14.2 VISUAL CHARACTERISTICS OF SEVERE STORMS

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1. INTRODUCTION

The visual characteristics of severe storms are an important source of data in the integrated warning process for the National Weather Service. Storm spotters regularly relay observations of severe weather and basic storm features to National Weather Service forecasters for use in real time warning decision making. These reports typically include the occurrence of severe weather (large hail, damaging wind, tornadoes, flash flooding) and the other visual cues like the presence of a wall cloud, rotation, funnel cloud, etc. Extensive online documentation of storms from storm chasers illustrates a diverse range of visual structures that have yet to be explored and incorporated into warning decision making.

In the scientific literature, severe storm visual observations have been incorporated into a wide range of research on supercells (Fujita 1965; Bluestein 1986; Bluestein *et al.* 1990; Kennedy *et al.* 1993; Markowski and Straka 2000; Moller *et al.* 1994; Wakimoto and Atkins 1996), tornadoes (Fujita 1970; Wakimoto and Wilson 1989; Wakimoto and Martner 1992), microbursts (Wakimoto and Bringi 1988; Wakimoto *et al.* 1994), hailstorms (Knight 1984; Chalon *et al.* 1976), and other aspects of clouds and precipitation (Battan 1964; Fraser and Bohren 1992; Hansen 1971; Knight *et al.*. 1983; O'brien 1970). Many of these studies have used the visual observations to complement radar analysis, while others have used visual observations to discuss conceptual models amongst a complex spectrum of storm types and visual appearances.

Visual observations of severe weather are also an important part of NWS training. The National Weather Service has incorporated some of the key research and anecdotal observations of the visual features of severe storms into basic and advanced severe storm spotters guides (NOAA PA 97050, NOAA PA 92055) that have been used to train storm spotters across the nation. Visual observations also play an important role in fundamental warning decision making training at the Warning Decision Training Branch. In particular, relating visual observations to radar data greatly assist in teaching conceptual models that guide the fundamental radar base data analysis techniques used in warning decision making. One motivation for our study comes from the anticipated need for more effectively incorporating visual observations into the training for the Four Dimensional Storm Cell Investigator (FSI; see Stumpf *et al.* 2006). The FSI is a significant improvement in radar base data analysis that is currently planned for AWIPS Operational Build 8.2 in late 2006.

The ever-growing number of severe convection images regularly documented on the Internet by professional and casual storm chasers over the last decade provides an unprecedented opportunity to incorporate visual observations into the conceptual models of severe convection. Furthermore, new tools to organize and query images are emerging with the growth of online photo libraries for consumers. Low-cost multi-media databases are becoming available on the Internet with simple query capabilities that provide a unique opportunity for analysis of images of severe storms.

This paper documents a wide variety of visual characteristics of severe storms and convection/precipitation using digital photography available from storm chasers. We also supplement the observations with our own experiences as members of the storm chase community. The visual characteristics are evaluated for a large number of storms, along with environmental sounding profiles for some select storms. In this study, we also raise questions of how these visual cues may relate to storm dynamics that could be more thoroughly explored with future observational research programs or high-resolution numerical

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models. Methods are then examined and developed to integrate digital media and observational data into a multi-media database. In addition, meta-data needs and structures are evaluated to assure broad usability of the data. Improved understanding of the visual aspects of severe convection can be useful for 1) establishing more detailed conceptual models of severe storms, 2) improved training relating radar analysis to observations, 3) improvements in storm spotting for NWS warning decision making, and 4) evaluating the capability of numerical models to represent observed phenomena.

2. VISUAL CHARACTERISTICS

Severe weather has an inherent drama and beauty that routinely inspires large numbers of "storm chasers" to drive hundreds or thousands of miles across the Plains of the United States to witness and photograph thunderstorms. While many chasers appreciate the broad diversity of basic convection, there is a distinct motivation to observe and document the visual characteristics of supercell thunderstorms and tornadoes. The large number of supercell photographs online has engaged much of our focus in this paper, though we have not made an attempt to exclude other types of severe convective storms. Our focus on the unique visual characteristics of supercells may not be fortuitous, though, given supercells' unique visual characteristics and propensity to produce severe weather (Moller *et al.* 1994). Though much of our discussion focuses on the unique visual characteristics of supercells, we plan on expanding our database to include other forms of convection.

With decades of evolution in technology and the science of forecasting, storm chasers and spotters have amassed a large number of observations that are described by unique jargon. While some of these features and terms are documented in published papers or training modules, many are not. In section 3 we will evaluate our current list of visual cues we have selected to use in our study. Before we review this large list, we will first describe some of the fundamental characteristics that are routinely used by storm chasers to understand their environment. *It is important to note that much of the following observations are anecdotal, and part of the motivation for this work is to document these observations in order to test their validity with future studies or field programs*.

Figure 1. View of the forward flank of the updraft from the June 2, 2005 Limon, CO storm. Image copyright 2005 Eric Nguyen.

2.1 Sharpness of Cumulus Clouds and Anvils

The sharpness of the bubbly crowns of cumulus clouds and the edges of the anvil near the updraft summit is one unique visual characteristic of severe convection. One commonly held belief that is worthy of further study is that more intense convection is associated with sharper cumulus crowns and sharper/thicker anvil.

2.2 Geometric Features of Clouds, Precipitation, Lightning, and Wind Tracers

The geometry and location of the cloud, precipitation, lightning, and wind tracers (e.g. blowing dust or smoke) provides a fundamental reference frame for identifying updraft, lightning, precipitation location and other characteristics of the flows they are embedded within. The forward flank of updrafts in supercell storms, in particular, contains a plethora of cloud bands at multiple levels (Figure 1). The geometry and curvature of clouds can reveal the height of the lifted condensation level, level of free convection, equilibrium level, anvil outflow characteristics, low-level boundary locations, storm-storm interactions, updraft tilt in sheared flows, curved flow, low-level inflow, tornado shape and size, low-level outflow, areas of entrainment of drier air, and the relative relationship between precipitation and updraft.

The geometry and location of precipitation can indicate the location of the rear-flank downdraft, precipitation tilt in sheared flows, size and shape of hail and raindrops, microburst tracers, and outflow locations.

The geometry and location of wind tracers such as blowing dust or smoke can indicate areas of inflow, areas of outflow, and curls at the leading edge of a microburst.

2.3 Color and Opacity of Clouds and Precipitation

The color and opacity of clouds and precipitation is a strong function of the location relative to the light source. Backscattered sunlight on the back side of storms is typically white, and forward scattered sunlight on the front side of storms is typically a dark blue color or black (and sometimes green). Very dark rear flanks of high-precipitation supercells can be indicative of significant concentrations of heavy rain and hail. Low-precipitation supercells can have translucent precipitation cores on the forward and rear flanks. Hook echo opacity is one particularly interesting feature of severe convection, given its association with tornadic supercells. Some hooks contain nearly translucent thin “curtains”, while others contain dark opaque walls. Hailstones also have opaque layers and translucent layers.

2.4 Horizontal Motions

Motions in clouds, precipitation, and other features can be difficult to perceive with the naked eye. “Scrubbing” long loops of videos forward and backward in accelerated time can often times reveal horizontal and vertical motions not perceivable in real-time. One of the fundamental features of supercell storms in strong vertical wind shear that is perceivable in video loops and in real time is the sheared flow between horizontal motions at low and mid levels.

Another significant horizontal motion that is perhaps more challenging to perceive is the first sign of the development of low-level rotation in supercells. The term “differential (horizontal) motion” is typically used to describe the condition where low-level clouds on the forward side of the gust front are typically moving from the right to the left flank, and clouds on the rear flank are moving from the left to the right flank. Perceiving the horizontal motions of rotation about a vertical axis in supercell cloud motions is usually easier at close range or with strong rotation, and significantly less so at farther ranges or with weak to even moderate rotation.

Other horizontal motions of cloud features, precipitation, or other tracers (dust or blowing smoke) indicate the direction and speed of the flow they are moving through.

2.5 Vertical Motions

Like horizontal motions, vertical motions can be difficult to perceive with the naked eye in real time, except for strong vertical motions. Highly unstable environments will typically feature cumulus towers that appear to slowly rise in middle and upper levels. Other vertical motions are typically observed in low levels as cloud tags rise into the base of the updraft or downward on the back side of the updraft along the rear-flank downdraft interface.

2.6 Turbulent Motions

Turbulent motions are usually apparent in well-defined rear-flank downdrafts, under deep arcing shelf clouds, and inside tornadoes at close range. In some situations, tracers in the flow can suggest a lack of turbulent flow. Large smooth and laminar clouds on the flanks of some deep updrafts suggest a distinct lack of turbulence.

3. TAXONOMY OF SEVERE STORM VISUAL CLUES

Developing a meaningful taxonomy of important visual cues related to severe convection is challenging. Many of the terms are not rigorously defined in scientific literature, and the diversity of visual structures is significant. Yet, after reviewing photos of hundreds of storms over decades, many common structures emerge. We have compiled a list of visual cues (Table 1) that we believe are unique for updrafts, miscellaneous cloud features, precipitation, tracers, and severe weather.

Some of the visual cues can be cataloged with a confidence of existence value. For example a 70% confidence level could be assigned to the observation of a truncated cone tornado if the condensation funnel occurs over unpopulated areas where there is some question about whether the feature was a tornado or not. Other cues can be described with a range of values. An example of this is a wall cloud being thin, average, thick, or not observed at all.

Cloud Related: updraft width, overshooting top, backshear anvil, updraft pulse, stair-stepped flanking line, corkscrew cumulus, anvil convective overturning, striations-corkscrew/horizontal, striations-rotation, striations-smoothe/rough, fuzzy/sharp updraft, laminar updraft, bell shaped updraft, wall cloud, collar cloud, tail cloud, forward flank updraft lip, barrel updraft, mid-level alto-cumulus deck, downshear mid-level updraft base, lifted condensation level (LCL) height, level of free convection (LFC) height, equilibrium level (EL), sharp/ragged updraft base, gust front arcus, shelf cloud, convective gust front, LFC crown, occluded tower, cloud base rotation, cloud base vertical motion, low precipitation supercell updraft, classic supercell updraft, high precipitation supercell updraft, forward flank boundary cloud line, low-level inflow band, mid-level inflow band, left-flank boundary cloud line, cloud rings, mammatus, pileus, differential motion, clear slot, updraft-precip-separation

Precipitation Related: wrapping rain curtains, hook echo blob, right-flank-anvil-precip, anvil sharpness, waterfall RFD, tilted hook precip, precip foot, hook echo opacity, forward flank core opacity, drop size (atomized, small, med, large), significant accumulation, significant rate of accumulation

Tornado Related: cinnamon swirls funnel cloud, needle funnel cloud, tapered funnel cloud, truncated cone funnel cloud, drill press, elephant trunk, pencil, stovepipe, cone, truncated cone, wedge, multi-vortex, rope, translucent sheath, horizontal ring vortex, satellite tornado

Hail Related: size, spiked hail, accumulation, opaque layer, non-opaque, hail fog

Lightning Related: cloud-cloud frequency**,** cloud-ground frequency, anvil crawlers, anvil zits, bolts from the blue,

Tracers/Wind Related: estimating wind speed**,** blowing dust outflow**,** blowing dust inflow**,** lofted debris

Table 1. List of visual cues related to severe convection to be used to describe characteristics in severe storm images.

One of the goals of this research is to apply the entire cue list to large numbers of photographs in a systematic way. Capturing a large sample size of photographs of visual cues can: 1) help refine the cue definition, 2) develop associations with other cues, 3) be used to develop insight into the environments containing the cues, and 4) be used to relate the cues to the dynamics of severe convection and the severe weather produced. As these cues are applied to a large database, we anticipate more cues being added and redundant cues being removed. As we refine our definitions and rule bases we intend to document our visual cues on the Internet with examples.

There are many caveats in determining the existence of a particular cue. The ability to capture a cue can be limited by viewing angle, range, visibility, and the characteristics of the imagery collected (field of view and temporal resolution). Thus, when cataloging features there must be a condition for "not applicable" when the documentation available is unable to clearly identify a feature. While the existence of a particular feature can be confirmed with one photo, the absence of a feature must be judged with a complete record of the life cycle of a storm.

4. LINKING VISUAL CUES TO DYNAMICS

Another goal of this research is to begin to raise the question of how the visual cues may relate to the dynamics of severe convection. While there are many theoretical models to describe the dynamics of severe weather, there has not been a robust linking of dynamics to visual cues. Among the questions we would like to see addressed are: 1) what are the visual manifestations of dynamic pressure forcing (Rotunno and Klemp 1982) including horizontally curved flow, vertically curved flow, and convergence/divergence?, 2) what are the visual manifestations of updraft and downdraft tilting?, 3) what is the visual evolution associated with a rotation-induced occlusion downdraft?, 4) what are the visual characteristics of relatively warm and unstable rear-flank downdrafts?, 5) what role do the precipitation streamers and blobs have on the development of rotation, and 6) how do some of the better tornado predictors, such as

0-1km shear, 0-1km storm relative helicity, and 0-3km cape relate to visual cues?

Two potential ways to approach relating visual observations to severe storm dynamics are to use high resolution numerical models or to collect high resolution datasets like those in the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX, Rasmussen *et al.* 1994). If visual characteristics can be correlated with important dynamical processes, then there is a new opportunity to incorporate dynamically significant information into storm spotting and ultimately the warning decision making process.

5. DATABASE NEEDS AND POTENTIAL SOLUTIONS

Currently there is no comprehensive and easily accessible archive database of severe storms characteristics or their environments. There is a vast collection of photograph imagery on storm chaser web pages, but it is not organized into a database. To get an hourly objective analysis of a representative sounding for a particular storm of interest for most years is very time consuming, and impossible for many years due to limitations with existing model data archives.

NWS radar data is another potential severe storm data set that is archived and readily available from National Climatic Data Center, but it is time consuming to process large amounts of archived data to identify and track a storm and its radar characteristics. Thus, we propose to remove some of the barriers to studying storms and their characteristics by leveraging new multi-media database technologies. In the following sections we will outline how we think a database should be set up, and we will show an example of the types of queries that can be done with existing solutions.

5.1 Database Example

To illustrate how visual photographs can be combined with environmental information, we used a free (for non-profit) web browser-based multimedia database software called 4images (http://www.4homepages.de/). This database contains one of the better search functions in the database options we have reviewed. In this database, images are stored as records. A description block is used to describe the image, and keywords are used to represent the contents. We have chosen pictures along with manually created sounding images and hodograph images as the primary records, though any images may be used. The database allows simple image queries with "AND", "OR", and "NOT" Boolean operators based on the keywords entered.

All the applicable terms from Table 1 are reviewed to create keywords for the pictures documenting the feature or the lack of a feature and the confidence of the observation. Additional data are added to the keywords such as the time, date, location, photographer, viewing angle, unique storm id, confidence level, and the keyword "picture". For one simple example, consider the bell-updraft keyword that is associated with an image of a bell shaped updraft. After entering numerous pictures of bell shaped updrafts into the system, a page of thumbnail images can be retrieved by querying the keywords "bell-updraft AND picture". This allows inspection of many images at once. Also, the image thumbnail can be selected to produce the full size image and the full description of the database entry including keywords and descriptions.

We also generated sounding and hodograph images from a sounding database organized by storm (Thompson *et al.*. 2003), where one vertical profile from the Rapid Update Cycle (RUC) hourly initialization is available per storm during the time of its production of severe weather. For generating sounding images, we used the NSHARP sounding display program (original sounding data format). We entered the environmental parameters available from the NSHARP readout into the database, with the raw values of the data entered in the description block, and a broader category range (e.g. low, moderate, and high) entered as key words and confidence values (as well as the keyword "sounding"). This can support queries, such as requesting all soundings with high convective inhibition (CIN) (e.g. "soundings AND high-CIN").

We also entered the visual characteristics organized by storm id into each sounding and hodograph, and we entered the environment data into each picture. This supports queries such as requesting all soundings for bell shaped updrafts ("bell-updraft AND sounding") or requesting all pictures of storms with high CIN ("high-CIN and picture"). The queries can be further refined by adding the confidence level to the search if there is ambiguity in the photographs.

More storms and soundings are being added to the database to begin to investigate a variety of visual features associated with severe convection and their environments. While this illustrates some of the power of multimedia databases linked with environmental data, there are more ideal solutions to consider.

5.2 Ideal Database Solution

Other database solutions are going to be evaluated that provide range-based queries from the numerical values of the attributes (e.g. request pictures AND 35 < CIN < 70). In addition we would like to set up a comprehensive storm-centric quasi automated database of severe storms and their environments. For our purposes, an ideal database solution for studying the visual characteristics of severe convection would include the following:

1) Pictures/Videos (cue list applied manually as events are reviewed, storm id, documentation throughout storm lifetime)
2) Hourly sounding files (RUC initialization or SPC mesoanalysis) for each storm, generated and stored automatically using radar identification of a storm's location
3) Severe weather occurrence (time, location, size, characteristics, storm ID of closest storm)
4) Closest radar data (0.5 degree Z, SRM) for each volume scan per storm and the radar algorithm output for storm tracking and general characteristics, all readily available in real time
5) Watches, warnings, and severe weather statements
6) Visible satellite gif image sector including the storm of interest
7) Horizontal environment fields such as cape plots

In creating a more comprehensive database, there is a trade off between amount of information and efficiency of data management. As more data is added to the database, it will likely become necessary to threshold the data collection and storage for stronger storms with certain radar algorithm characteristics, storms inside severe weather watch boxes, or within severe weather warnings.

6. CONCLUSIONS

The plethora of online storm chaser photo documentation coupled with the emergence of multimedia databases offers a unique opportunity to systematically study the visual characteristics of many storms. We have demonstrated a relatively simple approach to link digital storm photography images to environmental sounding characteristics in a way that can facilitate simple, but effective, inquiry into the relationship between visual characteristics and the storm's environment. Our multimedia database example can be greatly enhanced by including more and better inputs including hourly representative soundings from available objective analysis datasets, severe weather reports, radar algorithm-based storm identification, 0.5 degree radar reflectivity and storm-relative velocity radar data from the nearest radar, watches, warnings and severe weather statements, visible satellite imagery, and horizontal fields of objectively analyzed environmental parameters.

The desire to better utilize visual observations of severe weather has led us to investigate a new approach for establishing multimedia databases. Potential improvements we are considering address some of the current shortcomings in current data accessibility for fundamental severe thunderstorm research, training, and operations. We are promoting the creation of an automated national scale severe thunderstorm-centric storm identification and documentation system to include basic available radar data, hourly environmental objectively analyzed sounding profiles, NWS severe weather products, and more. These provide the critical data sources necessary to understand the visual characteristics of severe weather. This will be particularly important for future training initiatives as fundamental warning decision making analysis techniques are reevaluated with the implementation of the new radar base data analysis tool, the Four Dimensional Storm Cell Investigator (FSI; Stumpf 2006), in late 2006.

We believe that extending our current approach to more storms can significantly aid in refining existing and new definitions of important visual cues of severe weather. Other more advanced multimedia database solutions look even more promising. By incorporating environmental soundings into the analysis, this has the opportunity to provide insight into the environments of severe weather. Ultimately we would like the visual cues to be related to the dynamics of severe convection and the severe weather produced to improve training and also improve the way storm spotter information is incorporated into the warning decision making process.

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