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THE 22 MAY 2008 WELD COUNTY, COLORADO TORNADO: ANALYSIS OF METEOROLOGICAL CONDITIONS AND THE COMMUNICATION OF WEATHER INFORMATION

Russ S. Schumacher*, Daniel T. Lindsey@, Andrea B. Schumacher+, Jeff Braun+,
Steven D. Miller+, and Julie L. Demuth*
**National Center for Atmospheric Research, Boulder, Colorado*
@NOAA/NESDIS/STAR/RAMMB, Fort Collins, Colorado
+Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

On 22 May 2008, a strong tornado, rated 3 on the Enhanced Fujita scale, caused extensive damage along a 34-mile track through northern Colorado. The worst devastation occurred in the town of Windsor, where there was one fatality, numerous injuries, and hundreds of homes significantly damaged or destroyed. Windsor is situated in north central Colorado, east of the Front Range of the Rockies and about 10 miles southeast of Fort Collins, which is along the populated "Urban Corridor" (Fig. 1). Several characteristics of this tornado were unusual for the region from a climatological perspective: 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 northwest as opposed to more common eastward-component storm tracks away from population centers; and 3) the intensity of the tornado in such close proximity to the Front Range where weaker tornadoes are more commonly observed. The unusual meteorological aspects of the event and the high impact of this tornado also raised a number of questions about the communication and use of information from National Weather Service watches and warnings by decision makers and the public. In this study, we will use data regarding the meteorological conditions on 22 May 2008, the climatology of significant tornadoes near the Colorado Front Range, and the communication of weather information to provide an integrated analysis of this event. The primary questions we seek to answer are as follows:

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

*The National Center for Atmospheric Research is sponsored by the National Science Foundation.
Corresponding author address: Russ Schumacher, NCAR, Boulder, CO 80307-3000; rschumac@ucar.edu

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 positioned over the western US on 22 May 2008, with several jet streaks moving through it (Fig. 2a). At 1800 UTC, one of these jet streaks, with southerly winds exceeding 40 m s^{-1}, was located over eastern Colorado. At the surface (Fig. 2b), 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. In addition to the moisture gradient, a temperature gradient and wind convergence boundary also existed, and this boundary was oriented from approximately west to east.

A loop of the GOES-12 Visible band (available at `http://rammb.cira.colostate.edu/case_studies/20080522/goes_visloop.asp`) clearly shows the boundary between dry air to the south and moist air to the north. As the moist air noses to the southwest toward the north side of Denver between 1400 - 1600 UTC, the stratus clouds just

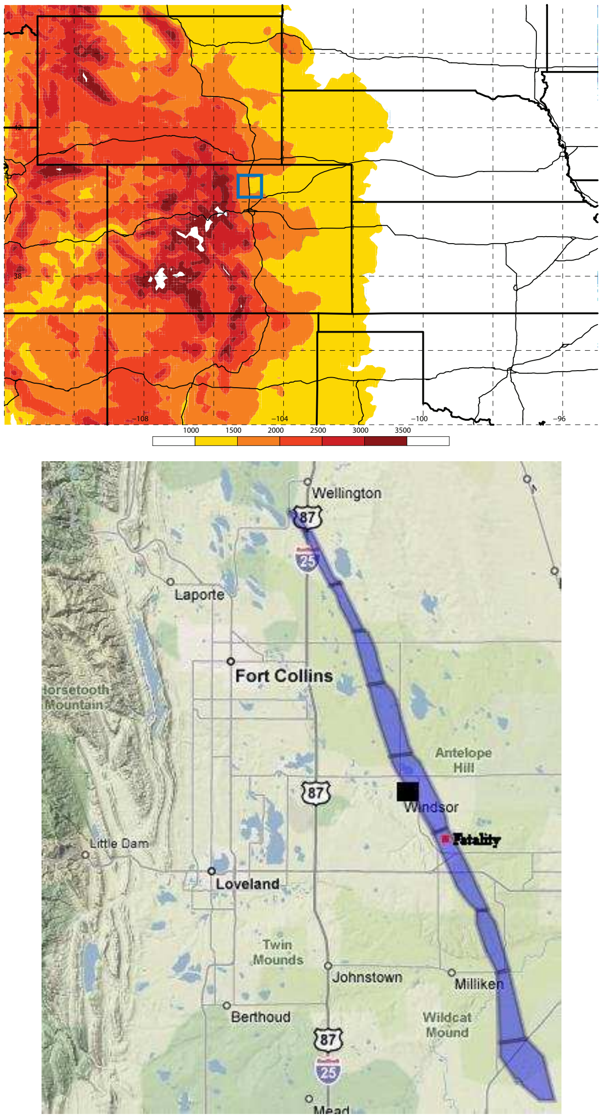

Figure 1: (a) Map of the western Great Plains and Rocky Mountains, with elevation (m) shaded, and the approximate location of the map in (b) shown by the blue rectangle. (b) Damage track of the tornado affecting portions of Weld and Larimer Counties, Colorado, in 22 May 2008. The storm moved from the southeast to the northwest. The location of Windsor is indicated by the black square, and the location of the one fatality is shown. Image courtesy of the National Weather Service Forecast Office in Boulder.

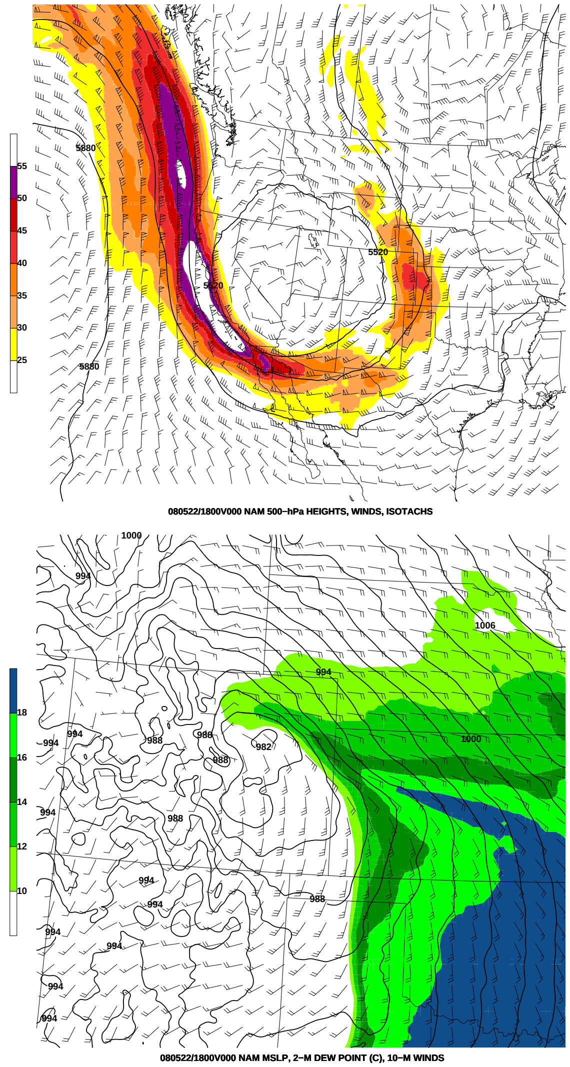

Figure 2: (a) Analysis of 500-hPa heights (black contours every 120 m), wind speed (m s^{-1}, color shading, and wind barbs from the North American Mesoscale model analysis at 1800 UTC 22 May 2008. (b) As in (a), but showing pressure corrected to sea level (black contours every 2 hPa), 2-m dew point temperature (C, color shading), and 10-m wind barbs, and zoomed in to focus on Colorado.

behind the boundary dissipate, allowing a narrow region to receive full sunlight. Fig. 3 shows an annotated visible image from 1615 UTC with the location of this boundary denoted with a black line. The storm 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 (not shown) indicated a temperature of 70 F, dewpoint of 55 F, and 30 kt easterly winds gusting to 41. This provides the best estimate of the low-level air that the storm was ingesting. Modifiying the special 1800 UTC sounding from Denver and 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. 4. Note the 2094 J kg^{-1} 100-mb mixed-layer CAPE,

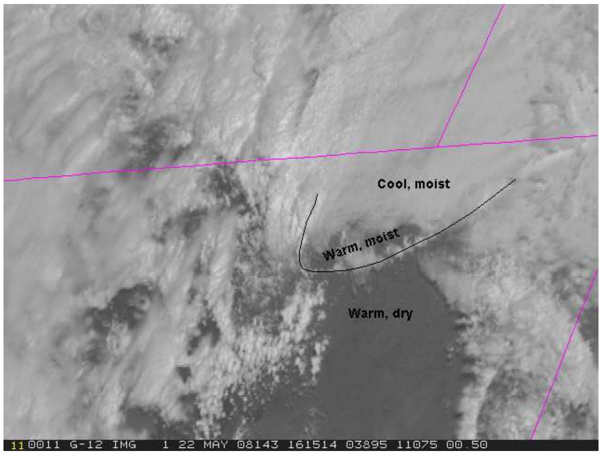

Figure 3: GOES-12 Visible image from 1615 UTC, with a frontal boundary and three air masses denoted. The image covers northeast Colorado, southeastern Wyoming, and the southwestern Nebraska panhandle.

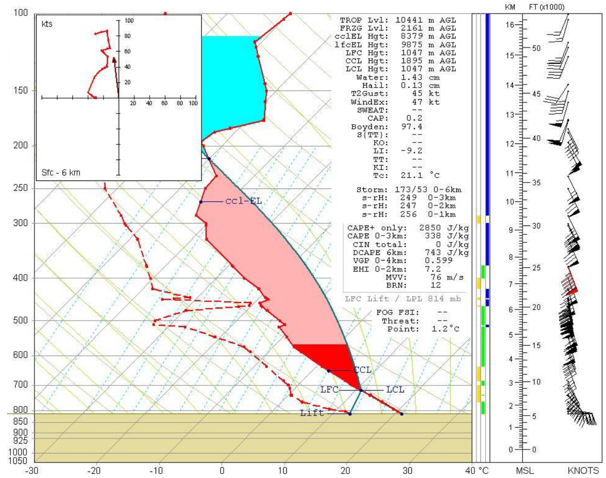

Figure 4: 1800 UTC sounding from Denver modified with 1700 UTC Greeley surface observation.

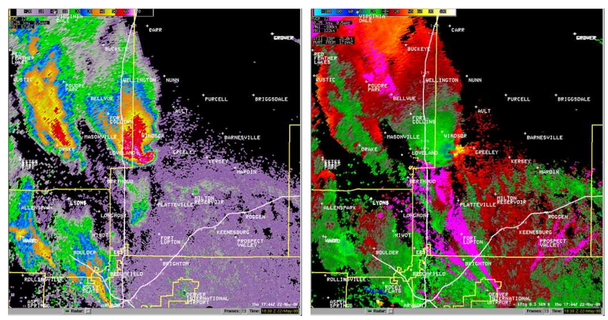

Figure 5: (a) Radar reflectivity and (b) storm-relative velocity data from the KFTG radar at 1744 UTC 22 May 2008. Images courtesy of the National Weather Service forecast office in Boulder.

and 219 m^2/s^2 0-1 km storm-relative helicity. Additionally, an LCL of only 1.3 km AGL is unusually low for Colorado. The strong upper-level trough, easterly surface winds with advecting moisture westward, the west–east-oriented surface boundary, and the conditionally unstable atmosphere combined to provide the necessary ingredients for severe convective storms.

Deep convection initiated around 1645 UTC (10:45 am local time) and the primary storm rapidly intensified, became supercellular and tracked quickly toward the north-northwest (Fig. 5). The first severe thunderstorm warning was issued by the National Weather Service (NWS) in Boulder at 11:09 am, and the first tornado warning was issued at 11:18 am. The first tornado was reported east of the town of Gilcrest at 11:26 am, and the tornado hit Windsor just before noon. The Boulder WFO 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.

3. CLIMATOLOGICAL CONTEXT

For experienced weather observers in Colorado, many aspects of this storm seemed unusual: the 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, we investigated the tornado climatology to understand how rare this event was. The datasets used in this section are the "SVRGIS" database from the NWS Indianapolis office (`http://www.crh.noaa.gov/ind/?n=svrgis`), which includes data from 1950–2006, and Grazulis (1993) for historical tornado information. 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 National Weather Service office.

We begin by examining the climatology of tornadoes near the Front Range in Colorado and Wyoming (Fig. 6a), defined here as tornadoes occurring west of 104 W longitude (the Wyoming/Nebraska border). Short-lived, weak tornadoes are quite common near the Front Range, with a few areas appearing to have "clusters", such as the areas just to the north and southeast of Denver International Airport. Weld County, with its huge size, also has a large number of tornadoes. An interesting aspect of the Windsor tornado was its track toward the northwest, and as a result all of the tornadoes with a component of motion toward the west have been highlighted in green in Fig. 6a to see how common such tracks are. It turns out that northwestward tracks have happened before, 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. Narrowing the data down further to look at significant tornadoes near the Front Range, and adding historical significant tornadoes, shows that long-track, significant tornadoes do indeed occur near the Front Range (Fig. 6b). 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. 7). 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. The May 2008 Windsor tornado still stands out on this map because of its unusual northwestward track, as almost all of the other tracks shown on the map were either toward the northeast or the southeast. A lot has changed about northern Colorado since these historical tornadoes took place, including a much larger population. This suggests that many residents of western Weld County had never experienced a significant tornado in the area prior to May 2008. The climatology shows that such events may be rare, but 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 11:26 AM Mountain time.) Fig. 8 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 2 and 7 pm. 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 suggests that although the individual aspects of the 22 May 2008 storm (such as its location, westward motion, and time of occurrence) are somewhat rare but not unprecedented, the *combination* of these aspects was quite unusual.

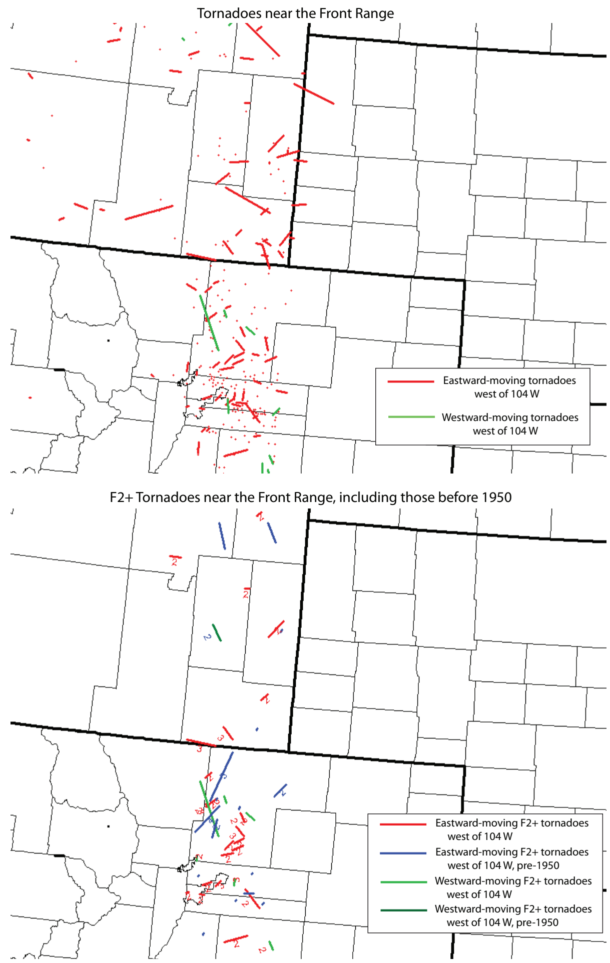

Figure 6: (a) All tornadoes near the Front Range (defined here as tornadoes occurring west of 104 degrees west longitude) in 1950–2006, plus the 22 May 2008 tornado. Tornadoes with a component of motion toward the west have been highlighted in green. (b) As in (a), except for only significant (F2+) tornadoes. Panel (b) also includes manually-added historical tornado tracks, obtained from Grazulis (1993). These tracks are shown in blue, with the westward-moving tornadoes in dark green.

4. COMMUNICATION OF WEATHER INFORMATION

4.1 *Introduction*

The unusual nature of this tornado raised additional questions about how warnings and other weather information were communicated to and interpreted by decision makers, and then passed on

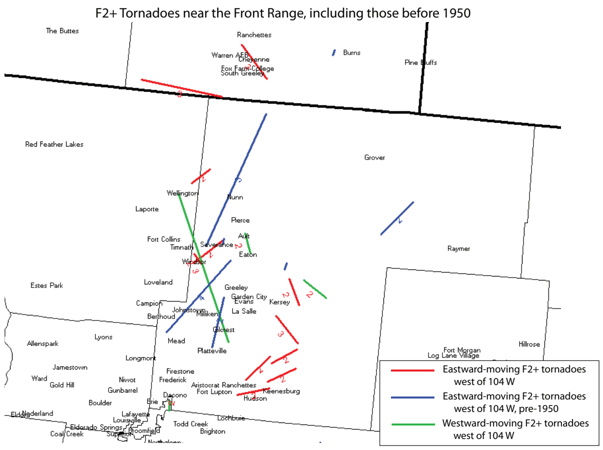

Figure 7: As in Fig. 6b, except zoomed in on Weld County.

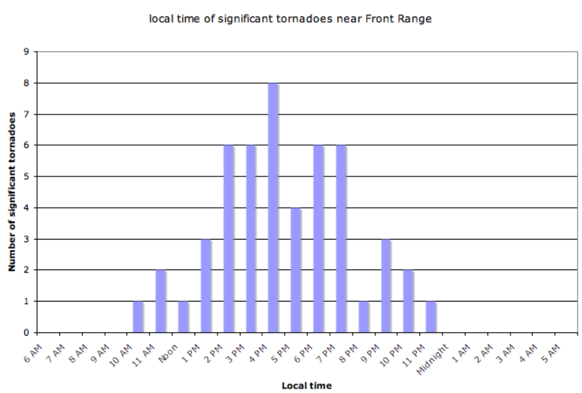

Figure 8: Time of occurrence of significant tornadoes near the Front Range. Tornadoes included in this figure are those in Fig. 6b, excluding those that occurred before 1950.

to the public. Although some studies of warning communication during tornadoes have been conducted in the past (e.g., Hammer and Schmidlin 2002, NWS 2009), such data is quite limited in comparison to meteorogical data (e.g., Golden and Adams 2000). During the 22 May 2008 tornado event, the issuance of warnings by the NWS office in Boulder was excellent by meteorological standards, especially when considering the fast-moving nature of the storm. There was approximately eight minutes lead time between the first tornado warning and the first reported tornado, and over 30 minutes lead time between the first warning and when the tornado impacted Windsor. These data regarding the time of warning issuance are readily available, but less is known about what happens to the information *after* the warnings are issued.

Table 1: Breakdown of the positions of the 16 decision makers interviewed.

School administrators	5
University officials	4
Emergency managers	3
School teachers	2
Small business manager	1
Broadcast meteorologist	1

How do people receive and interpret these warnings? To begin to answer some of these questions, interviews were conducted with decision makers within the tornado-warned areas to obtain qualitative information about how they heard about and interpreted warning information. Interviewing decision makers (rather than the public at large) was done since these officials had some responsibility for being 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" (Fig. 9) that is responsible for communicating with and protecting the public. To recruit interviewees, all public school districts, universities, and emergency managers within the warned areas were contacted. Schools were specifically chosen because they generally have well-defined plans of what to do in the case of severe weather, but are not often required to execute those plans in locations near the Front Range. In addition, we were referred to other potential interviewees. In total, 13 semi-structured interviews (with 16 total decision makers) were conducted in January–March 2009; 9 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 is not necessarily generalizable to other events or geographic areas. However, the interviews did offer a diversity of responses and points of view, and provided some initial data on warning communication and interpretation during this event.

Although not all of the interview data will be presented here, some of the most relevant questions asked of the interviewees are as follows:

- When did you *first* realize there was a threat of a tornado in the area?
  - What information did you get?
  - Approximately what time was that?
  - What message did you hear, and was it clear?

Figure 9: Illustration of the weather warning partnership between NWS, local media and meteorologists, and local officials. From Golden (2000).

- Repeat of the above questions for *the entire day.*
- Were there circumstances that prevented you from receiving weather information?
  - Did the fact that the tornado occurred in the middle of the day make a difference?
- In the past, have you been responsible for making decisions for your organization during severe weather?
- Did the information you received help you to execute your plan?

4.2 *Results*

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, 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. One area university used a text message system to pass along paraphrased warning information. Several interviewees also noted that visual cues were important to their interpretation of the threat: they stated that they had never seen the sky look so dark. In fact, the northward movement of the supercell may have been fortunate in some ways, in that the core of heavy rain and large hail preceded the arrival of the tornado—a few respondents stated that they sought shelter when the hail began to fall. None of the interviewees reported hearing the *initial* warnings via NOAA Weather Radio (NWR), but several said that they used the NWR to get later information. After hearing the initial warnings, many interviewees also reported accessing the Internet to obtain additional information. A few interviewees said that they were aware of the possibility of severe weather that day in advance of the warnings, but 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 Storm Prediction Center until after the issuance of first warnings.

Similarly, the lead time with which the respondents received the warnings was 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. In general, hearing *actual reports* about the tornado was key to their interpretation of the threat—almost all 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. In addition, some decision makers (including the broadcast meteorologist in particular) would have liked to have had even more specific information about the location of the storm. These results are in line with 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 statments such as "NWS Doppler Radar was tracking a large and extremely dangerous tornado," and "This is an extremely dangerous and life-threatening situation." Interviewees located farther "downstream" (i.e., 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. This raises the question of what the effective lead time is for warnings: even if a warning is issued far in advance of an actual tornado, when will people receive it, and will they respond right away?

This challenge 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 11:35 am. 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; he 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 2–3 minutes before the tornado hit, even though warnings and severe weather statements were being issued throughout this time. As a result, the first interviewee had an "effective" lead time that was similar to the warning's actual lead time; approximately 15-20 minutes, whereas the second official's effective lead time was only a couple minutes, even though they received the same initial information. Another interviewee also reported hearing the initial report of a tornado in Gilcrest and disregarding it because they thought that tornadoes generally move east, suggesting that this 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 years. Therefore, even those who had lived and worked in the area for 10+ years had not encountered a situation similar to this in the past.

Regarding the time of day, many officials stated that they thought it was quite fortunate that this event happened during the middle of the day when children were in school, so that they were accounted for and were in safe buildings. This was doubly fortunate because in Windsor, the schools are located on the west side of town, whereas the worst damage from the tornado occurred in residential areas on the east side of town. If children (and adults) had been at home, rather than at work or school, the human toll could have been much worse. As it was, only one fatality occurred, which was a man who was outdoors at a campground between Greeley and Windsor.

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. This emphasizes that although it is certainly desirable to continue advancing warnings and their communication through advanced technologies, they can not entirely replace more traditional 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.

4.3 *Discussion*

It is important to state once again that the data from the interviews presented here are limited and qualitative, so they do not provide any definitive answers and should not necessarily be generalized broadly. However, these data do re-emphasize several ongoing questions about warning communication and interpretation. For example, once the warning is issued, whose responsibility is it to deliver that information to decision makers and individuals? The NWS? Local governments? Private companies? How can we bridge the divide between the information that meteorologists have and how it is used? Is it possible to encourage people to respond to tornado warnings based on the warning alone, without a confirmed tornado report—and if it is possible, is it desirable? Does the information provided in NWS warnings have sufficient detail for decision makers to use? Is it feasible to give more detail with current science/technology? What is the best way to educate decision makers and the public about the climatology of tornadoes, 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, 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”?

Many of the officials we interviewed stated that their organizations have made changes to their organizations’ 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 cellphone 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 out 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, which 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 are summarized as follows:

- The large-scale environmental conditions were favorable for severe weather on that day, with an intense trough in the western US. 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 northwestward motion of the storm, the early time of day, and the proximity to the Front Range. However, the combination of these factors was indeed quite rare.

- 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 show that much can be learned about the societal impacts of weather forecasts and warnings from even small samples of decision makers and the public. Within many communities (e.g., Demuth et al. 2007), there is a growing realization that societal factors are often just as important to the effectiveness of weather warnings as the information provided in those warnings, and the results herein support that realization. Further research on these subjects is greatly encouraged, so that advances in scientific understanding and technology can be applied for maximum societal benefit.

6. ACKNOWLEDGMENTS

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