes. And following from this, how can the most important message in warnings be best communicated, which in this case may have been ''the storm is moving toward the north'' or ''this is more serious than most storms in this area''?

The finding here was that reports of tornadoes were important to the interviewees' perceptions of the warnings. This suggests that information about observed tornadoes (including local storm reports) should be disseminated as quickly as possible by the NWS, consistent with the recommendations of NWS (2009). Similarly, the broadcaster's desire for more frequent updates on the tornado's location suggests that severe weather statements or other mechanisms for communicating with the media and users, such as NWSChat, should be used as extensively as possible during major tornado events to provide the latest information.

Many of the officials we interviewed stated that their organizations have made changes to their communication procedures or severe weather plans as a result of the May 2008 tornado. One key change that several organizations mentioned is more preparedness for power and cell-phone outages. For example, one school official stated that they used to conduct their annual tornado drills with all the lights on, but now they turn the lights off for the drills to more accurately simulate what may happen in an actual event. There was also a campaign to encourage the purchase of NWRs by both organizations and the public in the days following the tornado, which was very successful. Furthermore, some organizations we interviewed were already in the process of upgrading their internal communication systems, and these upgrades are now available in the event that severe weather strikes the area again.

5. Summary and conclusions

This study included an integrated meteorological, climatological, and societal analysis of the 22 May 2008

Weld County, Colorado, tornado. The primary findings include the following:

- The large-scale environmental conditions were favorable for severe weather on that day, with an intense trough in the western United States. Smaller-scale processes, including a surface boundary, strong low-level wind shear, and differential solar heating, favored the development of significant tornadoes in parts of northern Colorado.
- The climatology of tornadoes near the Front Range of the Rockies shows that several aspects of the storm were unusual, though not unprecedented, including the north-northwestward motion of the storm, the long track, the early time of day, and the proximity to the Front Range. However, the combination of these factors was indeed quite unusual.
- The sources of warning information varied, as did the interpretations of those warnings.
- The sequence of processes by which decision makers processed the warning information was consistent with past social science research on the response of the public to warnings.
- In total, a variety of societal factors determined how decision makers received and interpreted severe weather information, and the results of interviewing these decision makers underscore the importance of considering these societal factors in the severe weather warning process.

The findings in this study demonstrate the value of performing studies that integrate methods from meteorology, climatology, and the social sciences. The authors' background knowledge of the meteorology and climatology of tornadoes near the Front Range helped to inform the questions that were asked in the interviews and to interpret the results. Additionally, the use of qualitative research methods from the social sciences added a component of analysis that is often not used in meteorological case studies, and provided data about the end users of weather information. The results of this study emphasize that the lead time is not the only factor that determines the effectiveness of a warning; its communication and interpretation are just as important. Though the results of this study are somewhat limited, they raise potential questions for larger-scale investigations of severe weather warning communication. One of the first steps toward providing warning information that has the most benefit to its users is to understand the needs, perspectives, and responsibilities of those users. Thus, further research on these subjects is strongly encouraged in addition to the attention given to improving detection and warning capabilities, so that these advances can be applied for maximum societal benefit.

Acknowledgments. The views, opinions, and findings in this report are those of the authors and should not be construed as an official NOAA, NSF, or U.S. government position, policy, or decision. The authors thank Bob Glancy and Larry Mooney of the NWS in Boulder; Rebecca Morss, Isabelle Ruin, Hannah Brenkert-Smith, and Mary Hayden of NCAR; Kelly Keene of Texas A&M University; and David Schultz of the University of Manchester for helpful discussions and suggestions regarding this work. The authors also thank the interviewees for their candid and informational responses. The authors are grateful to Stephen Hodanish and two anonymous reviewers for their helpful suggestions that improved the manuscript. RSS and ABS thank the organizers and sponsors of the Weather and Society* Integrated Studies (WAS*IS) program for inspiring this research. NAM model analyses and the text of warnings were obtained from the National Climatic Data Center.

REFERENCES

Baumgart, L. A., E. J. Bass, B. Philips, and K. Kloesel, 2008: Emergency management decision making during severe weather. *Wea. Forecasting,* **23,** 1268–1279.

Demuth, J. L., E. Gruntfest, R. E. Morss, S. Drobot, and J. K. Lazo, 2007: WAS*IS: Building a community for integrating meteorology and social science. *Bull. Amer. Meteor. Soc.,* **88,** 1729–1737.

Doswell, C. A., III, 1980: Synoptic-scale environments associated with High Plains severe thunderstorms. *Bull. Amer. Meteor. Soc.,* **61,** 1388–1400.

——, 1987: The distinction between large-scale and mesoscale contribution to severe convection: A case study example. *Wea. Forecasting,* **2,** 3–16.

——, and D. W. Burgess, 1988: On some issues of the United States tornado climatology. *Mon. Wea. Rev.,* **116,** 495–501.

Golden, J. H., and C. R. Adams, 2000: The tornado problem: Forecast, warning, and response. *Nat. Hazards Rev.,* **1,** 107–118.

Grazulis, T. P., 1993: *Significant Tornadoes, 1680–1991.* Environmental Films, 1326 pp.

Hales, J. E., Jr., 1988: Improving the watch/warning program through use of significant event data. Preprints, *15th Conf. on Severe Local Storms,* Baltimore, MD, Amer. Meteor. Soc., 165–168.

Hammer, B., and T. W. Schmidlin, 2002: Response to warnings during the 3 May 1999 Oklahoma City tornado: Reasons and relative injury rates. *Wea. Forecasting,* **17,** 577–581.

Keene, K. M., P. T. Schlatter, J. E. Hales, and H. Brooks, 2008: Evaluation of NWS watch and warning performance related to tornadic events. Preprints, *24th Conf. on Severe Local Storms,* Savannah, GA, Amer. Meteor. Soc., P3.19. [Available online at http://ams.confex.com/ams/pdfpapers/142183.pdf.]

Legates, D. R., and M. D. Biddle, cited 1999: Warning response and risk behavior in the Oak Grove–Birmingham, Alabama Tornado of 08 April 1998. Natural Hazards Center Quick Response Rep. 116. [Available online at http://www.colorado.edu/hazards/research/qr/qr116/qr116.html.]

Mileti, D. S., and J. H. Sorensen, 1990: Communication of emergency public warnings: A social science perspective and state-of-the-art assessment. Oak Ridge National Laboratory Rep. ORNL-6609, 145 pp.

Morss, R. E., and F. M. Ralph, 2007: Use of information by National Weather Service forecasters and emergency managers during CALJET and PACJET-2001. *Wea. Forecasting,* **22,** 539–555.

NWS, 2009: Service assessment: Super Tuesday tornado outbreak of February 5–6, 2008. National Weather Service, 29 pp. [Available online at http://www.weather.gov/os/assessments/pdfs/super_tuesday.pdf.]

Pingel, N., C. Jones, and D. Ford, 2005: Estimating forecast lead time. *Nat. Hazards Rev.,* **6,** 60–66.

Rocky Mountain Insurance Information Association, cited 2009: Windsor tornado one year later: Final insurance costs for cars and homes damaged in last May's Windsor tornado add up to $193.5 million in auto & homeowners insurance claims paid out. [Available online at http://www.rmiia.org/News_room/insurance_news/2009_05_19_CO_Windsor_A_Year_Later.asp.]

Sherman-Morris, K., 2009: Tornado warning dissemination and response at a university campus. *Nat. Hazards,* **52,** 623–638.

Sorensen, J. H., 2000: Hazard warning systems: Review of 20 years of progress. *Nat. Hazards Rev.,* **1,** 119–125.

Stensrud, D. J., and Coauthors, 2009: Convective-scale warn-on-forecast system: A vision for 2020. *Bull. Amer. Meteor. Soc.,* **90,** 1487–1499.

Szoke, E. J., M. L. Weisman, J. M. Brown, F. Caracena, and T. W. Schlatter, 1984: A subsynoptic analysis of the Denver tornadoes of 3 June 1981. *Mon. Wea. Rev.,* **112,** 790–808.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting,* **18,** 1243–1261.

Wakimoto, R. M., and J. W. Wilson, 1989: Non-supercell tornadoes. *Mon. Wea. Rev.,* **117,** 1113–1140.

Zipser, E. J., and J. H. Golden, 1979: A summertime tornado outbreak in Colorado: Mesoscale environment and structural features. *Mon. Wea. Rev.,* **107,** 1328–1342.