Hazard Strike Probability as a Measure of Warning Reliability

Peter L. Wolf

National Weather Service, Jacksonville, Florida

(Manuscript received 30 August 2011; in final form 03 November 2011)

ABSTRACT

Defined as the probability of being struck by a warned hazard while within the warning area, hazard strike probability for a tornado or other high-end severe weather hazard is incredibly small. With a focus on providing longer lead times, today's convective warnings yield hazard strike probabilities that are likely much too low for the products to effectively serve as the "go" step in the ready-set-go philosophy, and in fact may be better suited as the "set" step.

This document takes a closer look at hazard strike probability, and evaluates public perception of this concept. The value of the warning as the "set" product, and the need for a more precise community-based, short lead-time "go" product to complete the ready-set-go philosophy, are also examined.

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1. Introduction

Short-fused public warnings for severe thunderstorms and tornadoes are issued with sufficient lead time to allow the public the ability to confirm the existence of a threat at their location, and take immediate protective action if in danger. In 2010, the National Weather Service (NWS) issued 22,807 convective warnings, 3,469 of which were tornado warnings. The average tornado (severe thunderstorm) warning area was 437 (725) mi^2, with one out of every four (two) warnings verifying with an event. Average tornado (severe thunderstorm) warning lead time was 13.8 (17.6) minutes (NWS 2011).

A warning includes language that suggests dangerous weather is occurring, or will occur, within at least a portion of the area warned ([Fig. 1](#)). Warning-based false alarm rate (FAR) scores suggest this actually occurs a minority of the time. Furthermore, the actual

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Corresponding author address: Peter L. Wolf, National Weather Service, 1307 Fang Drive, Jacksonville, Florida 32218
E-mail: peter.wolf@noaa.gov

probability of being struck by life-threatening phenomena, while within the warned area, is much lower than FAR statistics suggest. The probability may be too low for the warning to serve as a reliable indicator of imminent danger, and thus serve as a "go" product in the ready-set-go philosophy that leads to immediate protective action.

Prior social science research on warning response (e.g. Mileti 1995, Mileti and Sorenson [1988, 1990], Lindell and Perry [1992, 2004]) have revealed the warning as the "set" product that prepares people for immediate action, and have discovered two key steps as part of the "go" process leading to warning response. *Threat confirmation* includes actions to confirm the existence of the threat in general. *Threat personalization* includes actions to confirm that one's specific location is in danger. Through these steps, recognition of an imminent local danger subsequently leads to protective action.

2. Hazard Strike Probability

Hazard strike probability (HSP) is defined as the probability of being struck by the warned hazard while located within the warning area (Wolf 2009). Quantitatively, it is defined as **HSP = R1 x R2**, where R1 is the ratio of the average area struck by the hazard to the average area warned, and R2 is the ratio of the number of warnings verified by the warned hazard to the total number of warnings issued. Similarly, it is defined as **HSP = E1/E2**, where E1 is the summation of all areas struck by a warned hazard, and E2 is the summation of all warning areas, including those for unverified warnings. As defined, HSP is directly proportional to hazard area struck, and inversely proportional to warning area and warning-based false alarm rate.

Fig. 2 demonstrates HSP values in relation to hazard strike area and warning area, with the assumption that one out of every four tornado (severe thunderstorm) warnings verifies with a tornado (2 inch or larger hail, or 65 kt or greater wind) report. The NWS does not generate verification statistics for severe thunderstorm warnings based on these "high end" conditions; therefore, the assumption that one in four verifies is suggested based on the fact that a large majority of reports that verify severe thunderstorm warnings are nearer to minimum severe thunderstorm criteria (1 inch hail, 50 kt wind gust or related wind damage).

An example of the HSP computation for tornadoes follows. Schaefer et. al (2002) computed an average tornado strike area of 1.19 km^2 (0.5 mi^2), based on data from the Storm Prediction Center database. The average tornado warning area is around 440 mi^2, and typically one-fourth of tornado warnings verifies with a tornado report (based on 2009-2011 data from NWS 2011). Based on this information, tornado HSP is (0.5/440) x (1/4), or 0.0003, which is equivalent to **1/32nd of 1%**. Some examples of tornado HSP for all of 2010 (NWS 2011), using actual path length and width data, are provided in Table 1 that confirm a minimal HSP value.

HSP is a more accurate representation of false alarms than the presently-computed false alarm rate (FAR). FAR is a warning-based statistic, in which an unverified warning represents one false alarm, regardless if the warning covers one community or one hundred communities, and whether the warning area totals 10 mi^2 or 1,000 mi^2. If a hazard occurs in one out of every two warning areas, yet strikes one out of every 20 communities within a warning area, warning-based FAR is computed to be 0.50, while community-based FAR is 1-HSP, or 0.95. A 0.0003 (0.03%) HSP relates to a location-based FAR of 0.9997 (99.97%).

3. Hazard Strike Probabilities for Extreme Thunderstorm Hazards

For tornadoes, hurricane-force (65 kt or greater) thunderstorm winds, or 2-inch diameter or larger hail, all defined here as "high-end" severe weather, HSPs are incredibly small. This is due to the rarity of the phenomena and the tiny percentage of the warning area affected. The HSP computation for tornadoes is easier than for other severe thunderstorm hazards, because damage path length and width data are generally not computed for hail or wind swaths. While swaths of extreme wind (65 kts or greater) and giant hail (2 inch diameter or greater) are believed to cover areas greater than that for tornadoes, they may still be associated with very low HSPs. For example, a wind damage swath twenty times greater than the average tornado damage path would be associated with an HSP below 1%.

Similarly, for very rare violent, long-track tornado events, average HSP is well below 1%. An examination of verification data from five Gulf Coast NWS offices (Memphis, Jackson, Nashville, Huntsville, Birmingham) during the tornado outbreak of 27 April 2011 which included numerous long-track tornadoes, revealed an average HSP around 0.5% (based on data from NWS 2011). This value related to a location-based FAR of 99.5%, despite the incredible damage that occurred.

An HSP value at or below 0.5% essentially means that a decision to ignore the warning would be "correct", meaning no damage, injury, or loss of life, at or above **99.5%** of the time. Furthermore, given an average tornado HSP of 0.03%, for the strike probability to accumulate (over all warnings received) to at least 5%, one would have to receive **over 160 tornado warnings**, which would take many decades to accomplish. This explains the idea that most people are never directly struck by a tornado in their lifetime.

Of course, strike probability is not uniform across the warning area. For tornado warnings, the tornado threat is maximized, perhaps close to 1% HSP, along the immediate mesocyclone track, dropping to zero away from the track, as conceptually illustrated by Fig. 3. 0.03% is the average tornado HSP for the entire polygon, and an average for all polygons.

NWS verification data indicate that annual national tornado warning-based FAR scores are typically close to 0.75 (NWS 2011), suggesting that 1 out of every 4 warnings verifies with a tornado report. However, for that to be relevant to the general public, it would mean that a person would be struck by a tornado once for every 4 warnings received, potentially once per year in some areas of the country. An HSP value of 1% suggests a person would be struck by the hazard, on average, once for every 100 warnings received. Average tornado HSP is well below 1%. Tornado warning FAR is **greater than 99%** when based on communities or locations struck, as indicated by HSP, rather than on tornado occurrences somewhere within the warning area.

4. Comparison Between Tornado and Hurricane HSPs

Hurricanes produce hurricane-force winds at a variety of diameters, with an average near 100 miles (based on a midpoint of the range provided by NOAA 1999). Tornadoes are dramatically smaller, with an average diameter under 100 m, or 0.06 mile (Schaefer et. al 2002). On average, hurricanes represent vortices **over 1600 times larger** than tornadoes (100 mile vs. 0.06 mile average diameters, respectively). Despite this, warnings issued for hurricanes have diameters generally **less than 30 times larger** than those for tornadoes (300 mi vs. 10-20 mi), assuming that the warning "diameter" is the axis that is most perpendicular to storm motion. In

addition, although precise statistics on hurricane warning verification are unknown, it is believed the ratio of warnings verified by the hazard to total warnings issued is much higher for hurricanes, especially since warnings are issued for *existing* hurricanes compared to *likely* or *potential* tornadoes most of the time. As a result, strike probabilities within a large hurricane warning are dramatically higher than within a small tornado warning. It should be noted that hurricane HSP refers solely to hurricane-force winds, the basis of hurricane warnings, whereas a previously operational Hurricane Strike Probability product focused on all hurricane-related hazards.

For the purpose of estimating a conceptual HSP for hurricane-force winds, let's assume an average area struck to area warned ratio of one-third for hurricanes (using 100 mi by 10 mi for hurricane path dimensions and 300 mi length by 10 mi coastal county width for average warning dimensions). Also assume at least 75% of hurricane warnings verify with a landfall within the warned area, given that a minority of systems weaken to below hurricane status, or change direction of motion away from the warned area. Given these assumptions, the resultant average HSP for hurricane-force winds, while within a hurricane warning area, is one-third of 75%, or around **25%**. This is about **800 times** the average HSP for tornadoes within tornado warning areas.

The difference in warning area is illustrated in Fig. 4, which shows the path of Hurricane Ike on 12 September 2008, and compares the hurricane warning area to a typical tornado warning area. Hurricane-force winds were expected over a 150 mi diameter (based on hurricane wind radii information within National Hurricane Center advisories), within a 500 mi long hurricane warning area.   For comparison, note the small tornado warning polygon over southwest Louisiana, representing a typical tornado warning. Based on HSP, a person is 400

times more likely to experience hurricane-force winds within a large hurricane warning area than to experience a tornado within a much smaller tornado warning area.

For tornado warnings to have even an average 2% HSP (one-tenth of that for hurricane warnings), assuming no change in the ratio of warnings verified to total warnings issued, average tornado warning polygon size would have to be reduced **98.5%** from around 440 mi^2 to around 6 mi^2. Such a tiny polygon, if achievable, would not provide the same average lead times achieved today.

5. Public Perception of Hazard Strike Probabilities

In a large-scale study of convective warning utilization led by UNC-Asheville's Atmospheric Sciences Department (Godfrey et. al 2011), a question on strike probability (Fig. 5) was included in the study's public survey. The scientifically correct answer was "less than 5%", while the answer suggested by warning text products of an imminent threat, and the need for immediate protective action, was "75 to 100%".

Interestingly, none of the 1,555 survey responses indicated "75 to 100%", and just under 1% indicated "50 to 75%", despite what the warning text products suggested. Also, one-fourth (26.7%) of responses indicated the correct "less than 5%" answer. The most popular answer was "5 to 25%", indicated in 43% of completed surveys, followed by "25-50%" in 29% of responses. Little difference in these results was seen between surveys based on severe thunderstorm warnings and ones based on tornado warnings. This suggests the public perceives the probability of being struck by life-threatening conditions, while under a warning, to be low. This result may

be due to the year-after-year accumulation of false alarms that most people experience, as suggested by the extremely low HSP values associated with tornadoes.

Despite the extremely small value of HSP, it is **non-zero**, meaning that homes and businesses occasionally get hit, as illustrated in news media reports when tornadoes occur in populated areas (Fig. 6). Public perception of HSP may help better define the true role of convective warnings for the public. The intent here is not to suggest warnings are not useful products; rather, it is focused on better understanding the role warnings play for the general public, either as a product that leads to immediate protective action, or one that provides notice of the potential near-term need for such action.

6. Discussion

The NWS mission statement focuses not only on *protection of life and property*, but also on *enhancing the national economy*. For warnings to meet both parts, they must be sufficiently timely and accurate to encourage people to take protective action, yet not cause people or businesses to unnecessarily take cover when not in immediate danger.

The NWS convective warning program generally follows the "ready-set-go" philosophy. An outlook provides pre-notification of the need for the ready-set-go approach on a given day. A watch is the "ready" product, issued to indicate potential for severe weather. For a watch, people are urged to continue normal activities, but be "ready" in case warnings are needed in or close to the watch area.

A warning is issued as if it were the "go" product, urging people to take immediate protective action. A warning is typically issued to provide from 10 minutes to over 45 minutes

lead time ahead of the warned storm. In reality, the warning effectively serves as a "set" product, notifying a set of communities within the warning area of the existence of a threat. The warning does not provide specific information, downscaled to a particular community, that would support the *threat confirmation* and *threat personalization* steps documented in numerous studies (e.g. Mileti 1995, Mileti and Sorenson [1988, 1990], Lindell and Perry [1992, 2004]). As defined in these studies, these steps include watching television coverage, viewing warning-related information on the Internet, or looking outside for the approach of threatening weather, with the aim of answering two key questions: (1) does a threat really exist (threat confirmation); and (2) does the threat exist for my specific location (threat personalization). They are critical for generating appropriate warning response, be it protective action when in immediate danger, or no action when not in immediate danger.

There are occasionally barriers that can prevent a warning from being an effective "set" product. As indicated by the above referenced studies, some examples include the following: late night events, when warnings may not be received; outdoor events and travel times, when one might be able to access a warning, but have difficulty confirming and personalizing the threat; and language and disability barriers, which may prevent someone from understanding a warning. Effective threat confirmation and personalization, leading to appropriate warning response, may be inhibited by these barriers.

The warning's role as the "set" step is reflected in the extremely low tornado HSPs, which suggest that ignoring the warning, or delaying protective action until threat confirmation is received, will be "correct" at least 99.9% of the time. NWS warnings do not provide specific community-level information on when to take shelter and when it is safe to exit from shelter. As a potential result, residents may never be in shelter until the storm is on top of them, or may exit

shelter too soon as a result of very long lead times. People are on their own when it comes to threat confirmation and personalization, relying on local TV coverage and what they observe outside, reducing the value of long warning lead times.

The NWS mission would benefit from a "go" product or service that provides specific community-based detail, focuses on the 30-second to 10-minute lead time window, and relates to an HSP of 5% or greater. Fig. 7 shows an example of the "set" and "go" steps from an NWS service perspective. Within a tornado warning polygon, individual "red alert" products would track immediately ahead of the hazard, alerting individual communities based on the immediate need to take protective action, with the alerts cancelled when people in a given community no longer need to be in shelter.

The "go" step could come in the form of live human broadcasts on NOAA weather radio, highlighting areas in immediate danger as well as areas no longer in danger, which could immediately boost the relevance of weather radio in the warning program. It could also come as an internet/smartphone graphical product accessible by a large majority of the population, using a green, yellow, red color scale to highlight when a particular community is in immediate danger (compared to just a large warning polygon). This could be used as a small on-air display by TV stations. Either suggestion can utilize existing technology, and involve a reasonable amount of interactive simulation training for forecasters. A successful "go" step would require a change in forecaster mentality that gives a similar level of priority to threat confirmation information (related to higher HSPs) as that for the initial warnings. While these "go" step suggestions cannot replace visual confirmation in encouraging immediate protective action for tornado warnings, they can provide meaningful information related to higher HSPs. They can support

threat confirmation and personalization, especially in situations such as nighttime events and rain-wrapped tornadoes, when visual confirmation may be nearly impossible.

Today's convective warnings cannot be issued with long lead times without sacrificing HSP, and thus without potentially impacting warning response. A "go" step product or service focused on community-based (10-20 mi^2 area) alerting would provide the public with a more credible HSP, better defining where and when people need to take cover, and when they can exit shelter. NWS offices provide statements indicating "Tornado Emergency" or "Extreme Wind Warning" to highlight the last-minute need to take shelter from an imminent large tornado or major hurricane, respectively. As smaller-scale alerts, they are associated with greater HSPs. However, these alerts are confined to the rarest circumstances, a minority of the tornado and hurricane threats that people face. A similar "go" product or service for all tornadoes, and other life-threatening hazards, could be beneficial to accomplishing the NWS mission.

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TABLES AND FIGURES

Table 1. HSP examples for six anonymous offices in 2010. Data include the assumption that all tornadoes occurring within warned areas were documented. *refers to sites with some longer-track tornadoes.

Office State	Region	Tornadoes	Total Strike Area	Warnings	Total Wrng Area	HSP
PA	Northeast	2	0.30 mi^2	12	3,360 mi^2	1/100 of 1%
NC	Mid Atlantic	10	1.81 mi^2	27	10,746 mi^2	1/64 of 1%
FL	Southeast	5	2.38 mi^2	19	7,448 mi^2	1/32 of 1%
TN *	Lower MS Valley	26*	37.14 mi^2 *	109	50,685 mi^2	1/14 of 1%
MN *	Upper MS Valley	42*	39.74 mi^2 *	97	49,567 mi^2	1/12 of 1%
KS	South-central Plains	24	4.13 mi^2	42	16,800 mi^2	1/40 of 1%
TOTAL		**109**	**85.5 mi^2**	**306**	**138,600 mi^2**	**1/16 of 1%**

THE NATIONAL WEATHER SERVICE HAS ISSUED A

* TORNADO WARNING FOR...
SOUTHEASTERN CANADIAN COUNTY IN CENTRAL OKLAHOMA...
NORTHWESTERN CLEVELAND COUNTY IN CENTRAL OKLAHOMA...
NORTHERN GRADY COUNTY IN CENTRAL OKLAHOMA...
OKLAHOMA COUNTY IN CENTRAL OKLAHOMA...

* UNTIL 545 PM CDT.

* AT 447 PM CDT...NATIONAL WEATHER SERVICE **RADAR INDICATED A SEVERE THUNDERSTORM CAPABLE OF PRODUCING A TORNADO** NEAR MINCO...MOVING NORTHEAST AT 60 MPH.

* LOCATIONS IN THE WARNING INCLUDE...
ARCADIA...BETHANY...CHOCTAW...DEL CITY...EDMOND...FOREST PARK...
HARRAH...JONES...LAKE ALUMA... LUTHER...MIDWEST CITY...MINCO...
MOORE...MUSTANG...NICOMA PARK...OKLAHOMA CITY...SPENCER...
TUTTLE...UNION CITY...VALLEY BROOK...WARR ACRES AND YUKON.

PRECAUTIONARY/PREPAREDNESS ACTIONS...

TAKE COVER NOW. LEAVE MOBILE HOMES AND VEHICLES. IF POSSIBLE... MOVE TO A BASEMENT OR STORM SHELTER. OTHERWISE MOVE TO AN INTERIOR ROOM OR HALLWAY ON THE LOWEST FLOOR. STAY AWAY FROM WINDOWS AND OUTSIDE WALLS.

Figure 1. Example of an NWS tornado warning text product.

Area affected by high-end severe weather (sq mi)	Warning Area (sq mi)									
	100	200	300	400	500	600	700	800	900	1000
1	1/4	1/8	1/12	1/16	1/20	1/24	1/28	1/32	1/36	1/40
3	3/4	3/8	1/4	3/16	3/20	1/8	3/28	3/32	1/12	3/40
5	1.25	5/8	5/12	5/16	1/4	5/24	5/28	5/32	5/36	1/8
7	1.75	7/8	7/12	7/16	7/20	7/24	1/4	7/32	7/36	7/40
10	2.5	1.25	5/6	5/8	1/2	5/12	5/14	5/16	5/18	1/4
20	5.0	2.5	1.67	1.25	1.0	5/6	5/8	3/5	11/20	1/2
30	7.5	3.75	2.5	1.87	1.5	1.25	1.0	15/16	7/8	3/4
40	10.0	5.0	3.35	2.5	2.0	1.67	1.43	1.25	1.11	1.0
50	12.5	6.25	4.2	3.13	2.5	2.0	1.80	1.56	1.39	1.25

Figure 2. HSP values (in percent) as related to average area struck (y-axis) and average area warned (x-axis), assuming one in four warnings verified with a hazard (Wolf 2009).
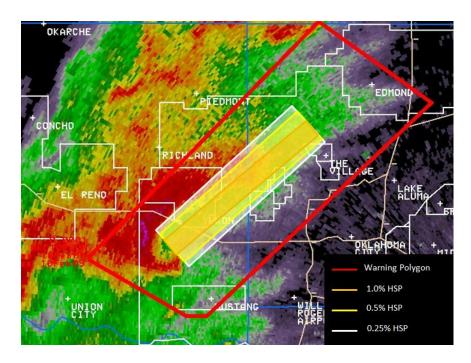
Figure 3. NOAA radar image of a northeastward-moving supercell, with a tornado warning polygon overlaid, along with an overlay of hypothetical HSP values, maximized along the track of the mesocyclone. Legend relates colors to HSP values.

Figure 4. Image of Hurricane Ike forecast path and warning areas, 12 September 2008, from the National Hurricane Center. Light blue shade represents 150 mi width of hurricane force winds expected, based on official advisory information, as Ike tracked inland. Red shade indicates a hurricane warning, while yellow shade represents a tornado warning. (Credit: NOAA)

8. For a given severe weather warning issued for your area, what do you think is the likely range of probability that your location would actually be struck by life-threatening weather (i.e., tornadoes, extreme winds, and/or destructive hail)? (Choose one)

- Less than 5%
- 5 to 25% range
- 25 to 50% range
- 50 to 75% range
- 75 to 100% range
- Unsure

Figure 5. Strike probability question from a public survey used in the 2010 Warning Success Rate study (Godfrey et. al 2011). The survey was completed by participants within severe thunderstorm or tornado warnings during the April-August 2010 time frame across the eastern half of the United States.

Figure 6. Damage photos illustrating the result of violent tornadoes in Smithville MS (left) and Tuscaloosa AL (right) on 27 April 2011. (Credit: NOAA.)
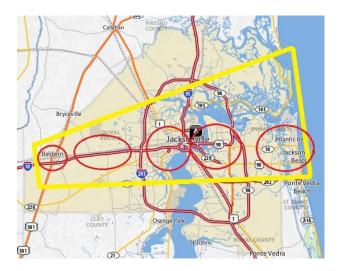
Figure 7. A fictitious illustration comparing a conventional tornado warning (yellow polygon) to higher HSP community-based alert areas (red ovals) leading a tornadic supercell eastward across the metro area of Jacksonville, Florida. The red areas represent areas where immediate protective action is needed ahead of the severe storm, with the alerts cancelled for a community when the threat has ended.