Connecting the Dots: A Communications Model of the North Texas Integrated Warning Team during the 15 May 2013 Tornado Outbreak

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ABSTRACT

On 15 May 2013, 19 tornadoes occurred across north and central Texas, killing 6, injuring over 50, and causing more than $100 million in property damage. The majority of the impacts to life and property were the direct result of category-3 and category-4 enhanced Fujita scale (EF-3 and EF-4) tornadoes that affected the communities of Cleburne and Granbury, Texas. This study focuses on an examination of the north Texas integrated warning team (IWT) communications through a thorough analysis of interactions between IWT members during this event. Communications from all members of the IWT were collected and organized so that a quantitative analysis of the IWT communications network could be performed. The results of this analysis were used to identify strengths and weaknesses of current IWT communications to improve the consistency of hazardous weather messaging for future high-impact weather events. The results also show how effectively communicating within an IWT leads not only to more consistent messaging but also to broader dissemination of hazardous weather information to the public. The analysis techniques outlined in this study could serve as a model for comprehensive studies of IWTs across the country.

1. Introduction

On 15 May 2013, 19 tornadoes occurred across north and central Texas, killing 6, injuring over 50, and causing more than $100 million in property damage (NCDC 2013). The majority of the impacts to life and property from this outbreak were in the communities of Cleburne and Granbury, Texas. The Cleburne tornado, rated as a category-3 tornado on the enhanced Fujita scale (EF-3), damaged dozens of homes along an almost 9-mi path. The Granbury tornado, rated an EF-4, was responsible for the outbreak's 6 fatalities as it moved along a nearly 3-mi path.

The warning system for hazardous weather, including events like the 15 May 2013 outbreak, consists of detecting an impending threat, providing information to those at risk, and enabling the at-risk population to make decisions for personal safety (Sorensen 2000). Entities that perform the hazard identification and communication functions of warning systems are known as integrated warning teams (IWTs). IWT members are most commonly identified as local emergency management and government officials, media representatives, amateur radio operators, and the National Weather Service (Doswell et al. 1999). IWTs work to provide a consistent message regarding a hazard because at-risk populations will not immediately take action in response to the first warning message they receive (Sorensen 2000) but will instead seek out additional sources of warning information to confirm the hazard is a realistic threat (Mileti and Sorensen 1990). Message inconsistency limits the ability of the at-risk population to personalize, or recognize the personal importance of, warning messages (Foster 1980). This, in turn, affects a much broader decision-making process that culminates in

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the decision to seek protective action (Lindell and Perry 1992, 2004).

While decision-making is not explicitly explored in this study, the availability of information for decision-making was explored through a thorough analysis of communication between north Texas IWT members during the 15 May 2013 outbreak. This analysis was conducted to evaluate the importance of providing hazardous weather messaging through the IWT framework. This analysis also seeks to determine the strengths and weaknesses of the north Texas IWT network and the impacts of these characteristics on information availability. Last, this study traces information as it filters through the IWT network to determine if patterns emerge when communicating different types of hazardous weather information. There has been relatively little published research investigating how the communication within an IWT impacts the dissemination of information from an IWT. Understanding the interactions of an IWT not only helps identify the strengths and weaknesses of current IWT hazardous weather messaging but is also an important step in building a resilient community. Community resiliency, or the ability to respond and recover from a disaster, is not solely based on the postdisaster decisions, but also on the decisions leading up to the event, which can be heavily influenced by information provided (or not provided) before the disaster occurs (Nigg 1995).

2. Data and methodology

To perform a quantitative analysis of communications within the north Texas IWT (hereinafter simply referred to as the IWT) during this event, the groups that compose the IWT had to be formally defined. In this study, the IWT is composed of four primary groups: the National Weather Service Forecast Office in Fort Worth, Texas (hereinafter referred to as the NWS), the primary television broadcast media outlets in the Dallas–Fort Worth area designated market area (hereinafter referred to as the media), north Texas local emergency management officials (EM), and a virtual operations support team (VOST; http://vosg.us/history). Each member of this IWT had a common goal of providing hazardous weather information to the general public during this event. The public is also included as a group in this analysis and is simply defined as those individuals in north Texas not included in the IWT. This very generic definition of the public was made because the primary focus of this study was on internal IWT communications and not a detailed analysis of response behaviors to the weather warning system as a whole.

All available communications were documented during this event, with the primary focus on those communications occurring between the times of 1900 and 2200 central daylight time (CDT), when 14 tornadoes, 6 instances of baseball-sized or larger hail, and 7 instances of damaging wind were reported to the NWS (Fig. 1) (NCDC 2013). Communications were collected from time-stamped, archived NWSChat logs (https://nwschat.weather.gov), NWS internal communications logs, and interviews with each NWS staff member that worked during this event. Media communications were documented minute by minute by reviewing archived tapes of coverage provided by the local American Broadcasting Company (ABC), CBS, National Broadcasting Company (NBC), and Fox affiliates. EM communications were documented by conducting semistructured interviews with EM officials in Montague, Hood, and Johnson Counties. These EM officials also provided a timeline of internal communications and operations of their respective emergency operations centers, including the activation of various methods of public notification of hazardous weather (e.g., outdoor warning sirens and the activation of "Reverse 9-1-1" types of technologies). Media, EM, and VOST communications that occurred within NWSChat were also documented, and VOST communications that occurred primarily on Twitter and Facebook were included in this study. Finally, communications that directly mentioned the NWS on Twitter (e.g., mentions of @NWSFortWorth) and any direct Facebook interactions between the NWS and public were documented. To capture some idea of what message the public received during this event, door-to-door surveys were conducted near the tornado damage paths of the Sunset, Granbury, and Cleburne tornadoes (see Fig. 1). Only 29 individuals were available or willing to respond, so the public survey results are not used directly as a point of analysis in this study, but to provide anecdotal context (Fig. 2). Amateur radio logs were also used to document communications with trained spotters and their storm reports. These groups were also included in the public group for communications purposes. These methods resulted in 1229 unique pieces of information documented for analysis.

To analyze how information moved within the IWT during the event, pieces of information were traced through the IWT in the same way that personal networks, or rumor networks, are modeled. This method utilizes a digraph (Poole 2011; Uzzi and Dunlap 2005). The pieces of information that were identified to trace through the IWT were chosen based on their relationship to a hazardous weather event that resulted in a significant societal impact. Significant societal impacts were determined by hazardous weather events that caused loss of life, injury, or substantial property damage. The pieces of information related to these events were chosen based on common themes identified in the

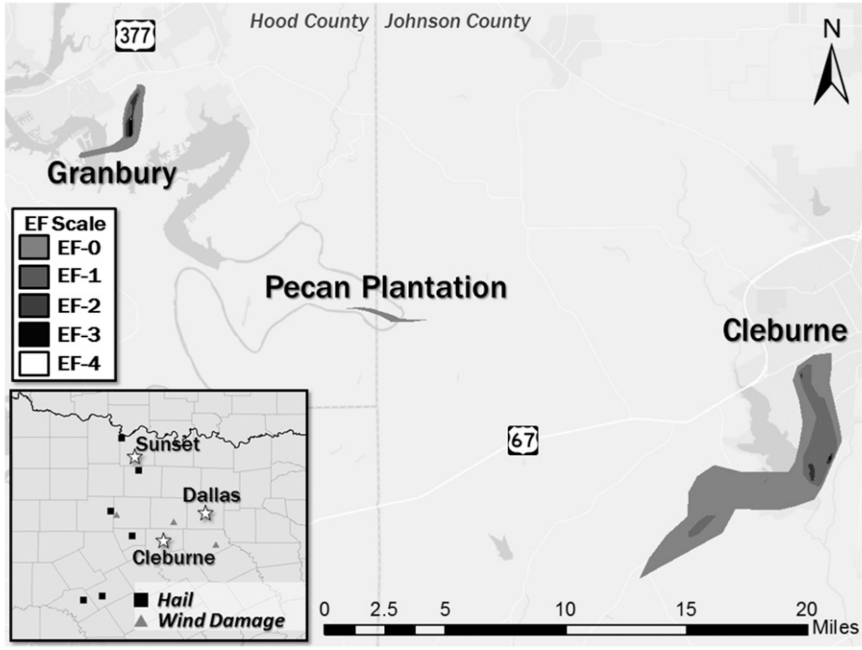


FIG. 1. Map of some of the significant severe weather events that occurred across north Texas from 1900 to 2200 CDT 15 May 2013. Tornado tracks for the tornadoes discussed within this paper have been outlined and shaded, with darker shades representing a stronger EF-scale rating from the ground survey. Squares in the inset image are baseball-sized or larger hail reports. Triangles represent nontornadic wind damage reports. City names are included in the inset image for reference, with the approximate center of each city labeled as a star.

documentation of communications mentioned earlier in this section. The following pieces of information were chosen for analysis:

1) First NWS tornado warning for Hood County (that mentioned Granbury, the location of the EF-4 tornado that resulted in 6 fatalities)
2) NWS tornado warning for Johnson County that mentioned Cleburne (the location of a mile-wide EF-3 tornado with no fatalities)
3) NWS tornado warning issued for the Cleburne tornado shifting to a northward track
4) NWS tornado warning for Tarrant County
5) The knowledge that the Cleburne tornado's track (Johnson County) was shifting north
6) The knowledge of a tornado debris signature in dual-polarization radar data on a supercell in Parker County
7) The report that the Cleburne tornado (Johnson County) was a "mile-wide wedge" tornado
8) The confirmation report of a tornado in Granbury (Hood County)
9) The confirmation report of a tornado in Pecan Plantation (Hood County)
10) The confirmation report of baseball-sized hail in Granbury (Hood County)
11) The confirmation report of a tornado in the Millsap area (Parker County)
12) The confirmation report of a tornado near Sunset (Montague County)
13) The report of significant damage from the tornado in Granbury (Hood County)

To construct a digraph modeling the flow of communication of each piece of information in the documented IWT interactions, each group (NWS, media, EM, VOST, and public) was defined as a vertex, and a directed edge connecting vertices was defined to represent a successful communication of the piece of information (1–13, defined above) from one group or vertex to another. For each diagraph, a successful communication was determined to be a piece of information that was communicated by a member of the IWT, with proof that the information was then received by another member of the IWT. For example, the NWS posted in NWSChat that they had received confirmation of a tornado near Sunset via amateur radio (information piece 12 above). This was determined to be a successful communication from the public to the NWS. When the local media mentioned the confirmed tornado on the air (as documented from review of the minute-by-minute archived video) this was documented as a successful

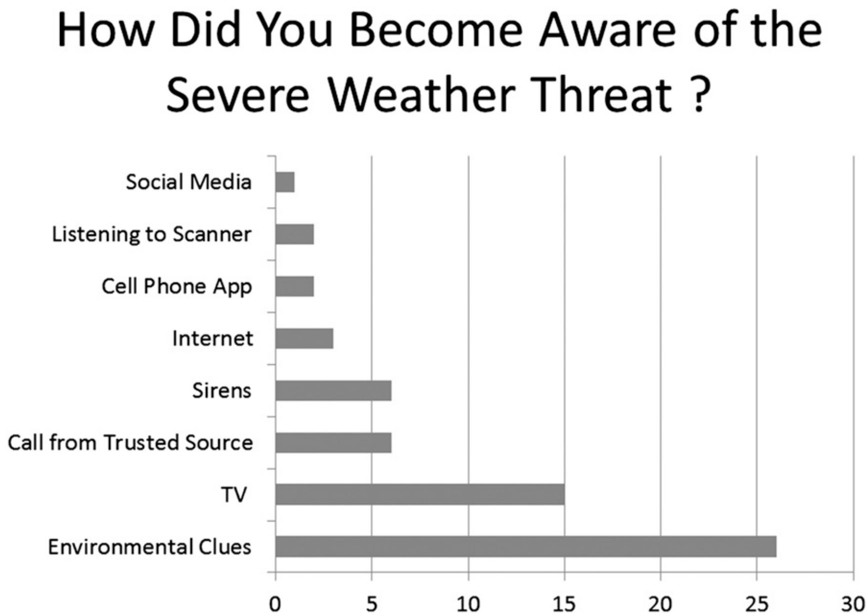
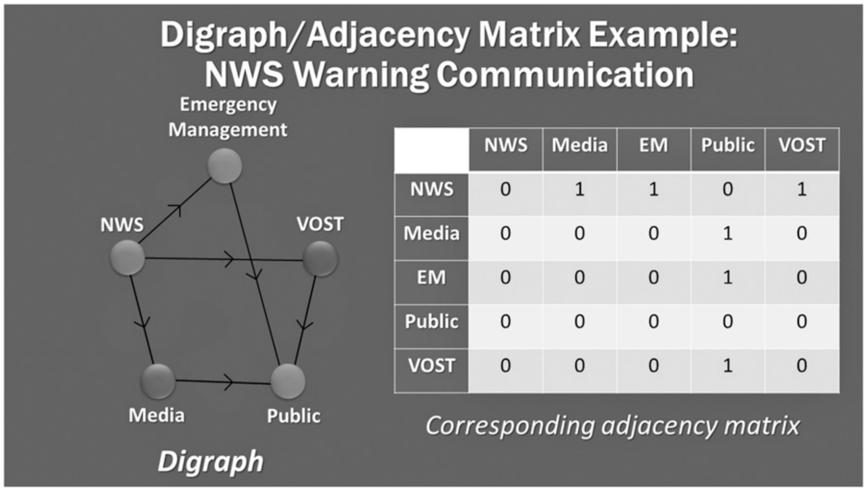


FIG. 2. Results of door-to-door surveys conducted by the NWS with members of the general public near the tornado damage paths affecting the communities of Granbury, Cleburne, and Sunset on 15 May 2013. There were 29 unique respondents, and these are the responses given to the open-ended question, ''How did you become aware of the severe weather threat before severe weather occurred near your location?'' Multiple responses were allowed, which explains why the total number of responses is greater than 29. ''Sirens'' are outdoor warning sirens, and environmental clues included responses such as ''winds got stronger,'' ''skies got darker,'' ''hail got larger,'' ''I heard a strange noise,'' etc.

communication from the NWS to the media. When there was documented evidence that the public was watching a television weather broadcast during the time of a particular event or that the public interacted with the broadcast media via Twitter regarding a particular piece of information (here the Sunset tornado), this was determined to be a successful communication from the media to the public. Each successful communication between IWT groups represents an edge in the associated digraph.

A successful communication had to occur within 15 min of the piece of information entering the IWT by any means. The requirement for a direct communication to occur within 15 min of entering the IWT was based on the advance tornado warning lead time goal defined by the National Weather Service (NWS National Performance Measures 2010). Additional support for the use of a 15-min time window for hazardous weather information consumption comes from Simmons and Sutter (2008), who determined "the effectiveness of warnings declines when lead time exceeds 15 minutes." Most of the successful communications documented occurred well below this time limit.

The collected data made the construction of the digraphs mostly straightforward. However, there were occasions where verification of a successful communication link was ambiguous. To reduce bias in the creation of the digraphs, each of the authors independently created digraphs for each piece of information (1–13) and then met to discuss discrepancies. The evidence used to assign an edge between vertices in each case has been documented but is not included in this paper. The digraph edges that were the most difficult to assign were those edges that resulted in the communication of a warning message directly to the public. There are many meteorologists within the National Weather Service community who think that, when forecasters issue a warning, that warning is being communicated directly to the public (NOAA 2013). While this is undoubtedly true in some cases, the authors were unable to find any evidence that this took place in all of the communications documented on this day. After scouring these data to see if something was overlooked, the authors collectively agreed that there was a lack of evidence of direct communication of NWS Fort Worth warnings to the public for the warnings tracked in this study (1–4). As a result, the communication of warnings from the NWS to the public was assigned a "0" for all of these types of adjacency matrices (Fig. 3). Further support for this decision is provided by J. Trainor (2012, meeting presentation), who strongly suggested that the general public does not typically receive warning messages



	NWS	Media	EM	Public	VOST
NWS	0	1	1	0	1
Media	0	0	0	1	0
EM	0	0	0	1	0
Public	0	0	0	0	0
VOST	0	0	0	1	0

FIG. 3. Description of (left) digraph and (right) its associated adjacency matrix using an example of the documented communications of an official NWS warning. Directed arrows within the digraph are equivalent to values of 1 in the adjacency matrix. All other values in the adjacency matrix are assigned a value of 0, indicating that there was no proof of this communication between vertices (IWT members) from the data collected.

directly from the NWS (Fig. 4). Our data analysis showed the VOST, EM, and media groups had successful direct communications with the public in this study because there was at least one piece of evidence indicating that the public successfully received a piece of information from each of these groups.

Once the digraphs for each piece of information 1–13 were constructed, a 5×5 adjacency matrix, $\mathbf{A}$, was created with each entry in the matrix assigned a "1" when it represented an edge of the digraph (i.e., for each entry in the matrix, $\mathbf{A}_{ij}$, a "1" was assigned when the vertex in the ith row successfully communicated with a vertex in the jth column); otherwise, a "0" was assigned. Because this communications analysis was modeled after a rumor network, the diagonal of each adjacency matrix (those cases where $i = j$) had to be zeros. That is, a group does not directly communicate with itself in this model. Figure 3 graphically demonstrates how a digraph and its associated adjacency matrix are related. Each of the adjacency matrices created using the criteria defined above are included as the appendix at the end of this paper.

With all adjacency matrices created, the next goal was to investigate how robust communications were within the IWT for the various pieces of information modeled in this study. A first step is to determine whether, given enough time, a piece of information would filter through the entire IWT. In rumor modeling, this is the same as determining if vertex i is connected to vertex j by a path of some length k. This can be calculated by using the equation (Poole 2012)

$$A_k = \sum_{k=1}^{n} A^k, \tag{1}$$

where n is the number of vertices. In this study, there are 5 vertices, so $n = 5$, and A_5 was calculated for each adjacency matrix. The results of these calculations are included in the appendix and are discussed in more detail in section 3. Each iteration (k) through this equation represents, at most, a 15-min message delivery between groups. For example, the adjacency matrix corresponding to the communication of the NWS tornado warning for the Granbury community (Table A1 in the appendix) indicates that the NWS successfully communicated the warning to the media, EM, and VOST groups of the IWT. It also shows that the media and VOST groups communicated the warning successfully to the public. Applying Eq. (1) for two iterations ($k = 2$) results in a matrix that shows that the NWS successfully communicated the warning to the public twice (there is a "2" in the 4th column of row 1 of the matrix). This was accomplished indirectly, meaning that the warning was communicated twice to the public via other members of the IWT (in this case, the media and VOST). When applying Eq. (1) for all vertices in the adjacency matrix ($k = 5$), a "complete" rumor matrix is defined as an A_5 that contains no zero entries; that is, each group has received the message from every other group within 75 min (but commonly much faster).

A second step is to determine if there was a way to classify the relative importance of each group in communicating a particular piece of information during this event.

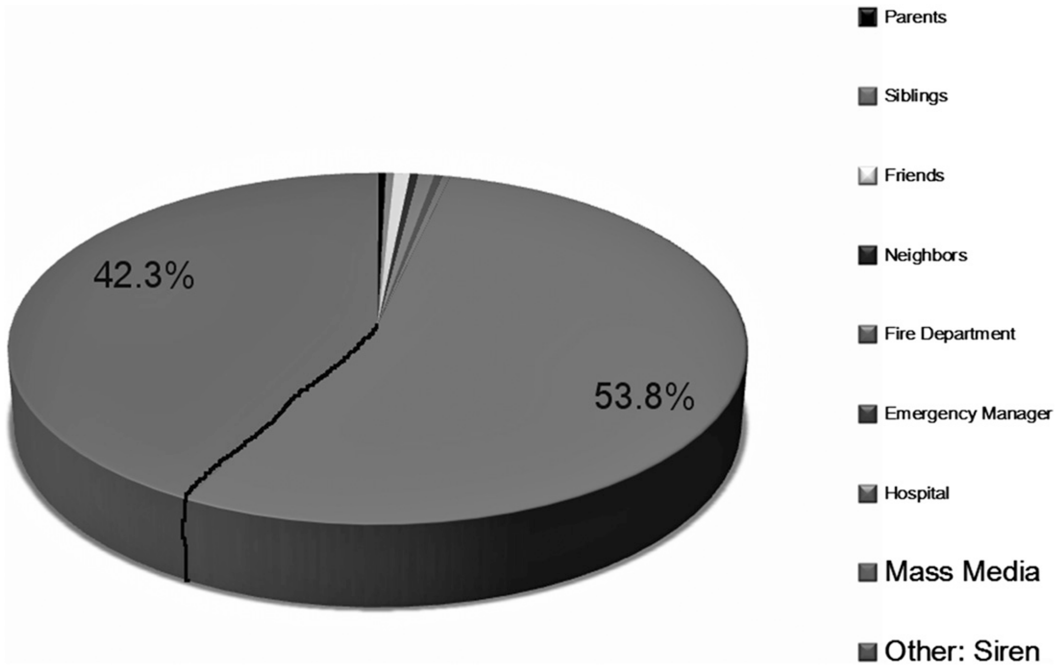


FIG. 4. Results of research conducted by J. Trainor (2012, meeting presentation). In a public response survey, this graph answers the following question: For those individuals that indicated they had received a tornado or severe thunderstorm warning in their region (169 responses), where did they receive this information from? The top two responses were mass media at 53.8%, followed by outdoor warning sirens at 42.3%.

As suggested by Poole (2011), the eigenvectors and eigenvalues for adjacency matrices can be broadly applied to rank which vertex (or, in this study, IWT member) played the most important role in communicating a selected piece of information.

Perron's theorem requires that each adjacency matrix be a positive $n \times n$ matrix (Poole 2011). Because adjacency matrices in this study could have all zero columns (meaning that vertex j never received a particular piece of information), Perron's theorem was not always fully satisfied. However, this does not prevent calculations of the eigenvalues or eigenvectors. It simply results in some trivial calculations (i.e., some values are zero) in the resultant eigenvectors. When Perron's theorem is completely satisfied, at least one positive eigenvalue is guaranteed to exist with a corresponding positive eigenvector. More important, Perron's theorem guarantees a unique eigenvalue of the adjacency matrix with a corresponding probability eigenvector that satisfies the equation

$$\mathbf{Ar} = \frac{1}{\alpha}\mathbf{r}, \tag{2}$$

where $\mathbf{r}$ is an eigenvector corresponding to the adjacency matrix $\mathbf{A}$, and α is the constant of proportionality (Poole 2011).

This allows the calculated eigenvector $\mathbf{r}$ to represent a unique ranking vector of $\mathbf{A}$ such that adding up the values of $\mathbf{r}$ will result in the value 1. Such a ranking gives insight as to which vertex, or IWT member, played the most important role in communicating the piece of information modeled, based on its relative value in its associated ranking vector $\mathbf{r}$. This is a basic application of the much more complex methodology that Google uses to rank Internet search results based on a user-defined query (Poole 2011). The calculation of eigenvectors in this study utilized EISPACK software routines [Smith et al. (1976); more recently available online at http://www.akiti.ca/Mathfxns.html]. The results of these calculations are also included in the appendix and are most meaningful as a ranking when there are no trivial results, or the vector $\mathbf{r}$ contains no zeros.

Last, a directed communication path to each nontrivial documented communication in this study was assigned in order to understand their frequency. These paths were assigned not only to document successful communications, but intended communications as well (e.g., if the NWS intended a message to go to the public, it was counted here). Communications within groups were also allowed. For example, if media members were speaking directly to one another, or if a different NWS office relayed a report to the NWS office in Fort Worth,

	NWS	Media	EM	Public	VOST
NWS	4	113	133	115	114
Media	40	16	19	461	15
EM	49	32	49	28	32
Public	66	76	36	28	30
VOST	26	21	21	46	0

FIG. 5. Results of the histograph approach to documenting all communications analyzed in this study from 1900 to 2200 CDT. While this information was not used as a direct point of analysis in the study, it offers a look at the breakdown of the communications analyzed to construct the adjacency matrices.

these results were counted as communications along the diagonal of the communications matrix. These communications were collected in one large matrix that represents a histograph of communications between various members of the IWT and the public (Fig. 5). Since all 1229 pieces of communication were not involved in the analysis of the 13 matrices discussed above, this matrix was created to provide some insight to the composition of all the documented communications in this study.

3. Interpretation of data

Once the matrices were constructed and the analysis completed as described in section 2, the interpretation analysis provided insight into the nature of hazardous weather communication within the IWT. This insight is discussed in the context of several broad categories related to the events on 15 May 2013. In the subsections that follow, individual matrices are referenced in the order and naming convention adopted in the appendix (e.g., A1 refers to the first adjacency matrix in Table A1 in the appendix, A2 refers to the first adjacency matrix in Table A2, and continues through A13 representing Table A13.). If a subscript is appended to the letter "A," it is referring to the value of k associated with the adjacency matrix from Eq. (1) [e.g., $A_5 1$ refers to the first adjacency matrix in Table A1, but is associated with the results of Eq. (1) for $k = 5$].

a. *Confirmed tornadoes*

The adjacency matrix modeling of information flow concerning the confirmation of tornadoes (A8, A9, A11, and A12) reveals the importance of open communication within an IWT.

For both A11 and A12, the rumor matrices were complete (i.e., there were no zeros in A_5) after 2 iterations through Eq. (1) (i.e., $k = 2$), indicating that the confirmation of these tornadoes was shared multiple times between all members of the IWT. For matrix A9, the rumor matrix is nearly complete after 3 iterations through Eq. (1) (i.e., $k = 3$), but further iterations confirm that the EM community never shared information regarding this tornado confirmation with other members of the IWT (i.e., row 3 in A9 representing the EM group remains zero when $k = 5$).

Analysis of A8, the confirmation of the Granbury tornado, revealed the least complete matrix after applying Eq. (1), indicating that this critical information was only received by the EM and public members of the IWT (i.e., all other columns are zero vectors). In this case, the tornado was reported to the emergency manager by a member of the public, but the information was never shared further within the IWT. Analysis of this matrix confirms that this information oscillates between these two IWT groups (see $A_5 8$ in the appendix Table A8) but never fully makes it through the IWT. A media member also showed live footage of the tornado, and a VOST group shared a report about the tornado on social media, but neither group directly shared this information with the other members of the IWT through other communication methods (e.g., direct communication or via NWSChat).

The communication of this information within the IWT would have been critically important, as this tornado was the violent EF-4 that resulted in 6 fatalities near Granbury. Caution must be used when interpreting $A_5 8$, as it appears the information successfully makes it to the public, but the "public" in this case is only a small set of county spotters. In fact, there is no evidence that those directly impacted by the tornado ever received the message of a confirmed tornado. No one surveyed near the tornado damage path in Granbury indicated that they had advance knowledge of a confirmed tornado as the storm approached.

The results of A_5 calculations associated with confirmed tornadoes during this event strongly suggest that, when information is not shared freely within the IWT, the information essentially perishes. Even though the numerical results of $A_5 8$ indicate that a tornado confirmation message was technically available to the public, the low values in the public column of this matrix (column 4) compared to the confirmation of the tornado near Millsap ($A_5 11$) suggest that this message was not available very frequently to this audience. Incomplete A_5 calculations, or A_5 calculations with low values, indicate a lack of consistent messaging from various IWT members or a lack of communication of critical information within the IWT in general. Comparing the results of A_5 for confirmed tornadoes that were communicated openly within the IWT ($A_5 11$ and $A_5 12$) to those that were not communicated as freely ($A_5 8$ and $A_5 9$) provides strong evidence that sharing information within the IWT results in faster, more frequent, and more complete information being made available to all members of the IWT and, perhaps most importantly, the general public.

b. Tornado damage in Granbury (Hood County)

Information concerning significant damage from the tornado in Granbury (A13) was communicated frequently among all members of the IWT. The information about the damage almost completely infiltrated the IWT at $A_2 13$ and was complete at $A_3 13$. Not only was the communications matrix complete at $k = 3$, but most of the IWT received the information multiple times. In this example, all members of the IWT played a strong role in sharing and communicating this piece of information. This case demonstrated that, as more information is shared within the IWT, the more completely and quickly this information is shared with the public. Door-to-door survey results downstream of the Granbury tornado (residents around Cleburne) indicated that a few of the residents were aware of the tornado damage in Granbury (A13). This is in contrast to survey results from Granbury, where no one in the Granbury community indicated they were aware of a confirmed tornado (A8) before damage was done.

c. Comparison of the confirmed tornado in Granbury versus report of significant damage from the tornado in Granbury (Hood County)

The analyses for the confirmation of the tornado in Granbury (A8) and the report of significant damage from the tornado in Granbury (A13) reveal the consequences of two different IWT communication approaches. When those with hazardous weather information attempt to communicate that information directly to the public and not to other IWT members, as in A8, an incomplete and low-value $A_5 8$ is found. $A_5 8$ shows that the NWS, media, and VOST groups never received the message of a confirmed tornado near Granbury from other members of the IWT. Without having this information, other members of the IWT were not able to amplify this message, making it less frequently available to the public.

However, when hazardous weather information was shared among all members of the IWT as well as with the public, as in A13, a dramatic amplification of the communication of this message was observed in $A_5 13$. This increases the likelihood that a consistent message is received and shared by all members of the IWT, increasing confidence in the validity of the information and making it available much more frequently for public awareness. This also makes the information more reliable in general and likely increases the chance that the information is believed and acted upon. As research by Lindell and Perry (1992, 2004) discussed, threat confirmation plays a large role in the public's protective action decision-making process. Information that is consistent and frequently repeated can limit the amount of time required to confirm a valid threat, thus cutting down on the amount of time it takes to make a decision to take protective action. $A_5 13$ also showed that the public had multiple opportunities to receive this message from multiple sources. During interviews with the public near Cleburne (downstream of the Granbury tornado), a few residents specifically stated that receiving the information about damage in Granbury from multiple sources helped spur their decision to take protective action. Of those surveyed near Cleburne, 33% received reports of tornado damage near Granbury, while no one surveyed near Granbury or Cleburne reported that they had received a message of a confirmed tornado near Granbury before the tornado directly impacted that community. These results provide strong evidence that consistent messaging within the IWT makes it more likely that the intended audience receives and believes the message being communicated.

d. Tornado warning matrices

Analysis of information flow regarding tornado warnings during this event (A1–A4) suggests that the NWS is consistently the originator for warnings within the IWT. The media, EM, and VOST play a large role in the dissemination of these tornado warnings to the public. From the application of Eq. (1) in these instances, by A_2 for matrices A1–A4, the public were shown to receive the tornado warning information indirectly from 2 or 3 sources. However, it is important to note that there was no evidence that the public received a tornado warning directly from the NWS. This demonstrates the key role that other members of the IWT have in communicating hazardous weather warning information. The 29 door-to-door surveys indicated that no one reported receiving a direct warning message from the NWS, even though those conducting the surveys identified themselves as NWS meteorologists. This does not prove that the public never receives warnings directly from the NWS. Instead, it provides strong circumstantial evidence that the public usually receives hazardous weather information directly from alternative sources. The results of this analysis also suggest that NWS partnerships with IWT members must be strong if a warning message is going to be communicated to the public. While the warning message does get to the public, it must first go through non-NWS members of the IWT. For better or worse, these IWT members have the powerful ability to filter or change the message that ultimately reaches the public.

It is interesting to note that the warning information was not shared well among members of the IWT (see A_5 for A1–A4). The directed path of communication for warnings modeled here indicates a warning is communicated from the NWS to nonpublic IWT partners and then to the public. After this initial communication, the information essentially stopped moving by $k = 2$, meaning it did not have as much residence time within the IWT as most other pieces of information tracked in this study. In particular, ground truth reports are communicated through the IWT much more frequently and completely (see $A_5$7–$A_5$13). It can be inferred that ground truth reports are much more effective in moving a hazardous weather message through the IWT and to the public when compared to the warning message alone. This analysis also suggests that the more members of the IWT communicate a message, the greater the chance of the public receiving this information and taking action.

e. *Ranking vectors*

The ranking vectors were an important part of this analysis as well and provided insight into which groups were most effective at communicating various types of information. Certain patterns were detected within three interpretive groups: official warning information, hazard detection, and ground truth.

Matrices A1–A4 that traced tornado warning dissemination were considered ''official warning information.'' The NWS ranked as the main communicator of this information in all four of these matrices, which is consistent with its role as the source of warnings.

Matrices A5 and A6 were considered ''hazard detection'' pieces of information. Once again, the NWS ranked as the main communicator of this information, but the EM group did play a role in A5 as one of the first to confirm the Cleburne tornado was deviating from its initial path via storm spotter and damage reports. The media could have also ranked highly here as a source of information if they had real-time video of a tornado and observed it changing track or intensity, but that was not observed during this event. These results highlight the importance of providing persistent tactical updates for the IWT, because this type of information was also shown to have a short residence time within the IWT (see $A_5$5–$A_5$6). While this type of information is important to help maintain the situational awareness of IWT members, these results show that it must be updated frequently to remain relevant.

The final matrices (A7–A13) were grouped as ''ground truth'' pieces of information and consisted of confirmation reports of hazardous weather from the field. The media, public, and VOST groups ranked as the most important sources and disseminators of ground truth information. In nearly all the ranking vectors for A7–A13, the VOST group was in or tied for the top spot. The NWS was found to be a secondary receiver of this information since it was not out tracking the storms in the field. What the ranking vectors show in these cases are the important roles that non-NWS groups serve in the IWT. The media and VOST groups are both key to sharing and amplifying the message of these ground truth reports with other groups in the IWT, thus giving the public multiple opportunities to receive this information. It is critically important for these ground truth reports to be communicated by the IWT in a timely manner during hazardous weather events. The communication of a warning itself seems to have very little residence time in the IWT, while the communication of ground truth reports resonates and persists through the IWT. As a whole, these results indicate that each member of the IWT plays an important role in the communication of hazardous weather information to the public. When the IWT engaged in strong internal communication, this resulted in significantly more effective communication of hazardous weather information to the public as opposed to instances where IWT members attempted to accomplish this task in isolation.

4. Conclusions

The analysis of IWT communication during the 15 May 2013 tornado outbreak reveals complex interactions among IWT members. Interesting relationships also exist between the nature of internal IWT communications and the likelihood of these messages reaching the general public. First, the NWS plays an important role as an originator of hazardous weather information but is not frequently disseminating this information directly to the public. Second, when members of the IWT do not share information with one another, there is an increased risk of an inconsistent or incomplete message of hazardous weather being communicated to the public. This point in particular is important because threat confirmation from multiple sources is a process that social science research has identified as an important component of the protective action decision-making process (Mileti and Sorensen 1990). Finally, our analysis of the communication within the IWT reinforces the idea that all members of the IWT play a critical role in delivering actionable messages to the public.

Analysis indicated that an ''official NWS warning'' by itself had a relatively short residence time within the IWT. In very few steps, the initial message that a warning was issued stopped being communicated within the IWT, and likely to the public as well. In contrast, ground truth information communicated to all IWT members maintained a long residence time within the IWT and gave the public multiple opportunities to receive this type of hazardous weather information. These results highlight the critical role of ground truth observations in the communication of hazardous weather information. The pace of information flow is also important. The faster hazardous weather information is shared with all members of the IWT, the faster and more frequently this information becomes available for public consumption.

Analysis also strongly suggests that communication between IWT members is essential for a consistent message reaching the public. Why is this important? This study documented the information flow of two critical pieces of hazardous weather information that led to different outcomes depending on the internal communication within the team. One piece of information is the confirmation of the Sunset tornado (A12). In this case, the tornado was reported by spotters and was communicated to the IWT through NWSChat. Within minutes, the media, NWS, and VOST were each communicating messages about a confirmed tornado near Sunset, Texas. In the case of the EF-4 Granbury tornado, information about a confirmed tornado was only shared within a small subset of IWT members (A8). Those who had the information only made attempts to communicate directly to the public and did not take the time to share this information internally within the IWT. As the results of $A_5 8$ suggest, this led to fewer opportunities to receive information for all members of the IWT, including the general public. This was primarily because most of the IWT was unaware of the confirmed tornado, thus ultimately limiting its potential transmission to the general public. Information that is less frequently available yields a decreased opportunity for people to receive, personalize, and confirm a threat. In turn, this may lead to a delayed or ignored response by the public to seek protective action. Sorensen (2000) describes an information void created during "rare or unfamiliar events" that necessitates "repetitive warning messages" to satiate this gap. The public is actively seeking information during an event, but differences in IWT delivery approaches may limit information exposure to the public and, consequently, public response.

Nurturing an IWT is hard work. Relationships must be built, trust must be gained, and everyone's role must be understood before high-impact weather events occur. When the time comes, these relationships are put to the test, with each member pursuing the same goal and fulfilling a crucial role. This study began with the idea of tracking information through the IWT to see what patterns exist in the communication of hazardous weather information. The in-depth look at the data from the 15 May 2013 tornado event shows that, when an IWT communicates well, the end users of weather information receive consistent pieces of data on a frequent basis. This study suggests avenues for future IWT development. Traditionally, the NWS has issued warnings, the media has broadcast the warnings, and the EM community has directed resources based on the warning. Perhaps it is now time to think beyond those narrow roles. This study provides strong evidence that, when IWT members are communicating comprehensively among themselves, the hazardous weather warning system works quite well. Specifically, the analysis in this study showed the following:

1) Strong intragroup communications among IWT members results in a consistent warning message that is frequently available to the public.
2) Ground truth reports of hazardous weather have significantly greater residence time in the IWT when compared to hazardous weather warnings.
3) All members of the IWT play a crucial role in delivering an actionable warning message to the public.

The communications matrix analysis shows that, when there are breakdowns in communication between IWT members, the message that ultimately leaves the IWT is far from complete and leads to less message availability for the public. Because this type of research has not been formally applied to IWT structures in the past, some of the conclusions drawn here may be limited in scope. Hopefully this research illustrates the complexities of communicating a hazardous weather message from detection to reception. This analysis highlights the importance of communicating a consistent hazardous weather message through an IWT and not only through traditional channels. Serving as one model of IWT interactions during one hazardous weather event in one part of the United States, hopefully this analysis will provide a basis for future avenues of research regarding IWT communications.

Further research is required to determine the reasons why specific communication breakdowns occur and to determine if communications in other IWTs behave in a similar fashion to those analyzed here. Future research may also investigate a finer resolution of the communications within an IWT by documenting the communications among individual IWT participants as opposed to combining many IWT participants into groups, as was done in this study. Instead of providing one model that shows how all IWTs operate and communicate, the authors hope that this study opens the door for further IWT research with the goal of improving IWT communications and interactions across the hazardous weather messaging enterprise.

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APPENDIX

Matrix Calculations

Matrices in this appendix will be displayed in the format shown in Fig. A1.

The piece of information or "rumor" being tracked through IWT communications, listed in the order presented in the paper. The related matrix mathematical results follow (Tables A1–A13).

		NWS	Media	EM	Public	VOST		
Adjacency matrix	NWS	___	___	___	___	___	A_5	Organized like the adjacency matrix, but showing the results of Eq. (1), where $k = 5$.
	Media	___	___	___	___	___		
	EM	___	___	___	___	___		
	Public	___	___	___	___	___		
	VOST	___	___	___	___	___		
Ranking vector	NWS						Ranking	Listing, in order, the ranking of importance from left.
	Media							
	EM							
	Public							
	VOST							

FIG. A1. The construction of the adjacency matrix is discussed in the body of the text, as well as the calculation and meaning of the ranking vector (eigenvector). The ranking is listing the order of the groups in terms of how they are numerically ordered in the ranking vector. The higher the ranking, the more important that group was in the communication of the information being tracked through the IWT. Intermediate calculations are not included for brevity but are available from the authors upon request.

TABLE A1. First NWS tornado warning for Hood County that included Granbury and Pecan Plantation. Note that the calculation for A_k for $k > 2$ is equal to A_2, as A^k for $k > 2$ results in zero matrices.

Adjacency matrix	0	1	1	0	1	A_5	0	1	1	2	1
	0	0	0	1	0		0	0	0	1	0
	0	0	0	0	0		0	0	0	0	0
	0	0	0	0	0		0	0	0	0	0
	0	0	0	1	0		0	0	0	1	0
Ranking vector	1					Ranking	1. NWS				
	0						2. Media				
	0						2. EM				
	0						2. Public				
	0						2. VOST				

TABLE A2. First NWS tornado warning for Johnson County that included the city of Cleburne. Note that the calculation for A_k for $k > 2$ is equal to A_2 as A^k for $k > 2$ results in zero matrices.

Adjacency matrix	0	1	1	0	1	A_5	0	1	1	3	1
	0	0	0	1	0		0	0	0	1	0
	0	0	0	1	0		0	0	0	1	0
	0	0	0	0	0		0	0	0	0	0
	0	0	0	1	0		0	0	0	1	0
Ranking vector	1					Ranking	1. NWS				
	0						2. Media				
	0						2. EM				
	0						2. Public				
	0						2. VOST				

TABLE A3. NWS tornado warning for the Cleburne tornado shifting north. Note that the calculation for A_k for $k > 2$ is equal to A_2 as A^k for $k > 2$ results in zero matrices.

Adjacency matrix	0	1	1	0	1	A_5	0	1	1	2	1
	0	0	0	1	0		0	0	0	1	0
	0	0	0	1	0		0	0	0	1	0
	0	0	0	0	0		0	0	0	0	0
	0	0	0	0	0		0	0	0	0	0
Ranking vector	1					Ranking	1. NWS				
	0						2. Media				
	0						2. EM				
	0						2. Public				
	0						2. VOST				

TABLE A4. NWS tornado warning for Tarrant County. Note that the calculation for A_k for $k > 2$ is equal to A_2 as A^k for $k > 2$ results in zero matrices.

Adjacency matrix	0	1	1	0	1	A_5	0	1	1	3	1
	0	0	0	1	0		0	0	0	1	0
	0	0	0	1	0		0	0	0	1	0
	0	0	0	0	0		0	0	0	0	0
	0	0	0	1	0		0	0	0	1	0
Ranking vector	1					Ranking	1. NWS				
	0						2. Media				
	0						2. EM				
	0						2. Public				
	0						2. VOST				

TABLE A5. The knowledge that the Cleburne tornado was moving north (instead of southeast).

Adjacency matrix	0	1	1	0	1	A_5	2	16	3	15	5
	0	0	0	1	0		0	2	0	3	0
	1	1	0	1	1		3	16	2	18	5
	0	1	0	0	0		0	3	0	2	0
	0	0	0	1	0		0	2	0	3	0
Ranking vector	0.5					Ranking	1. NWS				
	0						1. EM				
	0.5						2. Media				
	0						2. Public				
	0						2. VOST				

TABLE A6. Knowledge of a tornadic debris signature in southern Parker County. Note that the calculation for A_k for $k > 2$ is equal to A_2 as A^k for $k > 2$ results in zero matrices.

Adjacency matrix	0	1	1	0	1	A_5	0	1	1	2	1
	0	0	0	1	0		0	0	0	1	0
	0	0	0	0	0		0	0	0	0	0
	0	0	0	0	0		0	0	0	0	0
	0	0	0	1	0		0	0	0	1	0
Ranking vector	1					Ranking	1. NWS				
	0						2. Media				
	0						2. EM				
	0						2. Public				
	0						2. VOST				

TABLE A7. The report that the Cleburne tornado is a mile-wide wedge tornado.

Adjacency matrix	0	1	1	0	1	A_5	2	12	5	9	3
	0	0	0	1	0		0	2	0	3	0
	0	0	0	0	0		0	0	0	0	0
	0	1	0	0	0		0	3	0	2	0
	1	1	1	1	0		3	12	5	12	2
Ranking vector	0.5					Ranking	1. NWS				
	0						1. VOST				
	0						2. Media				
	0						2. EM				
	0.5						2. Public				

TABLE A8. The confirmation of a tornado in Granbury. Note that the ranking here is somewhat trivial because of the extremely low values in A_5. This information was not well communicated in general, so the ranking vector simply shows that a few members of non-NWS groups within the IWT had this information.

Adjacency matrix	0	0	0	0	0	A_5	0	0	0	0	0
	0	0	0	1	0		0	0	2	3	0
	0	0	0	1	0		0	0	2	3	0
	0	0	1	0	0		0	0	3	2	0
	0	0	0	1	0		0	0	2	3	0
Ranking vector	0					Ranking	1. Media				
	0.25						1. EM				
	0.25						1. Public				
	0.25						1. VOST				
	0.25						2. NWS				

TABLE A9. The confirmation of a tornado in Pecan Plantation.

Adjacency matrix	0	1	1	0	1	A_5	8	5	5	8	5
	1	0	0	1	0		9	6	6	7	6
	0	0	0	0	0		0	0	0	0	0
	1	0	0	0	0		5	4	4	4	4
	0	0	0	1	0		4	2	2	3	2
Ranking vector	0.3146					Ranking	1. Media				
	0.3427						2. NWS				
	0						3. Public				
	0.2068						4. VOST				
	0.1359						5. EM				

TABLE A10. Report of baseball-sized hail falling in Granbury.

Adjacency matrix	0	1	1	0	1	A_5	14	15	15	15	15
	0	0	0	1	0		9	8	8	9	9
	0	0	0	0	0		0	0	0	0	0
	1	0	0	0	1		18	18	18	17	18
	1	1	1	1	0		21	21	21	21	20
Ranking vector	0.2381					Ranking	1. VOST				
	0.1429						2. Public				
	0						3. NWS				
	0.2857						4. Media				
	0.3331						5. EM				

TABLE A11. Confirmation of a tornado near Millsap. Note that the rumor or information has been communicated from all groups to all groups by A_2 (there are no zeros in A_2).

Adjacency matrix	0	1	1	0	1	A_5	50	51	51	36	51
	0	0	0	1	0		25	25	25	19	25
	1	0	0	0	1		44	43	43	32	44
	1	1	1	0	1		69	69	69	50	69
	1	1	1	1	0		69	69	69	51	68
Ranking vector	0.1962					Ranking	1. VOST				
	0.0981						1. Public				
	0.1699						3. NWS				
	0.2679						4. EM				
	0.2679						5. Media				

TABLE A12. Confirmation of a tornado near Sunset. Note: the rumor or information has been communicated from all groups to all groups by A_2 (there are no zeros in A_2).

Adjacency matrix	0	1	1	0	1	A_5	54	74	55	45	55
	0	0	0	1	0		26	35	26	22	26
	1	1	0	0	1		55	74	54	45	55
	1	1	1	0	1		74	100	74	61	74
	1	1	1	1	0		74	100	74	62	73
Ranking vector	0.1929					Ranking	1. VOST				
	0.0922						1. Public				
	0.1929						3. NWS				
	0.2610						3. EM				
	0.2610						5. Media				

TABLE A13. Report of significant damage from the tornado in Granbury. Note that the rumor or information has been communicated from all groups to all groups by A_3 (there are no zeros in A_3).

Adjacency matrix	0	1	1	0	1	A_5	90	69	91	44	69
	1	0	1	1	1		121	90	121	61	91
	1	0	0	0	0		31	22	30	16	22
	1	1	1	0	1		121	91	121	60	91
	1	1	1	1	0		121	91	121	61	90
Ranking vector	0.1875					Ranking	1. VOST				
	0.2500						1. Public				
	0.0625						1. Media				
	0.2500						4. NWS				
	0.2500						5. EM				

REFERENCES

Doswell, C. A., III, A. R. Moller, and H. E. Brooks, 1999: Storm spotting and public awareness since the first tornado forecasts of 1948. *Wea. Forecasting*, **14**, 544–557, doi:10.1175/1520-0434(1999)014<0544:SSAPAS>2.0.CO;2.

Foster, H., 1980: *Disaster Planning: The Preservation of Life and Property*. Springer-Verlag, 276 pp.

Lindell, M. K., and R. W. Perry, 1992: *Behavioral Foundations of Community Emergency Planning*. Hemisphere Publishing Corporation, 630 pp.

——, and ——, 2004: *Communicating Environmental Risk in Multiethnic Communities*. Sage, 272 pp.

Mileti, D. S., and J. H. Sorensen, 1990: Communication of emergency public warnings. Oak Ridge National Laboratory Tech. Rep. ORNL-6609, 166 pp.

NOAA, 2013: The historic derecho of June 29, 2012. NOAA Service Assessment, 61 pp. [Available online at http://www.nws.noaa.gov/om/assessments/pdfs/derecho12.pdf.]

NCDC, 2013: Storm Data. [Available online at https://www.ncdc.noaa.gov/stormevents/.]

Nigg, J., 1995: Disaster recovery as a social process. Disaster Research Center, University of Delaware Research Paper 219, 31 pp.

NWS, 2010: Storm-based tornado warning lead time. National performance measures. [A summary of the performance measures is available online at http://focusky.com/wuwb/ggjv.]

Poole, D., 2011: *Linear Algebra: A Modern Introduction*. 3rd ed. Trent University, 728 pp.

——, 2012: *Student Solutions Manual for Linear Algebra: A Modern Introduction*. 3rd ed. Trent University, 540 pp.

Simmons, K., and D. Sutter, 2008: Tornado warnings, lead times, and tornado casualties: An empirical investigation. *Wea. Forecasting*, **23**, 246–258, doi:10.1175/2007WAF2006027.1.

Smith, B. T., J. M. Boyle, B. S. Garbow, Y. Ikebe, and V. C. Klema, 1976: Matrix eigensystem routines–EISPACK guide. *Math. Comput.*, **30**, 188–189.

Sorensen, J., 2000: Hazard warning systems: Review of 20 years of progress. *Nat. Hazards Rev.*, **1**, 119–125, doi:10.1061/(ASCE)1527-6988(2000)1:2(119).

Uzzi, B., and S. Dunlap, 2005: How to build your network. *Harv. Bus. Rev.*, **83**, 53–60.