The Tornadoes of 3 May 1999: Event Verification in Central Oklahoma and Related Issues

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ABSTRACT

The tornado events of 3 May 1999 within the county warning area of the Norman, Oklahoma, office of the National Weather Service are reviewed, emphasizing the challenges associated with obtaining accurate information about the existence, timing, location, and intensity of individual tornadoes. Accurate documentation of tornado and other hazardous weather events is critical to research, is needed for operational assessments, and is important for developing hazard mitigation strategies. The situation following this major event was unusual because of the high concentration of meteorologists in the area, relative to most parts of the United States. As a result of this relative abundance of resources, it is likely that these tornadoes were reasonably well documented. Despite this unique situation in central Oklahoma, it is argued that this event also provides evidence of a national need for a rapid-response scientific and engineering survey team to provide documentation of major hazardous weather events before cleanup destroys important evidence.

1. Introduction

During the late afternoon and evening of 3 May 1999, an outbreak of severe thunderstorms and tornadoes occurred across Oklahoma and southern Kansas. This outbreak affected the Oklahoma City, Oklahoma, and Wichita, Kansas, metropolitan areas with several violent tornadoes (F4–F5; see Fujita 1971). Sixty-two tornadoes occurred in Oklahoma and southern Kansas on 3 May (through 0500 UTC 4 May), 58 of which struck in central Oklahoma within the county warning area (CWA) of the National Weather Service (NWS) office in Norman, Oklahoma. The outbreak then continued into the early morning hours of 4 May in eastern Oklahoma, producing 4 more tornadoes, for an overall total of 66 tornadoes in Oklahoma and Kansas through 0900 UTC 4 May.

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The magnitude of this event required special attention to document as many of the tornadoes as possible. We present the results of the documentation effort for events within the NWS Norman CWA. Data from numerous sources were used to create a composite of information for each tornado. The data we present represent our best effort at incorporating all of the data that were available to the NWS Forecast Office in Norman.

In section 2, we provide some background information about the events of 3 May 1999. Section 3 discusses the methodology associated with documenting the events, and section 4 presents a number of important issues regarding documentation of the details of the outbreak. Section 5 presents a detailed analysis of tornado A9, the violent tornado that received the greatest attention, and section 6 provides discussion and offers conclusions about the documentation of major tornado outbreaks.

2. Background

Fifty-eight tornadoes were documented to have touched down in 16 countries of the NWS Norman CWA (Fig. 1) within less than 8 h. These tornadoes are doc-

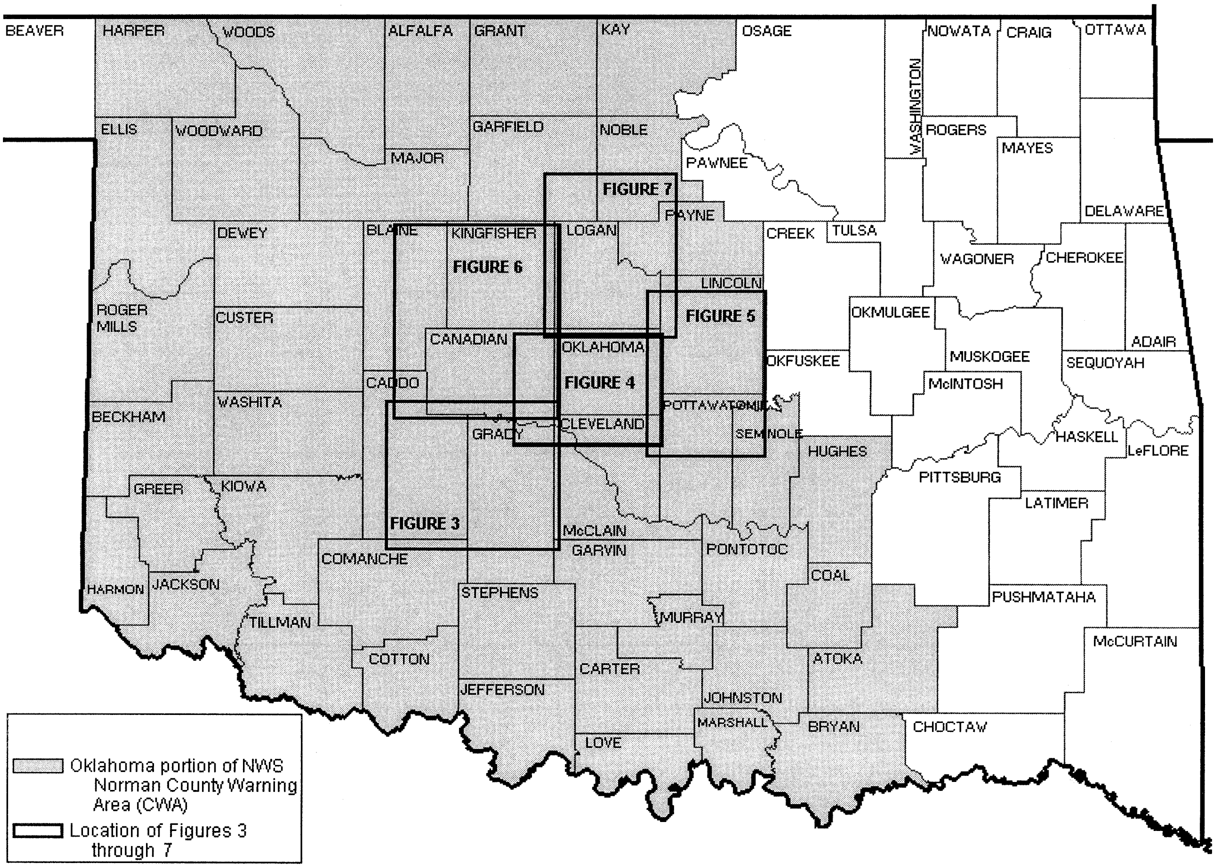

FIG. 1. Map of the OK portion of the Norman CWA (shown in gray) and the locations of Figs. 3–7.

umented in Table 1 and displayed in Fig. 2. Of these, 16 were ''significant'' tornadoes (Grazulis 1993), that is, rated F2 or greater on the Fujita (1971) intensity rating scale. This total includes an F5 tornado that moved through the rural community of Bridge Creek, the southern portion of Oklahoma City, and the Oklahoma City suburbs of Moore, Del City, and Midwest City. Two other violent (F4) tornadoes also occurred in central Oklahoma, one striking the town of Dover and another moving through rural Logan County before hitting the town of Mulhall. Thirteen additional tornadoes were rated as F2 or F3 events.

Available radar data revealed that eight supercell thunderstorms produced this outbreak of tornadoes across the NWS Norman CWA. Each of these storms was given a letter identifier from A to I, based on the chronological order of the first echo of the storm as seen from the Twin Lakes, Oklahoma, Weather Surveillance Radar-1988 Doppler (WSR-88D) 0.5° reflectivity scan. However, the identifier F was not used, to avoid confusion with Fujita-scale ratings. The tornadoes produced from each supercell thunderstorm were then given that storm's identifier and a number assigned to each tornado in sequence from that supercell. For example, the F5 Bridge Creek–Oklahoma City–Moore tornado was assigned identifier A9—the ninth tornado produced from supercell A.

3. Methodology

The lead author was given the task of compiling the surveys, videos, spotter reports, e-mail reports, and other sources of information to produce a listing of those tornadoes that struck within the NWS Norman CWA. Information about each tornado from each source was cross-referenced to every other source to create a composite of the events using all of the available data. Radar data from the Twin Lakes (KTLX), Frederick (KFDR), and Vance Air Force Base (KVNX) WSR-88D radars in Oklahoma and the Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR) near Will Rogers World Airport in Oklahoma City were also used to reconcile available information regarding times and locations of the events. Analysis from the Doppler on Wheels[1] (hereinafter DOW) Project research radar also was used in some locations, as were two independent series of aerial photographs.

[1] At the time of writing, information regarding this project was available online at http://aaron.ou.edu/xband.

TABLE 1. Times and locations of tornadoes [yd is yards (~0.914 m)].

Tornado	Time and date (UTC)	Length (mi)	Width (yd)	F-scale rating	Counties	Location	Primary source*
1) A1	2151–2152 3 May	0.5	25	F0	Comanche	7 mi ENE of Medicine Park	RC
2) A2	2155 3 May	0.1	25	F0	Comanche	3 mi W of Elgin	R
3) A3	2220–2235 3 May	6	100	F3	Caddo	3 mi E of Apache to 2 mi NE of Stecker	SMV
4) A4	2226 3 May	0.1	25	F0	Caddo	3 mi NW of Cyril	VRC
5) B1	2236 3 May	0.1	25	F0	Kiowa	3 mi S of Roosevelt	R
6) A5	2238 3 May	0.1	25	F0	Caddo	2 mi S of Anadarko	RP
7) A6	2246–2310 3 May	9	880	F3	Caddo/Grady	2 mi WSW of Laverty to 2.5 mi WNW of downtown Chickasha	SMV
8) A7	2307–2308 3 May	1	75	F0	Grady	5 mi W of downtown Chickasha	MV
9) A8	2312–2321 3 May	4	500	F2	Grady	2.5 mi NW of downtown Chickasha to 4 mi NNE of downtown Chickasha	SMV
10) B2	2320–2324 3 May	2	25	F0	Caddo	12 mi WNW of Apache	VC
11) A9	3 May 2326–0048 4 May	37	1760	F5	Grady/McClain/Cleveland/Oklahoma	2 mi SSW of Amber to SW Oklahoma City to Moore to Del City to Midwest City	SMV
12) B3	2338–2359 3 May	7	150	F1	Caddo	8 mi S of Fort Cobb to 1 mi W of Washita	SMV
13) B4	2356 3 May	0.1	25	F0	Caddo	5 mi W of Anadarko	RC(S)
14) C1	3 May 2358–0007 4 May	4	100	F0	Canadian/Kingfisher	1.5 mi W of Okarche to 4 mi N of Okarche	S
15) C2	0000 4 May	0.1	25	F0	Canadian/Kingfisher	Okarche	P
16) A10	0010 4 May	0.2	20	F0	McClain	Rural north Newcastle	V
17) B5	0012–0013 4 May	1	25	F0	Caddo	4 mi NNW of Anadarko to 5 mi NNW of Anadarko	RC(S)
18) B6	0020 4 May	0.1	25	F0	Caddo	4 mi ESE of Gracemont	RC(S)
19) A11	0031–0032 4 May	0.5	60	F0	Oklahoma	Southeast Oklahoma City (near SE 80th St. and Sooner Rd.)	RD
20) B7	0034–0035 4 May	0.5	25	F0	Caddo	9 mi E of Gracemont to 10 mi ENE of Gracemont	RC(S)
21) B8	0037–0040 4 May	2	300	F1	Grady	8 mi WSW of Minco to 6 mi WSW of Minco	VC(S)
22) B9	0037–0048 4 May	5	50	F1	Caddo	5 mi S of Cogar to 1 mi E of Cogar	SV
23) B10	0047–0100 4 May	4	60	F1	Grady	5 mi W of Minco to 4 mi NW of Minco	SV
24) A12	0053–0107 4 May	7	220	F2	Oklahoma	3 mi SW of Choctaw to Choctaw to 4 mi SE of Jones	SV
25) B11	0055 4 May	0.1	50	F1	Grady	5 mi SW of Minco	C
26) B12	0103 4 May	0.1	25	F0	Canadian	2.5 mi WNW of Union City	VC
27) A13	0109–0115 4 May	2	50	F0	Oklahoma	4 mi ESE of Jones to 3 mi E of Jones	SV
28) B13	0113–0114 4 May	0.75	100	F0	Canadian	2 mi NNE of Union City	VC
29) B14	0116–0118 4 May	1	75	F0	Canadian	4 mi NNE of Union City to 5 mi NNE of Union City	VC
30) A14	0117–0125 4 May	3	50	F1	Oklahoma	3.5 mi ENE of Jones to 6 mi NE of Jones	SV
31) E1	0121 4 May	0.1	25	F0	Blaine	3 mi W of Geary	R
32) B15	0125 4 May	0.1	25	F0	Canadian	3 mi ESE of El Reno	V
33) E2	0129–0141 4 May	9	150	F1	Canadian/Blaine/Kingfisher	3 mi NNE of Geary to 7 mi S of Omega	SV
34) B16	0134–0146 4 May	6	150	F1	Canadian	6 mi WNW of Yukon to 3 mi W of Piedmont	S
35) D1	0134–0152 4 May	9	30	F1	Cleveland/Pottawatomie	1 mi N of Etowah to Pink to 2 mi NNE of Pink	S
36) E3	0141–0206 4 May	12	450	F3	Kingfisher	7 mi S of Omega to 7 mi NW of Kingfisher	SV
37) B17	0148–0200 4 May	8	200	F2	Canadian/Kingfisher	1.5 mi W of Piedmont to 6 mi NNW of Piedmont	S
38) E4	0155–0156 4 May	0.5	50	F0	Kingfisher	6 mi W of Kingfisher	V
39) B18	0158–0222 4 May	10	150	F1	Canadian/Kingfisher	4 mi N of Piedmont to 4 mi NW of Cashion	S
40) E5	0203 4 May	0.1	25	F0	Kingfisher	6 mi WNW of Kingfisher	V
41) D2	0205–0220 4 May	7	250	F2	Pottawatomie	2 mi N of Bethel Acres to 7 mi E of McLoud	S

TABLE 1. (*Continued*)

Tornado	Time and date (UTC)	Length (mi)	Width (yd)	F-scale rating	Counties	Location	Primary source*
42) B19	0210–0212 4 May	1	100	F1	Logan	2 mi SSE of Cashion to 1 mi SE of Cashion	S
43) E6	0210–0238 4 May	15	880	F4	Kingfisher	4 mi SSW of Dover to Dover to 7 mi ESE of Hennessey	SV
44) D3	0220–0245 4 May	11	100	F1	Pottawatomie/Lincoln	6 mi NNW of downtown Shawnee to Meeker to 4 mi NE of Meeker	S
45) H1	0222–0224 4 May	0.8	50	F0	Kingfisher	2 mi ESE of Omega	C
46) B20	0225–0345 4 May	39	1760	F4	Logan/Payne/Noble	3 mi SW of Cimarron City to Mulhall to 3 mi ENE of Perry	SRC
47) E7	0230–0237 4 May	4	440	F1	Kingfisher	3 mi NE of Dover to 4 mi SE of Hennessey	S
48) H2	0250 4 May	0.2	30	F0	Kingfisher	3 mi NW of Dover	VS
49) G1	0256–0258 4 May	1	50	F0	Canadian	Southwest edge of El Reno	VS
50) H3	0257–0302 4 May	1	150	F2	Kingfisher	1 mi ESE of Hennessey	SVC
51) G2	0303–0337 4 May	22	350	F3	Canadian/Kingfisher	1 mi NNE of El Reno to 8 mi SE of Kingfisher	S
52) D4	0310–0348 4 May	15	750	F3	Lincoln/Creek	3 mi NNE Sparks to Davenport to Stroud to 1 mi S of Stroud Lake	S
53) H4	0318–0328 4 May	8	440	F2	Logan/Garfield	3 mi SW of Marshall to 5 mi NE of Marshall	(S)
54) I1	0328–0330 4 May	1	200	F1	Major	6 mi S of Ringwood	D
55) G3	0338–0344 4 May	3	150	F0	Kingfisher/Logan	2 mi SW of Cashion to 0.5 mi N of Cashion	S
56) G4	0340–0341 4 May	0.5	50	F0	Kingfisher	8 mi E of Kingfisher	S
57) G5	0356–0418 4 May	13	880	F3	Logan	2.5 mi S of Crescent to 4 mi SW of Mulhall	SR
58) G6	0433–0436 4 May	2	440	F2	Logan	3 mi SSW of Mulhall to 2 mi S of Mulhall	S

* S, NWS survey; (S), an emergency manager or other non-NWS survey; M, research meteorologist report; R, report from spotter, law enforcement, or emergency management; C, storm-chaser report; V, video; P, photograph; D, nonsurveyed damage.

Damage paths of 32 tornadoes were surveyed by National Oceanic and Atmospheric Administration (NOAA) ground survey teams, and one additional tornado was surveyed in detail by the local emergency manager (see Table 1). Based on these surveys, high-resolution maps of tornado paths were produced (Figs. 3–7). An additional five tornadoes were surveyed by a representative of a local television station, and, although they were not of the same level of geographic detail as the NOAA surveys, they provided valuable information of the tornadoes in Caddo County where NOAA surveys were not conducted and are included in Fig. 3.

The damage paths for the other 20 tornadoes were estimated as accurately as was possible, based on video evidence and on reports from spotters, research meteorologists, and storm chasers. The accuracy of these paths is dependent on the amount of detail in the reports, the number of independent reports for the same event, and the specific evidence that was available. Many of these tornadoes, especially those that occurred in daylight hours, had numerous independent reports that allowed a good triangulation of reported locations. The estimated locations of tornadoes that were not surveyed are also included in Figs. 3–7, and the caption identifies which paths are estimated.

Recent Oklahoma tornado outbreaks on 13 June 1998 and 4 October 1998 gave the authors valuable experience in this process of compositing tornado reports from multiple sources and familiarized us with the sources of error that typically arise with reports from the various sources. For example, conflicting information (especially with regard to time and location) is commonly found among different sources (Witt et al. 1998). The times of some final-tallied events (e.g., in *Storm Data*) have occasionally been listed as the time that the report was entered into a log or the time when a spotter called in a report, rather than the actual time of the event. Sometimes the times have been converted incorrectly from several time zone standards (e.g., standard time vs daylight time). Times shown on one video tape can be as much as 10 min different from those on another video of the same event. Many observers also can misjudge the distance to the tornado, or report the *observer's* location rather than the *tornado's* location. In these cases, we tried to determine, to the best of our ability, any obvious errors in the report (e.g., a clock on a video camera that was set incorrectly). Most of the differences among sources were relatively minor once the errors were identified. Nevertheless, several iterations were necessary to create the best composite of the times and locations. We estimate that the times listed in Table 1 have a margin of error of ± 1 min in most cases, and ± 3 min in the worst cases.

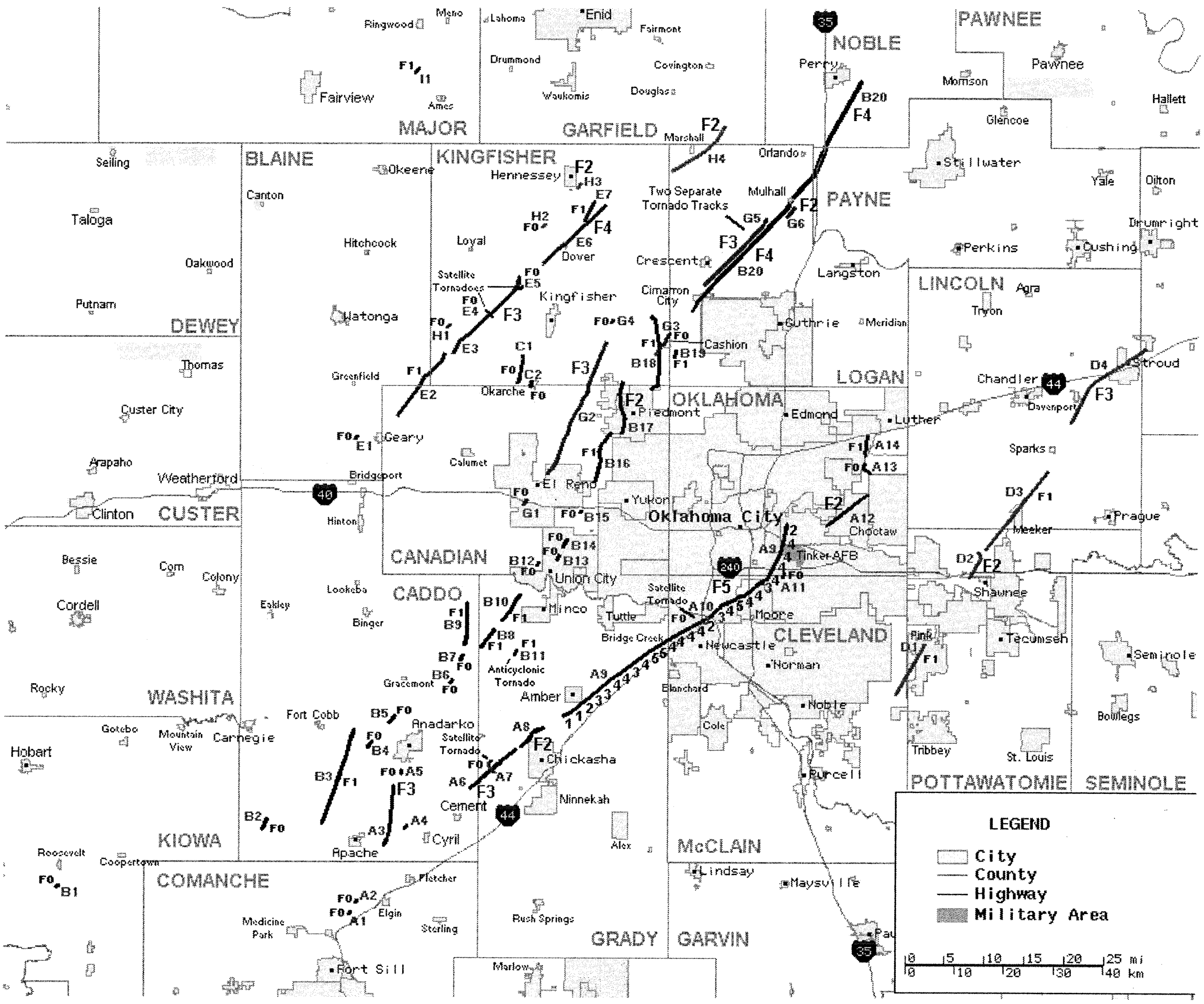

FIG. 2. Map of tornado paths in central OK on 3 May 1999 (Map by S. Kruckenberg of the NWS Forecast Office in Norman.)

Estimates of times were also made of the tornado movement into cities and counties along the tornado paths and are documented in Table 2.

As described above, not all tornadoes of this outbreak could be surveyed in detail, mainly owing to the large number of tornadoes and the long paths of some through metropolitan areas and other populated areas. Furthermore, ground surveys information was not always the *best* source of information. In three different cases, ground surveys that showed two tornadoes with an apparent discontinuity in damage could be combined into one tornado on the basis of eyewitness or video evidence. There conversely was one case of a ground survey showing one tornado that was broken into two distinct tornadoes (A6 and A8) based on eyewitness descriptions and video evidence of tornado evolution and thunderstorm wind damage between tornado damage paths (Fig. 3).

One of these changes occurred as late as 20 months after the event (January 2001). One of the ground survey teams initially indicated that tornado B20 had dissipated 1 mi northeast of Mulhall, with a second tornado, originally labeled B21, developing approximately 3 mi northeast of Mulhall and moving to near Perry in Noble County. High-resolution, low-elevation radar data from the DOWs and an account of the lead scientist associated with the field team provided substantial evidence that tornado B21 most likely was a continuation of tornado B20 rather than a separate tornado (J. Wurman 2001, personal communication). Therefore, the paths originally labeled B20 and B21 were combined into a single tornado path (Fig. 7).

On several occasions, a supercell storm was producing more than one tornado at the same time. This was especially evident with storm B, for which both an occluding mesocyclone and a recently developed mesocyclone were producing simultaneous tornadoes. There were also four satellite tornadoes documented during

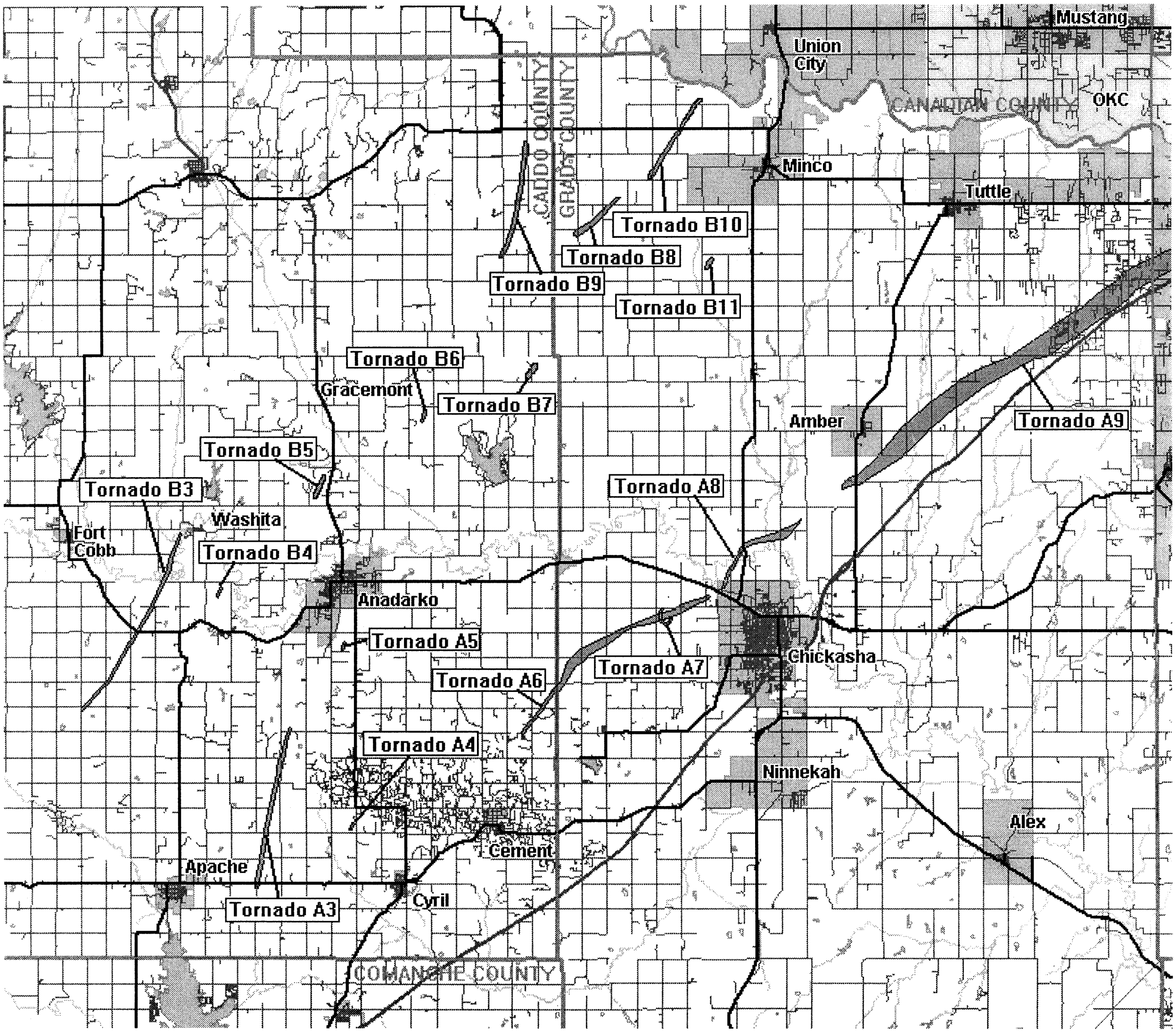

FIG. 3. Paths of tornadoes in Caddo and Grady Counties on 3 May 1999. Locations of tornadoes A4, A5, A7, B4, B5, B6, B7, and B11 are estimated.

this outbreak (A7, A10, E4, and E5) rotating around a larger tornado. Although from the same mesocyclone and rotating around the other tornado, these tornadoes were not part of a typical ''multiple-vortex'' configuration and appeared to be independent. Therefore, these satellite tornadoes were assigned their own identifiers.

With the extreme magnitude of the event, it is also entirely possible that some tornadoes were not observed or documented. For example, there was some evidence to suggest that an additional ''satellite'' tornado occurred with storm E in Kingfisher County; however, there was insufficient evidence to give a time or location of this event, and it was not included. This almost certainly would have been rated as F0 intensity. It is possible that other, similar events were missed.

Ground surveys were also hampered in at least one case because of overlapping damage paths from successive tornadoes. A violent F4 tornado (tornado B20) moved through Logan County between 0225 and 0320 UTC 4 May [2125–2220 central daylight time (CDT) 3 May]. Approximately 1 h later, another tornado (tornado G5) moved through central Logan County, occasionally overlapping the damage path from the previous tornado (Fig. 7). Real-time reports from spotters were used to attempt to distinguish between the two damage paths, when possible.

4. Issues

As a major tornado outbreak, there is a need to obtain detailed information for this event. That is, by careful study, we can learn important lessons for recognizing and handling events like this one in the future [e.g., as in Doswell and Brooks (2002)]. Although the 3 May

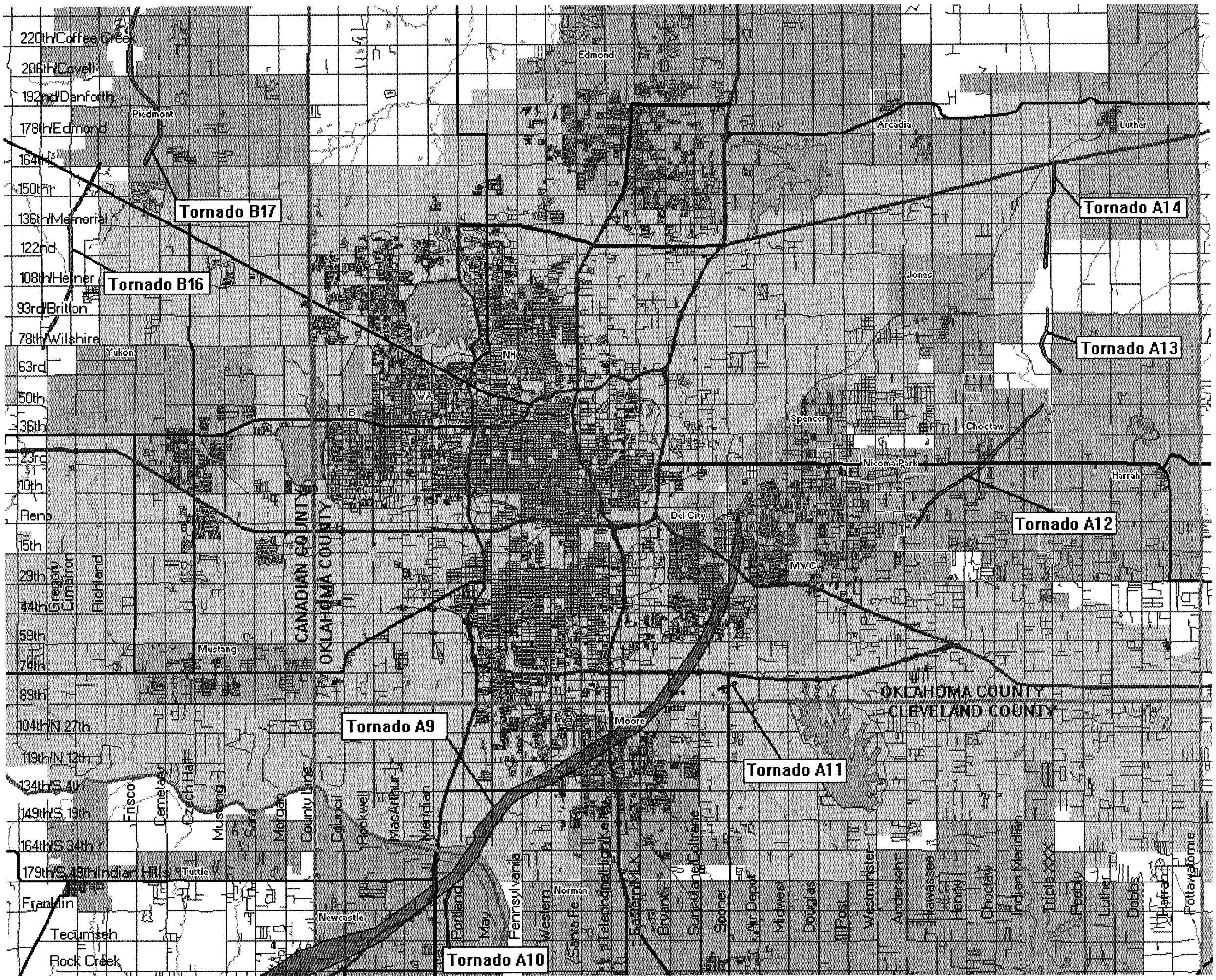

FIG. 4. Paths of tornadoes in the Oklahoma City metropolitan area on 3 May 1999.

1999 tornado outbreak in Oklahoma and Kansas presented many problems in conducting surveys and compiling the tornado information, in other ways the occurrence of most of the tornadoes within the NWS Norman CWA was fortuitous, as we will show.

Because of the redevelopment of severe thunderstorms and tornadic storms in the morning hours of 4 May, much of the NWS Norman staff needed to remain at the office to address the ongoing severe weather, fielding the many calls from emergency management and media personnel and the public about the previous evening's tornadoes and handling normal forecasting responsibilities. Only two members of the NWS Norman staff were able to conduct ground surveys on 4 May. For this particular outbreak, however, there were numerous resources that would not be available had the outbreak been somewhere else. Central Oklahoma is known to have one of the greatest concentrations of severe-storm meteorologists in the world. The University of Oklahoma is renowned for its severe weather meteorology program, and enthusiastic students are often available to participate in postevent surveys. Numerous NOAA meteorologists [from the NWS Forecast Office, the NWS Warning Decision Training Branch, the Next-Generation Radar (NEXRAD) Radar Operations Center, the National Severe Storms Laboratory, and the Storm Prediction Center] and individuals from other agencies were available for ground surveys. Thus, it was possible to dispatch eight ground surveys teams with a total of 18 meteorologists on 4 May, with the highest-priority areas being the locations of particularly damaging tornadoes or fatalities. Storm chasers from the media, local meteorologists from the University of Oklahoma and the NOAA agencies represented in central Oklahoma, and independent chasers followed these storms and made their video, chase logs, and reports available to the NWS. These reports were valuable, because many tornadoes would not have been documented without such sources.

The magnitude of the outbreak also brought engineers from Texas Tech University and the Federal Emergency Management Agency to central Oklahoma during the

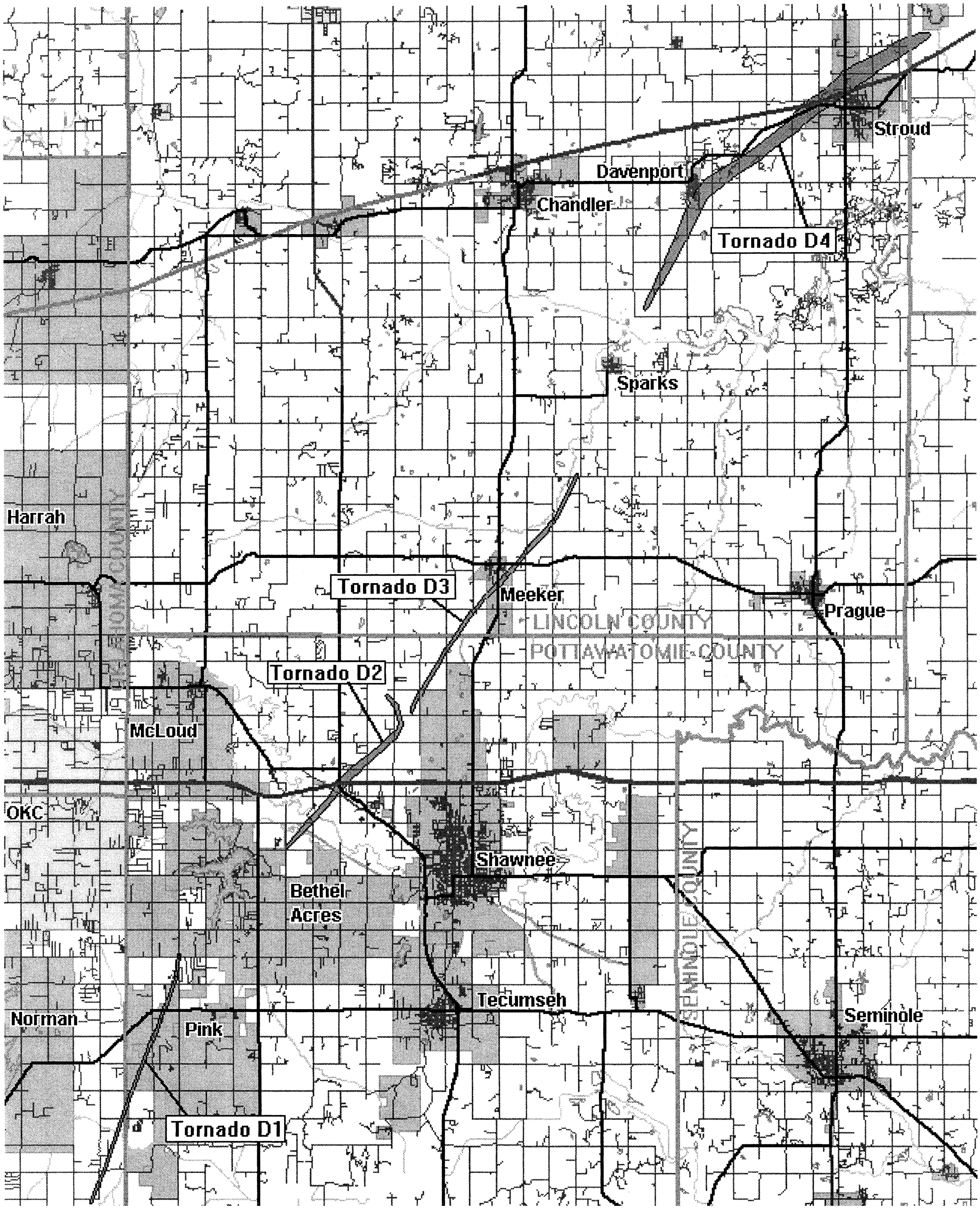

FIG. 5. Paths of tornadoes in Pottawatomie and Lincoln Counties on 3 May 1999.

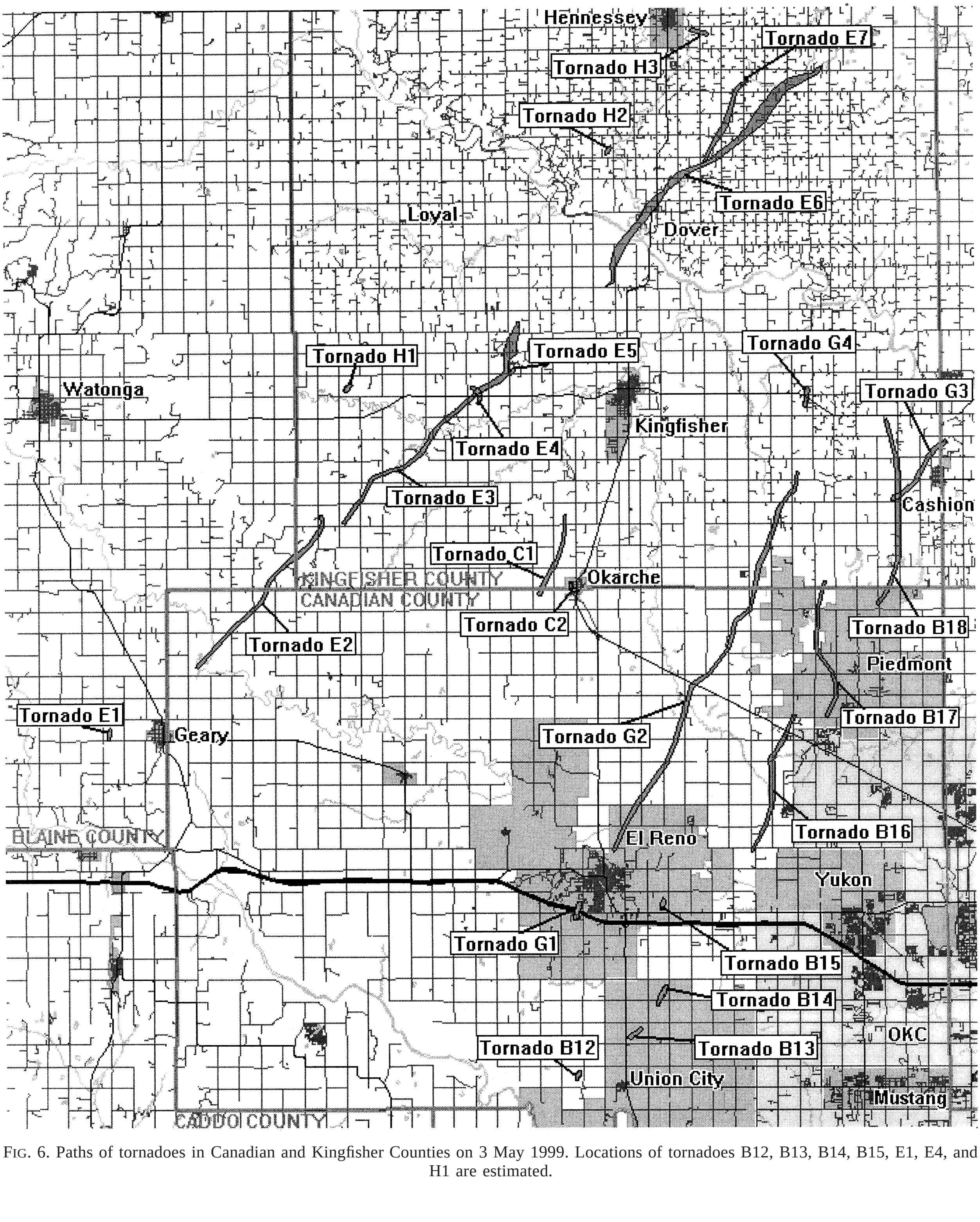

FIG. 6. Paths of tornadoes in Canadian and Kingfisher Counties on 3 May 1999. Locations of tornadoes B12, B13, B14, B15, E1, E4, and H1 are estimated.

days following the event. Information from their surveys also was available within the following months (see BPAT 1999; Marshall 2002). Aerial photographs from the private sector and from a team of U.S. Air Force pilots (who coincidentally happened to be available for an overflight on 7 May) were made available to the NWS within the weeks and months after the outbreak, which helped to fine-tune tornado paths.

Despite the relatively favorable local circumstances, it was still difficult to coordinate all the resources needed

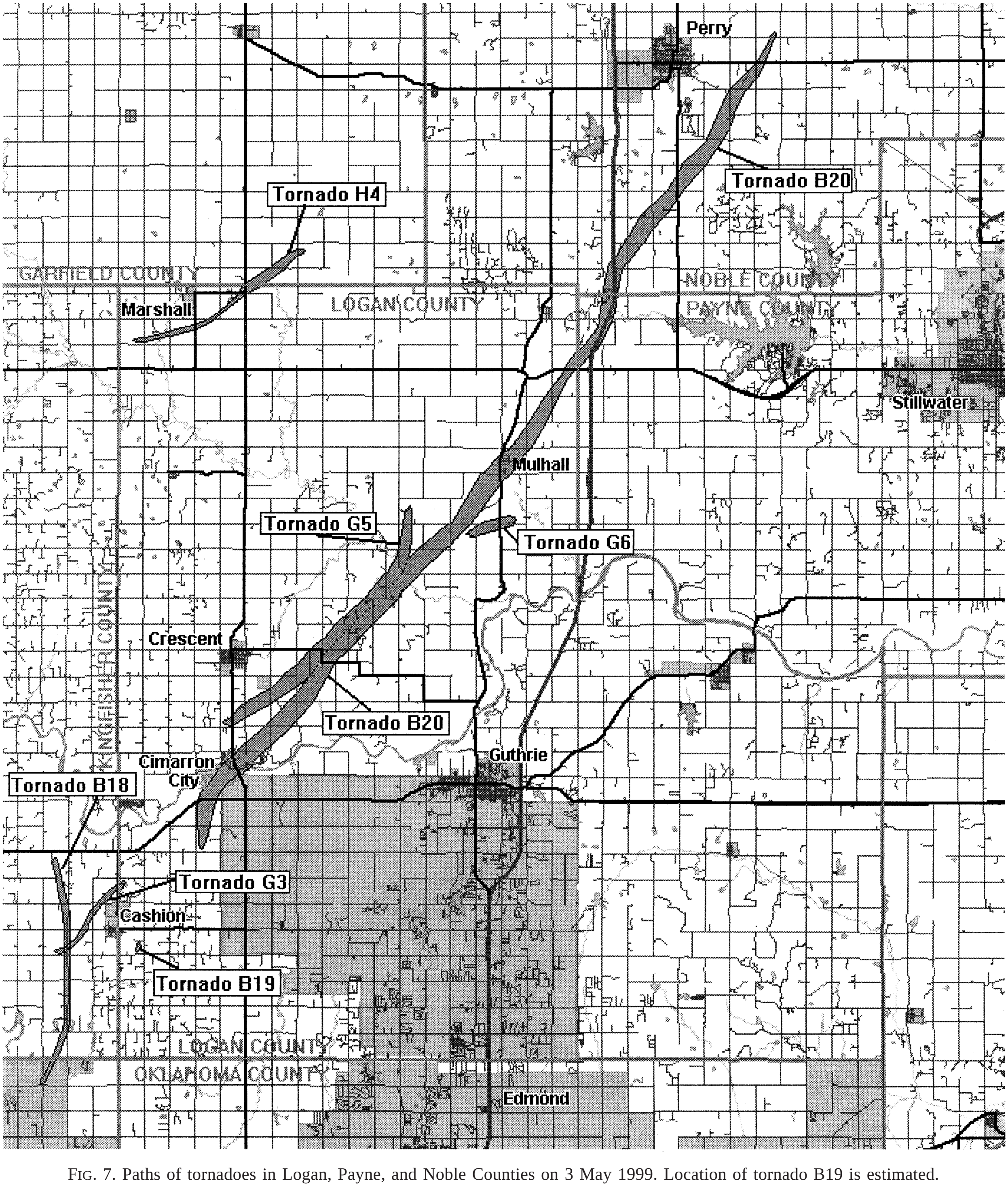

FIG. 7. Paths of tornadoes in Logan, Payne, and Noble Counties on 3 May 1999. Location of tornado B19 is estimated.

for the detailed scientific investigation that an outbreak of this magnitude should be given. The sheer number of tornadoes, the extent of the area affected by the storms, and the relatively remote locations for some of the tornadoes made it impossible to do everything that needed to be done before cleanup proceeded to the point that valuable evidence would be gone. For instance, no formal aerial survey with meteorologists was conducted on 4 May, and the earliest ground surveys of portions of the damaged area were begun on 4–5 May. Within a few hours of the tornadoes in any given location, cleanup of damaged areas was already removing or hid-

TABLE 2. Times of tornado strikes at selected cities and locales. Local daylight time is UTC − 5 h.

Locale	Time (UTC)	Tornado
3 May		
Tornado A6 moves into Grady County	2252	A6
Chickasha airport	2316	A8
Southeast edge of Amber	2328	A9
Bridge Creek	2347	A9
4 May		
Okarche	0000	C1
Tornado A9 moves into McClain County	0000	A9
Newcastle (near Interstate 44 and State Highway 76)	0002	A9
Newcastle (near Interstate 44 and State Highway 37)	0009	A9
Oklahoma City (southwest city limits at Canadian River and Cleveland County line)	0012	A9
Moore (west city limits)	0022	A9
Moore (Interstate 35 and Shields Blvd.)	0027	A9
Oklahoma City (city limits at Eastern Ave.)	0029	A9
Oklahoma City (SE 89th St. and Oklahoma County line)	0030	A9
Del City (city limits at SE 44th St.)	0038	A9
Tinker AFB (northwest corner of base)	0040	A9
Midwest City (city limits at SE 29th St. and Sooner Rd.)	0041	A9
Choctaw (downtown; crossing NE 23rd St.)	0100	A12
Tornado E2 moves into Blaine County	0135	E2
Tornado E2 moves into Kingfisher County	0137	E2
Tornado D1 moves into Pottawatomie County	0141	D1
Pink	0149	D1
Tornado B17 moves into Kingfisher County	0200	B17
Tornado B18 moves into Kingfisher County	0201	B18
Shawnee (Clarks Heights Addition near Interstate 40 and U.S. Highway 177)	0211	D2
Dover	0220	E6
Tornado D3 moves into Lincoln County	0228	D3
Cimarron City	0233	B20
Meeker	0233	D3
Mulhall	0308	B20
Davenport	0320	D4
Tornado B20 moves into Payne County	0320	B20
Tornado H4 moves into Garfield County	0324	H4
Interstate 35 at EW60 Rd. bridge	0325	B20
Tornado G2 moves into Kingfisher County	0327	G2
Tornado B20 moves into Noble County	0327	B20
Stroud (west city limits)	0333	D4
Stroud (Tanger outlet mall)	0338	D4
Tornado G3 moves into Logan County	0344	G3
Tornado D4 moves into Creek County	0346	D4

ing evidence of the events. Although the survey teams did as much as they could, many areas of damage were not surveyed at all, especially areas in Caddo County affected by storm B and much of the area affected by storms E and H. Only the tornado families from storms D and G were surveyed completely.

Events of this magnitude may have happened in the area in the past, but without the resources currently available in the region, many tornadoes from those past events probably went undocumented. That is, even though this event was by far the largest documented outbreak of tornadoes (in terms of the absolute number of individual tornadoes) ever to occur in Oklahoma, some events in the past may have possibly equaled or exceeded it. For example, despite the large number of spotters, chasers, and research meteorologists watching the storms on this day, there were 10 tornadoes (17%) that were included based on a single video, photograph, or report. Most of these tornadoes produced no known damage and were rated F0, although two reportedly produced minor damage and were rated F1 based on the descriptions of damage.[2] The relatively large number of these tornadoes reported by only one source suggests that tornadoes from *this* outbreak in the Norman CWA were quite possibly undocumented or unreported, even though the resources available clearly were able to document a number of tornadoes that likely would have been unreported in the past. Meteorologists from the National Weather Service also made numerous phone calls to local officials along the storms' paths to minimize the possibility of any unreported damaging tornadoes, so any unreported tornadoes would likely have been weak and had minimal effect on life and property.[3]

The tornado ratings using the Fujita scale are also subject to some uncertainty. First, the F scale was designed to be a wind speed scale but, owing to the absence of tornado-scale wind speed observations, Fujita nevertheless attempted to relate observable tornado damage (primarily that done to ''well-built'' frame homes) to wind speeds falling within the ranges of the proposed F scale. This effort to infer wind speeds from damage is replete with problems and was never ''calibrated'' in an objective way. The putative damage–wind speed relation is especially dubious over the upper part of the wind speed range. Second, in areas where there are no structures or even tall vegetation (about which the standard F-scale rating criteria offer no clear guidance) on the ground to receive damage (e.g., the treeless High Plains of the United States), it is virtually certain that strong and violent tornadoes are usually assigned ratings lower than their actual intensity, since they inflict no damage. Third, the reported F scale of a tornado is the subjectively determined maximum damage intensity along the entire path of the tornado, and the observed damage is below this maximum strength along the large majority of any tornado's path.

Our examination of the various data collected from this event (and others) suggests that defining what is or is not a separate tornado is not as easy as it might seem. Tornadoes are notably unsteady phenomena, the intensity and appearance of which can vary rapidly no matter what observational tool is being used (e.g., Doppler radar or visual observation). For example, Davies et al.

[2] We also point out that the rating associated with events documented by a single source is always open to some argument. If these events were given a careful survey, validated by several sources, the ratings might change.

[3] Because most tornadoes *are* weak, this is a reasonable assumption, but is still subject to uncertainty in specific cases.

(1994) have shown that the visible condensation funnel can dissipate and then re-form, even as surface damage continues. In a converse way, surface damage can be interrupted for a variety of reasons, even as the vortex is clearly continuing. Even with video evidence, it is sometimes difficult to define when a tornado actually begins or ends. The existence of satellite tornadoes is not widely known, and confusion with multivortex tornadoes is possible. In our documentation of this event, we have provided a solution to the complex data that represents one *possible* interpretation of the event. Others are possible.[4]

5. Tornado A9—The Bridge Creek–Oklahoma City–Moore tornado

The most damaging tornado of this outbreak was tornado A9—the F5 tornado that struck the community of Bridge Creek and the cities of Oklahoma City, Moore, Del City, and Midwest City. Because of the infamy and degree of damage, special attention was given this tornado. A high-resolution map with F-scale (Fujita 1971) contouring was the outcome of the integration of a variety of survey data sources (Fig. 8).

The initial ground survey, conducted on the first day after the event, was focused on documenting location, width, length, and the maximum F-scale damage-intensity rating of this tornado, primarily for information for a short-fused media press release deadline. In addition, the ground survey teams determined a broad spatial estimate of the F-scale damage-intensity rating of the tornado at various locations along the path that were accessible by vehicle and foot via passable roads. The damage suveys were carefully conducted using the guidelines recommended in Bunting and Smith (1993).

Three NOAA teams were dispatched on 4 May 1999 to conduct ground surveys in various sections of this tornado's path. One team surveyed the Grady and McClain Counties portion of the path; a second team surveyed the path in Cleveland County and a portion of Oklahoma County south of Interstate Highway 240. The third team surveyed damage in Oklahoma County north of Interstate 240. Ground teams were constrained by time and daylight, debris blockage, and areas still off-limits because of natural gas leaks and other hazards. The survey teams were generally limited by the negotiable roadways, so the initial strategy was to mark, along each road, a subjective estimate of a change in F scale. Figure 9 shows some of the handwritten notes from one of the survey teams depicting this process. After the first day of surveying, an estimate of the F-scale contours was developed by ''connecting the dots'' from the information gathered along the passable roadways. This first version of the survey inferred some of the damage estimates in areas that were inaccessible by vehicle or foot.

On days following 4 May 1999, the surveys continued, but with the emphasis on gaining more detailed information on the damage path. Some of the previously inaccessible areas became accessible and were surveyed. In addition, several high-detail datasets were collected and made available to the NOAA survey teams. A series of high-resolution aerial photographs from the private sector and the U.S. Air Force became available, as did a house-by-house survey of damage intensity from Texas Tech University engineers in portions of the Oklahoma City metropolitan area. Numerous storm-chaser videos were provided as time passed, allowing, in some instances, multiple views of the tornado from a variety of viewing angles. High-resolution WSR-88D and TDWR radar data from the Oklahoma City metropolitan sites were also analyzed. The video and radar data enabled the surveyors to determine the times at which the tornado crossed certain points along its path. The photography, video, and radar data were carefully examined and were used to fine-tune the detail of the survey, and they helped to add data to those areas not accessible from the ground.

Some of the aspects from the damage survey of tornado A9 and storm-chaser videos are noted. The early portion of the damage path was particularly wide—nearly 1.5 km in diameter—as it passed through the Bridge Creek community in rural Grady County. The wide tornado paralleled Interstate 44 (the H. E. Bailey Turnpike). The vortex then began to narrow to less than about 200–300 m wide as it struck an overpass on the turnpike (where a woman unfortunately lost her life seeking refuge). The tornado remained narrow from this location northeastward to the Canadian River. The tornado widened again (600–800 m) as it entered the densely populated areas of the Oklahoma City metropolitan area but never attained the extreme pathwidth noted earlier. As the low-level mesocyclone core occluded, the tornado finally curved to the left before dissipating in Midwest City. This occlusion process is similar to that described by Burgess et al. (1993).

The aerial photography (Fig. 10) showed evidence of a convergent centerline of the tornado debris field as evidenced by a narrow litter line on which debris was deposited and near which the vectors of the vegetation damage on either side are directed toward the centerline (Davies-Jones et al. 1978). Also observed were a number of oscillations and kinks in the path. For example, prior to tornado A9 crossing the Canadian River from McClain County to Cleveland County, several videos revealed that a small satellite vortex (depicted as tornado A10 in the 4th panel of Fig. 8) developed and rotated counterclockwise around the back side of the main vortex. Associated with the location of this satellite vortex and as evidenced by the aerial photography and storm-chaser video, the surveyors found a ''wobble'' in the damage path that might have resulted from this inter-

[4] At the time of writing, some informal discussion of the problems with defining what is a tornado was available online at http://www.nssl.noaa.gov/~doswell/a_tornado/atornado.html.

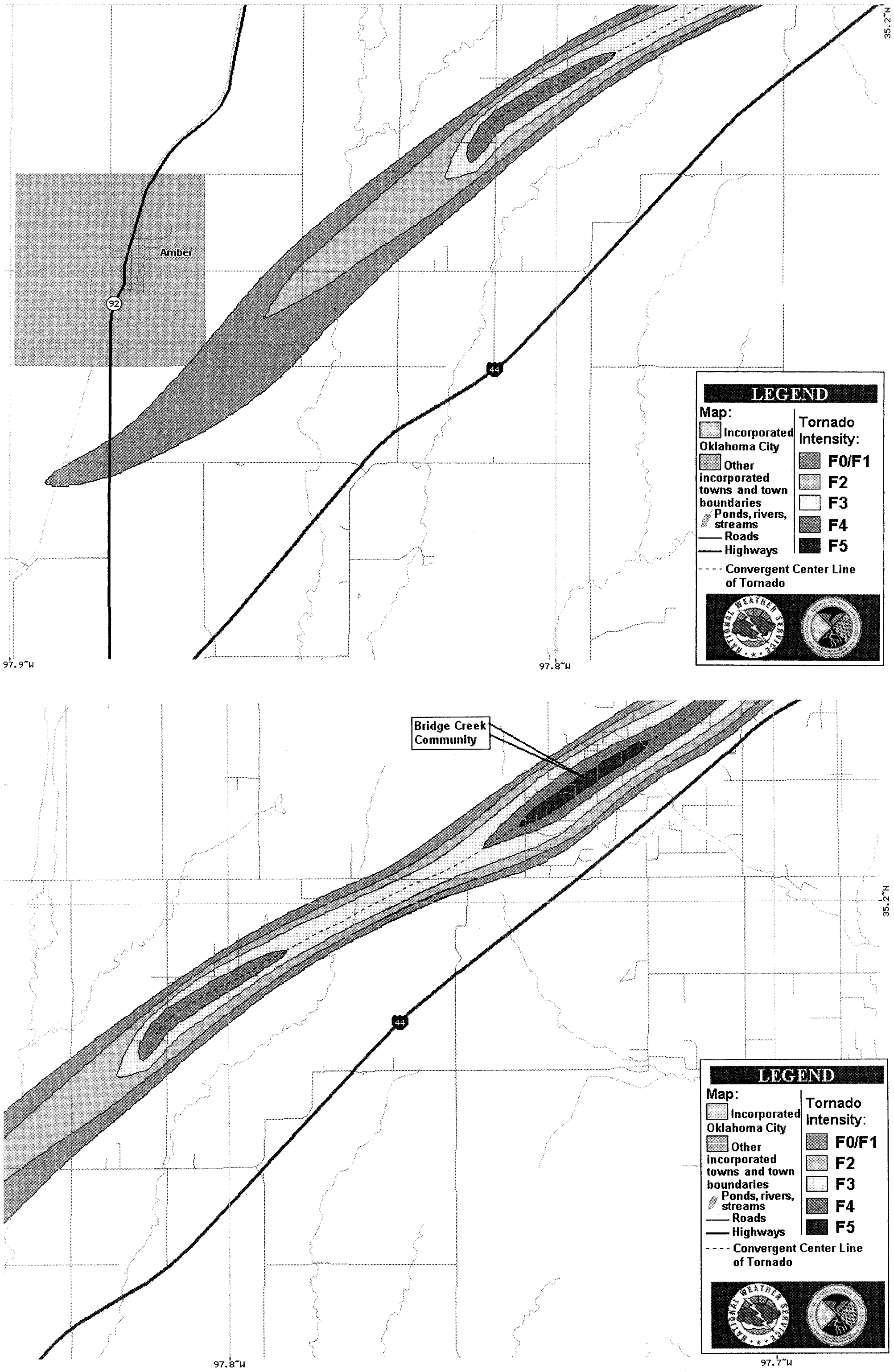

FIG. 8. High-resolution track of tornado A9. See Fig. 10 for aerial photography of area in inset A (third panel). See Fig. 11 for aerial photography and house-by-house F-scale ratings for area in inset B (fifth panel).

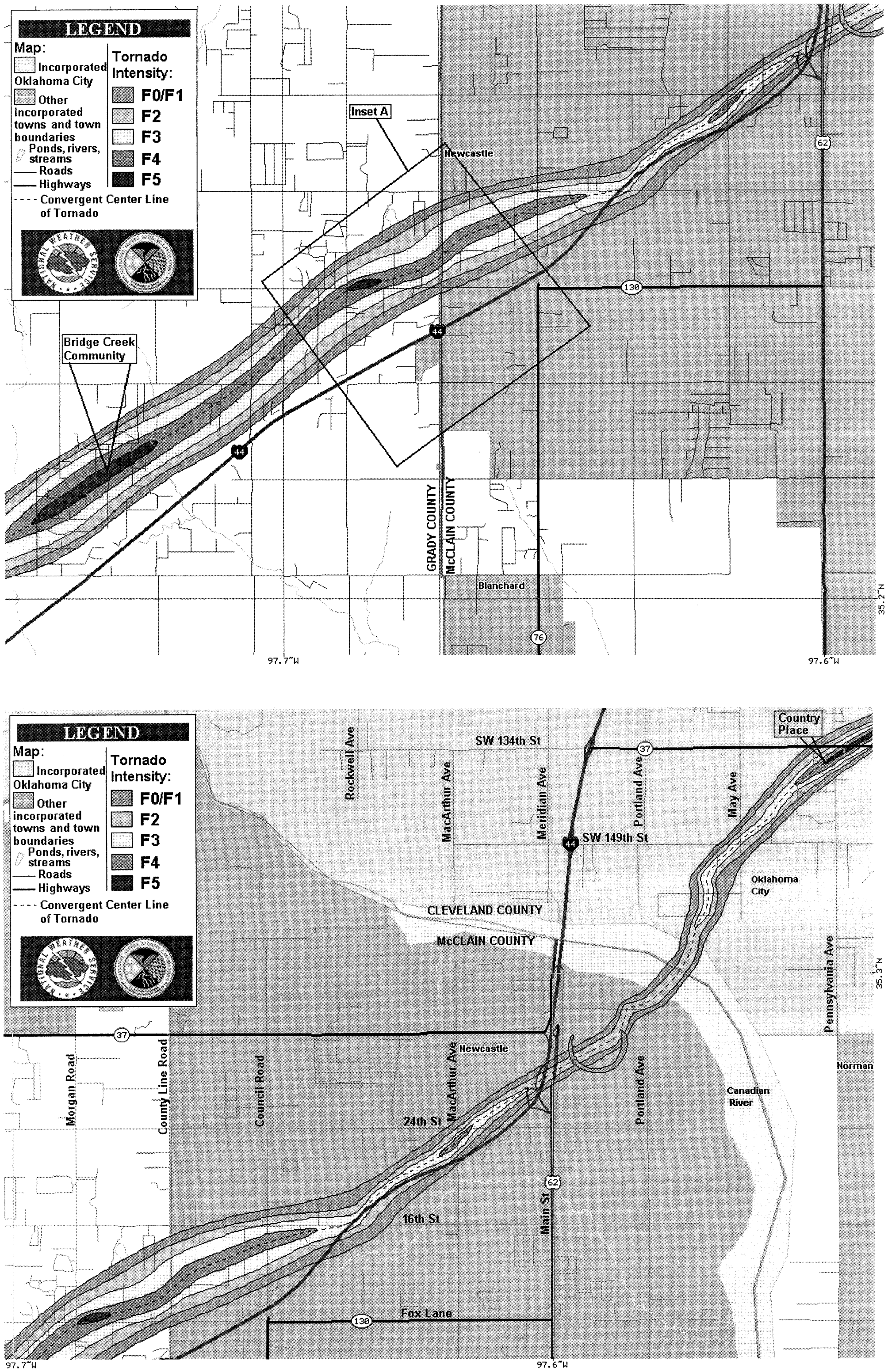

FIG. 8. (*Continued*)

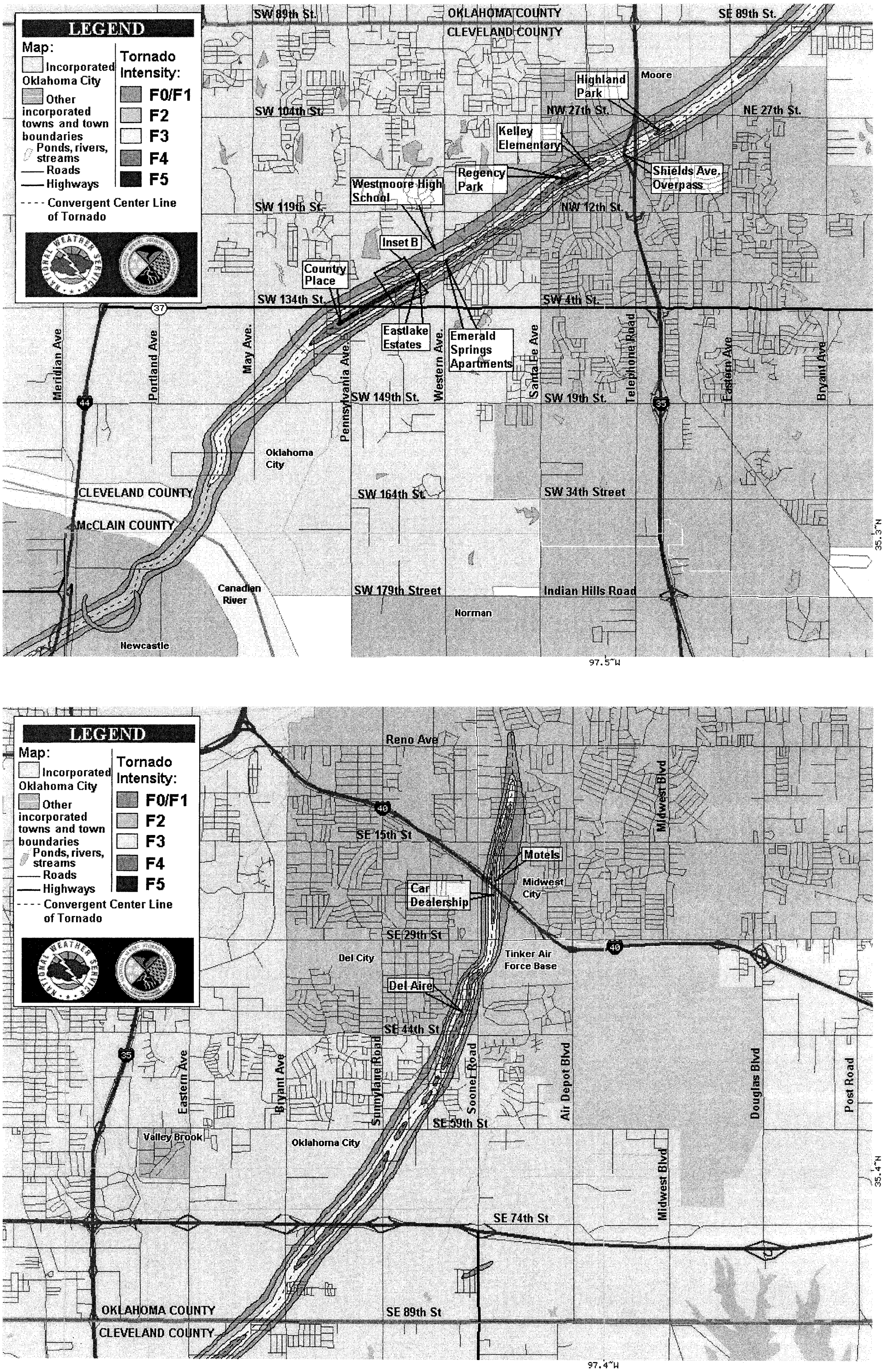

FIG. 8. (*Continued*)

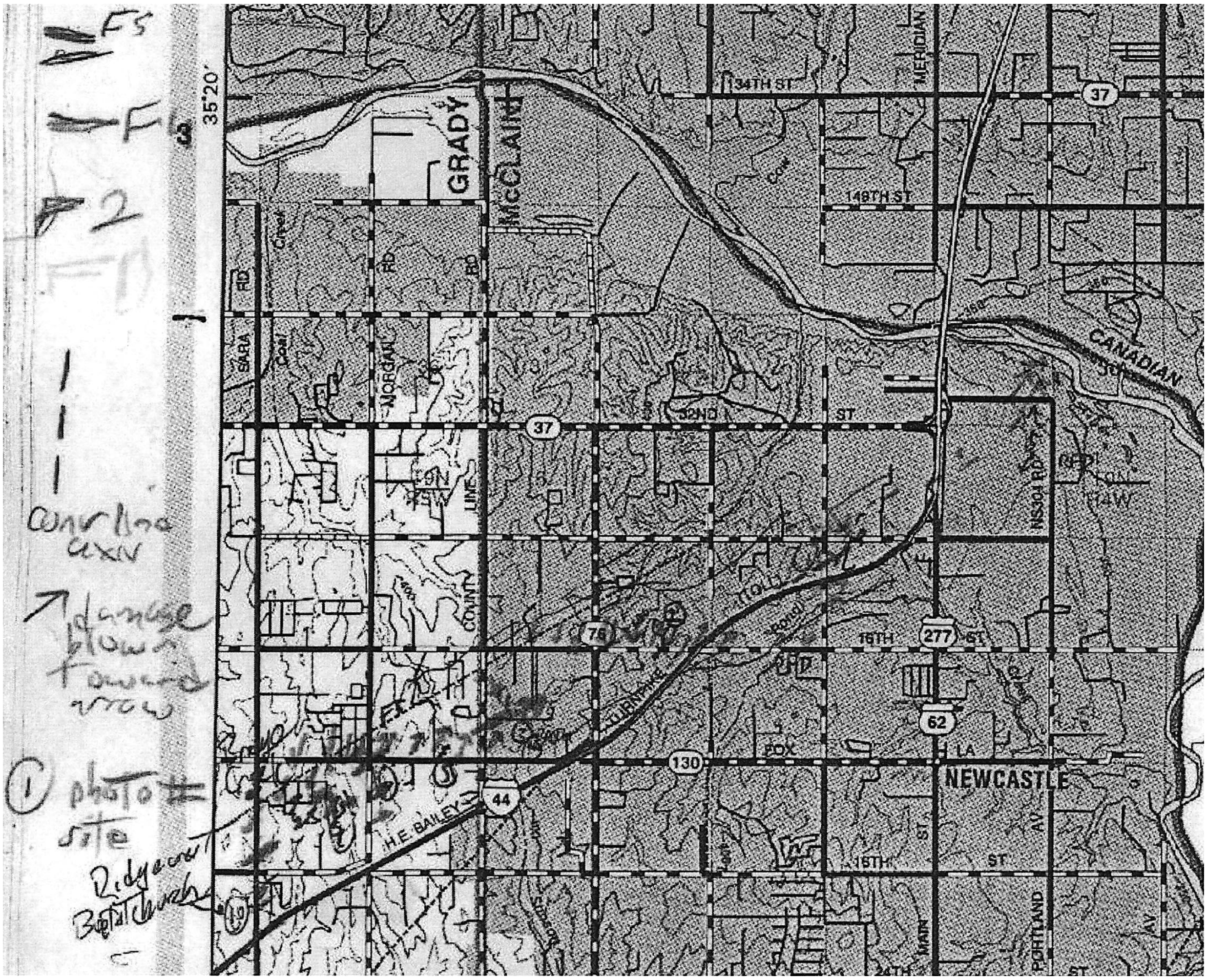

FIG. 9. Scanned image of handwritten notes on a map used during the initial field assessment of Tornado A9 (image is scanned from materials provided by G. Stumpf and J. LaDue).

action. Another wobble was discovered along the path of the tornado just north of the Canadian River in Cleveland County, where aerial photographs and storm-chaser video revealed that, for a short time, the tornado actually had a small westward component to its motion (see Fig. 8, 4th panel).

An independent engineering assessment team from Texas Tech University conducted house-by-house surveys of damage to single-family residences in portions of the Oklahoma City metropolitan area (Marshall 2002). High-detail mapping of damage made available from the Oklahoma City Department of Public Works provided additional detail of this tornado path. These additional, very high resolution data allowed for even finer tuning of the detail of the path and F-scale damage contours in those areas (Fig. 11).

All of these combined data sources made possible the detailed F-scale mapping of tornado A9 shown in Fig. 8. These maps were digitized in a geographic information system (GIS), which allowed for the calculation of the size of the areas affected by the individual F scales (Table 3). The digitized data for tornado A9 and for the entire outbreak have also proven invaluable in a variety of scientific and socioeconomic applications. Burgess et al. (2002) have related the tornado locations, times, and intensities to high-resolution data obtained from mobile X-band Doppler radars (Wurman et al. 1997) to understand better the radar sampling issues associated with the detection of tornadoes and the complex flow fields surrounding them. Yuan et al. (2002) used remote sensing techniques and a GIS to compare the F-scale contours with high-resolution, multispectral satellite data, with the hope that the satellite data could be used to supplement ground surveys where verification is problematic. Rae and Stefkovich (2000) transposed the central Oklahoma digital tornado path data over the Dallas–Fort Worth metroplex. Using an urban GIS containing information about appraisal records, land use classifications, demographic data, employment centers, building locations, and traffic flow, they were

FIG. 10. Aerial photography near Bridge Creek (inset A in Fig. 8). The F-scale contours are overlaid. Dashed line indicates convergent centerline of tornado path. Dotted line shows Interstate 44. (Photography courtesy of the U.S. Air Force.)

able to assess the potential social and economic impact of a similar outbreak of tornadoes over another major metropolitan area in ''Tornado Alley.''

6. Discussion and conclusions

When major tornado outbreaks occur and cause substantial damage and casualties, society stands to gain valuable new information if a careful scientific and engineering survey of the events can be done. To develop as accurate a final postevent analysis of the actual events as possible, considerable resources are needed in terms of knowledgeable personnel and time to reconcile possibly conflicting and often-confusing multiple sources of information. The importance of making this substantial investment of resources is manifest in 1) verification of severe weather outlooks, watches, warnings, and the various tools and guidance available to forecasters in making their decisions (e.g., signatures in radar data), to have an accurate picture of events, and 2) severe weather research, which requires an accurate historical record of events.

The 3 May 1999 tornado event and the lessons learned from the verification of the tornado information can

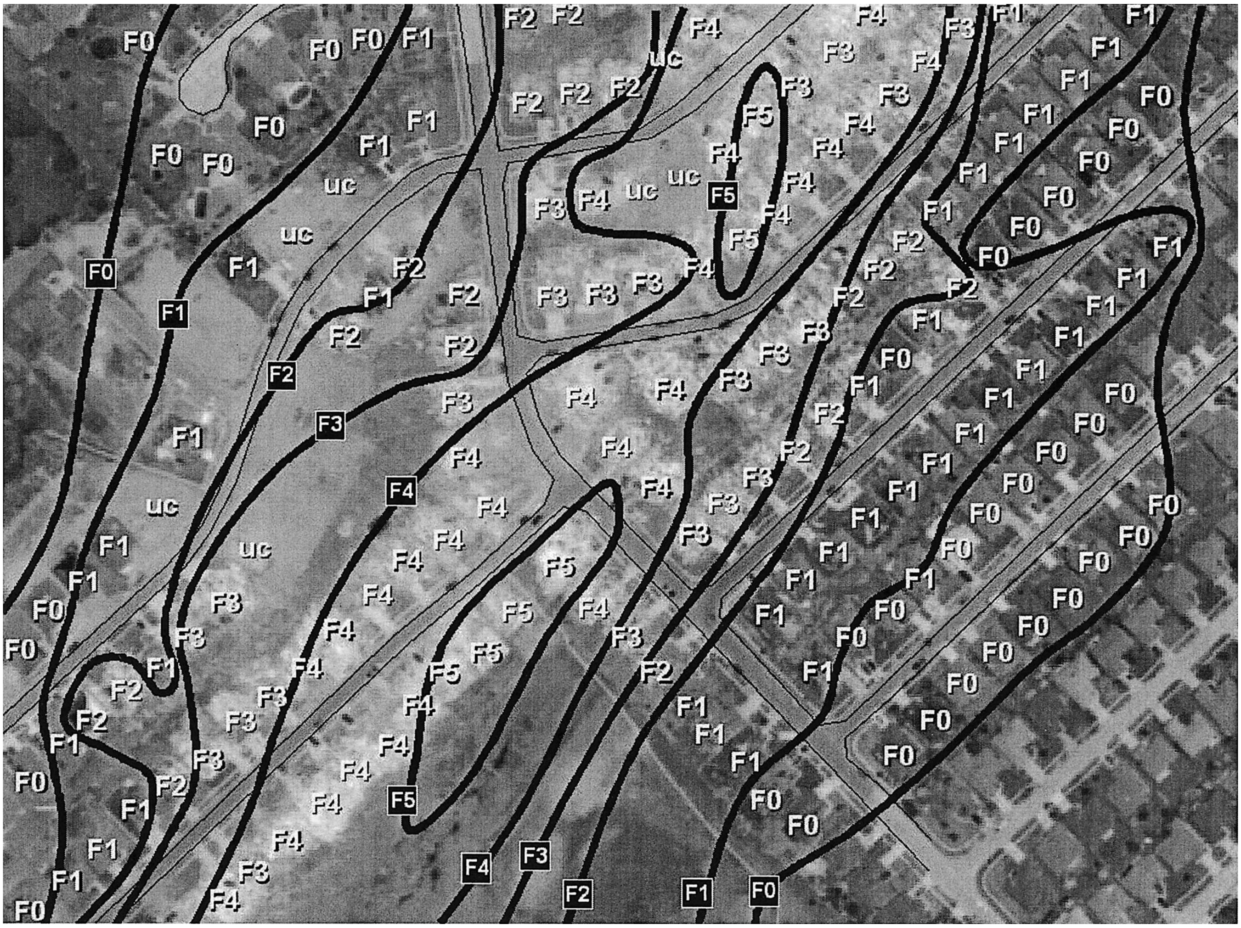

FIG. 11. Aerial photography of the Eastlake housing subdivision (inset B in Fig. 8). House-by-house F-scale ratings are indicated, and F-scale contours are overlaid. (Photography courtesy of the U.S. Air Force.)

serve as an example for future events. We recognize that not everyone has the same level of resources as was available in central Oklahoma for the 3 May 1999 event, so our recommendations for improving storm event analysis are presented in decreasing order of priority. That is, as resources permit, more and more of the following steps can be done. At the very least, regardless of resource shortages, meteorologists should replay any available radar data and compare the data with the real-time reports to try to match tornado beginning and ending times with radar signatures. Unless damage locations are known independently, radar can be used to correct locations if it is suspected that the spotter's location was given instead of the tornado location. Several iterations may be necessary in any of these steps to come to some kind of best conclusion about the events, given all the information available. Storm spotters and storm chasers, as well as any other eyewitnesses, should be interviewed, and the storm chasers' video and logs should be reviewed.

TABLE 3. The combined area of the five F-scale contour intervals for Fig. 8.

F-scale interval	Area (km^2)
F0/F1–F5	49.47
F2–F5	31.44
F3–F5	19.18
F4–F5	6.36
F5	0.87

The meteorologist should then survey the damage in the field (preferably using survey teams). It is highly recommended that the survey teams follow the guidelines for conducting windstorm damage surveys recommended in Bunting and Smith (1993). Going back for resurveys as new information becomes available is a desirable option. It is clear that, when resources permit, aerial surveys should be conducted; Civil Air Patrol, law enforcement, television stations, military sources, or private volunteers may be willing to do this without charge. Surveyors should try to document as wide an area as possible, to detect previously unreported events, and should use video and still imagery to record the event(s) observed from the air. Air surveys can be followed up with additional ground surveys. For the maximum level of detail, surveyors should obtain accurate neighborhood maps and do a house-by-house damage assessment.

At the time of this event, there was no ''fast-response'' team (or set of teams) formally funded and set up to conduct an organized and detailed scientific study. There still is no such team (or teams) as this is being written. Scientific surveys of major events were done in the 1970s and 1980s by a team led by T. Fujita, but no such team is now operating. Engineering surveys have been conducted by teams from Texas Tech University (among others) for several decades, but these are not the equivalent to a *scientific* study. The death of Dr. Fujita has left a large void in this regard, and our scientific community has yet to fill that void (McDonald 2001). The absence of a fast-response team was keenly felt during the aftermath of this event. Valuable information is being lost, along with the opportunities to learn new insights about how to forecast and handle these devastating tornado outbreaks. Depending on the specific meteorological and geographic circumstances associated with each outbreak, each major event can raise new issues and allow scientists to gain new insights. Without the resources to study these events with scientific rigor, each outbreak now represents lost opportunities.

Because the storms of 3 May 1999 happened to occur in a region that had a large concentration of severe-storm meteorologists, it was possible to recruit a large survey team at little or no cost. The voluntary contribution of so many technically educated and trained persons would simply not be possible in most parts of the nation. Minimal travel costs were involved, because of the proximity of the volunteers to the event. Such favorable circumstances are unlikely to be found for the next major tornado outbreak.

As we learn more about tornado outbreaks, it is obvious that we are seeing a growth in the *number* of reported tornadoes during such events. Comparable storm systems as recently as 20 years ago simply would not have been given the same level of scrutiny, in part because of the improvement in observational capability (as represented, for instance, by the WSR-88D radar network) and in part because of the growth of interest in storms and storm chasing in central Oklahoma. The proliferation of inexpensive consumer video equipment has meant that some sort of visual record is available for many events. This has the implication that our archive of tornado data is being affected by the changing ''landscape'' associated with the growth of knowledge about severe thunderstorms. In some sense, comparisons of recent events with those of the past are becoming increasingly difficult (Brooks and Doswell 2002).

Nevertheless, it seems obvious that we should be working as hard as possible to take advantage of any situation that can improve our ability to provide detailed documentation of major tornado events. Although it would be ideal to apply the same resources to every tornado event, it is obvious that we are unlikely ever to be able to do so. Therefore, when a major tornado event catches widespread attention, it behooves the scientific and engineering communities to use that situation to provide maximum documentation efforts, perhaps a handful of times each year (depending on what actually happens in any given year). Our hope is that our scientific and engineering communities can collaborate to find the means to document in detail at least these most noteworthy events every year.

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