Learning from Public Information Under Conflicting Signals: Evidence from U.S. Tornadoes

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Abstract

How does conflicting information impact the value of public information? We begin with a simple individual protection decision model with normal learning. Individuals receive two types of signals: official public risk information and additional information that is not always available. Our model predicts the heterogeneous value of public information across different information states. We bring our model to data with evidence from the history of U.S. tornadoes since 1986. Given anecdotal evidence that individuals need credible confirmation before seeking protection after a tornado warning, we analyze the impact of visibility, or the ability for individuals to visually confirm tornado risk. This information channel shuts off with sunset. We exploit exogenous variation in tornado touchdowns relative to the precise time of sunset to causally identify the impact of visibility on the value of public warnings vis-a-vis tornado injuries and fatalities. We find that visibility is an important source of information: tornadoes cause more harm just after sunset. However, we find that conflicting information can attenuate the effectiveness of public information, as public warnings are more protective after dark. Lastly, we present evidence of the heterogeneous impact of information across demographic groups.

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1 Introduction

Public information is rarely more immediate or salient that during the cry of a tornado warning. Signaling the imminent threat of an atmospheric twister with winds of up to 300 miles an hour, the National Weather Service recommends individuals seek immediate protection upon hearing the warning (NWS, 2015). However, countless examples of anecdotal evidence show that not everyone seeks shelter upon first hearing a tornado warning. The 2011 EF5 tornado that struck Joplin, Missouri caused 158 fatalities, despite a tornado warning sounded more than 20 minutes in advance. What happened? A National Weather Service report found that "[t]he majority of Joplin residents did not immediately take protective action upon receiving a... warning. Most first chose to further assess their risk by waiting for, actively seeking, and filtering additional information [and]... did not take protective action until processing additional credible confirmation of the threat and its magnitude" (NWS, 2011). When faced with conflicting information and no tornado in sight, individuals hesitated, thereby reducing the lifesaving value of the public information. How, then, is the value of public tornado warnings impacted by alternative sources of information? Would the protective value increase, were alternative information not available? This paper seeks to theoretically and empirically analyze the value of public information across alternative information states.

Understanding these questions begins with how individuals learn about risks. Risks abound in everyday life with many harmful consequences. Estimating the probability that an event may occur is, therefore, a critical task for individuals to both understand and optimally respond. Despite the importance, risk estimation can be costly and time consuming. This can result in inaccurate risk calculations that can lead to inefficient behavior (Carey, 1978) and can have grave consequences, especially in the context of natural disasters (United Nations, 2010). Individuals may also rely on heuristics or rules of thumb (Deryungina, 2013), further exacerbating inefficient decision making.

Risk information has characteristics of a public good, as costs to calculate event probabilities must be borne by one or few, but the benefits of the information can be spread across many. As a result, risk information is typically under-provided by individuals in the private market and a welfare enhancing role for public information exists (Stiglitz, 1999). However, the ultimate value of public information is unclear. Public information is always welfare enhancing if no alternative (private) information exists (Morris and Shin, 2002). The value of public information also depends on potential inefficiencies of information use by private individuals (Angeletos and Pavan, 2007). In addition, information may impact higher order beliefs, therefore leading to reductions in welfare (Cornand and Heinemann, 2006). Therefore, it is critical to understand the interactions between sources of public and alternative information, to gauge how individuals are synthesizing information across different sources and, ultimately, how individuals are motivated to respond to impending risk due to the information. However, information, once available, is difficult to shut off. Thus, it is often difficult to disentangle the impact of various information sources.

We examine the value of public information under different information states in the context of United States tornadoes. We begin with a simple individual protection model with normal learning. Individuals receive two types of signals: official public risk information and additional information that is not always available. Our model predicts the heterogeneous value of public information across different information states. Namely, that alternative information can reduce or eliminate the marginal value of public information, based on the timing and availability of information. We derive three propositions regarding the relative value of public tornado warnings under different information states that can be empirically tested.

We then empirically test our model propositions using a new and comprehensive dataset on tornado touchdowns across the United States from 1986 to 2015. We use official National Weather Service tornado warnings as a proxy for public information. Previous literature has found the development of this warning system to be hugely protective, reducing injuries and fatalities by as much as 50 percent (Sutter and Simmons, 2005; Miller, 2015). We examine the impact of visibility, or the ability to visually confirm a tornado warning, as an additional source of information. This alternative source of information has two useful qualities. First, there is evidence that visual confirmation matters greatly to individuals (NOAA, 2011; Silver and Andrey, 2013; Brotzge and Donner, 2013) as nighttime tornadoes are more fatal than daytime tornadoes, despite being less intense, on average (Ashley, Kremenc, and Schwantes, 2008; Simmons and Sutter, 2011). Second, visibility shuts off with sunset. We exploit the randomness in the precise minute of tornado touchdown relative to sunset to exogenously assign the visibility treatment to each touchdown. As much changes between night and day, we restrict attention to tornadoes just before and after sunset. We examine other potential confounding factors but find no evidence that other factors are systematically changing at the precise time of sunset. We then estimate the marginal impact of a warning across different information states. We test if the availability of visual information can mediate the effectiveness, and therefore protective value, of public risk information. Lastly, we provide evidence on heterogeneous impacts of public and private information across socioeconomic factors.

This paper offers three contributions to the literature. First, we create a protection model with learning. Combining well known adaptation models with a normal learning model, we are able to generate propositions surrounding the impact of alternative information on the value of public information. Second, we causally estimate the impact of alternative information on attenuating the value of public information. We find that alternative information can matter greatly. Lastly, we contribute to the natural disaster literature, finding additional causal determinants of losses and generate new injury and harm functions for tornadoes.

When we discuss the value of public information, this is not synonymous with welfare. Instead, we seek to identify the value in terms of the benefits of public information (i.e., injury or fatality reduction). We do not calculate overall welfare generated from different information states nor the costs of producing the public information. We simply compare the marginal impact of the public information in reducing damages and fatalities across information states. In an information state where the public information is less protective, it has lower value. Our paper proceeds as follows: in Section 2, we present our protection model with learning. In Section 3, we discuss our empirical approach and data. In Section 4, we present and discuss our results. Section 5 concludes.

2 Protection Model with Learning

We present a simple risk protection model inspired by the climate adaptation model of Mendelsohn (2000) and the hurricane adaptation model of Hsiang and Narita (2012). We add learning to the model. We assume that individuals do not perfectly observe the true risk probability and, instead, learn from sources of information that may not always be available. Individuals update beliefs through normal learning in the spirit of Foster and Rosenzweig (1995). Our model generates testable propositions regarding the value of public information across differing information states.

Assume a tornado will touchdown with probability π. An individual wants to minimize the costs generated from this tornado risk by choosing an optimal level of protection, P. Tornado costs include direct physical harm, H(P), and the costs of protection, D(P). The individual will do so by choosing a level of protection, $0 \leq P \leq 1$, which maximizes net benefits from protection, where the benefit from protection, B(P) is the value of physical harm avoided equal to the level of harm with no protection, $H(P_0)$, minus the level of harm with protection, H(P): $B(P) = H(P_0) - H(P)$. If no tornado hits, the benefit from protection is zero.

$$\max_{P} \pi B(P) + (1 - \pi)(0) + C(P) \tag{1}$$

The individual will protect until $\pi MB(P) = MC(P)$.

A few points are important to note regrading the driving factors of the protection decision. First, in this model, we consider very short run protection strategies such as retreat to tornado shelters or basements. We do not consider the important but longer run decision to construct shelters or strengthen existing structures.

Second, both physical harm and protection can be costly. Tornadoes cause an average of 60 fatalities and more than 1,200 individuals injuries per year across the United States alone. The value of these losses can be estimated in the non-market valuation literature. However, the cost of protection, C(P) is also not trivial. A large portion is the opportunity cost of time spent under protection. From 1996-2004, an estimated 234 million person-hours were spent under tornado warnings annually in the United States[1], equal to roughly \$2.7 billion per year. Thus, not everyone protects, as in some cases as few as 40 percent of individuals actually seek protection during an active tornado warning (Sutter and Erickson, 2010).

Third, an individual's marginal benefit of protection as well as costs of protection are are relatively fixed in the very short run. The Value of Statistical Life as well as value of bodily harm estimations change slowly over time, driven mainly by income growth (Viscusi, 1993). In the very short run, opportunity cost of time remains constant and is typically approximated by the wage rate (Shaw, 1992). Throughout the day, the ability to protect may change, given proximity to appropriate shelters, however in the very short run, the costs are more or less fixed.

Lastly, π is trivially small for most locations and at most times. However, π changes quickly across space and time. Therefore, given these factors, we argue that changes in π will drive protection decisions in the very short run. We now add learning about π to our model.

Now assume that the individual cannot perfectly observe π. Instead, she has some prior belief, π_0 surrounding the true probability with some precision, h. The individual then updates her belief surrounding π from two sources of information: a signal from official weather forecast, π_f, that is drawn from a normal distribution around the truth with precision h_f, $\pi_f \sim \mathcal{N}(\pi, \frac{1}{h_f})$, and a signal from visual confirmation, π_v, that is drawn from a normal distribution around the truth with precision h_v, $\pi_v \sim \mathcal{N}(\pi, \frac{1}{h_v})$. The official weather forecast is always available. However, the visibility channel is only available during day. Using Bayes Rule, the daytime posterior belief is:

$$\pi_d = \frac{h\pi_0 + h_f\pi_f + h_v\pi_v}{h + h_f + h_v} \tag{2}$$

where the weight placed on the warning is $\frac{h_f}{h+h_f+h_v}$ and the weight placed on visibility is $\frac{h_v}{h+h_f+h_v}$, where $h + h_f + h_v = 1$. At night, there is no visibility signal. Thus, the nighttime

[1] A city of one million under a tornado warning for one hour would equal one million person-hours.

posterior is:

$$\pi_n = \frac{h\pi_0 + h_f\pi_f}{h + h_f} \tag{3}$$

where the weight placed on the warning is $\frac{h_f}{h+h_f}$ and $h + h_f = 1$.

Using this framework the signal space consists of six distinct information cases, denoted in Table 1. A tornado touchdown could occur with or without an official public tornado warning, and at night – when no tornadoes are visible – or during the day, when a tornado may or may not be visible. Note that not observing a tornado during the daytime (Case 3) is different than not being able to observe a tornado at night (Case 5). Given this framework, we

Table 1: Tornado Signal Space

	Daytime		Nighttime
	See	Don't See	No Visibility
Warning	Case 1	Case 3	Case 5
No Warning	Case 2	Case 4	Case 6

generate propositions regarding protection behavior across different states within the tornado signal space. Each proposition will conclude with a remark on the differential value of public information across these information states. In this model, we define the value of public information in terms of comparative static comparisons of the level of protection that an individual undertakes due to public information across different information states. It is not a comment on the overall level of welfare.

Proposition 1 *An individual will undertake a higher level of protection when a public tornado warning is sounded in locations with higher forecast precision if a tornado is not visible.*

We show Proposition 1 holds across information states where warnings are levied if a tornado is not already visible (Case 3 and 5). We begin with Case 3. By definition, since a warning has been sounded by no tornado is visible, $\pi_f > \pi_v$. The optimal level of protection, $P^*_{f_L}$ under Case 3 with low forecaster precision solves:

$$\frac{h\pi_0 + h_{f_L}\pi_f + h_v\pi_v}{h + h_{f_L} + h_v} MB(P^*_{f_L}) - MC(P^*_{f_L}) = 0 \tag{4}$$

Since $h_{f_H} > h_{f_L}$, then higher weight is placed on the warning signals, $\frac{h_{f_H}}{h+h_{f_H}+h_v} > \frac{h_{f_L}}{h+h_{f_L}+h_v}$. The updated belief about the probability of a tornado increases:

$$\frac{h\pi_0 + h_{f_H}\pi_f + h_v\pi_v}{h + h_{f_H} + h_v} > \frac{h\pi_0 + h_{f_L}\pi_f + h_v\pi_v}{h + h_{f_L} + h_v} \tag{5}$$

Without changing the level of protection, and by definition of Case 3, the probability of tornado signaled by the forecast is greater than the probability signaled by visibility, $\pi_f > \pi_v$, the marginal benefits from protection exceed the marginal costs. This, Equation 4 becomes:

$$\frac{h\pi_0 + h_{f_H}\pi_f + h_v\pi_v}{h + h_{f_H} + h_v} MB(P^*_{f_L}) - MC(P^*_{f_L}) > 0 \tag{6}$$

Therefore, the level of protection must be increased until net benefits are maximized:

$$\frac{h\pi_0 + h_{f_H}\pi_f + h_v\pi_v}{h + h_{f_H} + h_v} MB(P^*_{f_H}) - MC(P^*_{f_H}) = 0 \tag{7}$$

Thus, $P^*_{f_H} > P^*_{f_L}$. Individuals will protect more when a warning is levied in an area with higher forecaster precision. Identical logic can be used to show higher levels of protection occur in Cases 5 when a warning is sounded in an area with higher forecaster precision.

Remark 1 *Public information, in a state of conflicting or absent alternative information, is more valuable when generated with higher precision.*

Proposition 1 leads to our first remark on the value of public information. Namely, we find that public information is more valuable (i.e., leads to a higher level of protection) when it is produced with higher precision.

Proposition 2 *Late warnings during the day are less protective, relative to early warnings. However, late warnings at nighttime are just as protective, relative to early warnings.*

We first turn to the case where public information is late during the day. Namely, a tornado has already made touchdown and has been seen (as in Case 1 and 2). With both cases, all weight is placed on the visibility channel, $h_v = 1$:

$$\pi_{C1,C2} = \frac{h\pi_0 + h_f\pi_f + h_v\pi_v}{h + h_f + h_v} = \frac{0\pi_0 + 0\pi_f + 1\pi_v}{0 + 0 + 1} = 1 \tag{8}$$

The optimal protection decision for Case 1, P^*_{C1}, and Case 2, P^*_{C2}, is one that solves:

$$\pi_v MB(P^*_{C1}) - MC(P^*_{C1}) = \pi_v MB(P^*_{C2}) - MC(P^*_{C2}) = 0 \tag{9}$$

Thus, when moving from Case 2 to Case 1, signifying a warning sounded after a tornado makes touchdown, the marginal value of the warning is equal to zero as the warning does not change the protection decision.

Of course, public warnings can still hold value when sounded late, as signal space may be heterogeneous across the population (i.e., some individuals may have already seen the tornado (Case 1) while others may not (Case 2). Thus, the conclusion of the model is not that warnings should not be sounded lated. Instead, late warnings may still hold value in the real world, although less value than if sounded early.

We next analyze the impact of late public information at night, when the visibility information channel is shut off, namely going from Case 6 to Case 5. The optimal protection decision in Case 6, P^*_{C6}, is:

$$\frac{h\pi_0 + h_f\pi_{f_{C6}}}{h + h_f} MB(P^*_{C6}) - MC(P^*_{C6}) = 0 \tag{10}$$

In moving from Case 6 to Case 5, when a warning is levied, by definition, a tornado touchdown is higher probability, $\pi_{f_{C5}} > \pi_{f_{C6}}$. Holding everything else constant, the higher probability from the forecast channel will lead to an higher probability in the updated belief:

$$\frac{h\pi_0 + h_f\pi_{f_{C5}}}{h + h_f} > \frac{h\pi_0 + h_f\pi_{f_{C6}}}{h + h_f} \tag{11}$$

All else equal, this will increase the marginal benefit term of protection. Without changing the optimal level of protection, net benefits will not be maximized:

$$\frac{h\pi_0 + h_f \pi_{f_{C5}}}{h + h_f} MB(P^*_{C6}) - MC(P^*_{C6}) > 0 \tag{12}$$

Thus, a late warning after dark will lead to a higher level of protection: $P^*_{C5} > P^*_{C6}$, where P^*_{C5} solves the following equality:

$$\frac{h\pi_0 + h_f \pi_{f_{C5}}}{h + h_f} MB(P^*_{C5}) - MC(P^*_{C5}) = 0 \tag{13}$$

Intuitively, a late warning after dark will still have value added, as individuals do not have an alternative source of updating information, unlike during the day. Thus, in this simple model, a late warning has higher marginal value after dark, leading to our second remark on the value of public information.

Remark 2 *Public information is less valuable when disseminated after alternative sources of information have already alerted the risk. This is not true for late public information in the absence of alternative information.*

Lastly, we compare the overall value of an early public warning, one that is sounded before a tornado is visible, during the day relative to an early warning at night. We find that an early warning should have more value when it is sounded at night, as there will be no conflicting information to attenuate its impact. However, during the daytime, individuals will seek credible confirmation through the visibility channel. By definition, as not tornado is visible in a daytime early warning, the protective value of the warning will be reduced, relative to at night. This leads to our final proposition.

Proposition 3 *Nighttime early warnings are more protective than daytime early warnings.*

First, we begin with an early warning at night (Case 5). The optimal decision to protect, P^*_{C5}, is the level of protection that satisfies the following equation:

$$\frac{h\pi_0 + h_{f_{C5}} \pi_f}{h + h_{f_{C5}}} MB(P^*_{C5}) - MC(P^*_{C5}) = 0 \tag{14}$$

Note that the relative weight placed on the public forecast is $\frac{h_{f_{C5}}}{h+h_f}$. Next, we change to an early warning during the daytime, Case 3. First, we note that less weight is placed on the forecast in Case 3, relative to Case 5, as the forecast has not changed, $\pi_{f_{C3}} = \pi_{f_{C5}}$, however the relative weight placed on the forecast decreases, $\frac{h_{f_{C5}}}{h+h_{f_{C5}}} > \frac{h_{f_{C3}}}{h+h_{f_{C3}}+h_v}$. Thus, the posterior belief of the probability of a tornado is lower during a daytime warning, relative to at night, assuming that the visibility channel as some positive level of precision, $h_v > 0$ and because $\pi_f > \pi_v$, based on the definition of Case 3 (a daytime early warning):

$$\frac{h\pi_0 + h_{f_{C3}}\pi_f + h_v\pi_v}{h + h_{f_{C3}} + h_v} < \frac{h\pi_0 + h_{f_{C5}}\pi_f}{h + h_{f_{C5}}} \tag{15}$$

Thus, applying the optimal level of protection in Case 5 to Case 3, we find that too much protection is taken, where the marginal costs exceed the marginal benefits of protection:

$$\frac{h\pi_0 + h_{f_{C3}}\pi_f + h_v\pi_v}{h + h_{f_{C3}} + h_v} MB(P^*_{C5}) - MC(P^*_{C5}) < 0 \tag{16}$$

Thus, the optimal level of protection from a daytime warning, P^*_{C3}, is lower than the optimal level at night. All else equal, the value of an early tornado warning sounded at night is greater than an early warning sounded at day. This brings us to our final remark regarding the value of public information.

Remark 3 *In the absence of conflicting information, public information is more valuable.*

We now turn to empirically validating these testable model propositions and estimating the differential value of public information across different information states, in the context of the tornado warning system in the United States.

3 Empirical Approach

Guided by our simple theoretical model, we test for empirical evidence of our three model propositions concerning the differential value of public information on tornado protection decisions. We do not directly observe an individual's protection decision. Instead, we observe the information states present at the time of tornado touchdown as well as the injuries and fatalities resulting from almost 30,000 tornadoes across the United States. From that, we estimate the value of public warnings as the marginal impact they have on reducing observed injuries and fatalities. Specifically, we analyze the impact of visibility, as a separate source of information, on the protective impact of tornado warnings. We assume the visibility channel is not available at night. However, many factors change from day to night that will impact the protection decision, potentially confounding our analysis. Therefore, we focus on a restricted set of tornado that touch down just before and after sunset. For causality, the timing of tornado touch down, relative to sunset, must be exogenous and uncorrelated with any unobservables. We argue that with a small enough bandwidth surrounding the time of sunset, this will hold. We present additional evidence in support of this claim in our results section. We the exploit this exogenous variation in the timing of tornado touchdown relative to the precise timing of sunset to identify the causal impact of visibility on tornado harm. Through this strategy, we identify the causal impact of visibility on the value of public information.

We begin with the key variables in our empirical harm functions to test for empirical evidence of each proposition. Given that our propositions detail the relative value of public information across various information states, we modify our harm functions to explicitly test for each proposition. Our dependent variable of physical harm (H_{it}) is the count of either injuries or injuries plus fatalities in county i from tornado t. We explain harm as a function of darkness (D_{it}, represented by minutes after sunset), and the occurrence of a tornado warning (W_{it}, taking the value 1 if a warning was sounded and 0 otherwise). The weather forecasting office's false alarm ratio, F, representing the fraction of warnings in our dataset that are sounded but not followed by a tornado, is included as a proxy for forecaster precision. We also include tornado (T_{it}) and socioeconomic (X_{it}) control variables, as well as the underlying tornado risk rate, R_i, or the count of tornadoes experienced in location i during our study. We also restrict our attention to tornadoes touching down within 65 minutes of sunset and test additional time windows for sensitivity.

Given the count variable as our dependent variable, we use the negative binomial estimator to estimate our harm equations. We also use decade and regional fixed effects in our robustness checks, but due to the debate over proper implementation of fixed effects in nonlinear models (Greene, 2007), we do not include them as our main results. However, our results do not change.

In order to test for evidence of Proposition 1, that forecaster precision matters, we estimate the following equation:

$$H_{it} = \beta_0 + \beta_1 W_{it} + \beta_2 F_{it} + \beta_3 F_{it} \cdot W_{it} + \beta_4 R_i + \beta_5 T_{it} + \beta_6 X_{it} + \epsilon_{it} \tag{17}$$

We expect the estimated coefficient on the interaction between forecaster precision and a tornado warning, β_3 to be positive and statistically significant. This would imply that, conditional on a tornado warning, the marginal impact of the warning in protecting citizens is reduced. Higher levels of harm occur in areas where forecasters are less precise.

In order to test for evidence of Proposition 2, that late warnings are less protective during daytime, relative to nighttime, we want to compare the marginal impact of an early versus late warning at day versus at night. If Proposition 2 is correct, then the impact of a late warning during daytime should be significantly less than the impact of an early warning. However, the differential impact of a late versus early warning should not be statistically significant after dark. Thus, we run the following specification four time, using subsamples of our data including: 1) early daytime warnings versus no warnings, to isolate the marginal impact of an early daytime warning, 2) late daytime warnings versus no warning, to isolate the marginal impact of a late daytime warning, 3) early nighttime warnings versus no warnings, to isolate the marginal impact of an early nighttime warning, and 4) late nighttime warnings versus no warnings, to isolate the marginal impact of a late nighttime warning. We do so with the following equation:

$$H_{it} = \beta_0 + \beta_1 W_{it} + \beta_2 R_i + \beta_3 T_{it} + \beta_4 X_{it} + \epsilon_{it} \tag{18}$$

Using the F-test, we can compare the estimated β_1 coefficient across each of the four subsample regressions to analyze if public information has a statistically different value across varying information states. Specifically, if our proposition is true, β_1 should be more negative (indicating a higher level of protective power) for daytime early warnings, relative to daytime late warnings. However, β_1 should not be significantly different across nighttime early and late warnings.

In order to test for evidence of Proposition 3, that tornado warnings are more protective after dark, we estimate the following regression equation:

$$H_{it} = \beta_0 + \beta_1 W_{it} + \beta_2 D_{it} + \beta_3 D_{it} \cdot W_{it} + \beta_4 R_i + \beta_5 T_{it} + \beta_6 X_{it} + \epsilon_{it} \tag{19}$$

We expect that warnings are protective, $\beta_1 < 0$, but that warnings are more protective after dark, $\beta_3 < 0$.

Lastly, using data on the characteristics of individual fatalities, we also present suggestive evidence on the heterogeneous impact of public information and visibility across demographic characteristics X_{ft}, including gender, age, and income, of individual fatalities f for tornado t.

$$X_{ft} = \alpha_0 + \alpha_1 D_{ft} + \alpha_2 W_{ft} + \alpha_4 T_{ft} + \epsilon_{ft} \tag{20}$$

We estimate the above equation using the logit model and interpret the estimated coefficient as the impact of a variable on the log odds that a fatality will have the dependent variable characteristic.

3.1 Data

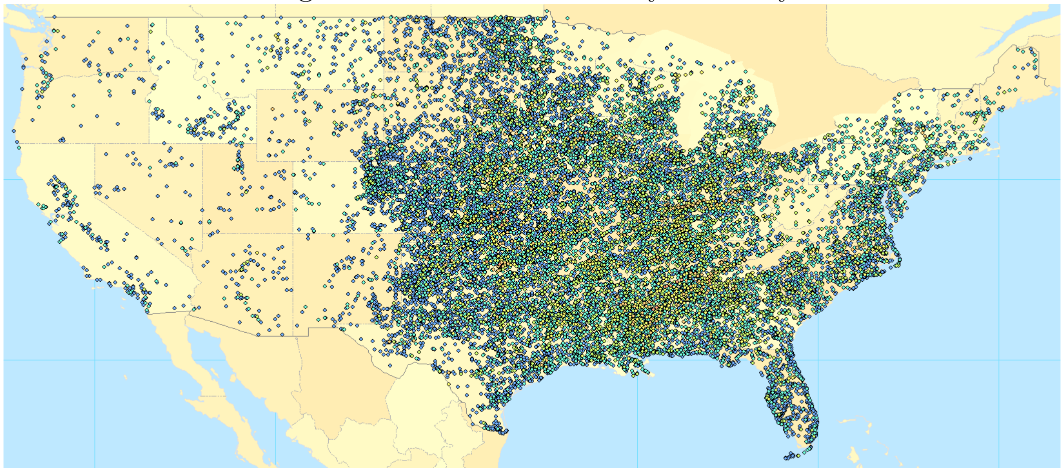
We construct an original dataset at the county-tornado level using the complete history of tornadoes in the United States from 1986 to 2015. We collect data on all tornado events from the NOAA National Center for Environmental Information's Storm Events Database. The database includes events at the county level with fatality and harm records. In addition, the database includes tornado characteristics such as the length, width, latitude, longitude, and F or EF scale category. This data source also provides basic demographic information for fatalities, including the individual's gender, age, and location of death. We match the events with data on tornado warnings from the National Weather Service's Performance Verification. Local NWS stations verify the truthfulness of tornado warnings, including warning lead time if the warning was accurate. This information is compiled by Performance Verification. We precisely calculate the time of sunset for each tornado using the recorded latitude and longitude coordinates from the events database and using NOAA's Solar Calculator[2]. Sunset times were randomly chosen and cross verified with external sunset information to be sure the Solar Calculator algorithm was properly implemented. Finally, we match the point and year of tornado touch down with county-level population and real income information from the U.S. Bureau of Economic Analysis.

All together, we have more than 33,000 tornadoes in our data set from 1986 - 2015 accounting for 1,925 lives lost and 29,612 injuries. Figure 1 maps all tornado touch downs by EF-scale included in our sample. The tornado events are color coded, with slower wind speeds indicated by blue and highest wind speeds in red. As shown in the figure, the Central and Eastern United States are most impacted by tornadoes, but events occur throughout the contiguous 48 states. We also have data on tornadoes in Hawaii and Alaska included in our dataset, but have excluded them from the figure.

Tornadoes provide a useful case to analyze the value of public information. First, tornadoes occur frequently and randomly. An average of 1,253 tornadoes touch down within the United States each year (NCEI, 2015). Contrary to popular belief, tornadoes touch down randomly within a weather system. Tornadoes do not avoid cities. In addition, human activity cannot cause a tornado to form or shift (SPC, 2015). Therefore, tornado touch downs are exogenous. Second, tornado risks change very quickly. Therefore, risk assessments must be made rapidly, sometimes in a matter of minutes, and with imperfect information.

[2] NOAA recently acknowledged some measurement error with the latitude and longitudes from some of the events in the Storm Events Database. However, these errors only miscalculate the true event location by as much as ten miles, which has no significant impact on the time of sunset.

Figure 1: Tornado Events by Intensity



Third, there is a clear, central source of public risk information through the National Weather Service's (NWS) tornado warnings. A tornado warning is sounded by the local NWS office and signals an imminent threat from potential tornado touch down. While visual sighting of tornadoes is one of the four methods by which a warning will occur, it represent a small fraction of warning triggers[3]. Due to current technology, warnings are overwhelmingly sounded due to atmospheric conditions and radar signatures consistent with elevated tornado threat[4]. Previous work has shown the clear value of warnings at reducing fatalities and injuries (Simmons and Sutter, 2005; Miller, 2015). However, no work has examined potential attenuation of value due to competing sources of information.

Fourth, there is existing evidence that alternative sources of information, including heuristics, matter for tornadoes. For example, nighttime tornadoes are more deadly than daytime tornadoes (Ashley, Kremenc, and Schwantes, 2008), despite being weaker and less frequent, on average (Davies and Fischer, 2009; Kis and Straka, 2010). In addition, there is a nonlinearity between warning lead time and fatalities, with lead time being protective until approximately 15 minutes before a tornado, after which the beneficial impacts decrease (Simmons and Sutter,

[3] The four sufficient conditions to sound a tornado warning are: 1) a tornado touchdown reported, 2) a funnel cloud reported, 3) a low-level and strong rotation is present in the radar, or 4) a waterspout over water is moving toward land.

[4] This information was gathered through a telephone interview with a tornado meteorologist at the National Weather Center's Storm Prediction Center and discussions with meteorologists at the Southern Arizona Office of the National Weather Service.

2008)[5]. The credibility of the warning system matters (Ripberger et al., 2015). Fifth, while protecting infrastructure from tornado damage can be difficult do to the very high wind speeds, with top winds of more than 300 miles per hour, more than twice the wind speed of a Category 5 hurricane. Protection from bodily harm and mortality is possible if suitable infrastructure, such as a basement, tornado shelter, or even ditch, is available. Therefore, individuals must make calculated decisions in the moment, but have options for protection available. Lastly, the impact of tornadoes are immediately observable. Unlike climate change, where misinformation may take decades or more for impacts to be observed, harm from tornadoes can be observed immediately following an event. Therefore, error in calculating impending probabilities can be observed immediately as well. For these reasons, we believe tornadoes to be a useful study for this question.

4 Results and Discussion

We present and discuss results in this section, in order of our model propositions. We begin with Proposition 1 regarding forecaster precision. While Proposition 1 does not give insight into the impact of conflicting or alternative sources of information on the value of public information, it is a useful empirical test to verify the signal precision matters. Empirical support of Proposition 1 will support the normal learning assumption of the protection model. Precision mattering is a necessary but not sufficient condition of the normal learning model. The proposition also gives insight into additional factors that impact the value of public information.

We present our empirical estimates of Equation 17 in Table 2. Note that the proposition does not predict differential impact of precision across day and night. Therefore, we use all tornadoes in our dataset across all 24 hours of the day. We find strong evidence of Proposition 1 as precision matters. The frequency of false alarms increases injuries. In addition, conditional on a warning, the count of injuries from a tornado increases by, on average, two percent for every three false alarms sounded by a local weather forecasting office. This interaction between

[5] However, the authors note that this relationship is mainly driven by a handful of very intense tornadoes.

a warning and the false alarm frequency is statistically significant.

In addition, the control variables are included statistically significant and of the expected signs, with larger tornadoes causing more injuries. Areas with higher populations also have higher levels of injury. In addition, areas with more frequent tornadoes have fewer injuries on a per-tornado basis. This is evidence of adaptation (Bakkensen and Mendelsohn, 2016).

Table 2: Public Information Precision

	Injuries
Warned	-0.597***
	(0.151)
False Alarm Frequency	0.00323
	(0.00246)
Warned X False Alarm Frequency	0.00602**
	(0.00276)
Tornado Length	0.212***
	(0.0107)
Tornado Width	0.00389***
	(0.000234)
Underlying Risk	-0.0156***
	(0.00199)
County Population	1.95e-06***
	(1.92e-07)
Constant	-2.378***
	(0.135)
Observations	22,833

Note: Standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

We next turn to empirical evidence of Proposition 2 and 3, which are the main empirical results of this paper. Recall that our identification strategy is based on the assumption that the precise timing of tornado touchdown is random with respect to the minute of sunset, and sunset is orthogonal to any unobservable factors. We first analyze if sunset correlates with any systematic differences across our observable data. Are tornadoes, warnings, or landfall locations different just before and after sunset? If so, our identification strategy would be confounded. We present summary statistics in Table 3 for relevant variables in our analysis for subsamples of our data that occur within 65 minutes before or after sunset. We use a difference in means (t-test) to statistically examine the relationship between these data. We find no statistically significant differences. We find that tornado event intensity and size are not different just before and after sunset. In addition, we find no evidence that warnings are sounded with any difference in frequency, lead time, or accuracy surrounding sunset. This is consistent with conversations with National Weather Service meteorologist regarding information they use to sound warnings. Lastly, we find no different in socioeconomic or damage impact just before and after sunset. This gives us confidence that other factors are not changing before and after sunset, although we will explore this more formally in the paper.

Table 3: Summary Statistics: Before and After Sunset

	Light	Dark	Probability
Tornado EF Scale (1-5)	1.50	1.48	0.41
	(.79)	(.74)	
Tornado Length (Miles)	2.72	2.78	0.68
	(6.87)	(4.41)	
Tornado Width (Yards)	222.53	232.13	0.42
	(329.97)	(306.26)	
Warning (1 if warned)	0.74	0.75	0.37
	(.44)	(.43)	
Warning Lead time (Min)	12.96	13.32	0.32
	(14.46)	(14.30)	
False Alarm (1 if false alarm)	0.33	0.35	0.26
	(.47)	(.48)	
Population (Ppl)	89,231	80,959	0.23
	(294,691)	(228,468)	
Income ($2008)	3,071,811	2,713,037	0.18
	(1.18e+07)	(8,578,875)	
Damage ($2008)	1,316,795	1,268,602	0.88
	(1.14e+07)	(1.01e+07)	

We next turn to empirical evidence for Proposition 2, that a late warning during the day (night) is less (just as) protective than an early warning. We run the four regression equations described in Equation 18 and present our results in Table 4. Each of the four columns include identical variables but are estimated using subsamples of the data to analyze the impact of early daytime warnings (Column 1), late daytime warnings (Column 2), early nighttime warnings (Column 3) and late nighttime warnings (Column 4). We find evidence in support of Proposition 2. A late daytime warning (Column 2) has no statistically significant impact on injuries. Thus, a late daytime warning has, on average, no marginal value to protect. However, an early warning during the day is very protective, reducing injuries, on average, by 60 percent when sounded. Using an F-test, these two coefficients are statistically different from each other. At nighttime, the impact of a late warning is just as protective as an early warning and both are statistically different from zero. These results are consistent with the theory that individuals weight a daytime warning with other information. However at night, when the visibility channel is shut off, more emphasis is placed on the warning. Note, however, that this does not imply that tornado warnings should not be sounded late during daytime as the could provide additional useful information. Rather, that the late public information loses much of its value when individuals can already access the information from a different source.

Table 4: The Value of Late Warnings

	(1)	(2)	(3)	(4)
	Daytime Early Warning vs No Warning	Daytime Late Warning vs No Warning	Nighttime Early Warning vs No Warning	Nighttime Late Warning vs No Warning
Variables	Injuries	Injuries	Injuries	Injuries
Warning	-0.618***	0.131	-1.050***	-1.061*
	(0.235)	(0.350)	(0.270)	(0.592)
Tornado Length	0.241***	0.164***	0.204***	0.263***
	(0.0317)	(0.0449)	(0.0438)	(0.0855)
Tornado Width	0.00490***	0.00605***	0.00508***	0.00450**
	(0.000653)	(0.00142)	(0.000934)	(0.00203)
Underlying Risk	-0.0158***	-0.00989	-0.0302***	-0.0269**
	(0.00576)	(0.00783)	(0.00768)	(0.0111)
County Population	2.52e-06***	2.01e-06***	2.75e-06***	2.62e-06*
	(5.35e-07)	(6.93e-07)	(6.58e-07)	(1.42e-06)
Constant	-2.800***	-2.847***	-1.660***	-1.821***
	(0.254)	(0.440)	(0.306)	(0.758)
Minute Bin	+- 65	+- 65	+- 65	+- 65
Observations	3,164	1,170	2,250	781

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

We now present detailed evidence regarding Proposition 3, that public information is more valuable in the absence of alternative information. In other words, a nighttime warning should be more protective than a daytime warning. Similar to Proposition 2, we examine tornado touchdowns occurring just before and after sunset. Since tornadoes occur randomly across space as well as time of day, we consider these results to be causal with respect to the private visibility information as well as for the interaction between visibility and public warnings. We present our regression results in Table 5. Column 1 presents results for injuries and column 2 presents results for all harm (injuries plus fatalities) from tornadoes that made touch down within 65 minutes of sunset.

We find significant evidence of the differential impact of public warnings across different information states. First, tornado events just after sunset cause more harm than events during daylight minutes. The negative binomial estimated coefficients imply that a tornado occurring 15 minutes after nightfall would lead to an 18 percent increase in injuries, or about 0.25 additional injuries per tornado. We find warnings to be very protective, similar to previous literature. A warned event will have 70 percent fewer injuries, or roughly 1 fewer injury per event, translating to more than 1,200 fewer injuries per year. Lastly, as predicted by Proposition 3, a warning sounded at night almost cancels out the loss of visibility, with a warning sounded 15 minutes after sunset would reduce harm by 15 percent. Thus, tornado warnings sounded when credible confirmation through the visibility channel is not possible are significantly more protective than warnings levied during the day. We argue that this is causal evidence on the differential value of public information across information states.

4.1 What Changes with Sunset?

To argue a causal relationship between visibility and the impact of tornado warnings, we must show that nothing else changes with sunset that could potentially confound the relationship we observe. In the section, we present evidence against alternative explanations, including variation in the sounding of public tornado warnings, the intensity of tornado, changes in

Table 5: The Value of Public Information in the Absence of Alternative Information

	(1)	(2)
	Injuries	All Harm
Minutes After Sunset	0.0117***	0.0117***
	(0.00404)	(0.00403)
Warning	-0.763***	-0.712***
	(0.169)	(0.167)
Minutes After Sunset x Warning	-0.00952**	-0.00832*
	(0.00463)	(0.00461)
Tornado Length	0.214***	0.211***
	(0.0228)	(0.0225)
Tornado Width	0.00486***	0.00517***
	(0.000486)	(0.000490)
Underlying Risk	-0.0205***	-0.0198***
	(0.00416)	(0.00410)
County Population	2.69e-06***	2.71e-06***
	(4.06e-07)	(4.20e-07)
Constant	-2.247***	-2.251***
	(0.180)	(0.178)
Minute Bin	+- 65	+- 65
Observations	5,871	5,871

Note: Standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

availability of information, and the marginal cost of protection. We do not find evidence in support of these alternative explanations.

First, we explore the potential that tornado warnings may differ before and after sunset. It is possible that tornado warnings may be sounded with greater probability before sunset due to visibility or may be sounded with longer lead times. As shown in our summary statistics, we find neither in the data as there is no significant change between the frequency or lead times in warnings just before and after sunset. In addition, a tornado meteorologist at the National Weather Service's Performance Verification department confirmed this during an interview, saying that the majority of tornado warnings are sounded before a tornado occurs and forecasters rely greatly on radar evidence instead of waiting for visual confirmation. The goal of a warning is to sound before the tornado touches down, so reliance on visual confirmation conflicts with this objective. Therefore, we do not find evidence that tornado warnings are systematically different just before and after sunset.

Second, we explore if tornado characteristics are different before and after sunset. There is a documented relationship between tornado intensity, frequency, and time of day. Tornadoes are, on average, strongest in the later afternoon (Davies and Fischer, 2009; Kis and Straka, 2010). However, this would lead to a bias in the opposite direction of our findings, implying that tornadoes just before sunset are more fatal. In addition, we control for intensity through both the size and duration of the storm. In addition, we find no significant difference between tornado characteristics just before and after sunset.

Third and fourth, we explore the potential that the marginal cost of protection or the availability of public information differs before and after sunset. We cannot directly control for surviving individuals' locations nor do we observe information intake at the individual level. There could be key times throughout the evening when both the marginal cost of protection and the dissemination of information alters. For example, for sunsets occurring early in the evening during winter, many individuals are still at work or school. It is likely that information would be quickly transmitted within a school or workplace, and locations to shelter in have been systematically thought out. However, when individuals commute home, protection and information opportunities change. Cars remain vulnerable to tornadoes and, other than listening to the radio or looking out the window, many sources of information are not available. Once at home, individual marginal costs of protection would once again change, depending on the availability of a basement or storm shelter nearby. So, throughout the evening, multiple events could systematically confound our analysis.

Instead of directly controlling for this factors, we run binned regressions across varying time windows throughout the evening. Thus, any confounding factor would have to systematically act upon our data for each time bin, disrupting the observed relationship. However, if these factors are not systematically related to tornado touch downs and the variance of sunset, we would expect to find significant and consistent results across each time bin. We run binned regressions in Table 6, where we replicate the injury regressions from Table 5 for tornadoes occurring before 5:30pm (in column 1), between 5:30pm and 7:00pm (in column 2) and after 7:00pm (in column 3).

Our main results hold in sign and significance, with the small exception of the the warning variable in column 3. However, the interaction term remains significant and negative. In addition, our control variables perform as expected. These results reassure that, to the extent that some changes occur throughout the evening, they are not systematically confounding our variables of interest. Given that the sun sets anytime between 4:00pm and 10:00pm for much of the contiguous United States and varies across the year, it would be difficult for other variables to match this pattern.

4.2 Robustness Checks

We perform additional robustness checks to gain confidence on our results. We test alternative specifications of our visibility variable, including a binary dark/light specification and find no significant changes in the results. In addition, during an interview with a tornado meteorologist at the NWS Storm Prediction Center discussing the potential for measurement error in the storm events data, we were alerted to the possibility that some very weak tornadoes may be

Table 6: The Value of Public Information: Sunset Bin Results

	(1)	(2)	(3)
Hour	Before 5:30pm Injuries	5:30 to 7pm Injuries	After 7pm Injures
Minutes After Sunset	0.0370***	0.0220***	0.0226***
	(0.0108)	(0.00714)	(0.00856)
Warning	-2.233***	-1.102***	0.376
	(0.548)	(0.294)	(0.361)
Minutes After Sunset x Warning	-0.0276**	-0.0224***	-0.0165*
	(0.0140)	(0.00817)	(0.00941)
Tornado Length	0.243***	0.217***	0.195***
	(0.0436)	(0.0361)	(0.0394)
Tornado Width	0.00539***	0.00398***	0.00517***
	(0.000922)	(0.000808)	(0.000753)
Underlying Risk	-0.00513	-0.0187***	-0.0307***
	(0.00889)	(0.00621)	(0.00807)
County Population	2.01e-06***	2.52e-06***	2.92e-06***
	(6.71e-07)	(5.59e-07)	(7.61e-07)
Constant	-1.343***	-1.731***	-3.307***
	(0.428)	(0.311)	(0.373)
Minute Bin	+- 65	+- 65	+- 65
Observations	660	2,308	2,759

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

either missed after dark or over reported during daytime hours. This may be driven, in small part, by incentive for local NWS forecast office to correctly forecast tornadoes and decrease the frequency false alarms. This type of misreporting, to the extent that it exists, would likely only impact the weakest storms, as storms of even modest intensity will leave clear marks at the location of touch down and could not be fabricated. Therefore, for robustness, we re-run our results dropping all F and EF 0 storms, representing the weakest event. We find no significant change in the results. In addition, we test additional windows around sunset, ranging from 20 minutes to 120 minutes. The results are robust to windows between 40 and 75 minutes. When the window becomes too small, our sample size reduces and, given the gradual onset of sunset, the difference between light and dark reduces. On the other hand, when the window becomes to large, other factors may be systematically changing. However, our results remain robust across a variety of time windows.

In addition, we employ a falsification test with fictitious sunsets occurring exactly 120 minutes before or 120 minutes after the true time of sunset and re-estimate our regressions. We chose these time lengths such that they would not overlap with the beginning or ending of the true sunset. We present our results in Table 7. While we continue to find a significant relationship between tornado warnings, our control variables, and tornado injuries, we find no significant relationship between our fictitious sunset or our warning/false sunset interaction term.

[Note: For robustness, I will also include analysis of time use data from the American Time Use Survey to see if people are modifying their behavior at the time of sunset. In addition, I will examine traffic flow data to look at peak times in relation to sunset. My hypothesis is that most daily activity is uncorrelated with the time of sunset and more strongly associated with the time of day. In addition, I will also run a regression using time zones as a discontinuity to check for exogenous variation in sunset times, comparing tornadoes that touch down just on either side of a change in the time zone. I will include these results in the Appendix. I will also run a spline regression across the visibility variables (minutes until sunset) in order to relax the parameter assumption of my model.]

Table 7: Falsification Tests: False Early and Late Sunsets

	(1)	(2)
	Injuries	Injuries
Warning	-0.602***	-0.790***
	(0.208)	(0.173)
False Dark Late	0.145	
	(0.197)	
False Dark Early		0.128
		(0.167)
False Dark Late x Warning	0.0534	
	(0.343)	
False Dark Early x Warning		-0.153
		(0.219)
Tornado Length	0.219***	0.223***
	(0.0258)	(0.0236)
Tornado Width	0.00296***	0.00336***
	(0.000576)	(0.000462)
Underlying Risk	-0.000819	-0.0168***
	(0.00484)	(0.00371)
County Population	2.29e-06***	3.29e-06***
	(6.40e-07)	(4.26e-07)
Constant	-2.283***	-2.076***
	(0.235)	(0.191)
Minute Bin	+- 65	+- 65
Observations	2,460	6,930

Note: Standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

4.3 Information Impact Heterogeneity

In this section, we examine the differential impact of public versus private information across three key demographic characteristics: gender, age, and income. In Table 8, we analyze individual-level fatality data to examine the impact of visibility and warnings on the log odds that an observed fatality is female, elderly, or living in a mobile home. Our dependent variable for column 1, the gender regression, is 1 if the death was female and 0 if male. Our dependent variable for column 2, the age regression, is 1 if the individual's age was 65 or older when loss of life by tornado occurred and 0 otherwise. In column 3, our income regression, takes the value of 1 if the individual was killed in a mobile home and 0 otherwise.

We estimate the regressions using a logit model. We explain the fatalities with tornado controls (storm length and width), as well as visibility and warning. Similar to Proposition 1, we use all tornado touchdowns across all hours. We also run the results using the sunset time restriction, but the results were noisy. We did not find any significant impact of the interaction between visibility and warning, indicating that individuals do not differentially trade off between public and private information across these variables. We therefore exclude the variable from our results below. As this is a logit model, the coefficients estimate the impact of each variable on the log odds that a given fatality was female, elderly, or in a mobile home, and does not estimate the overall level of fatality.

We find several key results. First, gender plays significant role in the log odds of death surrounding sunset, as a fatalities after dark is more likely to be female but less likely to be female if warned. We find strong results for both elderly and mobile home residents. A fatality is less likely to be elderly and more likely to be in a mobile home at night. Visibility is an important protective factor for mobile home residents, relative to other locations. In addition, we find that mobile home residents are less likely to perish when a warning is sounded, relative to other locations. This dispels the view that mobile home residents may be less sophisticated or disconnected from public information. On the contrary, they are heeding warnings. The elderly results present interesting findings. Opposite to mobile home residents, the elderly

Table 8: Heterogeneous Information Impacts Across Demographics

	(1)	(2)	(3)
Variables	Mobile Home	Female	Elderly
Dark	1.274***	0.171*	-0.469***
	(0.107)	(0.0998)	(0.0957)
Warned	-0.991***	-1.048***	1.475***
	(0.244)	(0.238)	(0.279)
Tornado Length	0.0175***	0.00271	-0.00243
	(0.00558)	(0.00393)	(0.00391)
Tornado Width	-0.000190**	0.000783***	-0.000921***
	(8.98e-05)	(7.47e-05)	(7.66e-05)
Constant	-0.824***	-0.368	-0.425
	(0.256)	(0.246)	(0.284)
Observations	2,398	2,398	2,398

Note: Standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

are less likely to perish after dark, but if a warning is sounded, the fatalities has a higher chance of being elderly. Future work should examine evacuation and protection strategies at nursing home or elderly care facilities, as it is likely that some elderly individuals may not have autonomy over their decision to seek protection. Therefore, we find evidence of heterogeneous information impacts across key demographic characteristics, especially age and income. These results complement previous work that examined fatalities during the day and night, but did not focus on the precise timing of sunset (Simmons and Sutter, 2011).

5 Conclusion

Transmission and understanding of risk information is critical to minimize losses from impending events, especially during times of natural disaster. However, little evidence exists examining the causal impact of public sources of information on observed event outcomes as well as the impact of alternative information on attenuating or improving the effectiveness of public information. In this paper, we begin with a protection model with learning. From the model, we generate three propositions surrounding the value of public information across different information states. We then analyze these propositions in the context of United States tornadoes since 1986. We exploit the exogenous variation of tornado touch down relative to the precise time of sunset to causally identify the impact of visibility, one important source of private information for tornadoes. While information, once disseminated, is typically hard to remove, this particular treatment effectively eliminates the information channel.

We also interact the availability of private information with official public tornado warnings. We find that private information can be helpful, as tornadoes are more harmful just after sunset. However, the removal of one source of information increases the reliance on public information. We cannot comment the overall level of information efficiency before and after sunset. Even though fatalities and injuries reduce, people may be overly cautious. However, public policy may have the normative objective of harm minimization rather than efficiency, so it may be compatible with public goals.

Lastly, we present evidence on the heterogeneous impact of information across demographic groups. We find important evidence of differential risk information synthesis across age and income, but no differential impact of gender just before and after sunset. These results can help inform public policy on information dissemination as well as resilience. Above all, these results show that private information impacts the effectiveness, and therefore the ultimate value of, public information. In addition, the value of public information is contingent on seemingly irrelevant factors, such as the timing of sunset. If a policy maker's objective is to increase credibility and effectiveness of official public information, care must be taken to ensure that potential conflicting sources of private information are kept in mind.

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