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Verification and Analysis of Impact-Based Tornado Warnings in the Central Region of the National Weather Service

Holly B. Obermeier
University of Nebraska-Lincoln, holly.obermeier@huskers.unl.edu

VERIFICATION AND ANALYSIS OF IMPACT-BASED TORNADO WARNINGS IN THE CENTRAL REGION OF THE NATIONAL WEATHER SERVICE

by

Holly B. Obermeier

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Adviser: Mark R. Anderson

Tornado warnings are one of the most critical products issued by the National Weather Service (NWS), and favorable verification statistics are desirable. The 2011 NWS statistics for traditional tornado warnings indicate that the probability of detection (POD) is 70%, while the false alarm rate (FAR) is 76%. The recent Joplin, Missouri EF5 tornado event on 22 May 2011, which resulted in massive devastation and loss of life, prompted the NWS to re-evaluate the current tornado warning format. After the Joplin, MO event, the Central Region of the NWS implemented the impact-based tornado warning (IBTW) experiment in 2013. IBTWs consist of tiers including damage tags and impact wording which convey increasing levels of damage. The damage wording within an IBTW is shown to relate to the Enhanced Fujita (EF) Scale. Wording included in non-tagged IBTWs corresponds to EF0-EF2 tornado damage, while the damage wording for tagged IBTWs corresponds to EF3-EF5 tornado damage. This study investigates the accuracy of IBTWs by examining if a tornado occurs during the warning time frame, and whether the resulting damage matches the damage wording in the IBTW. All IBTWs from 1 April 2013 through 30 November 2013 are collected, as well as tornado survey information, including EF Scale intensity, for every tornado which occurred in the Central Region during the same time period. Using these survey data, IBTWs are

verified by the intensity of the tornado, if one occurs. POD and FAR statistics are calculated through 2x2 contingency tables for both non-tagged and tagged IBTWs. Results indicate that the majority of both non-tagged and tagged IBTWs are false alarms, and tagged IBTWs have a very low POD. Case studies of several events explore successful and unsuccessful implementation of damage tags, revealing that limitations in current technology and scientific knowledge may contribute to false alarms and missed detections. These findings suggest that more advances in technology and the understanding of tornadogenesis are necessary for more successful implementation of IBTWs.

ACKNOWLEGMENTS

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ACRONYMS

CASA …..………………………….. Collaborative Adaptive Sensing of the Atmosphere

DDC ……………………………………………………………….. Dodge City (KS)

DLH………………………………………………………………. Duluth (MN)

DMX ……………………………………………………………. Des Moines (IA)

DTX ………………………………………………………………. Detroit (MI)

FAR ……………………………………………………………… False alarm rate

FSD ……………………………………………………………... Sioux Falls (SD)

GID ……………………………………………………………….... Hastings (NE)

GJT ………………………………………………………… Grand Junction (CO)

IBTW……………………………………………………. Impact Based Tornado Warning

ICT ……………………………………………………………….. Wichita (KS)

ILX ………………………………………………………………... Lincoln (IL)

IND ……………………………………………………………... Indianapolis (IN)

IWX ……………………………………………………………….. North Webster (IN)

LOT ………………………………………………………………. Chicago (IL)

LSX ……………………………………………………………. St. Louis (MO)

NCDC ……………………………………………………….. National Climatic Data Center

NWS ………………………………………………………... National Weather Service

OAX ……………………………………………………………… Omaha (NE)

PAH ………………………………………………………………... Paducah (KY)

POD ……………………………………………………… Probability of detection

SAILS …………………………. Supplemental Adaptive Intra-Volume Low Level Scans

SPC …………………………………………………… Storm Prediction Center

TOP ………………………………………………………………. Topeka (KS)

WFO ……………………………………………………. Weather Forecast Office

CHAPTER ONE: INTRODUCTION

Recent events such as the Joplin, Missouri tornado on 22 May 2011, which killed 158 people, have prompted an effort to restructure the existing National Weather Service (NWS) tornado warning format. Before this event, no single tornado had resulted in more than 100 deaths since 1953 (NWS 2011). An NWS assessment (NWS 2011) conducted after this deadly tornado event determined that a majority of Joplin residents did not fully perceive the danger upon reception of the tornado warning, and therefore did not take protective action. To combat this behavior in the future, the report suggested the initiation of warnings which are more “impact-based rather than phenomenon-based” while “diminishing the perception of false alarms and their impacts on credibility” (NWS 2011 page iv). In addition, the assessment proposed a tornado warning structure consisting of tiers. Impact-based tornado warnings (IBTWs) were introduced in 2012 and are a tiered system of warnings which employ the use of tornado damage tags (Table 1.1), along with corresponding damage-related wording (NWS 2013a). Warning forecasters are to include damage tags in IBTWs as confidence in the occurrence of a tornado and damage increases. Three tiers of tags exist: non-tagged, considerable and catastrophic. The lowest, non-tagged tier does not include a damage tag. However, this tier of IBTWs still includes impact wording which conveys damage to mobile home structures, siding, roofs, windows and trees. The middle tier includes the considerable tag, as well as more elevated impact wording in regard to damage to mobile homes, single family homes, businesses and vehicles. The highest IBTW tier contains the

Table 1.1. The three IBTW tiers – no tag, considerable tag, and catastrophic tag. Each tier has corresponding impact wording.

IBTW Tier	Impact Wording
No Tag EF0 - EF2 Tornadoes	Mobile homes will be damaged or destroyed. Significant damage to roofs...windows and vehicles will occur. Flying debris will be deadly to people and animals. Extensive tree damage is likely.
Considerable Tag EF3 - EF5 Tornadoes	You are in a life threatening situation. Mobile homes will be destroyed. Considerable damage to homes...businesses and vehicles is likely and complete destruction is possible. Flying debris will be deadly to people and animals. Expect trees to be uprooted or snapped.
Catastrophic Tag EF4 - EF5 Tornadoes	You could be killed if not underground or in a tornado shelter. Complete destruction of neighborhoods...businesses and vehicles will occur. Flying debris will be deadly to people and animals.

catastrophic tag and impact wording which conveys complete destruction to most structures. IBTWs were initially used experimentally in 2012 by five forecast offices in the NWS Central Region. In 2013, the IBTW experiment was expanded to encompass the entire Central Region (Fig. 1.1). NWS regions are divided into smaller Weather Forecast Offices (WFOs), each of which is each responsible for issuing severe weather warnings, including IBTWs, for their geographic area. Each WFO has a three-letter identifier which, for the Central Region, are listed in the Acronyms section.

An intended outcome of the IBTW experiment is an evaluation of forecasters' ability to distinguish between high and low impact events (NWS 2013a). Although the NWS states that an IBTW is not meant to address tornado intensity, the tag and associated damage wording within an IBTW can become stronger with each tier. The different levels of damage wording are generally related to the Enhanced Fujita (EF) Scale. Ultimately, the inclusion of a damage tag in a warning should be reserved for very strong and violent tornadoes, capable of producing considerable or mass destruction. The tornado warning decision-making process is already very complex, and a number of factors must be considered by the warning forecaster when issuing a warning. Brotzge and Donner (2013) as well as Andra et al. (2002) address these factors, ranging from availability of storm spotter information and real-time weather information such as Doppler radar, to situational awareness and storm history, among others. The decision to include a tornado damage tag adds additional dimensions to this intricate process.

Tornado warnings are one of the most critically important products issued by the NWS. Since tornadoes pose such a great risk to human life and property, it is vital that

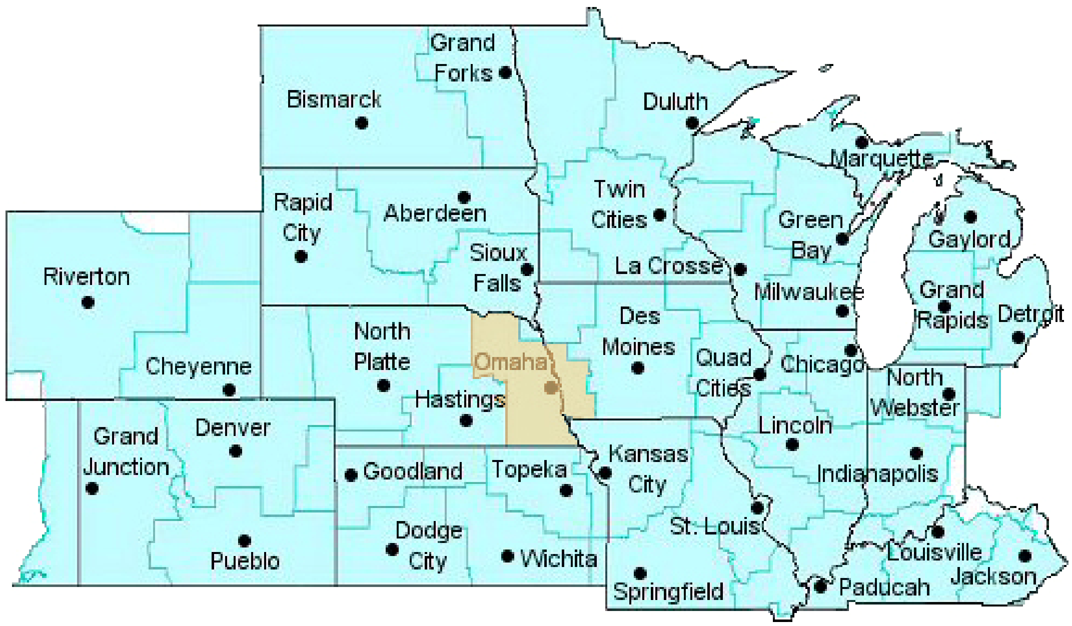


Figure 1.1. The 38 National Weather Service (NWS) Weather Forecast Offices (WFOs) which compose the Central Region. The Omaha, NE (OAX) WFO is shaded differently since it did not partake in the IBTW experiment in 2013 (image adapted from NWS 2014a).

IBTWs perform at an optimum, with high probability of detection (POD) and low false alarm rate (FAR). This study will investigate the accuracy of IBTWs through verification and calculation of POD and FAR. All the IBTWs issued in the Central Region from 1 April 2013 to 30 November 2013 are gathered, as well as damage surveys from each tornado which occurred in the Central Region during the same time period. Each IBTW is verified by tornado occurrence or lack of occurrence. If a tornado occurs, the strength, path length and duration are also recorded. Each IBTW is then compared to the tornado characteristics. Non-tagged IBTWs are verified by EF0-EF2 tornadoes, while tagged IBTWs are verified by EF3-EF5 tornadoes. Once verified, this study statistically analyzes the performance of IBTWs through calculation of POD and FAR. These statistics are performed through the use of 2x2 contingency tables (Table 1.2). Two 2x2 contingency tables are calculated, one for non-tagged IBTWs and one for tagged IBTWs. It is hypothesized that IBTWs will have similar POD and FAR as the current format of tornado warnings used by the NWS (traditional tornado warnings). Nationally, traditional tornado warnings have a FAR of 76% and a POD of 70% (NWS 2011). POD is even higher for traditional tornado warnings issued for tornado events of EF3-EF5 intensity (94%). Considering such a high POD for very strong and violent tornadoes, it is thought that considerable and catastrophic tagged IBTWs will have favorable statistics. This study will also explore when and where tags were most often issued across the Central Region, as well as how they were issued. To gain additional understanding of the IBTW process, specific tornado events are studied along with Weather Surveillance Radar (WSR)-88D Doppler radar data to determine what may contribute to the successful or unsuccessful use of IBTWs.

Table 1.2. A 2 x 2 contingency table used for forecast verification by calculating false alarm rate (FAR), probability of detection (POD), and success rate (SR) (Doswell et al. 1990).

		Observation		
		Yes	**No**	**Sum**
Forecast	**Yes**	*a*	*b*	*a+b*
	No	*c*	*d*	*c+d*
	Sum	*a+c*	*b+d*	

POD = a / (a+c)
FAR = b / (a+b)
SR = 1 - FAR

CHAPTER TWO: BACKGROUND

Verification statistics for traditional tornado warnings (Table 2.1) for the entire United States indicate a FAR of 76% (NWS 2011). This high ratio leads to concerns about a false alarm effect or a “cry wolf” syndrome, in which warnings are deemed less credible by the public. With this rate of over-warning, it has typically been thought that the public is desensitized and less likely to take action. Barnes et al. (2007) argues that false alarms are actually not detrimental, and the calculation of FAR does not take into account close calls which may not be perceived as a false alarm by the public. However, Simmons & Sutter (2009) indicate that high a FAR increases fatalities and injuries. The perception of tornado warning false alarms for many Joplin residents may have been high leading into the 22 May 2011 event (NWS 2011). From 2007 through early May 2011, 12 different tornado warnings (Fig. 2.1) were issued which included part or all of the city of Joplin (NIST 2014). Of these 12 warnings, only one verified with an actual tornado event, leading to a FAR of 92% (NIST 2014) before the 22 May 2011 event. The NWS Joplin Assessment (NWS 2011) notes that according to survivor interviews, a relationship between false alarms and warning response does exist, indicating that a reduction in FAR is likely desirable. Lowering FAR while still maintaining or increasing POD is difficult, considering the relationship between the two quantities. Less warnings could be issued in order to decrease FAR, however this would also lead to a decrease in POD (Brooks 2004). Three common factors typically lead to a false alarm (Brotzge et al. 2011):

Table 2.1. NWS tornado warning verification statistics from 1 October 2007 to 1 April 2011 for the United States (NWS 2011).

Event	**POD**	**FAR**
All Tornado	70%	76%
EF0-EF1	68%	NA
EF2-EF5	84%	NA
EF3-EF5	94%	NA

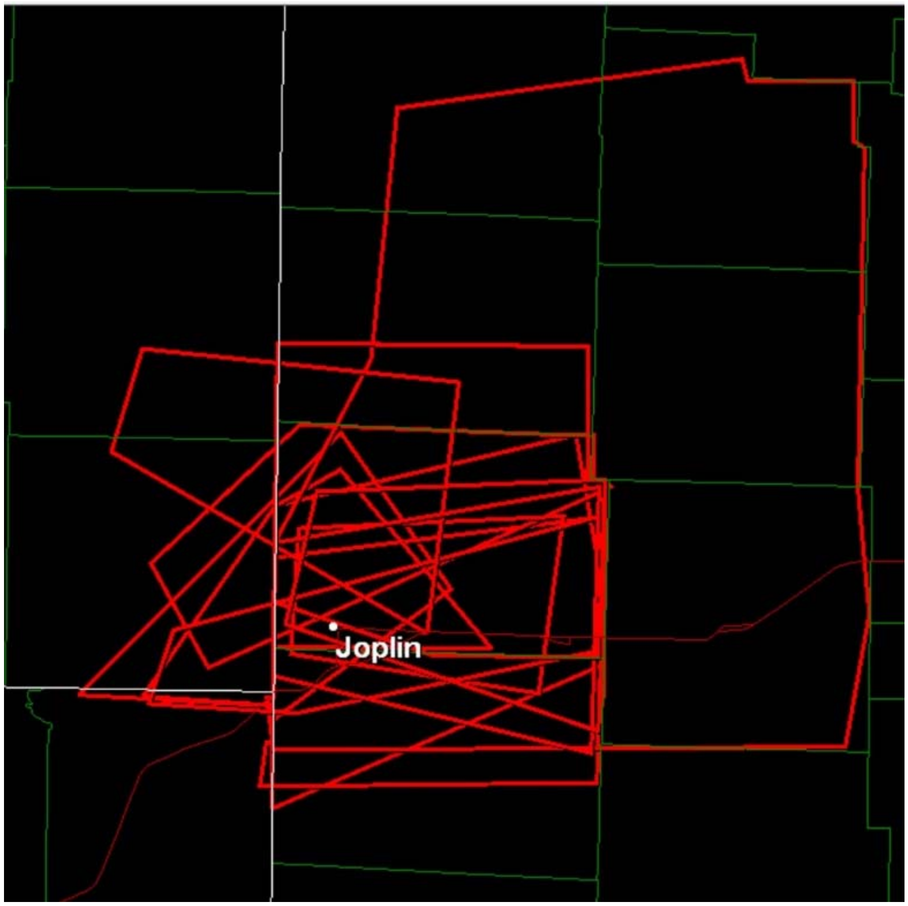


Figure 2.1. Twelve tornado warning polygons which included all or part of the city of Joplin, issued from 2007 through early May of 2011 (warnings polygons available from IEM 2014).

1. A confirmed, warned tornado is warned on for locations downstream. The tornado dissipates before it moves into the newly warned area.
2. Radar/spotters indicate that a storm environment is capable of producing a tornado. A warning is issued, yet a tornado never forms.
3. A warning is issued and a tornado forms, yet is never observed/does not cause any damage and is therefore never verified.

Perhaps an additional reason for false alarms is erroneous visual reports. Credible ground observations provide valuable information. When combined with radar evidence, these reports can play an instrumental role in the warning decision process (McCarthy 2002). However, reports which are deemed credible, yet are incorrect, could have the opposite effect.

To obtain more ideal statistics in both FAR and POD, advances in scientific knowledge and technology are necessary. The question of why some storms produce tornadoes and others do not has yet to be fully answered. Results from large field projects such as VORTEX (Verification of the Origin of Rotation in Thunderstorms Experiment) have contributed to improved guidance in the use of tornado warnings (Brooks 2004), however, more advancement is necessary. Better understanding of tornadogenesis and improvements in technology could lead to improved detection. Current statistics (Table 2.1) indicate that POD for traditional tornado warnings is 70% (NWS 2011). However, POD has been found to vary with tornado intensity. For tornado events of EF2-EF5 intensity, POD is 84% (NWS 2011). For tornado events of EF3-EF5 intensity, POD is 94%. Brotzge et al. (2013) indicates that weaker tornadoes of EF0-EF2 intensity have a lower POD of 72.5%. Convective mode also makes a difference; tornadoes which result from supercellular structures are much more likely to be warned

than those which form in quasi-linear convective systems (Brotzge et al. 2013). Brotzge et al. (2013) also found that POD for tornadoes within supercells (discrete, cluster, or supercells in lines) averages 85.4%, while POD for tornadoes within quasi-linear convective systems and disorganized storms averages 45.8%. As detailed above, POD improves with increasing tornado intensity (Brotzge et al. 2013, NWS 2011). POD also improves with increasing mesocyclone intensity, as well as closer range to a radar site. Certainly POD could be increased by issuing more warnings, however this would also lead an increase in FAR (Brooks 2004).

Doppler radar is the most critical tool for tornado detection available to warning forecasters at this time. With the nationwide installation of WSR-88D radars in the early 1990s, detection of local severe storms and tornadoes improved significantly (Polger et al. 1994, Simmons and Sutter 2005). Simmons and Sutter (2005) found that the percentage of detected tornadoes increased from 35% before the installation of WSR-88D radars to 60% in the years immediately after the installation. Not only has tornado detection improved, a 34% reduction in casualties has been noted (Simmons and Sutter 2005).

Situational awareness is also important for POD. The Storm Prediction Center issues convective outlooks which highlight regions in which severe weather is probable (Fig 2.2). There are three levels of severe risk which can be included; Slight, Moderate and High. The definitions of these risks areas are as follows (SPC 2014b):

1. Slight Risk. This category is used when forecasters expect well-organized severe thunderstorms, but in relatively small numbers and small coverage.

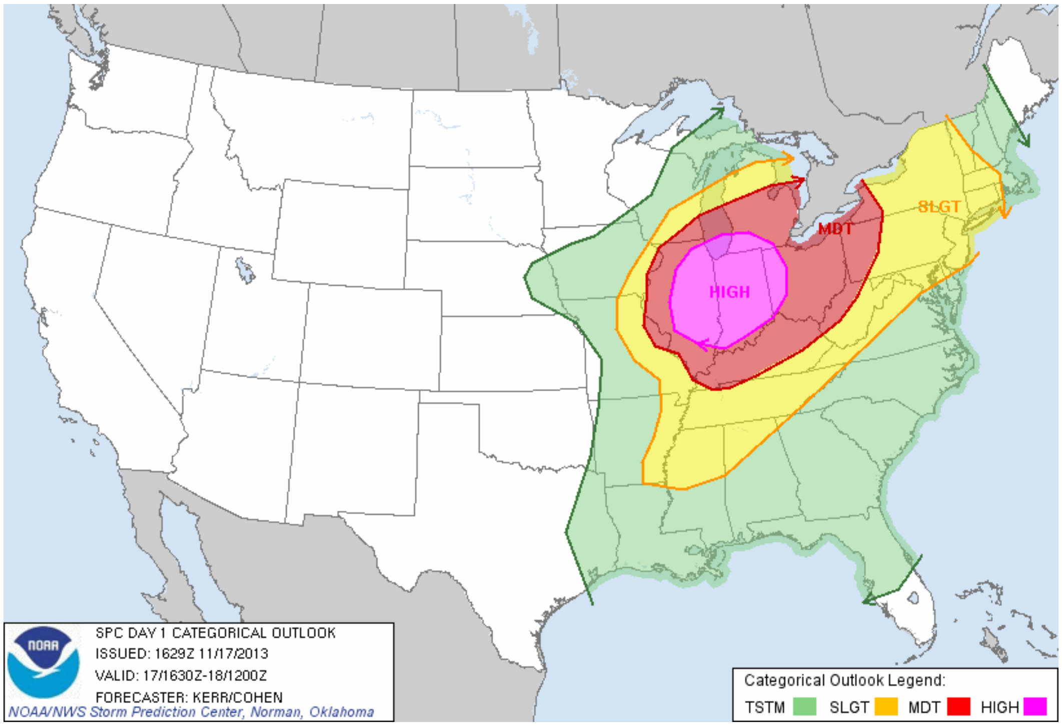


Figure 2.2. The SPC Day One Convective Outlook for 17 November 2013 (SPC 2013c).

2. Moderate Risk. This category is used when a greater concentration of severe thunderstorms are expected. The moderate risk is reserved for days with substantial severe storm coverage, of which some storms are expected to be tornadic supercells with large hail.

3. High Risk. This category is used when a major severe weather outbreak is expected, and there is a high likelihood of the most extreme severe weather events, such as violent tornadoes. The high risk is used most rarely.

The SPC Day One Convective Outlook can provide forecasters with important information before a major severe weather episode, and sets the level of awareness for warning operations throughout the remainder of the day.

The primary reasons for missed detections include incomplete conceptual models, partial knowledge of causes of tornado formation, inadequacies in existing technology, limited spotter networks (and therefore limited tornado reports) and data overload on the warning forecaster (Brotzge & Donner 2013). The near-surface processes which lead to tornadogenesis typically occur over short time scales, which could be missed between radar scans. Even the best mesonet networks are not dense enough to provide the temporal or spatial information about a storm's surface environment which may lead to rapid tornadogenesis. The 22 May 2011 Joplin, MO tornado formed and moved through the city so quickly that warning forecasters were initially unaware (NWS 2011). There was a tornado warning in effect 19 minutes before the tornado hit Joplin; however, due to the quick formation of the tornado, forecasters did not issue an updated SVS with a tornado emergency for the city.

IBTWs use elevated wording, including adjectives such as "considerable" or "complete" (in regard to tornado damage) in an attempt to allow warnings forecasters to

convey the seriousness of a situation. The IBTW experiment is not the first time that elevated wording has been used in NWS warnings and bulletins. A tornado emergency is one such example. Used within the context of a tornado warning, a tornado emergency is designed to alert a population that a violent tornado is imminent or occurring. The first tornado emergency was issued on 3 May 2003 for Moore, OK, as a major tornado outbreak was underway in central Oklahoma. Warning forecasters at the Norman, OK WFO decided to include wording such as “life-threatening” and “large devastating tornado” in many of the warning statements (McCarthy 2002). As it became increasingly clear that a catastrophic event was about to unfold in Moore, warnings forecasters at the Norman, OK WFO (many of whom had loved ones in the path of the tornado) decided to implement a tornado emergency (McCarthy 2002). These kinds of statements and elevated wording are now used more commonly across all of the NWS WFOs, especially after the Super Tuesday tornado outbreak on 5-6 February 2008. The NWS Super Tuesday Assessment (NWS 2009) found that warnings and statements during the outbreak did not make enough use of heightened wording, and that statements were unclear about whether tornadoes and damaged were confirmed. Several tornado emergencies were issued during this outbreak; however there was confusion about specific protocol for their use. The NWS subsequently defined guidance for tornado emergencies, indicating they are only to be used when all of the following criteria are met (NWS 2014b):

1. Severe threat to human life is imminent or ongoing,
2. Catastrophic damage is imminent or going, and

3. Reliable sources confirm the tornado (may be visual or ongoing).

Ideally, tornado emergencies would have a FAR of zero. Little to no peer-reviewed research about the verification of tornado emergencies exists. However, in a National Severe Weather Workshop presentation, the 83 tornado emergencies issued from 1999-2010 were examined more closely. When verified for a tornado of any strength, the FAR was comparatively low, at 29% (Marsh 2012). However, tornado emergencies are only meant to be issued in the event of imminent or ongoing catastrophic damage or severe threat to human life. When verified for catastrophic tornadoes (EF4-EF5), the FAR rose dramatically to 88%. In the IBTW experiment, a tornado emergency is to be issued in conjunction with a catastrophic damage tag. In addition to the catastrophic damage tag and impact wording, the tornado emergency wording for a specific geographic area would be included. The public reception of tornado emergencies is also little-studied, and the effects of tornado emergency false alarms are unknown.

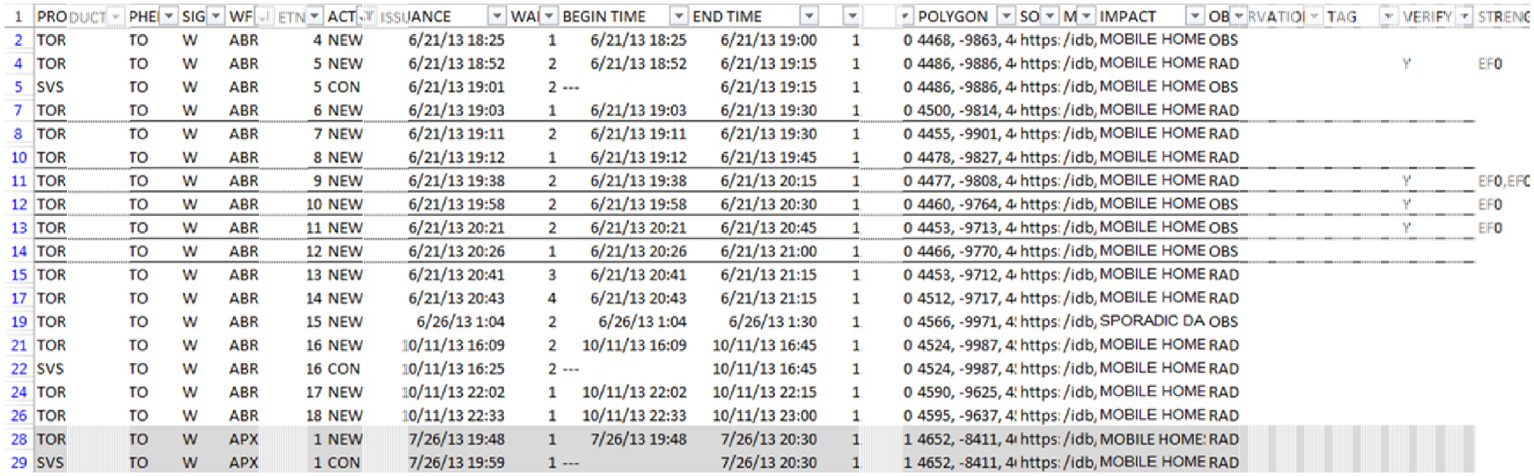
CHAPTER THREE: METHODOLOGY

The Central Region of the NWS encompasses 38 WFOs through much of the geographical central and northern Great Plains, as well as the Midwest and parts of the Great Lakes region (Fig. 1.1). Terrain and population density vary greatly throughout the region. Much of the Central Region is also considered to be part of the traditional Tornado Alley. The 2013 IBTW dataset used in this study was gathered from the NWS Performance Management website (NWS 2014c). This includes all IBTW statements (TORs) and subsequent IBTW severe weather statements (SVSs) issued in the Central Region from 1 April 2013 through 30 November 2013. An SVS is a continuance or update to the original TOR issuance. These updates often include the most recent information about whether a tornado is radar indicated or observed, and can include upgrades or downgrades in tornado damage tags. Typically an initial TOR and the following SVS(s) are grouped and verified as a single event. Yet, considering the upgrades or downgrades in damage tags that can occur, each TOR and SVS is verified individually in this study. Within the NWS dataset, it was discovered that a number of SVSs (some including damage tag upgrades/downgrades) were missing. Therefore the NWS data were supplemented with the IBTW dataset available from the Iowa State Mesonet (IEM 2014). Only SVSs which are continuances (CON) were kept; cancellation (CAN) and expiration (EXP) SVSs were eliminated. Also, the Omaha/Valley (OAX) WFO did not participate in the 2013 IBTW experiment, choosing not to issue tags in any tornado warnings. Therefore, data from OAX were not used in this study. Severe

thunderstorm warnings which occurred during this study were not collected or analyzed. Even though a severe thunderstorm warning can be verified by a tornado event, this study focuses on the use of IBTWs. Using a spreadsheet, each TOR and SVS was organized in tabular manner in which the data could be filtered through a number of criteria, including issuing WFO, event number, time of issuance, impact wording, radar indication versus visual observation, and damage tag (Fig 3.1). Once all TORs and SVSs are verified, they are filtered in order to fill contingency tables. A total of 1598 TORs and SVSs were issued during this study. Of the 1598 statements, 87 contained damage tags (approximately 5%).

The tornado dataset used for verification was gathered from the NWS Storm Data Publication, available from the National Climatic Data Center (NCDC 2014a). This information is also available from the NWS Performance Management website (NWS 2014c). The Storm Data Publication contains data about each tornado which occurred in Central Region, including Enhanced Fujita (EF) Scale intensity, path length, duration, and resulting damage (Fig. 3.2). All tornado data are county-based. This means if a tornado crossed a county (or state) line, it is counted as two tornado events in Storm Data. However, this does not matter when verifying IBTWs, since they are verified by the occurrence of a tornado.

The impact wording within an IBTW indicates the expected damage if a tornado occurs by mentioning specific structure types and increasing levels of damage to these structures. In this way, the warnings can be verified through the EF rating of the tornadoes which occur. The EF Scale (Table 3.1) is an intensity scale used to rate



1	PRODUCT	PHE	SIG	WF	ETN	ACT	ISSUANCE	WA	BEGIN TIME	END TIME			POLYGON	SO	M	IMPACT	OB	RVATIO	TAG	VERIFY	STRENG
2	TOR	TO	W	ABR	4	NEW	6/21/13 18:25	1	6/21/13 18:25	6/21/13 19:00	1	0	4468, -9863, 4	https:	/idb,	MOBILE HOME	OBS				
4	TOR	TO	W	ABR	5	NEW	6/21/13 18:52	2	6/21/13 18:52	6/21/13 19:15	1	0	4486, -9886, 4	https:	/idb,	MOBILE HOME	RAD			Y	EF0
5	SVS	TO	W	ABR	5	CON	6/21/13 19:01	2	---	6/21/13 19:15	1	0	4486, -9886, 4	https:	/idb,	MOBILE HOME	OBS				
7	TOR	TO	W	ABR	6	NEW	6/21/13 19:03	1	6/21/13 19:03	6/21/13 19:30	1	0	4500, -9814, 4	https:	/idb,	MOBILE HOME	RAD				
8	TOR	TO	W	ABR	7	NEW	6/21/13 19:11	2	6/21/13 19:11	6/21/13 19:30	1	0	4455, -9901, 4	https:	/idb,	MOBILE HOME	RAD				
10	TOR	TO	W	ABR	8	NEW	6/21/13 19:12	1	6/21/13 19:12	6/21/13 19:45	1	0	4478, -9827, 4	https:	/idb,	MOBILE HOME	RAD				
11	TOR	TO	W	ABR	9	NEW	6/21/13 19:38	2	6/21/13 19:38	6/21/13 20:15	1	0	4477, -9808, 4	https:	/idb,	MOBILE HOME	RAD			Y	EF0,EFC
12	TOR	TO	W	ABR	10	NEW	6/21/13 19:58	2	6/21/13 19:58	6/21/13 20:30	1	0	4460, -9764, 4	https:	/idb,	MOBILE HOME	OBS			Y	EF0
13	TOR	TO	W	ABR	11	NEW	6/21/13 20:21	2	6/21/13 20:21	6/21/13 20:45	1	0	4453, -9713, 4	https:	/idb,	MOBILE HOME	OBS			Y	EF0
14	TOR	TO	W	ABR	12	NEW	6/21/13 20:26	1	6/21/13 20:26	6/21/13 21:00	1	0	4466, -9770, 4	https:	/idb,	MOBILE HOME	OBS				
15	TOR	TO	W	ABR	13	NEW	6/21/13 20:41	3	6/21/13 20:41	6/21/13 21:15	1	0	4453, -9712, 4	https:	/idb,	MOBILE HOME	RAD				
17	TOR	TO	W	ABR	14	NEW	6/21/13 20:43	4	6/21/13 20:43	6/21/13 21:15	1	0	4512, -9717, 4	https:	/idb,	MOBILE HOME	RAD				
19	TOR	TO	W	ABR	15	NEW	6/26/13 1:04	2	6/26/13 1:04	6/26/13 1:30	1	0	4566, -9971, 4	https:	/idb,	SPORADIC DA	OBS				
21	TOR	TO	W	ABR	16	NEW	10/11/13 16:09	2	10/11/13 16:09	10/11/13 16:45	1	0	4524, -9987, 4	https:	/idb,	MOBILE HOME	RAD				
22	SVS	TO	W	ABR	16	CON	10/11/13 16:25	2	---	10/11/13 16:45	1	0	4524, -9987, 4	https:	/idb,	MOBILE HOME	RAD				
24	TOR	TO	W	ABR	17	NEW	10/11/13 22:02	1	10/11/13 22:02	10/11/13 22:15	1	0	4590, -9625, 4	https:	/idb,	MOBILE HOME	RAD				
26	TOR	TO	W	ABR	18	NEW	10/11/13 22:33	1	10/11/13 22:33	10/11/13 23:00	1	0	4595, -9637, 4	https:	/idb,	MOBILE HOME	RAD				
28	TOR	TO	W	APX	1	NEW	7/26/13 19:48	1	7/26/13 19:48	7/26/13 20:30	1	1	4652, -8411, 4	https:	/idb,	MOBILE HOME	RAD				
29	SVS	TO	W	APX	1	CON	7/26/13 19:59	1	---	7/26/13 20:30	1	1	4652, -8411, 4	https:	/idb,	MOBILE HOME	RAD				

Figure 3.1. An example of the organization method of the 2013 IBTW dataset. Data can be filtered by a number of different criteria.

SMITH COUNTY --- 2.6 N LEBANON [39.86, -98.54], 3.1 NE LEBANON [39.85, -98.50]

	05/27/13 18:04 CST		1.40M	Tornado (EF3, L: 2.18 mi , W: 1580 yd)
	05/27/13 18:10 CST	1	3M	Source: NWS Storm Survey

This tornado affected two counties in north central Kansas, touching down north of Lebanon in Smith County and lifting north of Esbon in Jewell County. The maximum wind speed was estimated to be near 140 MPH, with a maximum path width of 1580 yards. Along its path, this tornado caused minor to major tree damage, overturned irrigation pivots, snapped power poles and damaged or destroyed grain bins and outbuildings. Four homesteads suffered damage, with the hardest hit locations approximately 3 miles northeast of Lebanon in Smith County. Two homes in this area were heavily damaged or destroyed, with one losing its entire second level. This location also completely lost grain bins, a large outbuilding and newly constructed garage. One person suffered minor injuries and was treated and released from an area hospital.

Figure 3.2. An excerpt from the NCDC Storm Data Publication. Storm survey information and EF ranking data are used to verify IBTW.

Table 3.1. The Enhanced Fujita Scale (WSEC 2006) adopted by the National Weather Service in 2007.

Operational EF-Scale	
EF Number	Wind Speed m s^{-1} (mph)
0	29-38 (65-85)
1	30-49 (86-110)
2	49-60 (111-135)
3	60-74 (136-165)
4	75-89 (166-200)
5	> 89 (200)

tornadoes based upon the resulting damage (WSEC 2006), and was adopted by the NWS in 2007 as a replacement to the original Fujita Scale. By identifying different damage indicators (DI), the EF Scale assigns a wind speed according to the degree of damage (DOD) inflicted upon the DIs. DODs are numerical values which correspond to descriptions of the amount and type of damage, and to specific wind speeds and therefore tornado intensities. Since IBTWs predict tornado damage, tornado intensity will be used to verify each TOR and SVS. Specific DIs are mentioned in the three tiers of damage wording, as well as DOD. The damage wording in each IBTW tier will be examined, sentence by sentence, to identify these DI and DOD values. Once identified, each warning tier is assigned a most expected tornado intensity which must occur for the warning to verify. The lowest, or non-tagged tier, contains damage wording which generally corresponds to EF0-EF2 tornadoes. The DI and DOD values are identified in each sentence as follows:

Sentence 1: **Mobile homes will be heavily damaged or destroyed.**

In this sentence, mobile homes are the DI. “Heavily damaged or destroyed” describes the DOD. Since this sentence does not distinguish between single wide or double wide mobile homes, both will be considered. Table 3.2 describes the different DOD values which correspond to “heavily damaged or destroyed” for both kinds of mobile homes. “Heavy damage” in a single wide mobile home starts as low as DOD 4, in which the unit loses its roof. “Destruction” of a single wide occurs when the roof and walls are removed from the structure, which is described by DOD 6. The wind thresholds for a double wide mobile home are only slightly higher. “Heavy damage” could be described by DOD 6,

Table 3.2. Adapted from the EF Scale (WSEC 2006), most likely tornado ratings given "heavy damage or destruction" to a mobile home. Mobile homes typically sustain heavy damage from relatively weak tornadoes. DOD levels and corresponding wind speeds are directly from the EF-Scale. For full descriptions of each DOD level, see WSEC 2006.

Wind Speeds at Which Mobile Homes are "Heavily Damaged or Destroyed"				
Damage Indicator (DI)	**Degree of Damage (DOD)**	**Wind Speeds (Lower Bound-Upper Bound) m s^{-1} (mph)**	**Expected Wind Speed m s^{-1} (mph)**	**Mostly Likely Tornado Rating**
Single Wide	DOD 4	33-50 (73-112)	40 (89)	EF1
Single Wide	DOD 6	47-55 (105-123)	47 (105)	EF1
Single Wide	DOD 9	49-66 (110-148)	57 (127)	EF2
Double Wide	DOD 6	34-49 (77-110)	42 (93)	EF1
Double Wide	DOD 9	42-59 (93-131)	51 (113)	EF2
Double Wide	DOD 12	51-69 (113-154)	51 (113)	EF3

while DOD 9 describes the point at which the double wide mobile home is considered "destroyed". Using these DOD values, this damage would be achieved by an EF0 - EF2 tornado. It is also worth noting, the usage of the word "will" implies a sense of high confidence that the damage is certain to occur. The word "will" is used several times in regard to damage impacts in all tiers of IBTWs.

Sentence 2: **Significant damage to roofs, windows and vehicles will occur.**

Roofs and windows are the DIs within this sentence. Vehicles are not currently considered a DI in the EF scale. "Significant damage" describes the damage. The word "significant" is rather subjective and could be interpreted differently on an individual basis. For the purposes of this study, "significant" will be defined as it is used in the EF-scale. "Significant" roof damage describes a situation in which at least 20% of the roof is damaged. For most building structures, this damage is described by DOD values which would be the result of an EF0 to EF2 tornado, with EF1 strength winds most expected (Table 3.3). "Significant" window damage is described as windows which have been broken. Similar to roof damage, window damage is described by DOD values which are a result of EF0-EF2 strength winds, with EF1 strength most expected (Table 3.4).

Sentence 3: **Flying debris will be deadly to people and animals.**

This sentence could be true in any strength tornado, especially if persons or animals are caught outdoors.

Sentence 4: **Extensive tree damage is likely.**

Table 3.3. Adapted from the EF Scale (WSEC 2006), most likely tornado ratings given "significant" damage to roofs for a number of home and business structures. "Significant" damage begins when at least 20% of a roof is damaged (WSEC 2006). DOD levels and corresponding wind speeds are directly from the EF-Scale. For full descriptions of each DOD level, see WSEC 2006.

Wind Speeds at Which "Significant Damage" to Roofs Occurs				
Damage Indicator (DI)	**Degree of Damage Value (DOD)**	**Wind Speeds (Lower Bound-Upper Bound) m s^{-1} (mph)**	**Expected Wind Speed m s^{-1} (mph)**	**Mostly Likely Tornado Rating**
Single Family Home	4	36-52 (81-116)	43 (97)	EF1
Apartment	3	48-65 (107-146)	55 (124)	EF2
Motel	4	36-52 (80-116)	42 (95)	EF1
Small Retail Building	4	36-53 (81-119)	44 (98)	EF1
Small Professional Building	5	38-52 (84-117)	45 (100)	EF1
Large Shopping Mall	4	41-57 (92-128)	45 (108)	EF1
Elementary School	5	37-54 (82-121)	45 (101)	EF1
Low Rise Building	3	37-54 (83-120)	45 (101)	EF1

Table 3.4. Adapted from the EF Scale (WSEC 2006), mostly likely tornado ratings given "significant" damage to windows. DOD levels in this table correspond to the occurrence of broken windows. DOD levels and corresponding wind speeds are directly from the EF-Scale. For full descriptions of each DOD level, see WSEC 2006.

Winds Speeds at Which "Significant Damage" to Windows Occurs				
Damage Indicator (DI)	**Degree of Damage Value (DOD)**	**Wind Speeds (Lower Bound-Upper Bound) m s^{-1} (mph)**	**Expected Wind Speed m s^{-1} (mph)**	**Mostly Likely Tornado Rating**
Single Family Home	3	35-51 (79-114)	43 (97)	EF1
Apartment	Not Specified	n/a	n/a	n/a
Motel	3	35-48 (79-107)	40 (89)	EF1
Small Retail Building	3	32-46 (72-103)	46 (103)	EF1
Small Professional Building	3	33-48 (74-107)	39 (87)	EF1
Large Shopping Mall	3	34-51 (75-114)	41 (92)	EF1
Elementary School	3	32-47 (71-106)	39 (87)	EF1
Low Rise Building	4	37-55 (83-122)	45 (101)	EF1

Tree damage is not defined in terms of coverage or amount in the EF scale, yet rather in terms of specific damage to the trees (tree uprooted or snapped, snapped or lost branches). Large tree branches can be lost in winds as low as EF0 strength (Table 3.5). It is also interesting to note that many of the WFOs located in the Central Region cover geographic locations which may not feature trees as extensive vegetation, especially in the western half. In other words, extensive tree damage does not reflect a true impact of tornadoes in tree-less areas.

After examining each sentence in the impact wording for the first tier of IBTWs, the damage described generally represents the results of an EF0-EF2 tornado. TORs and SVSs without tags should be issued when EF0-EF2 tornado damage is expected to occur. If a tornado of this intensity occurs during such a TOR or SVS, then the TOR or SVS verifies. For tornadoes of greater intensity, tagged warnings should be issued. The second tier of IBTWs, including the considerable tag, should be included when tornado intensity is expected to increase to at least EF3. The middle, or considerable damage tier, contains damage wording which generally corresponds to EF3 tornadoes. The DIs and DOD values are identified in each sentence as follows:

Sentence 1: **You are in a life-threatening situation.**

Any strength tornado poses a threat to life; however, the likelihood of death is dependent on many factors. Ashley (2007) identifies some of these factors as time and date of event, geographical location, shelter type, and, importantly, tornado intensity. Past tornado deaths (dating from the years 1880-2005) largely have been due to EF2 or greater strength tornadoes, with the majority of deaths resulting from EF4 and EF5 tornadoes

Table 3.5. Adapted from the EF Scale (WSEC 2006), most likely tornado rating given damage to trees. Both soft and hard wood trees are typically damaged by weak tornadoes. DOD levels and corresponding wind speeds are directly from the EF-Scale. For full descriptions of each DOD level, see WSEC 2006.

Winds Speeds at Which Tree Damage Occurs				
Damage Indicator (DI)	**Degree of Damage (DOD)**	**Wind Speeds (Lower Bound-Upper Bound) m s^{-1} (mph)**	**Expected Wind Speed m s^{-1} (mph)**	**Mostly Likely Tornado Rating**
Soft Woods	2	28-39 (62-88)	34 (75)	EF0
Hard Woods	2	27-39 (61-88)	33 (74)	EF0

(Ashley 2007). Although this particular damage phrase does not apply to a specific DI or DOD value, it does imply an expectation that a higher intensity tornado will occur.

Sentence 2: **Mobile homes will be destroyed.**

Mobile homes are identified as the DI in this sentence. Unlike the first tier of IBTWs, "destroyed" is now the only DOD mentioned. The DOD values which correspond to "destroyed" begin at DOD 6 for a single wide mobile home and DOD 9 for a double wide mobile home. The use of the word "will" implies a strong certainty that at least this level of damage will occur. Total destruction of either type of mobile home, in which debris is swept away, occurs at DOD values 9 and 12 (Table 3.2). Assuming the mobile homes are relatively well-constructed, this type of damage is the result of a high-end EF2 or an EF3 tornado. Mobile homes do not particularly serve as a useful DI for identification of higher intensity tornadoes (although if the unit is completely swept away, the upper bound wind speeds would be indicative of an EF4 tornado).

Sentence 3: **Considerable damage to homes, businesses, and vehicles is likely...and complete destruction possible.**

Homes and businesses are the DIs. "Considerable damage likely" and "complete destruction possible" describe the level of damage. It is difficult to exactly define "considerable damage", due to the subjective nature of the phrase. For the purposes of this paper, "considerable damage" is defined to have occurred when a home or business begins to experience a loss of roof and perhaps exterior walls. Corresponding DOD values suggest this is typically a result of an EF3 tornado for most structures (Table 3.6).

Table 3.6. Adapted from the EF Scale (WSEC 2006), most likely tornado rating given "Considerable" damage to a number of damage indicators considered homes and business. DOD levels and corresponding wind speeds are directly from the EF-Scale. For full descriptions of each DOD level, see WSEC 2006.

Wind Speeds at Which "Considerable" Damage Occurs to Homes & Businesses				
Damage Indicator (DI)	**Degree of Damage Value (DOD)**	**Wind Speeds (Lower Bound-Upper Bound) m s^{-1} (mph)**	**Expected Wind Speed m s^{-1} (mph)**	**Mostly Likely Tornado Rating**
Single Family Home	7	51-68 (113-153)	59 (132)	EF2/EF3
Apartment	5	62-82 (138-184)	62 (138)	EF3
Motel	7	54-70 (121-156)	62 (138)	EF3
Small Retail Building	7	54-71 (120-159)	62 (138)	EF3
Large Isolated Retail Building	6	53-71 (118-158)	61 (137)	EF3
Small Professional Building	8	55-74 (123-165)	64 (144)	EF3
Large Shopping Mall	7	55-74 (124-166)	64 (144)	EF3
Elementary School	8	52-72 (117-162)	62 (139)	EF3
Low Rise Building	6	51-70 (114-157)	59 (133)	EF3

The “complete destruction possible” phrase means the considerable tag could apply to higher strength tornadoes. The word “complete” is key, since “complete” destruction describes the highest DOD values for any DI in the EF scale. In regard to the DIs in this example, this damage is the result of an EF4 or EF5 tornado (Table 3.7). The word "likely" implies a higher probability of considerable damage, while "possible" conveys lesser probability of complete destruction. This wording implies that EF3 damage is mostly likely to occur, however, the considerable tag could suffice in the event of more intense damage.

Sentence 4: **Expect trees to be uprooted or snapped.**

The EF scale is specific about the wind speeds necessary for trees to be uprooted or snapped. These winds speeds generally fall in the EF1 threshold, with upper bounds as high as EF2 (Table 3.8). The use of the word “expect” implies certainty, suggesting a higher intensity tornado that would undoubtedly destroy trees.

The impact wording in the second tier of IBTWs tends to represent the damage expected from an EF3 tornado, however, it could also apply to a higher intensity tornado. With this in mind, TORs and SVSs with considerable tags should be issued when EF3 tornado impacts are most expected to occur (although the considerable tag could suffice in the event of a greater intensity event). If an EF3 or greater tornado occurred during a considerable-tagged TOR or SVS, then the TOR or SVS would verify.

The third tier of IBTWs, including the catastrophic tag, should be used when violent tornado impacts are expected. The impact wording included along with the catastrophic tag correlates best to EF4-EF5 intensity. The DIs and DOD values

Table 3.7. Adapted from the EF Scale (WSEC 2006), most likely tornado rating given "Catastrophic" damage to a number of damage indicators considered homes and business. DOD levels and corresponding wind speeds are directly from the EF-Scale. For full descriptions of each DOD level, see WSEC 2006.

Wind Speeds at Which "Complete Destruction" Occurs to Homes & Businesses				
Damage Indicator (DI)	**Degree of Damage (DOD)**	**Wind Speeds (Lower Bound-Upper Bound) m s^{-1} (mph)**	**Expected Wind Speed m s^{-1} (mph)**	**Mostly Likely Tornado Rating**
Single Family Home	10	74-98 (165-220)	90 (200)	EF4
Apartment	6	69-92 (155-205)	80 (180)	EF4
Motel	10	73-97 (163-217)	85 (190)	EF4
Small Retail Building	8	64-86 (143-193)	75 (167)	EF4
Large Isolated Retail Building	7	66-90 (147-201)	77 (173)	EF4
Small Professional Building	9	66-89 (148-200)	70 (157)	EF3
Large Shopping Mall	9	79-110 (176-247)	91 (204)	EF5
Elementary School	10	68-90 (152-203)	79 (176)	EF4
Low Rise Building	7	72-99 (161-221)	84 (188)	EF4

Table 3.8. Adapted from the EF Scale (WSEC 2006), most likely tornado rating given trees are uprooted or snapped. DOD levels and corresponding wind speeds are directly from the EF-Scale. For full descriptions of each DOD level, see WSEC 2006.

Winds Speeds at Which Trees Are Uprooted or Snapped				
Damage Indicator (DI)	**Degree of Damage (DOD)**	**Wind Speeds (Lower Bound-Upper Bound) m s^{-1} (mph)**	**Expected Wind Speed m s^{-1} (mph)**	**Mostly Likely Tornado Rating**
Soft Woods	3 (Uprooted)	41-53 (91-118)	39 (87)	EF1
	4 (Snapped)	49-60 (110-134)	46 (104)	EF1
Hard Woods	3 (Uprooted)	39-51 (87-113)	41 (91)	EF1
	4 (Snapped)	46-57 (104-128)	49 (110)	EF1

are identified in each sentence as follows:

Sentence 1: **You could be killed if not underground or in a tornado shelter.**

This statement has similar implications as the first sentence under the considerable tag. Although this wording does not apply to a specific DI or DOD value, it does imply an expectation that a higher intensity tornado will occur. The use of the word "killed" adds a heightened sense of urgency, and this statement is ultimately meant to spur public action to protect life. Certainly the chances of survival in a violent tornado increase when sheltering underground or in a tornado shelter. However, Brooks et al. (2008) argues that even when violent tornadoes destroy residential areas, including homes which may be without basements or proper shelters, the death rate is estimated to be around 1%.

Sentence 2: **Complete destruction of neighborhoods, businesses and vehicles will occur.**

It is assumed that a neighborhood in this context describes an area comprised of single-family homes, apartment complexes and perhaps schools. These structures, as well as business structures, are the DI in this phrase. "Complete destruction" describes the DOD. As mentioned under the second tier of IBTWs, complete destruction is the result of an EF4 or EF5 tornado (Table 3.7). Again, the use of the word "will" implies that the damage is certain to occur.

Sentence 3: **Flying debris will be deadly to people and animals.**

This statement was used in the first tier of IBTWs, and is included again here. As stated before, this statement could be true in any strength tornado, especially if persons or animals are caught outdoors.

After considering the impact wording included with the catastrophic tag, this tier of IBTWs should only be used when EF4-EF5 intensity winds are expected to occur. Considering the rarity of EF4 and EF5 tornadoes, this tier should be used infrequently.

The method of verification in this study varies somewhat from past tornado warning verification studies. Before the launch of IBTWs, a tornado warning would verify depending on the occurrence of a tornado, regardless of the intensity. In this manner, verification is a relatively simple binary result. However, to correctly verify IBTWs, the strength of any tornado which occurs must be taken into account. For this study, the strength of the tornado will be assigned the EF ranking of the particular tornado. This results in positively-verified warnings, over-warnings and under-warnings. Both over-warnings and under-warnings are considered misses.

Consider a TOR or SVS which has been issued containing the first tier of damage wording (non-tagged). If an EF0-EF2 tornado occurs during the TOR or SVS, then the TOR or SVS verifies. If an EF3-EF5 occurs, then the TOR or SVS is considered an under-warning and does not verify. If no tornado occurs at all, the TOR or SVS is considered an over-warning and also does not verify. The only exception occurs if an EF0-EF2 tornado does not touch down during a TOR or SVS, yet touches down during a subsequent SVS within the same event number. In this case, any proceeding TOR or SVS(s) still verify. This way, lead time does not penalize the overall statistics of the

warning. This is true only if the subsequent SVS has not been upgraded to the second or third tier (a tag is added). If an upgrade occurs, any proceeding TOR or SVS(s) do not verify.

Now, consider a TOR or SVS containing a considerable or catastrophic tag, which would include the second or third tier of damage wording. If an EF3-EF5 tornado occurs during the TOR or SVS, then the TOR or SVS verifies. If an EF0-EF2 tornado occurs, then the TOR or SVS is considered an over-warning and does not verify. If no tornado occurs at all, the TOR or SVS is considered an over-warning and does not verify. Again, the exception occurs if an EF3-EF5 does not touch down during a TOR or SVS, yet touches down during a subsequent SVS in the same event number. In this case, the previous TOR or SVSs still verify. This is true only if the subsequent SVS has not been downgraded a tier. If a tag is removed, any proceeding TOR or SVS(s) do not verify.

To illustrate this method of verification, an IBTW issued for the Ottawa County, Kansas tornado on 28 May 2013 (Fig. 3.3) is more closely examined. Three IBTWs were in effect at different times during the life of the tornado. The second IBTW, which covers the majority of the tornado's lifespan, is the subject of focus in this example. The initial TOR for this IBTW and first SVS (issued at 2251 and 2258 UTC respectively), contained the first tier of damage wording. The second, third and fourth SVSs (issued at 2303, 2308, and 2320 UTC respectively) were all upgraded to the considerable damage tag, and contained the second tier of damage wording. Storm Data (NCDC 2014a) indicates that an EF3 tornado was on the ground from 2245 to 2345 UTC, for a total life time of 60 minutes. Under the guidelines described above, the initial TOR and first SVS,

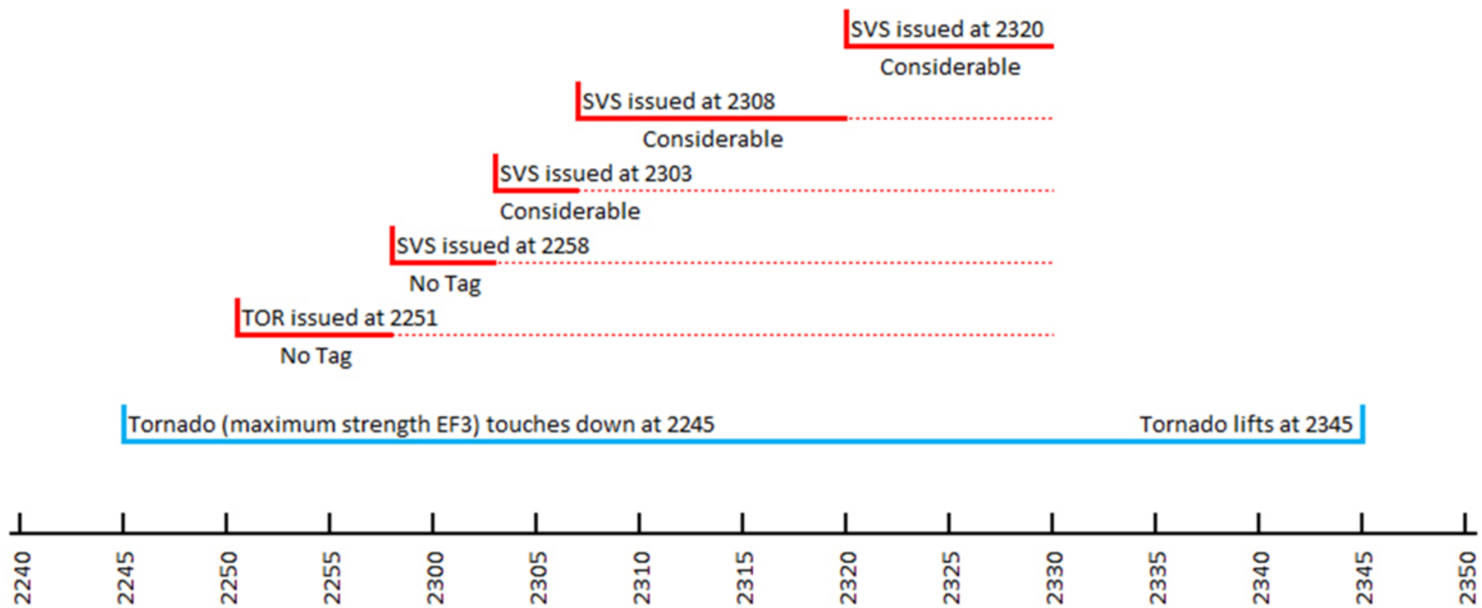


Figure 3.3. A timeline of the 28 May 2013 Ottawa County, KS tornado (blue line), along with a IBTW which covered the lifespan of the tornado. The IBTW is examined in detail, broken down into the TOR and SVS segments (bright red line).

which did not contain damage tags, are considered under-warnings and do not verify. The subsequent three SVSs, which contain considerable damage tags, verify. Each of the 1598 TORs and SVSs from the database are verified in this manner, and verification is documented within the spreadsheet. To account for all tornadoes which occurred in the Central Region during this study, each tornado was identified one-by-one in the Storm Data Publication. If no TOR was in effect or issued during the life of the tornado, the tornado is considered unwarned. All unwarned tornadoes and their intensities are documented, as this information is necessary for calculating POD.

Statistical information such as POD, FAR and success rate (SR) are calculated through 2x2 contingency tables (Table 1.2). Success rate is calculated by subtracting FAR from one (1-FAR = SR). Two separate contingency tables are calculated, one for non-tagged ITBWs and the other for tagged IBTWs. Considerable and catastrophic tags are grouped together since both are verified by EF3-EF5 tornadoes. Also, a low number of catastrophic tags are expected and an additional contingency table for these tags may not lead to relevant statistics. Table 3.9 describes the contingency table for non-tagged TORs or SVSs, while Table 3.10 describes the contingency table for tagged TORs or SVSs. It is important to note that the FAR definition is somewhat non-traditional in this study. FAR consists of both over-warnings and under-warnings when calculated for non-tagged TORs and SVSs. FAR consists of only under-warnings when calculated for tagged TORs and SVSs. In other terms, a tornado can occur during an IBTW, yet still

Table 3.9. Method for calculation of a 2 x 2 contingency for non-tagged IBTWs. Each category (a,b,c) represents the total of IBTWs which fall under the specified criteria, listed below the table. Category **c** also contains unwarned EF0, EF1, and EF2 events.

2 x 2 Contingency Table (Non-Tagged IBTWs)

		Observation		
		Yes	**No**	**Sum**
Forecast	**Yes**	*a*	*b*	*a+b*
	No	*c*	*d*	*c+d*
	Sum	*a+c*	*b+d*	

a = No tag is included in the TOR or SVS, and an EF0, EF1, or EF2 tornado does occur.
b = No tag is included and no tornado occurs, or an EF3, EF4, or EF5 tornado occurs
c = No TOR is issued, or a TOR or SVS is issued and a considerable or catastrophic tag is included, and an EF0, EF1, or EF2 tornado occurs
d = Not available

Table 3.10. Method for calculation of a 2 x 2 contingency for non-tagged IBTWs. Each category (**a,b,c**) represents the total of IBTW TORs or SVSs which fall under the specified criteria, listed below the table. Category **c** also includes unwarned EF3, EF4, or EF5 tornado events.

2 x 2 Contingency Table (Tagged IBTWs)

		Observation		
Forecast		**Yes**	**No**	**Sum**
	Yes	*a*	*b*	*a+b*
	No	*c*	*d*	*c+d*
	Sum	*a+c*	*b+d*	

a = A considerable or catastrophic tag is included in a TOR or SVS, and EF3, EF4, or EF5 tornado does occur
b = A considerable or catastrophic tag is included in a TOR or SVS, and no tornado occurs, or an EF0, EF1, or EF2 occurs
c = No TOR is issued or a TOR or SVS is issued without a considerable or catastrophic tag, and EF3, EF4 or EF5 occurs
d = Not available

not verify the IBTW if it is not within the specific intensity threshold. In this way, an IBTW can still be considered a false alarm if a weaker or stronger tornado occurs than what is expected.

Once verification is complete, several individual events are analyzed more closely through construction of event timelines and maps, as well as analysis of radar imagery. All radar data comes from the NWS network of WSR-88Ds. The data are available from NCDC (NCDC 2014b), and are examined using GR2 Analyst software. In addition, SPC Day One convective outlooks on the days of the different case studies are collected (SPC 2014a). These convective outlooks provide more information about the severe weather potential for the day and provide insight about situational awareness. IBTW polygons used in construction of maps are collected from the Iowa Environmental Mesonet (IEM 2014). More in-depth exploration into these case studies may provide additional understanding about when and how damage tags were used.

CHAPTER FOUR: RESULTS

The IBTW dataset for the dates of 1 April 2013 through 30 November 2013 totaled 702 TORs and 896 SVSs, for a total of 1598 statements issued by the NWS Central Region. The majority of TORs and related SVSs were issued during the spring months, however, 2013 also featured a robust autumn severe weather season (Fig. 4.1). Of the 1598 TORs and SVSs issued during this study, 84 contained the considerable tag and three contained the catastrophic tag. These 87 tagged TORs/SVSs account for approximately 5% of the total. Two autumn tornado outbreaks (4-5 October 2013 and 17 November 2013) resulted in the issuance of 74% of the tags during this study. The remaining 26% of the tags were issued during the months of May, June and August. There were eight different dates on which tags were issued (Fig. 4.2). On these eight days, an EF3 or greater intensity tornado occurred, although a tagged warning did not always correspond to the EF3 tornado. The SPC Day One convective outlook included a slight risk on four of the eight days, a moderate risk on three of the eight days, and a high risk on one of the eight days (Fig. 4.2). The high risk day corresponds to the tornado outbreak over the Midwest on 17 Nov 2013; when the greatest one-day total of tags occurred. There was only one day (12 June 2013) on which an EF3 or greater intensity tornado occurred in the Central Region, and no tagged warning was issued. Perhaps elevated situational awareness is an important factor in determining the potential use of IBTWs.

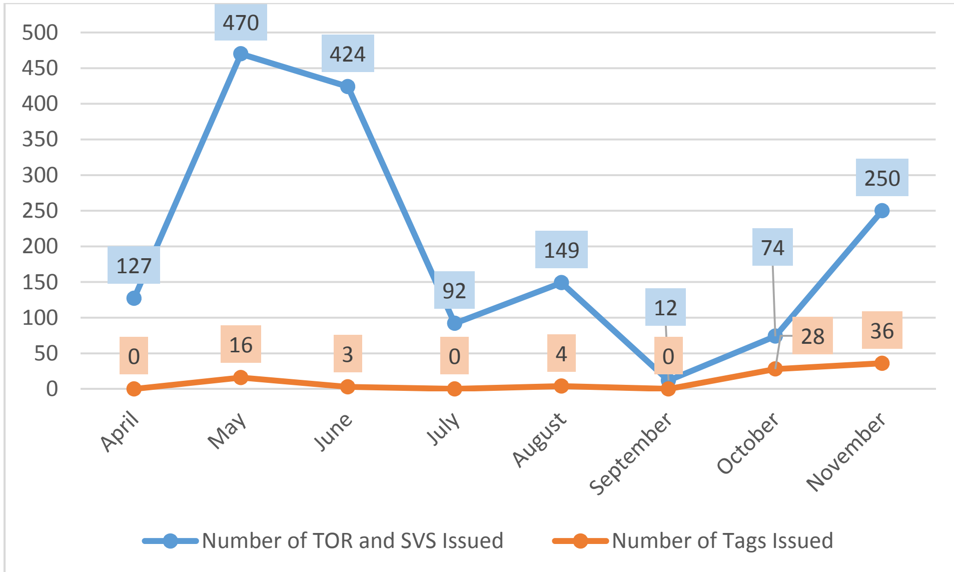


Figure 4.1. Total TOR and SVS (blue) and total tags, both considerable and catastrophic, (orange) for each month during the study.

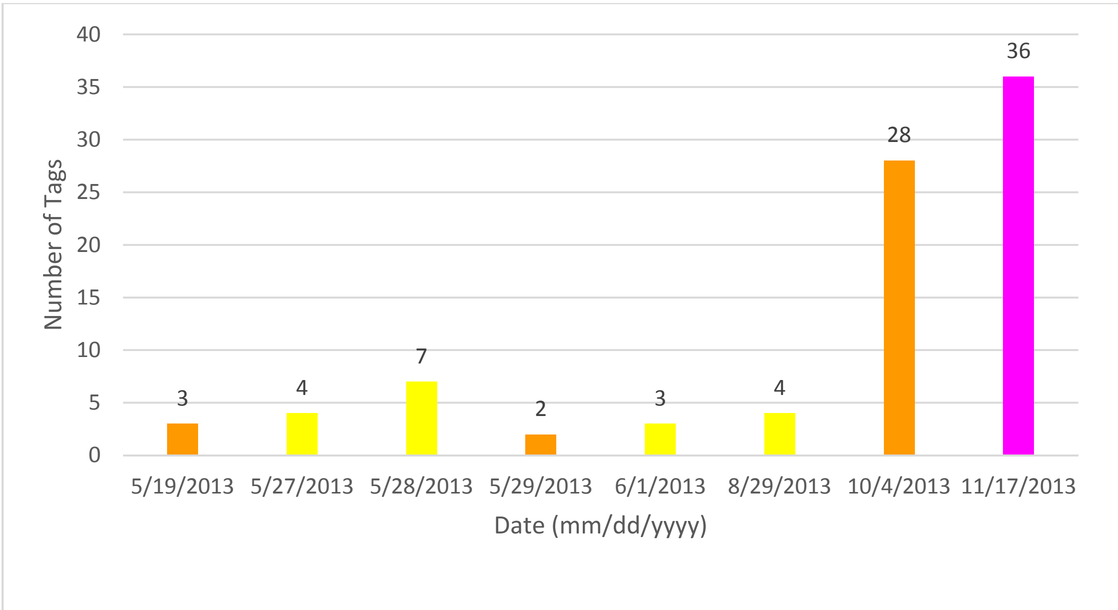


Figure 4.2. Dates on which tags were issued (dates are defined as 12 UTC – 12 UTC), and the total number of tags issued. The color of the bar corresponds to the SPC Day One Convective Outlook; yellow = slight, orange = moderate, pink = high.

Every participating office in the Central Region issued at least one IBTW during this study, with the exception of the Grand Junction (GJT) WFO. Of the 37 offices which issued tornado warnings, 11 issued at least one TOR/SVS which included a tag (Fig. 4.3). Again, data from OAX were not included in the results of this study. Out of the Central Region WFOs, the Paducah (PAH) and Sioux Falls (FSD) WFOs issued the majority of the tags, for a combined 50 out of 87 (59.5%). All tags issued by the FSD WFO occurred during the large tornado outbreak on 4-5 October 2013 in northeastern Nebraska, southeastern South Dakota and western Iowa on 4-5 Oct 2013. The PAH office issued all tags during the 17 November 2013 tornado outbreak. EF3-EF4 tornadoes occurred during this study in the coverage areas of 3 WFOs which did not issue tags at all (Des Moines (DMX), Dodge City (DDC) and North Webster (IWX), remembering that OAX opted not to issue tags in 2013). No EF5 occurred in the Central Region in 2013.

Tags were generally issued in an SVS and not in the initial TOR (Fig. 4.4). This is perhaps because additional information became available after the initial TOR which enabled the warning forecaster to become confident enough to issue a tag. Detection of a tornado through reports of damage or visual observation after the initial TOR could prompt a tag in an SVS. Of the 22 tags issued in TOR statements, 7 verified for the occurrence of an EF3-EF5 tornado, a 32% success rate (Table 4.1). Interestingly, tags issued in an SVS statement verified less often, with a 25% success rate. When analyzed in combination, the majority of tags were issued in SVS statements with visual observation of a tornado (Fig. 4.5). A smaller number of tags were included in SVS statements with radar indication of a tornado.

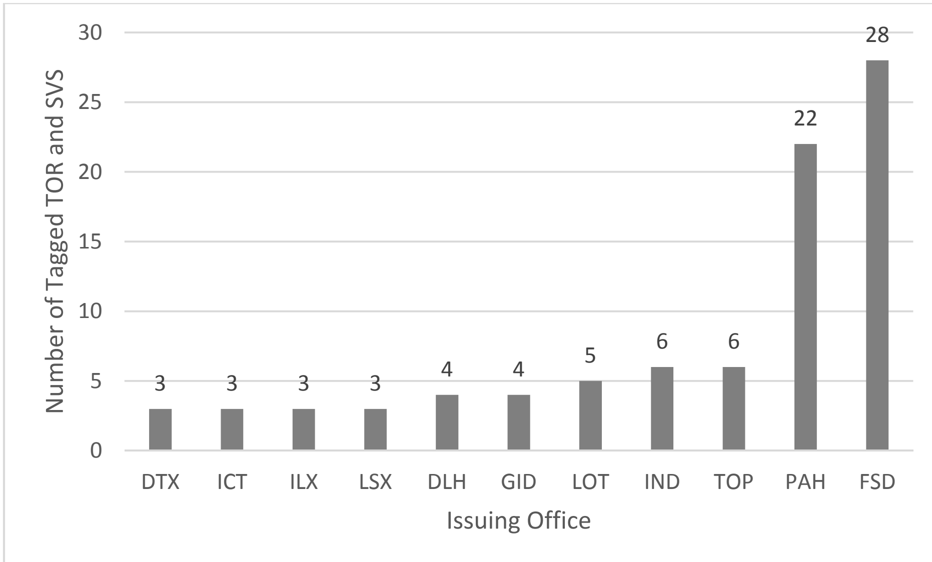


Figure 4.3. NWS Weather Forecast Offices (WFOs) which issued tags during this study, and the number of tags issued.

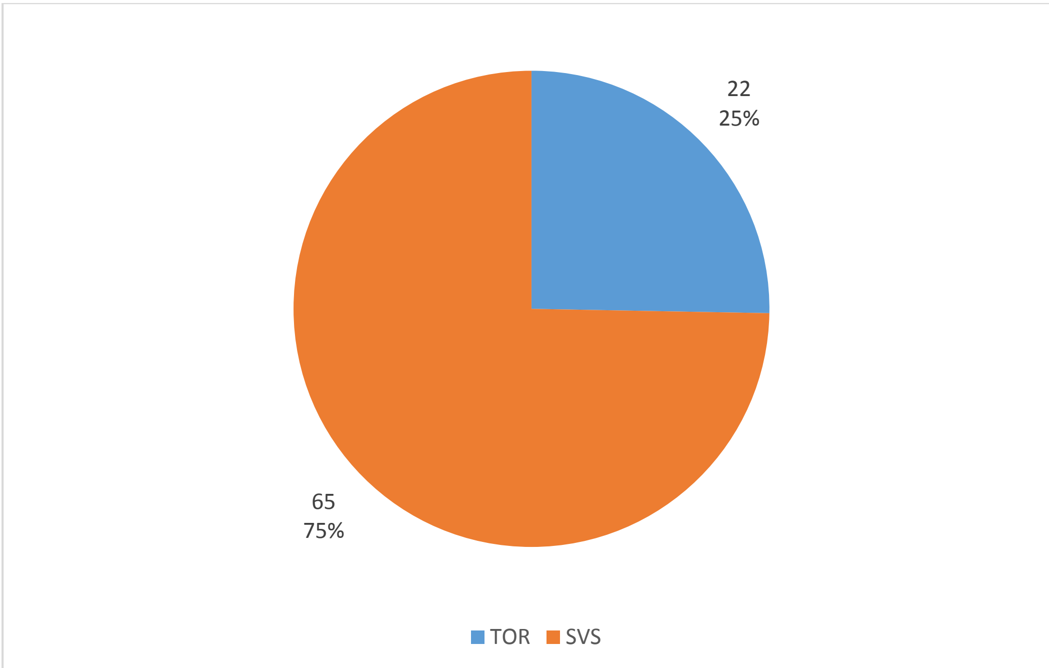


Figure 4.4. The number of tags issued in a TOR versus an SVS.

Table 4.1. The number of considerable or catastrophic tags issued in an IBTW TOR or SVS statement, along with the success rate for the tags according to the statement type (which are verified by the occurrence of an EF3-EF5 tornado).

IBTW Statement	Considerable	Catastrophic	Total	Percent of Total	Verify for EF3-EF5 Tornado	Success Rate
TOR	22	0	22	25%	7	32%
SVS	62	3	65	75%	16	25%
Total	84	3	87	100%	23	26%

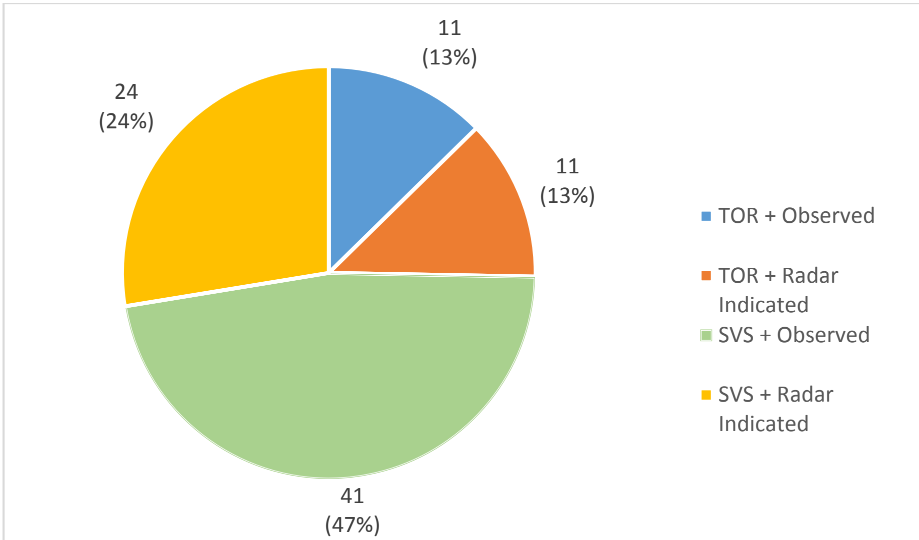


Figure 4.5. The number of tags which were included in the combinations of TOR and observed tornado, TOR and radar-indicated tornado, SVS and observed tornado, and SVS and radar indicated tornado.

Tornado segments which occur during a tagged IBTW during this study have a longer average duration and path length when compared to tornado segments which occur during a non-tagged IBTW. The average lifespan of a tornado segment which was covered by a tagged warning was 10.66 minutes, and the average path length was 9.4 km (5.82 mi). The average lifespan of a tornado which covered by a non-tagged warning was 6.56 minutes, and the average path length was 6.0 km (3.74 mi). This difference likely represents why tags were most often issued in an SVS. Also, tags were most often used when a tornado was observed, rather than radar indicated (Fig. 4.6). This result seems logical, considering the report of a confirmed tornado likely increases confidence for issuing a tag. However, tornado-observed tagged TORs/SVSs verified slightly less often than radar-indicated tagged TORs/SVSs (Table 4.2). This suggests that the tornadic evidence (observation versus radar-indicated) by which a tag is issued does not necessarily facilitate the ability to distinguish tornado intensity, or whether the tornado will continue at the status at which it was reported. Tornado observation reports come from a variety of different sources, ranging from the public, to law enforcement, to trained weather spotters. Some of these sources are deemed more credible than others, however, even reliable reports of a tornado did not always result in tagged IBTWs which verified. In some cases, this was perhaps due to erroneous reports; other times the tornado dissipated before causing any damage. Sometimes, a tornado occurred, but was weaker than anticipated. The variability in reliability of observation reports must be difficult for warning forecasters who rely on the best available information to make judgments about whether to issue a tag. For example, a considerable-tagged TOR issued by GID at 2143 UTC 29 May 2013 indicated a tornado was observed by law enforcement

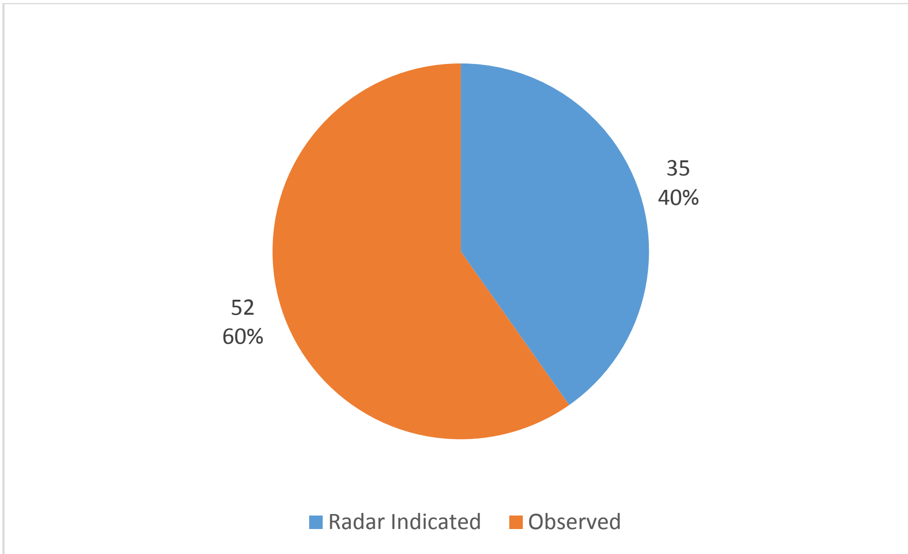


Figure 4.6. The number of tags issued in a TOR or SVS in which a tornado was visually observed versus radar-indicated.

Table 4.2. The number of considerable or catastrophic tags issued in an IBTW for which the tornado status was radar-indicates or observed, along with the success rate for the tags according to the tornado status (which are verified by the occurrence of an EF3-EF5 tornado).

Tornado Status	Considerable Tag	Catastrophic Tag	Total Tags	Percent of Total	Verify for EF3-EF5 Tornado	Success Rate
Radar-Indicated	35	0	35	40%	10	29%
Observed	49	3	52	60%	13	25%
Total	84	3	87	100%	23	26%

within two miles of a small township. This tornado had a history of destroying an outbuilding and causing tree damage prior to this particular TOR issuance. The inclusion of a tag means at least EF3 impacts would be expected, however, no damage was reported and the warning did not verify. The storm survey indicates the tornado had lifted at 2129 UTC, well before the tagged TOR was issued. The two SVSs which followed the initial TOR were radar indicated and were not tagged, and also did not verify as the storm was no longer tornadic. This example illustrates some of the difficulty involved with the warning decision process, and the additional step of deciding whether or not to include a tag.

Initially, IBTWs in this study were verified in the same manner as traditional tornado warnings. Using this method, a TOR and the following SVS(s) were grouped and verified as a single event. Each IBTW was verified by the occurrence of a tornado, regardless of tornado intensity or IBTW tags. This method yielded statistics by which to compare to the national averages. For the Central Region during this study, FAR is found to be nearly 70%, which is about 6% lower than the national average (Table 4.3). POD is 62%, about 8% lower than the national average. POD is also calculated with regard to tornado intensity (Table 4.4). Similar to the national statistics, POD increases with increasing tornado strength. In fact, no EF3 or EF4 tornado occurred without warning in the Central Region during this study, leading to a POD of 100% for tornadoes of EF3 or greater intensity.

Further statistical analysis through contingency tables reveals additional information about the performance of non-tagged and tagged IBTWs (Tables 4.5 and 4.6). Past

Table 4.3. Contingency table for IBTWs using the traditional method.

Forecast	Observation			
		Yes	No	Sum
	Yes	*212*	*490*	*702*
	No	*129*		*129*
	Sum	*341*	*490*	*831*

POD = 62.2%
FAR = 69.8%
SR = 30.2%

Table 4.4. Central Region verification statistics from 1 April 2013 to 30 November 2013, found using the traditional method.

Event	**POD**	**FAR**
All Tornado	62%	70%
EF0-EF1	55%	NA
EF2-EF5	92%	NA
EF3-EF5	100%	NA

Table 4.5. Contingency table for non-tagged IBW.

Forecast	Observation: Yes	No	Sum
Yes	*283*	*1264*	*1547*
No	*163*	*n/a*	*163*
Sum	*446*	*1264*	*1710*

POD = 63.5%
FAR = 81.7%
SR = 18.3%

Table 4.6. Contingency table for tagged IBW.

Forecast	Observation		
	Yes	**No**	**Sum**
Yes	*23*	*64*	*87*
No	*36*	*n/a*	*36*
Sum	*59*	*64*	*123*

POD = 39.0%
FAR =73.6%
SR = 26.4%

statistical analysis for traditional NWS tornado warnings indicates that POD for EF0-EF1 tornadoes is 68%, while POD for EF3-EF5 tornadoes is 94% (NWS 2011). This increase in POD with increasing tornado intensity is important, because it indicates that EF3-EF5 tornadoes are well-warned. Considering the traditional POD for EF3-EF5 tornadoes is higher than the traditional POD for weaker tornadoes, it might be expected that the POD concerning tagged TORs/SVSs would be higher than non-tagged TORs/SVSs. However, POD statistics for both non-tagged and tagged TORs/SVSs are lower than the traditional numbers, and POD for tagged TORs/SVSs is much lower than POD for non-tagged TORs/SVSs. Non-tagged TORs/SVSs (corresponding to EF0-EF2 tornadoes) have a POD of 64%, while tagged TORs/SVSs (corresponding to EF3-EF5 tornadoes) have a POD of 39%.

There were 129 unwarned EF0-EF2 tornado events during this study. In addition, there were 32 over-warned TORs/SVSs in which an EF0-EF2 tornado occurred, meaning a tag was issued when it was not warranted. There were 36 under-warned TORs/SVSs in which an EF3-EF4 tornado occurred (no EF5 tornado occurred in the Central Region during this study), and no considerable or catastrophic tag was included. The reason behind these low POD statistics is likely complicated. Despite the fact that all EF3-EF4 tornadoes in the Central Region were warned during this study, it appears that forecasters did not have the needed information to issue tags in these warnings. On the other hand, tags were issued for tornadoes which were less than EF3 intensity on several occasions. This might suggest the ability of a warning forecaster to distinguish a weak tornado from a violent tornado as it occurs is precluded by the lack of necessary operational data and/or

accurate observational reports in regard to ongoing damage. Further speculation suggests that perhaps warning forecaster hesitance to use a tag may also contribute to low POD. Since tagged warnings are a new product, it is also possible warning forecasters may not be utilizing them. Ultimately, a definite explanation for low POD in regard to tagged warnings would require much more in-depth study and is beyond the scope of this paper.

As discussed earlier, the FAR for tornado warnings is around 76% (NWS 2011). In the case of IBTWs, FAR values are slightly lower for tagged TORs/SVSs and higher for non-tagged TORs/SVSs. Non-tagged TORs/SVSs have a FAR of 82%, which is 6% higher than the traditional FAR. The total number of false alarms in the non-tagged IBTW category is almost entirely comprised of TORs/SVSs in which no EF0-EF2 tornado event occurs at all (over-warnings). The rest of the false alarms account for non-tagged TORs/SVSs during which EF3-EF4 tornado events occurred (under-warnings).

Tagged IBTW TORs/SVSs have a FAR of 74%, which is slightly lower than the traditional tornado warning FAR. All false alarms were over-warned events in which no tornado occurred, or a tornado weaker than EF3 occurred. A tornado of any strength occurred during 60 of the 87 tagged TOR or SVS (69%). If the tags were verified by the occurrence of a tornado regardless of intensity, the FAR would be 31%. This number suggests that tagged TORs/SVSs are most often issued when there is substantial evidence that a tornado will occur/is occurring, although not necessarily because the forecaster can successfully distinguish intensity from this evidence. The fact that tornadoes are often occurring during tagged TORs/SVSs is encouraging, because it indicates the warning forecaster's ability to realize situations in which a tornado is likely. However, there

seems to be less ability to distinguish whether a very strong or violent tornado is likely or occurring.

More careful analysis of individual tornado events shows the varied ways in which tags were, or were not, used during this study. A successful use of damage tags occurred on 17 November 2013 in two IBTWs issued for a supercell in southeastern Missouri (Fig. 4.7). While portions of the Midwestern states were under a high risk as delineated by the SPC, the area of interest in this example was under slight and moderate risks. In the 1630 UTC Day One convective outlook, the text describes an environment suitable for severe storms, and notes “clockwise curved low-level hodographs will also be conducive to the potential for strong tornadoes…some of which could be relatively long-lived/long-track” (SPC 2013a). The storm of interest was located approximately 93 km west of the PAH WSR-88D radar site (Fig 4.8), and was quickly traveling east at 29 m s^{-1}(57 kts). Warning forecasters issued a TOR at 1850 UTC, including a considerable damage tag (Fig. 4.9). This was not the first IBTW issued on this particular storm that day, however, the storm had not yet produced a tornado. At 1856 UTC, Doppler radar indicated a broad area of rotation within the storm (Fig. 4.8). All Doppler radar data in this example are analyzed at the 0.5° elevation angle. Several Doppler radar radial velocity bins indicated inbound velocities of over 36 m s^{-1} (70 kts) on the southern side of the storm. There were no apparent outbound velocities at this particular time, though this was because of the extreme easterly storm motion. Several Doppler radar radial velocity bins of inbound velocities of around 10 m s^{-1} (20 kts) were located approximately 2.5 km north of the stronger inbound velocities.

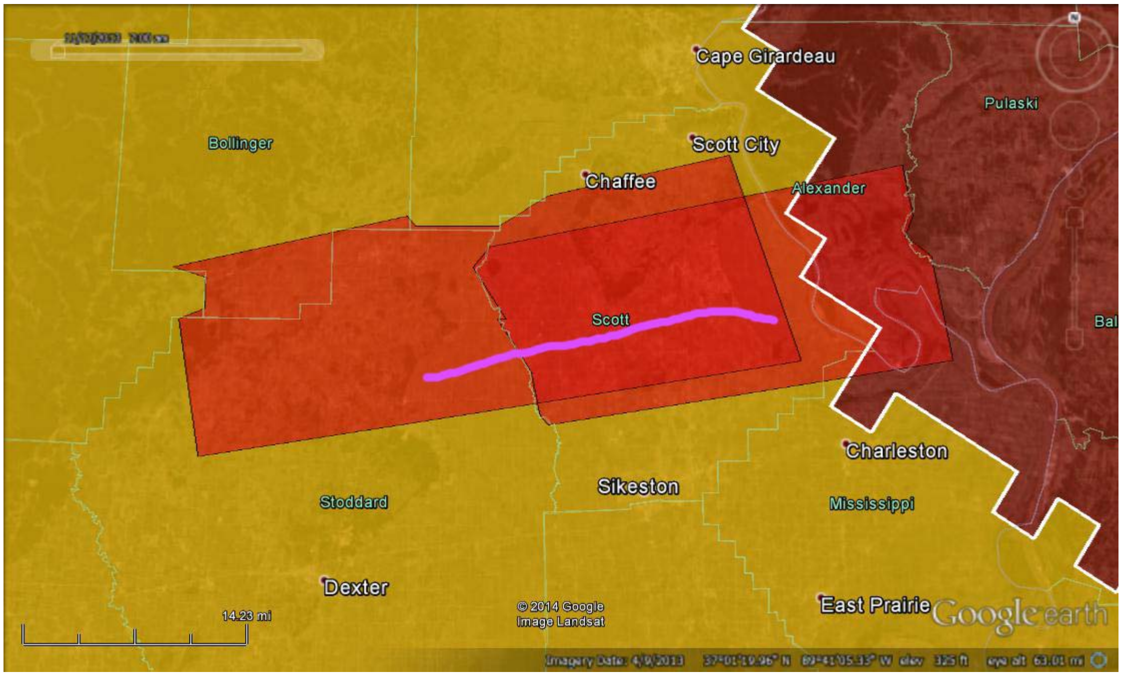


Figure 4.7. The SPC Day One Convective Outlook for southeast Missouri on 17 Nov 2013, overlaid with the two IBTW polygons for this case study. Slight risk is represented by the yellow shaded region, and moderate risk is represented by the red shaded region. The purple line represents the approximate path of the EF3 tornado (NWS PAH).

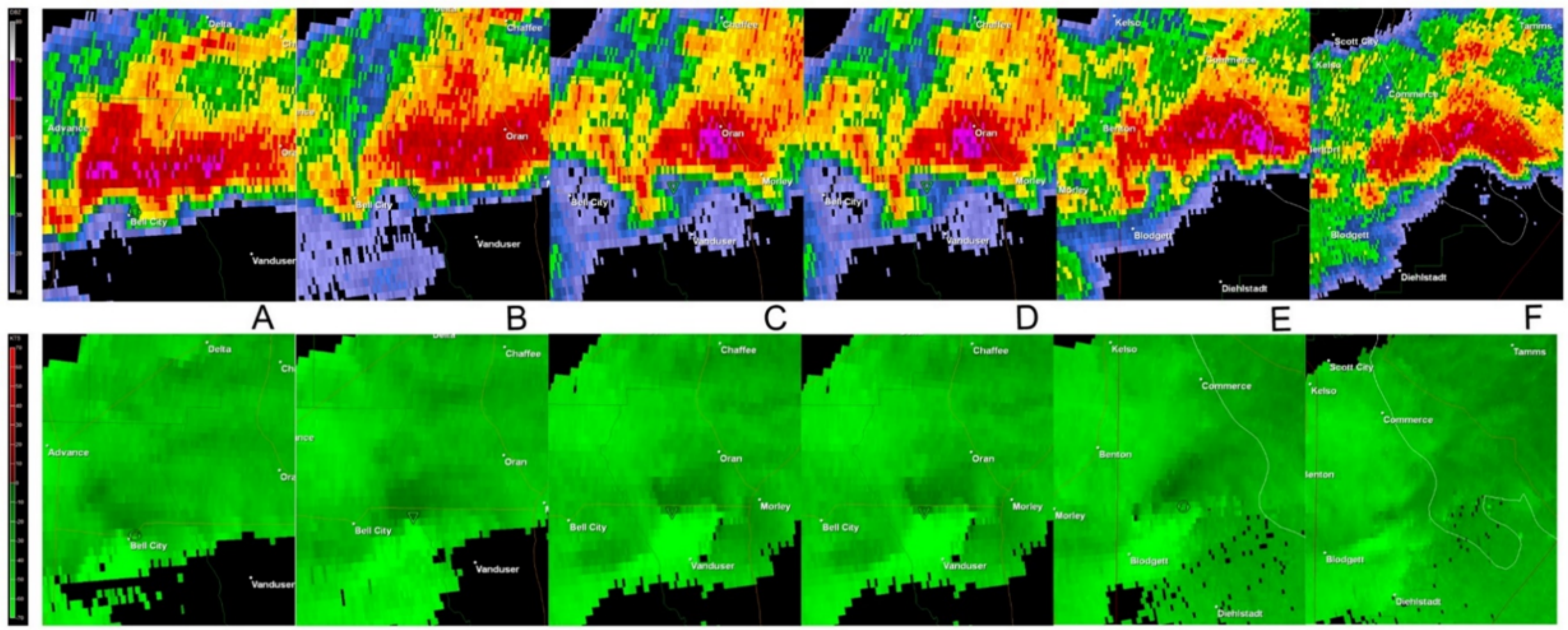


Figure 4.8. Images from the PAH WSR-88D on 17 Nov 2013. The top row of images are reflectivity and the bottom row are the corresponding radial velocity (both at 0.5° elevation). Times for each image are as follows: A (1856 UTC), B (1905 UTC), C (1910 UTC), D (1915 UTC), E (1924 UTC), F (1929 UTC)

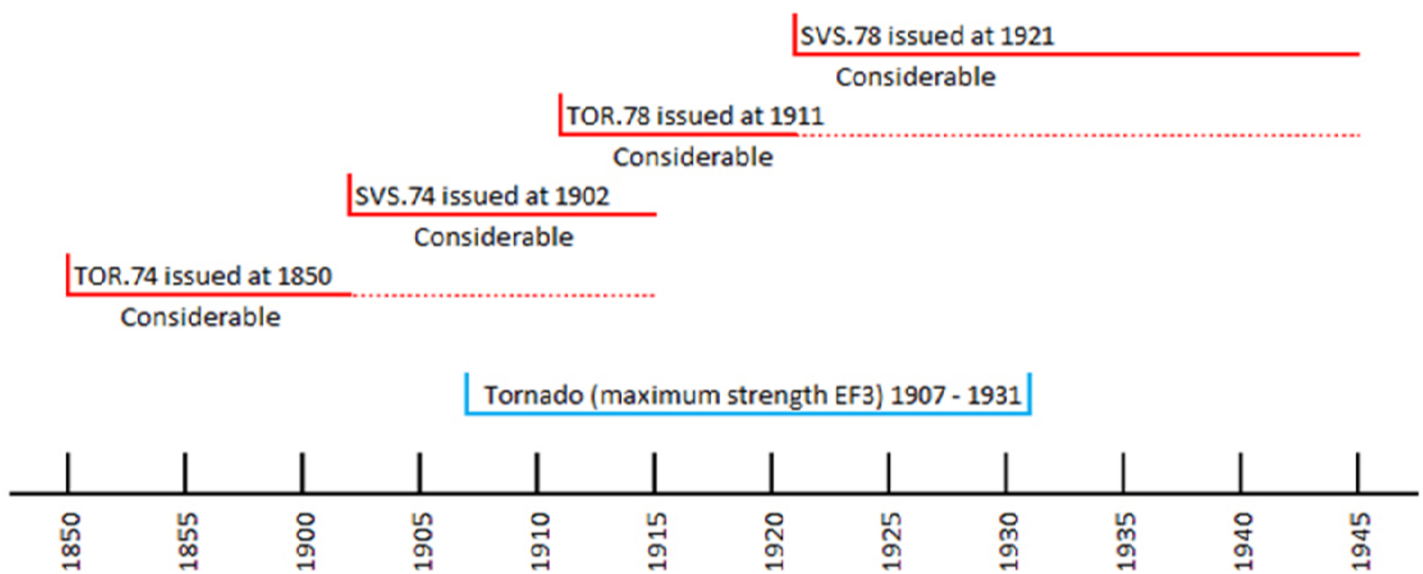


Figure 4.9. An event timeline on 17 November 2013 in which four considerable tags were used in two IBTW. All times are UTC.

At 1902 UTC, an SVS was issued which still contained the considerable damage tag (Fig 4.9). By 1905 UTC, Doppler radar radial velocity indicated the strongest inbound velocities still reached 36 m s^{-1} (70 kts). However, inbound velocities 1.8 km to the north had slowed to around 5 m s^{-1} (10 kts), indicating a strengthening of the rotation. The storm produced an EF3 tornado at 1907 UTC, which would remain on the ground until 1931 UTC, a total of 24 min. An additional TOR was issued at 1911 UTC which once again included the considerable tag, but the warning text stated radar-indicated rotation. Despite the fact that the storm was producing a tornado, observation reports may not have initially reached the PAH WFO. At 1915 UTC, Doppler radar reflectivity indicated a well-defined hook echo. Doppler radar radial velocity imagery continued to indicate strong rotation and the storm still raced eastward, now at 27 m s^{-1} (52 kts). Peak inbound velocity was 41 m s^{-1} (80 kts), with a bin of much lower inbound velocity of about 3 m s^{-1} (5.8 kts) approximately 1.5 km north. The storm continued to produce an EF3 tornado, and by 1921 UTC an SVS was issued. The considerable tag was included again, and the text stated the tornado was observed by weather spotters (NWS 2013b). Doppler radar radial velocity imagery still exhibited an area of rotation at 1924 UTC, however, the rotation was much broader. The greatest inbound velocity was 38.5 m s^{-1} (74.8 kts) and a bin of much lower inbound velocity of 0.9 m s^{-1} (1.9 kts) was located 3.6 km north. The circulation continued to weaken by 1929 UTC. Although the greatest inbound velocity was still around 39.4 m s^{-1} (76.7 kts), the slower inbound velocities to the north had increased to 9.5 m s^{-1} (18.5 kts) and the circulation was much broader. The EF3 tornado lifted at 1931 UTC. The PAH WFO issued another IBTW downstream, but did not issue additional damage tags.

In this case study, all four of the considerable damage tags verified. Warning forecasters correctly indicated the potential for EF3 or stronger impacts, and correctly made the choice to issue the considerable damage tags. A factor which led to this decision likely included the Doppler radar radial velocity imagery which indicated robust, well-organized rotation within the storm. Given the elevated situational awareness, warning forecasters were aware of the potential for very strong tornadoes. Also notable was the warning forecasters' correct decision to exclude the damage tag in the downstream IBTW. The circulation had weakened considerably and the storm was no longer producing a tornado.

Other case studies showed the varied results of the use of damage tags. Of particular interest are the situations in which the catastrophic damage tag was used. This third tier of damage wording should only be used on rare occasions when EF4-EF5 impacts are undoubtedly expected. The catastrophic damage tag was used in three SVSs during this study. It was first used in an SVS issued by the Wichita (ICT) WFO on 19 May 2013. The SPC outlook from that morning indicated a slight risk was in place across central Kansas, with a moderate risk over eastern Kansas (Fig. 4.10). The text stated "initial storms will likely be discrete supercells…the overall environment appears quite favorable for tornadoes" (SPC 2013b). Considering the SPC outlook and favorable environmental conditions, situational awareness was elevated. By the early afternoon, a discrete supercell had formed southwest of Wichita, KS. A TOR for this storm was issued at 2005 UTC, and did not include a tag. During this IBTW, two EF0 tornadoes occurred. No SVS was issued. Considering the storm's history of producing tornadoes

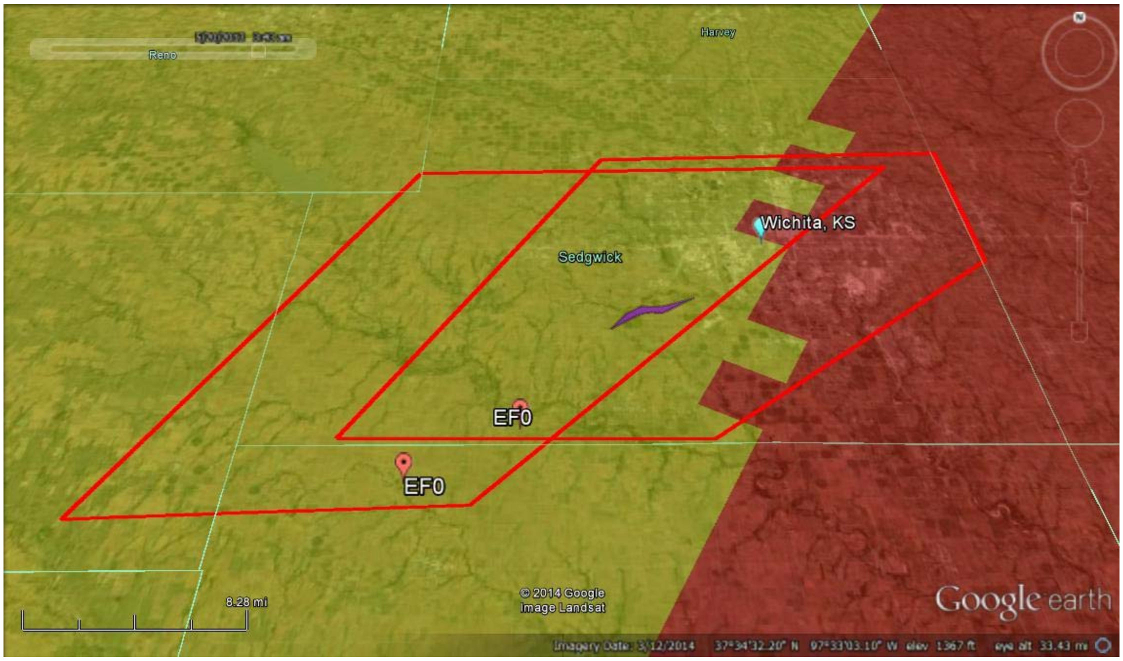


Figure 4.10. The SPC Day One Convective Outlook on 19 May 2013 overlaid with the two IBTW polygons for this case study. Slight risk is represented by the yellow shaded region, and moderate risk is represented by the red shaded region. The purple track is the path of the EF2 tornado (NWS ICT). The location of the city of Wichita, KS is indicated by the blue marker.

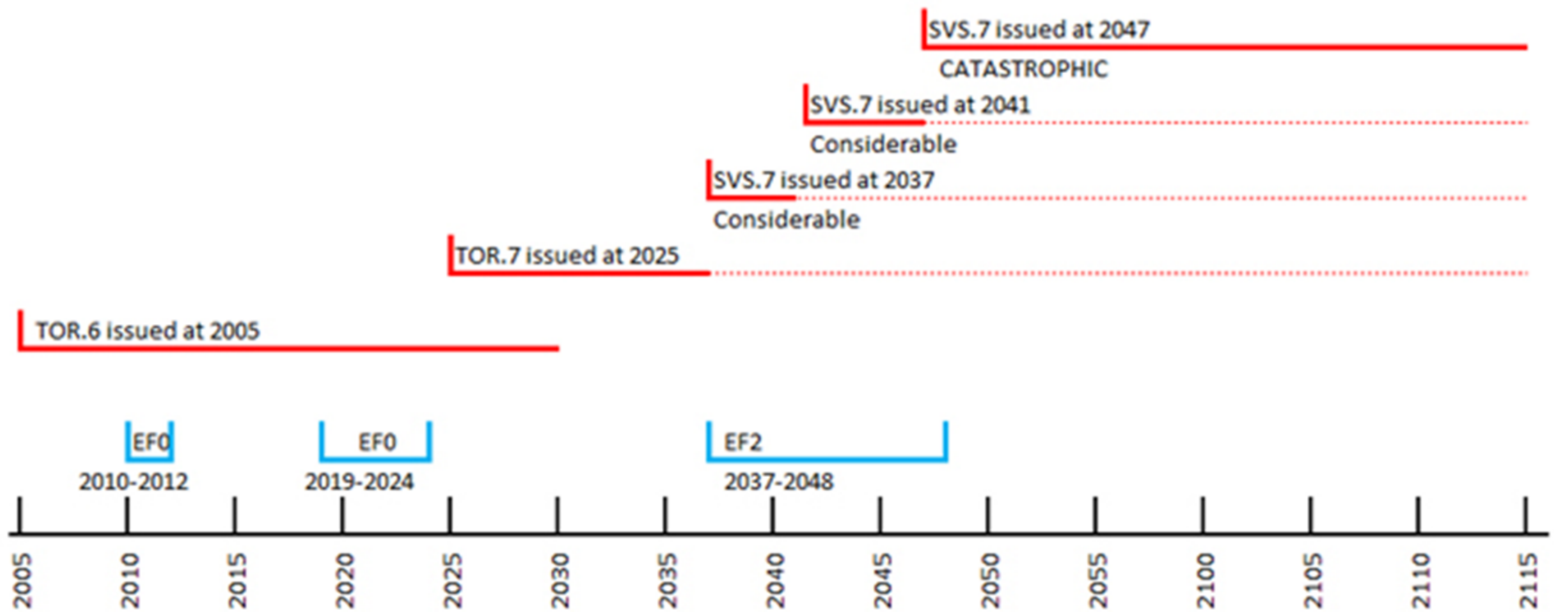


Figure 4.11. An event timeline on 19 May 2013 in which a catastrophic tag was used in an IBTW. All times are UTC.

(Fig. 4.11), another TOR which included the city of Wichita, KS was issued at 2025 UTC as the strengthening supercell was moving northeastward at 13 m s^{-1} (26 kts). The TOR did not include a damage tag. Considering the close range of the storm to the radar site, radar imagery provided excellent sampling of the low levels of the storm. This sampling is of benefit to the forecaster, considering the higher spatial resolution (smaller radar bin size) and the fact the radar beam is sampling the lower levels of the storm. At 2036 UTC, radar reflectivity from the ICT WSR-88D indicated a well-defined hook echo southwest of Wichita (Fig. 4.12). At the same time, radar radial velocity at 0.5° elevation indicated 37.5 m s^{-1} (72.8 kts) of outbound velocity and 44.0 m s^{-1} (85.5 kts) of inbound velocity along adjacent azimuths over a distance of 0.5 km (Fig. 4.12). Considering this part of the storm was located about 7.6 km from the ICT radar site, it is likely that the radar was sampling what became the tornadic circulation.

At 2037 UTC, the storm produced an EF2 tornado, which was observed by storm spotters. At the same time, ICT issued the first SVS, which included a considerable damage tag. The EF2 tornado remained on the ground, causing sporadic damage just southwest of Wichita. At 2041 UTC, radar reflectivity continued to indicate a well-defined hook echo. This part of the storm was now located within 5.6 km of the radar site. The tornadic circulation had weakened, with 19.5 m s^{-1} (37.9 kts) of outbound velocity and 40.0 m s^{-1} (75.8 kts) of inbound velocity along adjacent azimuths, still over a distance of about 0.5 km and at an elevation of 0.5° (Fig. 4.12). However, at 2047 UTC, the ICT WFO issued an SVS with the catastrophic damage tag, along with the tornado emergency text for the city of Wichita. At 2048, the tornado lifted before entering the

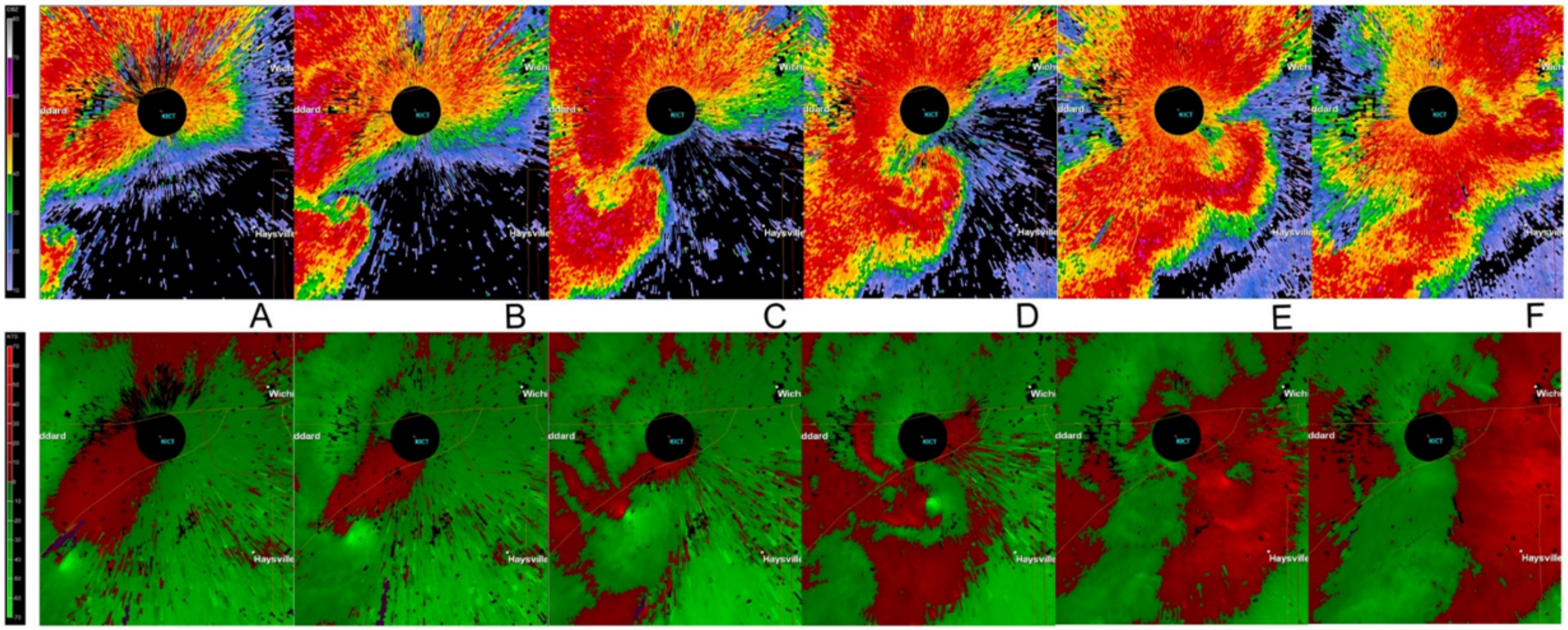


Figure 4.12. Images from the ICT WSR-88D on 19 May 2013. The top row of images are reflectivity and the bottom row are the corresponding radial velocity (both at 0.5° elevation). Times for each image are as follows: A (2026 UTC), B (2031 UTC), C (2036 UTC), D (2040 UTC), E (2045 UTC), F (2050 UTC)

city. The circulation continued to weaken, and the storm did not produce another tornado during the span of the IBTW, which expired at 2115 UTC. Interestingly, no additional SVS were issued before the expiration of the IBTW, despite changes in storm intensity. This means the SVS which carried the catastrophic tag was in effect for 28 minutes, even though the tornado had lifted and the circulation continued to weaken substantially.

In this example, the considerable and catastrophic tags, as well as the tornado emergency, were false alarms. However, this example also illustrates the level of complication involved with issuing tags. Clearly, this could have been a very serious situation for the city of Wichita. A warning forecaster would much rather err on the side of over-warning. Considering the impressive radar signature at 2036 UTC, it seemed probable the storm would produce a violent tornado potentially tracking into Wichita. However, this case study shows how quickly a storm can change in intensity. The supercell lost its tornadic circulation, and resulted in a null event for Wichita.

The second and third catastrophic damage tags were issued in consecutive SVSs issued by the FSD WFO on 4-5 Oct 2013 (Fig. 4.13). The SPC outlook from the morning of 4 Oct 2013 included extreme northeast Nebraska and western Iowa in a moderate risk for severe weather (Fig. 4.14). The outlook text describes an environment supportive of "supercells capable of producing very large hail and tornadoes" (SPC 2013c). This particular storm had been previously warned several times, and had a history of producing a tornado. However, that tornado had lifted at 0010 UTC 5 October 2013 (Fig 4.13). Unlike the Wichita example, the distance of the storm from the radar site in this example is much greater (135 km). At this distance, the radar resolution is less

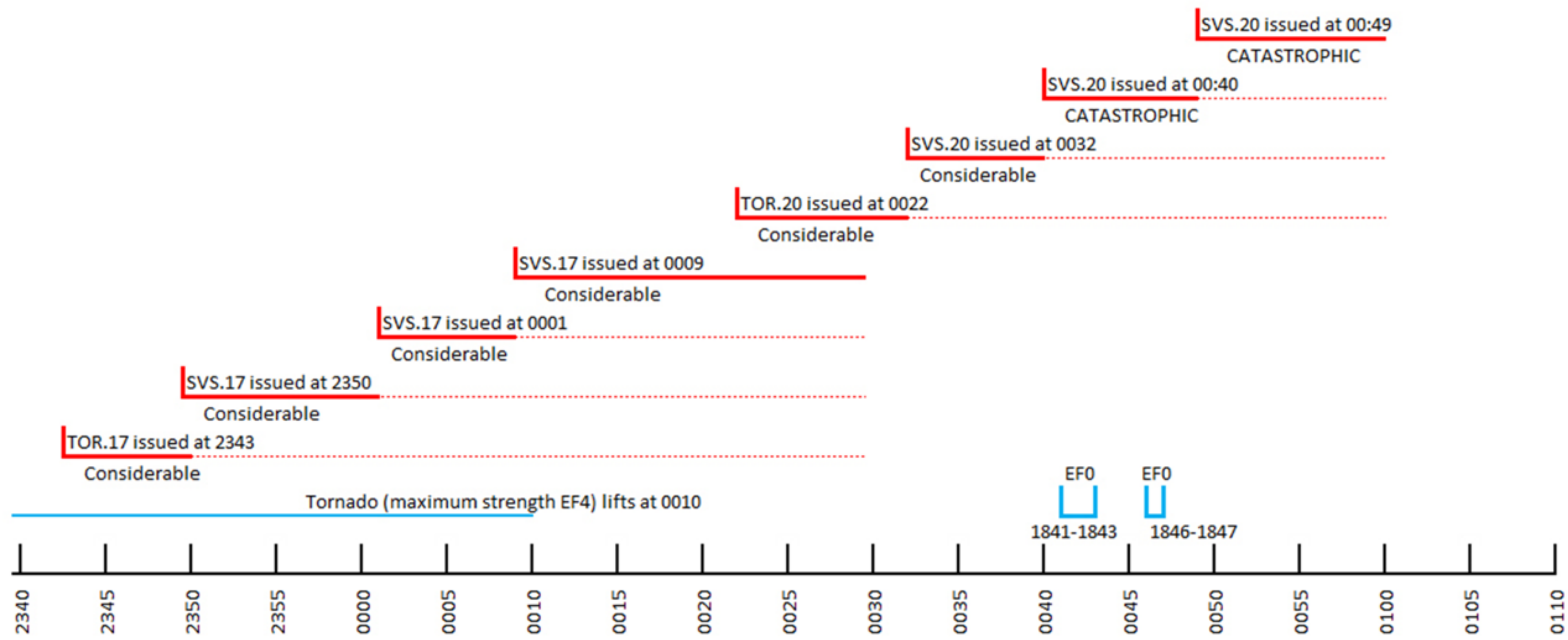


Figure 4.13. An event timeline on 4-5 Oct 2013 in which catastrophic tags were used in the IBTW. All times are UTC.

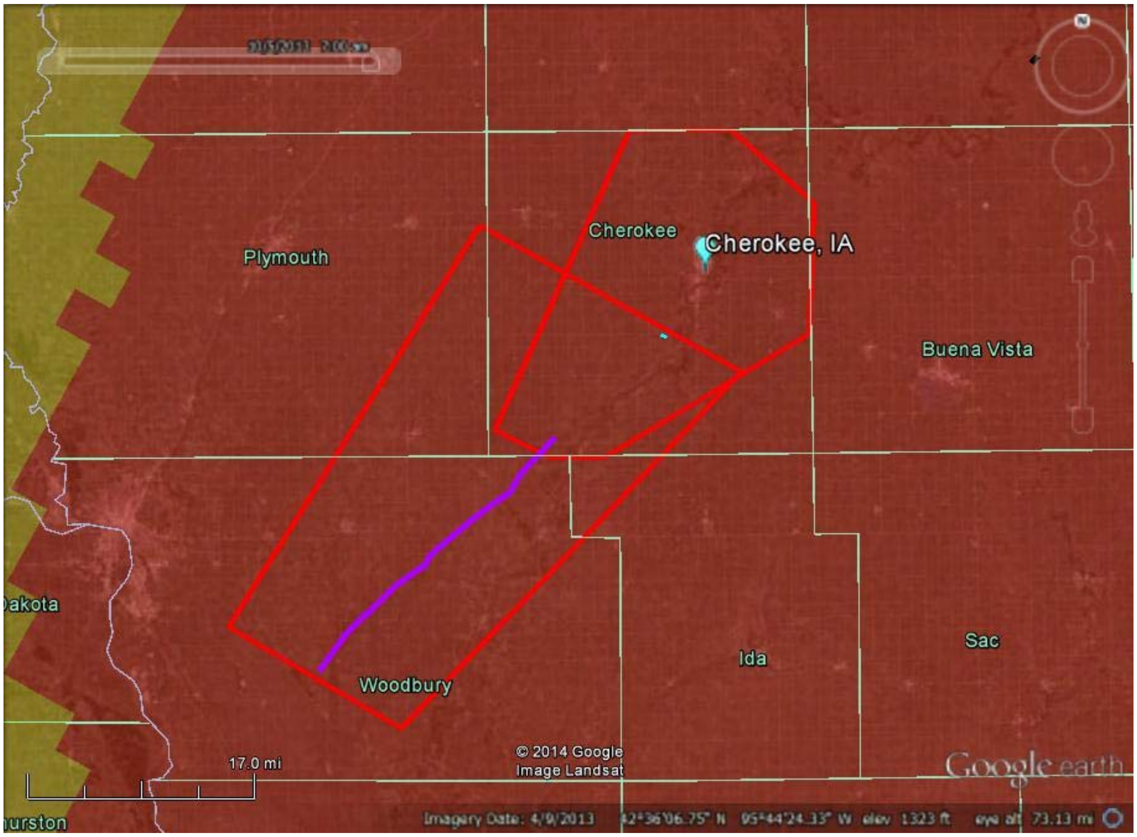


Figure 4.14. The SPC Day One Convective Outlook on 4-5 Oct 2013 overlaid with the two IBTW polygons for this case study. Slight risk is denoted by the yellow shaded region, and moderate risk is denoted by the red shaded region. The purple track is the path of the EF4 tornado (NWS FSD). The location of the town of Cherokee, IA is indicated by the blue marker.

(larger bin sizes) and the radar beam is intercepting the storm at a higher altitude. The storm was traveling northeast at 13 m s^{-1} (26 kts). At 0020 UTC, a somewhat broader circulation was evident in radar radial velocity from the FSD WSR-88D (Fig 4.15). Peak inbound velocity was 30.1 m s^{-1} (58.5 kts), while peak outbound velocity was 28.0 m s^{-1} (54.4 kts), over a distance of 4.7 km. A TOR was issued at 0022 UTC and included the considerable damage tag. A SVS with a considerable damage tag was issued at 0032 UTC. The 0.5° radar radial velocity scan from 0037 UTC indicated a circulation with peak inbound velocity of 18.0 m s^{-1} (35.0 kts), and peak outbound velocity of 19 m s^{-1} (36.9 kts) over a distance of 2.76 km (Fig. 4.15). At 0040 UTC, another SVS was issued with catastrophic damage tag, along with the tornado emergency text for the town of Cherokee, IA. The IBTW text stated at 0037 UTC, a spotter "confirmed… large and extremely violent tornado was located near Quimby" (NWS 2013c). Quimby, IA is located approximately 10 miles southwest of Cherokee. Unfortunately, this must have been an erroneous report. The storm survey reveals that the storm had not been tornadic since 0010 UTC 5 October. The storm did produce an EF0 tornado from 1841 UTC 4 October until 1843 UTC, and another EF0 tornado from 1846 UTC until 1847 UTC. Both tornadoes were located outside of Cherokee and did not produce damage. At 0049 UTC 5 October, another SVS was issued with the catastrophic damage tag, but the storm did not produce another tornado during the span of the IBTW. As a result, the catastrophic damage tags and tornado emergency were false alarms, or over-warned events. However, considering the spotter report which still indicated a strong

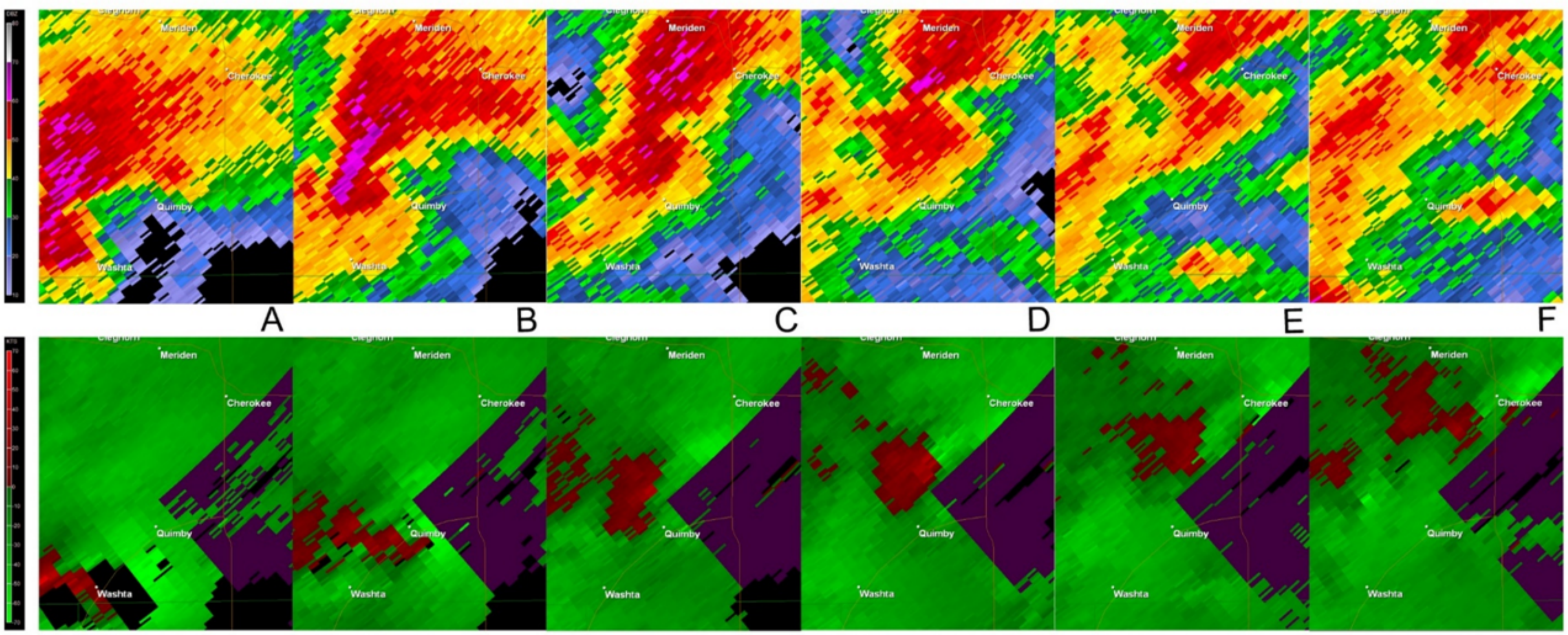


Figure 4.15. Images from the FSD WSR-88D on 5 October 2013. The top row of images are reflectivity and the bottom row are the corresponding radial velocity (both at 0.5° elevation). Times for each image are as follows: A 0020 UTC), B (0029 UTC), C (0037 UTC), D (0042 UTC), E (0046 UTC), F (0050 UTC)

tornado was occurring, warning forecasters had to use the best information available to make a decision whether to include a damage tag. This report, along with storm's tornadic history, radar evidence, and environmental conditions seemed to justify the inclusion of a tag. However, it is impossible to truly know the warning forecasters' reasoning under the scope of this study.

During this study, there were several incidents in which an EF3 or greater tornado occurred, and no tag was included in the IBTW. One such incident occurred on 17 November 2013 in southern Illinois (Fig. 4.16). As noted earlier, a moderate and high risk from the SPC were in place for this region on this date (Fig. 4.17). The 1630 UTC Day One convective outlook text describes an environment suitable for severe storms, and notes "clockwise curved low-level hodographs will also be conducive to the potential for strong tornadoes…some of which could be relatively long-lived/long-track" (SPC 2013a). A supercell had formed by early afternoon southeast of the St. Louis metropolitan area (Fig. 4.18), about 100 km from the St. Louis (LSX) WSR-88D radar site. The 0.5° radar radial velocity scan from the LSX WSR-88D at 1752 UTC shows an area of rotation with 7 m s^{-1} (13.6 kts) inbound velocity, and 25 m s^{-1} (48.6 kts) outbound velocity over a distance of approximately 1.4 km (Fig. 4.18). A radar-indicated TOR was issued by the LSX WFO at 1753 UTC and did not include a damage tag (Fig. 4.16). This TOR was the first issued for this particular storm, although other tornado warnings had been issued already for nearby storms. This particular storm had no history of producing a tornado, nevertheless, considering the SPC outlook and environmental conditions,

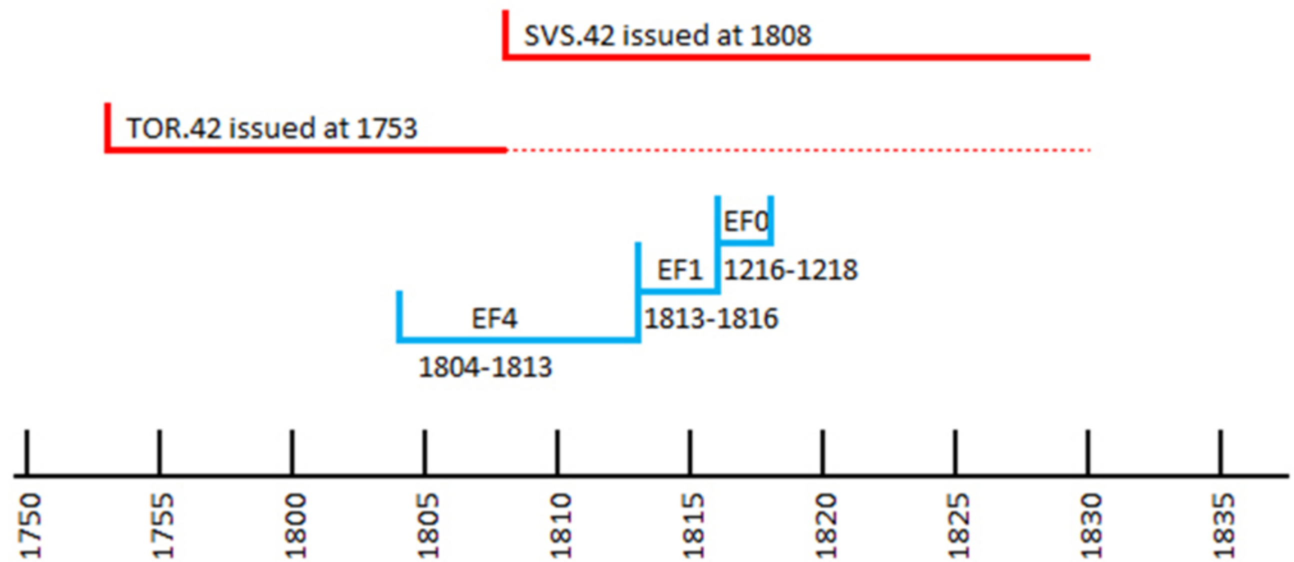


Figure 4.16. An event timeline on 17 November in which an EF-4 tornado occurred, but no tags were included in the IBTW.

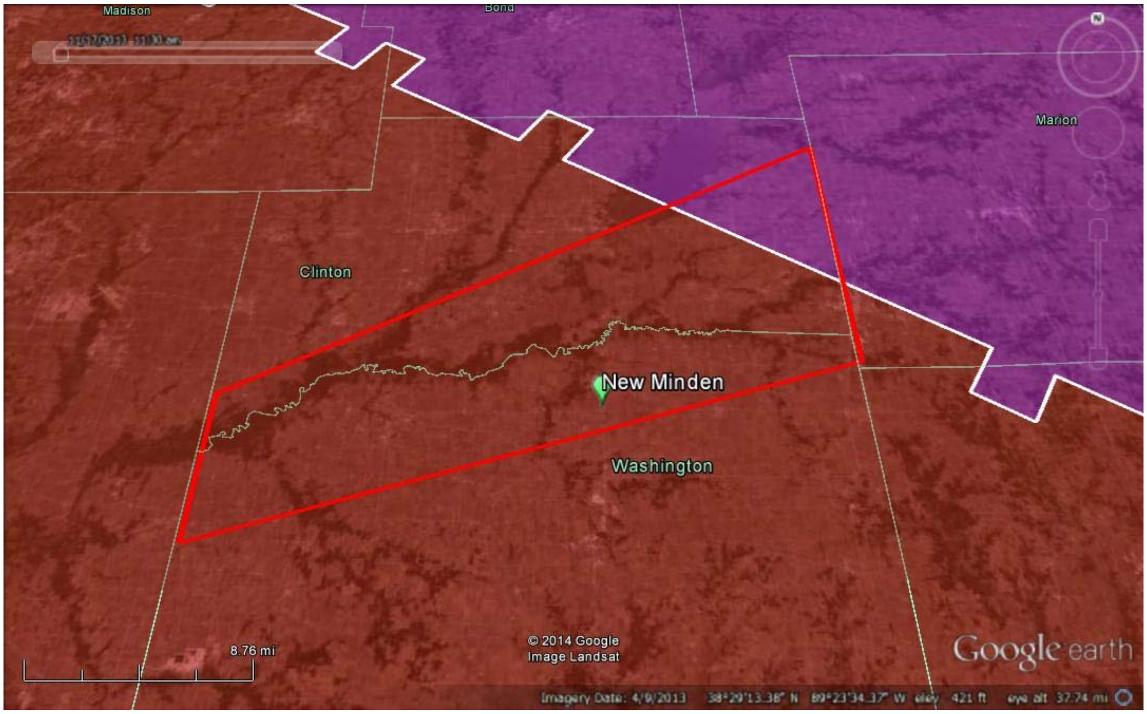


Figure 4.17. The SPC Day One Convective Outlook overlaid with the IBTW polygon for this case study. Moderate risk is represented by the red shaded region, and high risk is represented by the purple shaded region. The location of the town of New Minden, IL is indicated by the green marker.

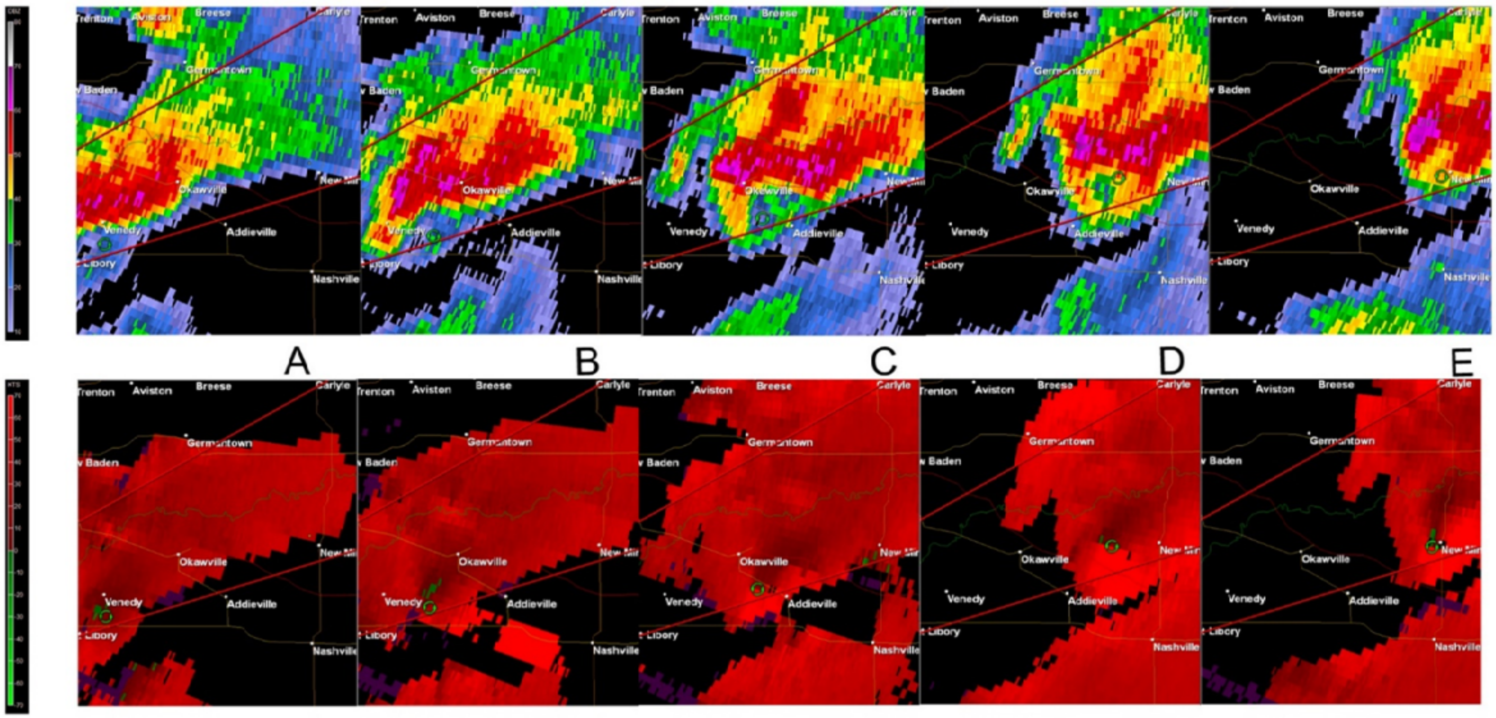


Figure 4.18. Images from the LSX WSR-88D on 17 Nov 2013. The top row of images are reflectivity and the bottom row are the corresponding radial velocity (both at 0.5° elevation, with the exception of). Times for each image are as follows: A 1752 UTC), B (1756 UTC), C (1800 UTC), D (1804 UTC), E (1809 UTC).

situational awareness was high. By 1800 UTC, the 0.5° radar radial velocity scan indicated 49.5 m s^{-1} (96.2 kts) of outbound velocity (Fig. 4.18). There were no apparent inbound velocities at this particular time, though this is because of the easterly storm motion of 29 m s^{-1} (57 kts). At 1804 UTC, the storm produced an EF4 tornado, which tracked into the town of New Minden, IL. Radar radial velocity imagery at the same time indicated 1.49 m s^{-1} (2.9 kts) inbound velocity, and 37.0 m s^{-1} (71.9 kts) of outbound velocity over a distance of about 1 km (Fig. 4.18). These radial velocities come from the 0.9° elevation; there appears to be a data error at 0.5° elevation. At 1809 UTC, the LSX WFO issued the first and only SVS (Fig. 4.16) which indicates an increase in easterly storm motion to 33 m s^{-1} (65 kts). The tornado was observed, although no damage tag was included. Radial velocity imagery at 1809 UTC indicated 5.5 m s^{-1} (10.7 kts) of inbound velocity and 49.5 m s^{-1} (96.2 kts) of outbound velocity over a distance of about 2 km (Fig. 4.18). The EF4 tornado lifted at 1813 UTC. The storm produced two more tornadoes within the IBTW polygon, an EF1 at 1813 UTC and an EF0 at 1816 UTC (Fig 4.16).

It is difficult to assess why no damage tag was issued at any time during the span of the IBTW. Warnings forecasters could have been hesitant to issue a tag for varied reasons. As mentioned before, the storm had no history of producing a tornado. Perhaps if the storm had a tornadic history, a tag would have been considered. However, no tag was issued even when the tornado was confirmed and the additional SVS was issued. Perhaps damage reports from the New Minden, IL, area did not reach the LSX WFO until much later. These explanations are speculative; a more in-depth study would be required

to understand the warning forecast decision-making process during this event and is beyond the scope of this study.

Analysis of several IBTW examples reveals more details about the scenarios in which tags were or were not used during this study. Tags were occasionally used well, such as seen in the case study of the 17 November 2013 IBTW damage tags issued by the PAH WFO. However, there were many situations in which the inclusion of damage tags resulted in false alarms, specifically in situations in which the catastrophic tags were used. Swift changes in tornado/storm intensity made successfully issuing tags more difficult. While radar evidence and spotter reports were critical tools used to make IBTW damage tag decisions, limitations in these tools certainly have an unfavorable impact on the POD and FAR of tagged IBTWs.

CHAPTER FIVE: CONCLUSION

Experimental IBTWs issued in the Central Region of the NWS from 1 April 2013 through 30 November 2013 were collected and verified in this study. A total of 1598 IBTW TORs and SVSs were gathered and statistically analyzed through the use of 2x2 contingency tables. During this study, 84 considerable and 3 catastrophic damage tags were issued in IBTW TOR or SVS statements, for a total of 87 tags. The majority of these tags were included in a SVS (75%) rather than a TOR (25%), indicating that warning forecasters were likely gathering additional evidence before issuing a tag. In addition, the majority of tags were issued for observed tornadoes (60%) rather than radar-indicated (40%). Ultimately, most tags were issued in SVS for observed tornadoes (47%). Two autumn tornado outbreaks (4-5 October 2013 and 17 November 2013) resulted in the issuance of 74% of the tags during this study. The remaining 26% of the tags were issued during the months of May, June and August.

POD and FAR statistics for both non-tagged and tagged IBTW TORs/SVSs are obtained. POD statistics for both non-tagged and tagged TORs/SVSs are lower than those of traditional tornado warnings. POD for non-tagged TORs/SVSs, corresponding to EF0-EF2 tornadoes, is 64%. This POD statistic is partially accounted for by 129 EF0-EF2 tornadoes which were unwarned during this study. The remainder of the POD statistic is comprised of TORs/SVSs which were under-warned events. POD for tagged TORs/SVSs, corresponding to EF3-EF5 tornadoes, is only 39%. This is much lower than the POD of traditional tornado warnings corresponding to EF3-EF5 tornadoes, which is

94% (NWS 2011). A total of 36 TORs/SVSs were issued for EF3-EF4 events in which no considerable or catastrophic tag was included and should have been. The stark difference between these two numbers seems to suggest that despite the ability of warning forecasters to detect very strong and violent tornadoes, forecasters did not actually use tags to warn because they could not determine tornado intensity. Forecasters perhaps know when a tornado is very probable, likely due to storm mode, environmental/situational awareness, radar evidence, or spotter reports. These factors do not necessarily allow the forecaster to correctly anticipate tornado intensity. In addition, forecaster hesitance to use tags may be an explanation for the low POD of IBTWs. However, a more in-depth study, including study of forecaster warning behavior, would have to be conducted to explore reasons behind the low IBTW POD.

Analysis of IBTWs indicated FAR statistics which were near or slightly higher than the FAR of traditional tornado warnings. FAR for non-tagged IBTWs, corresponding to EF0-EF2 tornadoes, is 82%. This number is somewhat higher than the traditional tornado warning FAR, corresponding to any strength tornado, of 76% (NWS 2011). FAR for tagged IBTWs is 74%, which is slightly lower. Closer analysis of the three catastrophic tags included in IBTW SVSs issued in 2013 indicated all were false alarms for the occurrence of a violent tornado. The reasons why these tags resulted in false alarms is complicated. The case study of the catastrophic tag issued in the IBTW for Wichita, KS on 19 May 2013 revealed a tornadic circulation which rapidly dissipated as the parent supercell passed over the city. Environmental conditions, radar evidence and the storm’s history of producing tornadoes would suggest that the probability of the

storm to continue to produce tornadoes was elevated. This reasoning likely played a role in issuance of the catastrophic tag. The other two catastrophic tags issued for Cherokee, IA on 4 Oct 2013 were influenced by both radar evidence and a false spotter report, in additional to environmental conditions and the storm's tornadic history. In both case studies, the warning forecasters had evidence which may have supported the issuance of catastrophic tags, however, changes in storm intensity resulted in the false alarms.

Other case studies analyzed in this study provided a more in-depth understanding of events in which tags were or were not used. The 17 November 2013 LSX case study is an example in which an EF4 tornado occurred, but no damage tag was included in the IBTW. Analysis of the event reveals no ultimate reason why a damage tag was never issued. The IBTW polygon covered part of two counties in southern Illinois which were part of the moderate and high risk areas as outlined by the SPC Day One convective outlook, and situational awareness was high. WSR-88D radar imagery indicated rotation within the storm indicative of tornadic potential. Warning forecast behavior likely played a role in the event as well, although this study cannot fully address the role of the forecaster. Events such as this untagged EF4 tornado may be cause for concern. Future studies should address if under-warned events have detrimental societal impacts.

This study raises additional questions which should be addressed in future research. Since IBTWs are a new product, only data for 2013 for the Central Region are available. The IBTW experiment will continue into future years and has been expanded to several offices in other regions of the NWS for 2014 (NWS 2014d). As additional data become available over the coming years, the current study should be expanded to explore

any variability in verification statistics. Due to the rarity of violent tornadoes, any one year may only have a few catastrophic tags. Additional data over the years may provide interesting verification results to compare to the data collected in 2013.

This study further suggests that improvements in FAR while maintaining or increasing POD may only be achieved through advancements in technology or increased knowledge in regard to tornadogenesis. The introduction of dual-polarization to the WSR-88D Doppler radars may provide an avenue by which tornado intensity could sometimes be determined. Use of the tornado debris signature, which incorporates dual polarimetric variables such as correlation coefficient, has been shown to relate to changes and trends in damage intensity during a tornado event (Bodine et al. 2013; Van Den Broeke and Jauernic, in press). This information, used operationally, may allow warning forecasters to issue tags with more success. The operational introduction of SAILS (Supplemental Adaptive Intra-Volume Low-Level Scan) is a new scanning method for the WSR-88D Doppler radars which will allow warning forecasters additional low-level scan with less elapsed time between scans (NWS 2014e). The higher temporal resolution will provide forecasters additional information that may be valuable in the IBTW process. Increases in the spatial resolution of radar data and greater coverage near the ground may only be achieved by the installation of more radars. The CASA project (Collaborative Adaptive Sensing of the Atmosphere) operated several X-band Doppler radars throughout southwestern Oklahoma, which provided radar data in areas not well-sampled by the WSR-88D Doppler radars in the region (CASA 2014). The CASA Doppler radars were operational from 2005-2011, and the data were not available to on-

duty NWS forecasters. In the future, a higher density radar network similar to CASA and available for operational use by NWS forecasters may provide critical data leading to more successful use of tags. In addition, research resulting from the second installment of the VORTEX project, which operated from 2009-2010, will likely lead to even more understanding of tornadogenesis and tornado structure (Wurman et al. 2012). These increases in the knowledge of tornado-genesis, including why some supercells produce tornadoes and other do not, could eventually improve IBTW statistics.

A different facet of study in regard to IBTWs revolves around the potential societal impacts. In the NWS assessment of the Joplin, Missouri EF5 tornado, one of the stipulations for a new warning system was that it would be “easily understood and calibrated by the public to facilitate decision making” (NWS 2011 page iv). There are many questions about how damage tags are communicated to the public, and how the public perceives and reacts to the tags. How much of the general public is even aware of the existence of IBTWs or what IBTW tags mean? Will individuals react to protect themselves differently according to elevated damage tags? Will IBTW false alarms have any impact on the perception of ITBW tags? These are all questions which need to be studied more over the coming years.

IBTWs are meant to convey expected impacts of tornadoes in a tiered structure through the use of damage tags. This study reveals that the majority of IBTWs are false alarms, and tagged IBTWs have a very low POD. Examination of specific events indicates that IBTWs can occasionally be used with success, although more often the tags result in false alarms for the occurrence of EF3 or greater strength tornadoes. In addition,

many EF3 or greater events occurred, and no damage tag was included in the IBTW. Additional in-depth studies are required in coming years to see if IBTWs continue to perform with similar results. Future advances in technology and the understanding of tornadogenesis will hopefully lead to more successful implementation of IBTWs in the years ahead.

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