Determining Tornadic Near-Misses via Oklahoma and Kentucky Mesonet Observations

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ABSTRACT

Determining a definition of a near-miss is a frequent frustration in regard to natural disasters. While previous definitions of a near-miss seek to define it as any event that has a significant chance of causing significant property damage or casualties but did not due to chance, this framing of a near-miss fails when analyzing individual disasters and the footprint they leave within a community. This is especially prevalent with tornadic storms, as relatively small distances can be the difference between a direct hit or a miss when compared to larger, synoptic scale systems. By analyzing both direct and distant tornado encounters via mesonet station observation data, a rough figure of tornadic vicinity can be determined. Doing so results in tornadic signatures being present for all observations within one kilometer of a confirmed tornado, indicating a tornadic vicinity of one kilometer beyond the diameter of the damaging winds of a tornado. This vicinity range can be applied to generate a rough post-tornado model of what communities were particularly at risk enough to be deemed a near-miss encounter.

1. Introduction

A scientific consensus of the definition a near-miss for any severe weather event is a persistent difficulty. The current definition of a near-miss in the meteorological context, first established by Dillon et al. (2011) and later summarized by Hatzis et al. (2019) defines a near miss as ". . . an event that had a nontrivial probability of causing loss of life or property but did not due to chance." This definition, while understandably broad to encompass a wide variety of different types of severe storms, is far too vague to be of value when communicating risk to given communities impacted by these storms. This vagueness has the potential to be incredibly dangerous, with issues such as ignoring important weather alerts and warnings, which in turn can lead to an increase in fatalities as people assume that danger is not present when it is (Hatzis et al. 2019). Therefore, the ability to derive a more definite concept of what a near-miss is can be critical in effectively analyzing the risk a community either faced or could have faced.

This research sought to numerically define a near-miss by analyzing the observation patterns associated with direct hits from tornadoes and how these patterns change as a station gets further away from a tornado. Conceptually, once a "radius of influence" is determined, a potential definition of near-miss tornadic events can be built upon it. The patterns analyzed are established from various observations from both mobile and fixed stations in a variety of different regions (Blair et al. 2008; Fox-Hughes et al. 2018; Karstens et al. 2010). This pattern (Fig. 1) is characterized by the peak wind speeds observed increasing as the tornado approaches the station, and the atmospheric pressure observed decreasing alongside the increasing winds.

As the tornado moves away, the opposite occurs, with wind speeds decreasing and pressure rising. This pattern occurs very quickly, creating a distinct signature. It is this distinct signature that is the focus, as any changes to it

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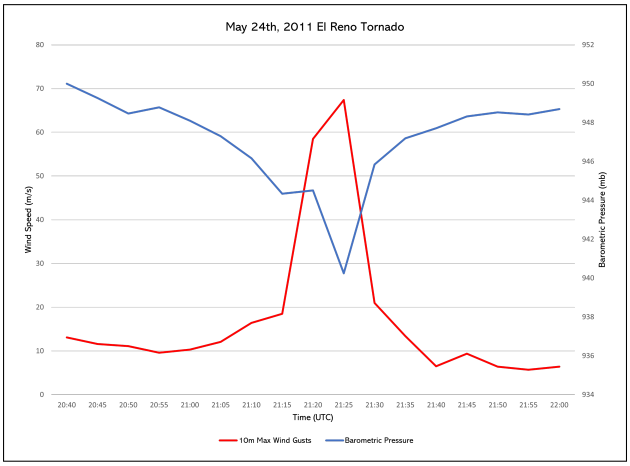

FIG. 1. Graph of peak 10-meter winds (in red) and barometric pressure (in blue) for the El Reno, OK Mesonet station on May 24th, 2011, as the station directly impacted an EF-5 tornado. Source: Oklahoma Mesonet

over a distance will help further understand the area of influence surrounding a given tornado.

While much of the published literature regarding station observations have previously focused on the use of "mobile mesonet stations", which are trucks that have a series of meteorological instruments attached to them to collect data as the truck is moving into and near a storm, not much literature is published regarding the use of state mesonet networks, which are a series of fixed stations established over an entire state to provide mesoscale weather observations, on tornadic systems. This is despite several state mesonet stations encountering direct hits with tornadoes. This is, in part, due to the scale of mesonet networks. Since mesonet stations operate on a mesoscale basis, whereas tornadoes are inherently microscale, there is an disparity between potential tornadoes and their coverage by mesonet stations. This makes direct hits, while possible, quite rare. However, this problem of tornadoes moving closely but not directly reaching mesonet stations can become a major benefit when analyzing distant/near-miss encounters, and this combined with their use serving lower population areas, areas at higher risk of tornadic direct hits and near-misses (Hatzis et al. 2019) makes the usage of state mesonet networks a potentially great tool when analyzing near-misses.

Therefore, this paper seeks to use state mesonet stations from Oklahoma and Kentucky to analyze tornadic encounters to provide greater context to what can be classified as a near-miss distance-wise.

2. Methodology

This study seeks to analyze tornadic hits and near-misses in a three-phase process. First, a database of known tornado tracks via the National Weather Service's Damage Assessment Toolkit was utilized. These tracks were then overlaid onto a map of Oklahoma and Kentucky Mesonet station locations where they are measured from the station points via the use of ArcGIS Pro software. Finally, using the metadata included in the tornado track database, station data for the times of the corresponding tornadoes are referenced and catalogued based on the properties of the signatures.

a. Kentucky and Oklahoma Mesonets

A mesonet, short for "mesoscale network", serves as a series of stations distributed over a mesoscale, larger than a microscale/microclimate, but smaller than a larger, synoptic scale that can extend to the size of entire continents. In the past, mesonets have been useful for analyzing local features that larger station networks, such as the Automated Surface/Weather Observing Systems (ASOS/AWOS), cannot process. These include both regional phenomena such a droughts, flooding, and isolated storms, as well synoptic features within the context of a region, such as squall lines, fronts, heat waves, and cold snaps (Fig. 2). While there are many mesonet station networks established throughout the United States, two of the most prevalent are the Oklahoma Mesonet and the Kentucky Mesonet.

While both mesonet networks operate in functionally the same manner, collecting observations of a variety of atmospheric and soil conditions within a mesoscale region and having stations over a similarly dense area, their respective states provide differences that for the purpose of this research are particularly noteworthy. For a start, Oklahoma and Kentucky have differing topographic profiles, with Oklahoma having on average much flatter terrain then that of Kentucky, especially when comparing the Western Oklahoma plains to the mountains of Eastern Kentucky.

These differences in topography will allow analysis of terrain influences the flow of winds into a tornado and by extension how perceptions change of what the vicinity of a given tornado could be.

Another geographic difference of note are the differing storm structures between Oklahoma and Kentucky. Oklahoma, existing in the long-infamous "Tornado Alley", frequently encounters supercells and other scattered thunderstorms, which have unified features. In contrast, Kentucky, as a part of the increasingly active Deep South, encounters more QLCS-like storms and systems, which have features that are shared with other storms within the squall line or front. Because of this, analyzing encounters from both Kentucky and Oklahoma Mesonets allow the accounting for both system types and see what, if any, differences these storm types can generate.

b. NWS Damage Assessment Toolkit

To be able to analyze tornadic encounters on Oklahoma and Kentucky Mesonet stations, a database of confirmed tornadoes must first be acquired to reference. There are also several requirements that such a database must be able to fulfill for the purposes of this research. Those requirements being that the database in question must be currently maintained, the database must account for tornado diameter in some way to account for varying tornado sizes and must include data over a prolonged period. One such database that fulfills these requirements is the National Weather Service's Damage Assessment Toolkit, a publicly accessible database of damage survey reports. While the database at this time is still listed as a preliminary dataset, and not fully encompassing of all tornadoes that have gone through the states of Kentucky and Oklahoma, the database does allow for the factoring in of tornado size via the "damage polygon" feature and includes data from 2011 to 2022. In addition, the database is notably lacking in the first couple years of operation, with some known tornadoes, like the direct hits of the Tipton and Fort Cobb Oklahoma Mesonet stations in 2011, not being recorded into the Damage Assessment Toolkit. For storms like these, where it is known that a direct hit occurred but not much is known regarding information such as rating, time of impact, date, et cetera, the National Centers for Environmental Information's monthly storm data publication was referred. While this source does provide much of the additional information regarding a tornado necessary for this research, it does not provide enough information to definitively deduce the distance from a station a tornado's track was, therefore it can only be used in the context of validating known hits.

c. Determining Distance of Tornadoes from Stations

To determine tornadic events distance from the mesonet stations, the tornado database and station location database for each mesonet network were inserted into GIS software where geoprocessing tools native to ArcGis Pro were utilized to create a table of the tornado paths and their respective distances to the stations. Tornado tracks within a given distance were then further analyzed for their meteorological conditions. Because some tornadoes have multiple damage polygons nested inside each other depending on the damage surveys done and the scale of the damage reported (Fig. 2), additional manual processing of these tracks were performed to flag and mitigate any potential issues.

d. Station Data Analysis Process

To analyze the previously established tornadic signature regarding station observations, 10-meter peak winds and atmospheric pressure were analyzed for each station

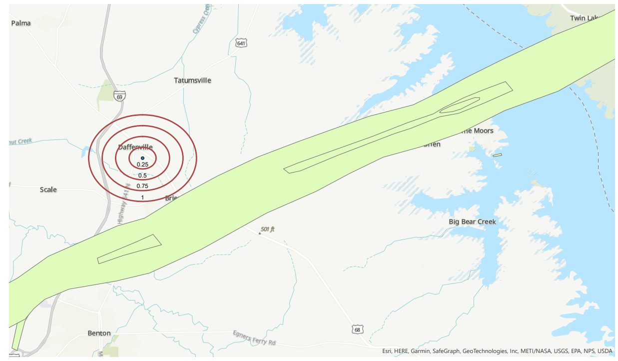

FIG. 2. Map of the area near Daffenville, KY in ArcGIS Pro. In red are range rings around the Daffenville mesonet station and in green are the Damage Assessment Toolkit damage contours of a tornado that went through the area on 11 December 2022. Note that within the main damage contour there are 3 additional contours. For the purposes of this research, the primary, outer-most contour is used when making measurements.

which had an encounter with a tornadic system. Both variables were chosen to stay consistent with what previous literature analyzed regarding tornadoes impacting mesonet stations (mobile or stationary). However, several considerations were made to determine 10-meter peak winds as the optimal choice. The first is its location on a state mesonet station. As seen in Figure 3, the 10-meter anemometer is unobstructed from any other instruments on the station, providing clear measurements of a tornadic storm coming from any direction.

In addition to this, the increase in altitude allows for the wind measurements to be clear of any nearby surface obstructions, whether from trees and downed branches to small terrain features and slopes. And while many mesonet stations are intentionally placed in open fields and areas to avoid the impacts that obstructions can have on standard observations, this research's focus to analyze tornadic systems from an extended distance means special consideration must be made to reduce potential interference from obstructions and terrain as much as possible. However, in the case of larger terrain features such as hills and mountains, such a desire is impractical. Hence why both Kentucky and Oklahoma Mesonet networks are analyzed, to additionally see how these larger terrain features play into the radius of influence observations. Additionally, because the wind observations are from an elevated height, they will not be completely accurate to the observations that would be observed on the ground, in part due to obstructions as alluded to before. Despite this fact, previous research shows that the frictional component of the tornado boundary layer extends up to around ten meters above ground level (Bluestein et al. 2014). The same also applies to the inflow component of a tornado, whose constraints are defined as from surface level to 10-14 meters above ground level (Kosiba and Wurman 2013). There-

FIG. 3. Image of the Oklahoma Mesonet station at the National Weather Center in Norman, Oklahoma. Annotated in orange is the 10-meter anemometer and barometer locations on the station, with the 10-meter anemometer located at the top of the station, and the barometer located inside the metal instrument box affixed to the central beam of the station.

Date	Station Location	State	Max Rating	Distance (in km)
8/19/2018	Inola	OK	EF1	Direct
11/7/2011	Fort Cobb*	OK	EF1	Direct
5/18/2017	Porter	OK	EF1	Direct
11/7/2011	Tipton*	OK	EF4	Direct
5/24/2011	El Reno	OK	EF5	Direct
12/11/2021	Madisonville	KY	EF3	Direct
12/11/2021	Princeton	KY	EF3	Direct
12/11/2021	Mayfield	KY	EF3	Direct
5/9/2016	Sulphur	OK	EF3	0.06
12/11/2021	Munfordville	KY	EF2	0.06
5/24/2011	Chickasha	OK	EF4	0.08
4/28/2020	Clayton	OK	EF1	0.19
4/30/2019	Talala	OK	EF2	0.30
3/29/2020	Henderson	KY	EF2	0.58
5/1/2019	Lane	OK	EF3	0.95
4/18/2013	Jay	OK	EF2	1.09
5/10/2015	McAlester	OK	EF1	1.19
5/20/2013	Skiatook	OK	EF1	1.29
1/11/2020	Cadiz	KY	EF0	1.29
3/30/2013	Sallisaw	OK	EF1	1.46
4/13/2012	Norman	OK	EF1	1.60
4/30/2019	Miami	OK	EF1	1.64
4/27/2016	Bixby	OK	EF1	1.70
12/11/2021	Benton	KY	EF3	1.80
4/29/2017	Sallisaw	OK	EF1	1.80
4/30/2012	Nowata	OK	EF0	1.82
5/24/2011	Guthrie	OK	EF5	1.91
12/11/2021	Greenville	KY	EF3	1.92
5/25/2015	Wister	OK	EF2	1.93
5/10/2016	Hugo	OK	EF1	1.97

TABLE 1. List of all observable tornadoes that came within two kilometers of a Kentucky or Oklahoma Mesonet station, with dates, tornado strength, and distance listed. All locations marked with an asterisk are stations that are not a part of the NWS Damage Assessment Toolkit dataset but are confirmed by the NCEI's storm data publications.

fore, while wind speed intensities may differ from their surface counterparts, the overall flow characteristics, patterns, and signatures identifying them should remain unchanged between the surface and the measurement altitude.

3. Data

Analyzing all tornadoes logged within the NWS Damage Assessment Toolkit, thirty observable tornadoes were flagged as being within two kilometers of a mesonet station. These stations are outlined in Table 1.

From Table 1, of these thirty tornadoes, eight encounters resulted in a direct hit of the given mesonet station, with an additional seven tornadoes coming within one kilometer of a station. An additional ten stations had tornadic encounters within this range but are excluded from our pool of data due to incomplete data. This is outlined in Table 2.

4. Discussion

From the encounters that can be measured by the mesonet stations (Table 1), encounters can be split into 3 significant groups. The first group consists of observation measurements that correlate with the pre-established tornadic observation signature as seen in Figure 1, a set of station measurements that show a sharp increase in maximum wind speed gusts at 10 meters and a sharp decrease in barometric pressure corresponding with the wind speed spike. The same trend previously observed in other pieces

Date	City	State	Distance (in km)
4/4/2018	Mayfield	KY	0.19
7/4/2016	Louisa	KY	0.42
2/29/2012	Hodgenville	KY	1.20
3/10/2017	Murray	KY	1.32
5/10/2016	Hartford	KY	1.37
4/27/2017	Mayfield	KY	1.84
4/27/2016	Madisonville	KY	1.89
3/10/2017	Hickman	KY	1.92
6/23/2017	Hodgenville	KY	1.93
2/25/2018	Franklin	KY	1.98

TABLE 2. List of all stations whose encounter data were incomplete. For all ten potential encounters, data points were discarded from the pool due to a lack of pressure observations, which are not present for the Kentucky Mesonet station observations prior to 2018. Since atmospheric pressure is critical to the analysis of tornadic signatures, a conclusion cannot be reasonably be made regarding the nature of the encounter if even present.

of literature (Blair et al. 2008; Fox-Hughes et al. 2018; Karstens et al. 2010).

The second grouping are measurements that definitively show a differing pattern than that of a tornadic encounter. While this criterion, in theory, could be met by other sets of patterns, in our analysis one pattern of note became particularly noteworthy. As can be seen in Figure 4, while winds speeds sharply increase, the station observed an increase in barometric pressure aligned with the increase in wind speeds. This barometric pressure trend is counter to that of our established trend for a tornadic encounter and given that it only occurs at extended distances and is similar pattern to that common with standard, non-tornadic gust fronts, can be implied as being a non-tornadic signature.

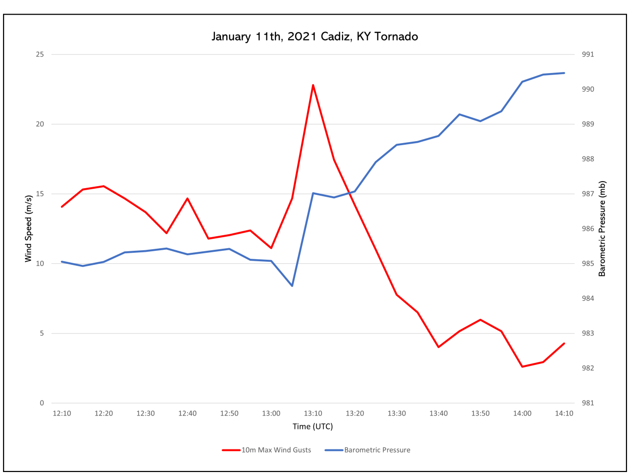

FIG. 4. Graph of peak 10-meter winds (in red) and barometric pressure (in blue) for the Cadiz, KY Mesonet station on 11 January 2021, as the station encountered a tornado 1.29 kilometers away. Source: Kentucky Mesonet

The final group consists of observation trends that do not align with either of the two other signature groups. One example of this would be a situation in which a sharp increase in wind speed is observed, but the barometric pressure observations did not have a definitive increase or decrease. A good example of this can be seen in Figure 5. Here, as the wind speeds increase, the barometric pressure remains somewhat steady throughout. While there is a wide decrease in pressure prior to the increase in winds, and a steady increase briefly afterwards, the atmospheric pressure during the wind gust increase is fairly level. Given that a tornadic encounter involves a sharp decrease in barometric pressure and a non-tornadic encounter the reverse, this ”flat” pressure profile indicates that the station is in a transitory area between the two zones.

For the purposes of this analysis this pattern, as well as all observations where a tornadic or non-tornadic signature is difficult to conclusively determine, will be referred to as a ”intermediate” signature.

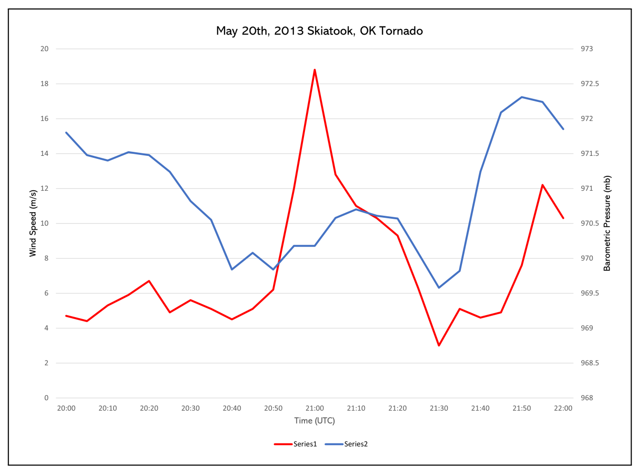

FIG. 5. Graph of peak 10-meter winds (in red) and barometric pressure (in blue) for the Skiatook, OK Mesonet station on 20 May 2013, as the station encountered a tornado 1.29 kilometers away. Source: Oklahoma Mesonet

Another potential point of interest involves the distribution of tornadic intensities, outlined in Figure 6.

While potential observations encompassed the full spectrum of tornado intensity categories, the two most frequent intensities observed are of EF1 and EF3 tornadoes, with EF1 tornadoes encompassing 40 percent of the overall population and EF3 tornadoes comprising 23.3 percent of the population. These two categories are also the most frequent of each mesonet network with all EF1 encounters originating from Oklahoma Mesonet stations and a large majority of EF3 encounters originating from Kentucky Mesonet stations (with a large portion of those coming from the 11 December 2021 outbreak). While this in-

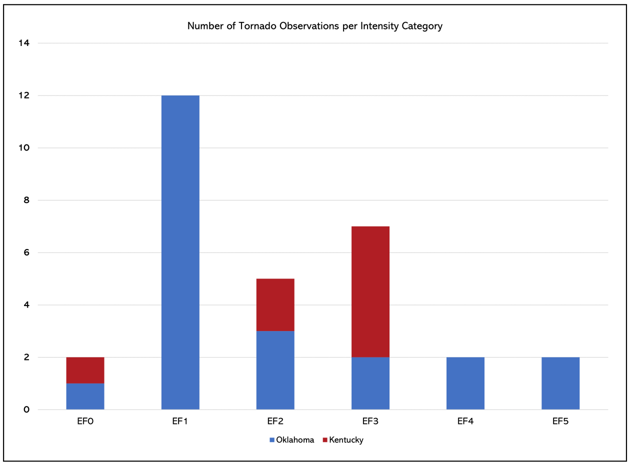

FIG. 6. Stacked bar graph of the frequency of different tornado intensities observed via Kentucky and Oklahoma Mesonets, which each mesonet network's observations separated by color.

formation is of potential interest, not much can be concluded probability-wise due to the limited sample size.

With both points in mind, by cataloging station observations into the 3 categories and understanding that all potential intensities are included in the dataset, a clear trend between the distance away from a tornado and the type of signature obtained can be determined (Fig. 7).

In the set of confirmed tornado observations (Table 1), all observations taken within approximately one kilometer of a confirmed tornado resulted in similar signatures to that of a direct tornadic hit. The only difference between a direct hit and these sets of observations are the intensity of the features. Once observations are attempted beyond one kilometer, the signature features of the tornado begin to break down, either yielding a non-tornadic signature or an inconclusive, intermediate signature. However, once observations occur over 1.6 kilometers away, non-tornadic signatures begin to appear with regularity, confirming the end of or radius of influence. Using this info, a rough model of potential observations observed for a given tornado can be generated (Fig.8).

5. Conclusions and Further Work

By analyzing observation data from Kentucky and Oklahoma Mesonet stations it can be determined that tornadic signature patterns can be definitively observed as far away as one kilometer from the area of confirmed tornadic damage. It can therefore be concluded that the effective radius of influence of a given tornado is one kilometer past a tornado's given radius. With this radius of influence defined, the area within this radius can be treated as the vicinity of a given tornado and therefore communities paced within it can be potentially defined as encountering a near-miss

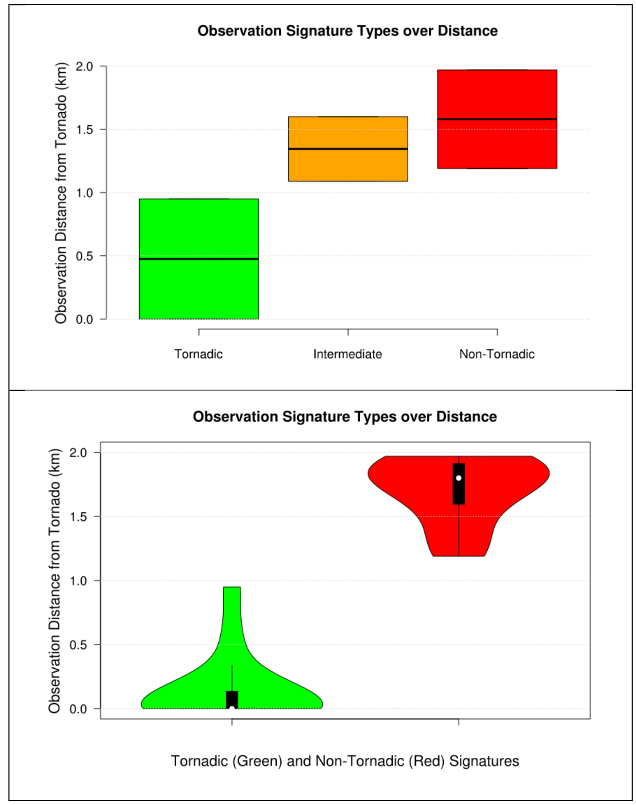

FIG. 7. Box plot (top) of the tornadic, non-tornadic, and intermediate signatures and the distance ranges that these signatures were detected relative to the tornado track, as well as a violin plot (bottom) of the tornadic and non-tornadic signatures. Due to a lack of enough data points, the intermediate signature is excluded.

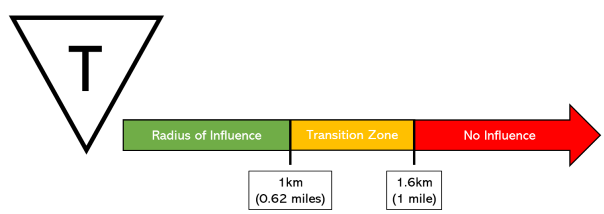

FIG. 8. Diagram of a potential model for outlining potential observations, based upon prior mesonet observations. The area in green represents the area beyond a tornado where tornadic signature patterns are still observed. The region in orange represents the region where observations are either inconclusive or non-tornadic in nature. Finally, the region in red represents the area away from a tornado where signature patters are firmly non-tornadic.

(especially given the strong winds still present at these distances).

While the results indicated show the presence of a rough radius of influence, it is important to understand that there are several limitations that open the possibility of continued research. As evident in Table 1, there are several gaps in the distances observed that could benefit from ad-

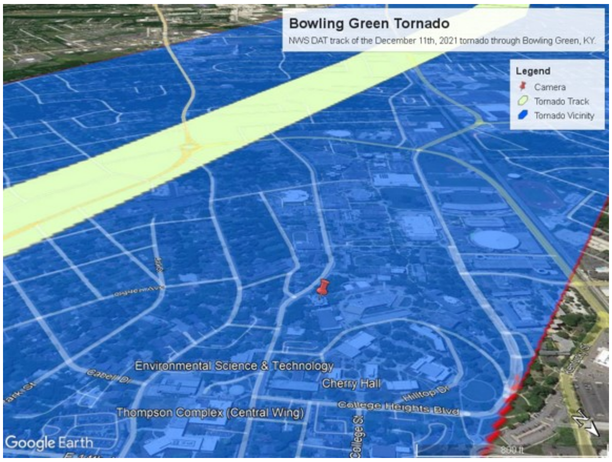

FIG. 9. Google Earth imagery of the NWS DAT track for the 11 December 2021 Bowling Green, KY tornado. The one-kilometer vicinity figure (blue) is overlaid on top of the DAT track (green). The red pin represents the location of an on-campus camera at the time of the tornado's impact. In this case, the camera would be in the vicinity of the tornado.

ditional measurements. One region where this is particularly true is the one kilometer region, where the pattern evident in Figure 7 indicates a transition from tornadic to non-tornadic signatures should begin to occur but there are no data points to exactly confirm the transition.

It also should be noted that mesonet observations are continually improving. Several mesonet networks, including both Oklahoma and Kentucky Mesonets, have begun experimenting with one-minute data intervals for their observations. This increase in temporal resolution could greatly improve signature identification as well as clarify intermediate cases where the signature type is hard to discern. Even without this, smaller improvements such as the recent introduction of barometric pressure measurements into the Kentucky Mesonet from 2018 and the standardization of not only how measurements are made but what variables could all improve the potential database of potential tornadic observations to analyze in the future.

Finally, the introduction and opening of many new mesonets across the United States within the last couple of years have opened the door to the potential for this project topic to expand into a larger geographic scope. In the future, enough tornadic observations may have occurred to where it may be possible to include mesonet observations from not just Oklahoma and Kentucky but the whole of the Great Plains and Deep South.

Regardless of the potential avenues of additional research regarding this topic, the defining and further revising of what tornadic near-misses are can hopefully help local communities assess and communicate how at-risk parts of their communities were from a given tornado and help assess which communities have been impacted by a near-miss.

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