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Tornado Visualizer: Analyzing the Destructive Impact of Tornadoes in the United States

N. Hansen, S. Lorentzen, S. Widell, J. Kusnick and S. Jänicke

Department of Mathematics and Computer Science, University of Southern Denmark, Odense, Denmark

Abstract

We present a visual exploration system that supports investigating multifarious inquiries on trends in the destructive impact of tornadoes in the United States. Based on the publicly available data on storm events from the National Oceanographic and Atmospheric Administration (NOAA), we designed linked views for all attributes that indicate destruction such as property damage, crop damage, and the numbers of deaths and injured people. Interactive filters support analyzing geospatial as well as temporal trends. The unique feature of our solution is our focus on the Enhanced Fujita (EF) scale, which has not yet been subject to related visual exploration environments. Our usage scenario documents the potential value of our system for a diversity of target users like urban planners or environmental scientists.

1. Introduction

In the recent years, climate change has become more and more noticeable in everyday life. This is obvious in cases of extreme natural phenomenons. For example, the intense 2019/20 Australian bushfire season was mainly caused by unusually high temperatures and drought [Aus20, Lin20]. Similarly, the UN has recently published a historic temperature record for the Arctic of 38°C, measured on 20 June 2020 in the Russian town of Verkhoyansk, which is located 115 kilometers north of the Arctic Circle [Uni21]. These extreme natural phenomenons have been increasing over the last decades [DST13], both in their occurrence and in their intensity, along with growing destruction costs. A further increase in global warming will likely amplify these extreme natural phenomenons [DST13].

Molloy and Paul [MK18] have specifically investigated the relationship between frequency of tornadoes and regional climate change. The goal of their study was to determine whether regional climate change influenced the frequency of tornadoes in Kansas. They did not find any relationship between tornado frequency, temperature and precipitation. Nevertheless, tornadoes are one of the most destructive natural hazards in the US. In the last decade, tornadoes alone have caused the highest number of fatalities and third highest economic losses among all natural hazards in the US [Mv18]. While no direct link between increasing temperatures and tornado activity has been proven, tornadoes are still a force to be reckoned with.

Although it is beyond the scope of this paper to determine whether an increase in tornado activity and damage is related to climate change, we aim to supply environmental scientists with a visualization tool that sheds a light on a particular aspect of tornados, the Enhanced Fujita (EF) scale, which can be observed over time and thus can indicate relations to climate change.

The vast amount of research in this area has primarily focused on death and injuries caused by tornadoes but not much on the damage caused by tornadoes, e.g., the damage on property and crops. Further, not much research has been done solely in relation to the new EF scale for categorizing tornadoes, which is based on the tornadoes' wind speeds and related damage. Our paper fills this gap. We present an interactive visualization tool, Tornado Visualizer, which is designed to support the visual exploration of the frequency and destructive impact of EF-rated tornadoes in the US from 2007-2021 in relation to this scale. Our solution targets users from different groups such as politicians, urban planners, real estate developers, farmers, insurance companies and environmental scientists, and it can be used to support decision making processes on a national as well as on a regional level. Tornado Visualizer can be used to investigate geospatial-temporal trends, e.g., where do tornadoes cause how much damage in relation to their EF scale, and how destruction change throughout time. Our results document the value of our system for domain-specific inquiries.

2. Related Work

Related work falls into broad two categories. First, interactive visualization tools like ours, and second, machine learning based forecasting tools. The common emphasis for research papers in both of these categories are casualties or injuries in relation to tornado paths and other geospatial parameters. Suckling and Ashley [SA08] published one of the first studies that examined tornado paths with a spatio-temporal analysis. This study prepared the ground for several subsequent studies in the same area, most of them with a main

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focus on casualties and injuries, e.g., Shen and Hwang [SH15] and Hatzis et al. [HKH20]. To the best of our knowledge, property and crop damage caused by tornadoes has not been subject to the development of explorative visual interfaces to support experts in urban planning decision making tasks.

The dynamic behaviour of tornadoes has previously been visualized using the NOAA [LTM15] data set, which is also the basis for our research. A tool that visualizes the trajectories of tornadoes was developed in 2014 [JCCS14], once again focusing on analyzing deaths and injuries of people. While the authors use the F scale, a distinction between F and EF scale has not been done. A few examples of interactive visualization tools include GeoTemCo [JS14], Tornado Travel Map [Nel], Twisters [twi] and Tornado Dashboard [tor]. Note that these tools are also based on the NOAA data set, but they go much further back than 2007, and, consequently do not differentiate between the outdated F scale and the modern EF scale.

In summary, none of the related works supports the visual analysis of the correlation between EF scale, property and crop damage, which is addressed in this paper.

3. Visualization Design

Tornado Visualizer, implemented in Python with Dash and Plotly, is based on the NOAA's Storm Events Database [NOA]. It consists of 71 individual CSV files containing storm data from 1950-2021 and includes information on the occurrence, coordinates and destruction of tornadoes. Since the United States changed how to rate the damage intensity of tornadoes in 2007, we only used the data from February 2007 to September 2021. Before February 2007, the now decommissioned Fujita scale (F scale) was used to categorize Tornado intensity.

The current scale in use is the aforementioned EF scale, which is also based on estimated wind speeds and related damage [Nat]. However, as the two scales differ in how they measure the force of a tornado, it is a difficult task to compare the two. The EF scale better reflects the damage caused by a tornado in comparison to its wind speed. Therefore, Tornado Visualizer depicts the destruction caused by tornadoes over time more precisely complying to modern standards.

3.1. Data

The NOAA's database contains a lot of information regarding tornadoes. However, for this project not all variables are used, as they are not related to our target to analyze the destructiveness of tornadoes. We make use of the following attributes for a tornado to support a multifaceted visual exploration:

- BEGIN_LAT and BEGIN_LON mark the tornado's geospatial origin, and are used as vector representations on the map
- DAMAGE_PROPERTY and DAMAGE_CROPS refer to the total property and crop damage in USD. It is not indicated whether or not these are caused directly or indirectly by a tornado.
- DEATHS_DIRECT refers to the number of casualties directly caused by a tornado
- INJURIES_DIRECT refers to the number of injured people directly caused by a tornado

The data set also contains attributes for the length and width of the tornadoes. One of the last attributes that we use is the TOR_F_ SCALE that specifies each recorded tornado's scale, i.e. an EF0, EF1 etc. rated tornado. Like stated above, we only use data for the period after the EF scale was implemented. The variable TOR_F_SCALE also includes EFU as a category. However, as this data is not surveyable, it is not included in the data used for visualization.

3.2. Visual Design

The main target of Tornado Visualizer is analyzing the destructive force of tornadoes with regards to damage, injuries and deaths. We developed an interactive dashboard that consists of several linked views [Rob05] aiming to support detecting correlations among the attributes of our data set through interactive filtering, linking and brushing. Some views are controlled by a time-range slider and others are controlled by a drop down menu. In all instances of our system, the color of a glyph reflects its EF scale, the main focus of our tool. We use a color scale where bright colors indicate lower EF values and darker colors indicate higher EF values, i.e., yellow is used for a category EF0 tornado and red for a category EF5 tornado (see Figure 1(C)).

The time-range slider controls a United States map (see Figure 1B) where the tornadoes are plotted according to their origin location. The scatter plot (see Figure 1D) shows the relationship between a tornado's length and width. With the time-range slider, the user can control which year should be visualized on the map, in the scatter plot and in the four bar charts below it. Figure 1A shows a drop down menu with the different US states as options. Another option, 'Select all', is also featured. This drop down menu is used to control the map, the scatter plot and bar plots (Figures 1(E) to (H)) below with respect to the state. Figure 1C shows an interactive map of the US, visualizing the origin location of each tornado. If the user hovers on a point on the map, information about the tornado is shown, including the state of origin, the date of the event, how much property damage and how many direct deaths the tornado caused. In the scatter plot shown in Figure 1D the user is able to inspect the widths and lengths of the tornadoes according to their EF scale. This is used to visualize the relationship between the size of a tornado and how destructive and forceful it is. The bar plots (Figures 1(E) to (H)) show a graphical display of the four attributes DAMAGE_PROPERTY, DAMAGE_CROPS, DEATHS_DIRECT, INJURIES_DIRECT grouped by EF scale. This provides a visual overview for each tornado category's destructive impact. The drop down menu and time-range slider provide a visual overview for the destructive force of tornadoes and include the opportunity to examine the tornadoes on both a yearly level and on a state level. Figure 2 shows a time series of the evolution of tornadoes from 2007-2021. Figures 3A and B also show the evolution of property- and crop damage throughout the same time period, where each tornado is stacked with respect to their EF scale. Finally, the last two bar plots (see Figures 4A and B) show an overview for property damage and crop damage on a state level where each tornado is stacked with respect to their EF scale. This allows the user to hover over the

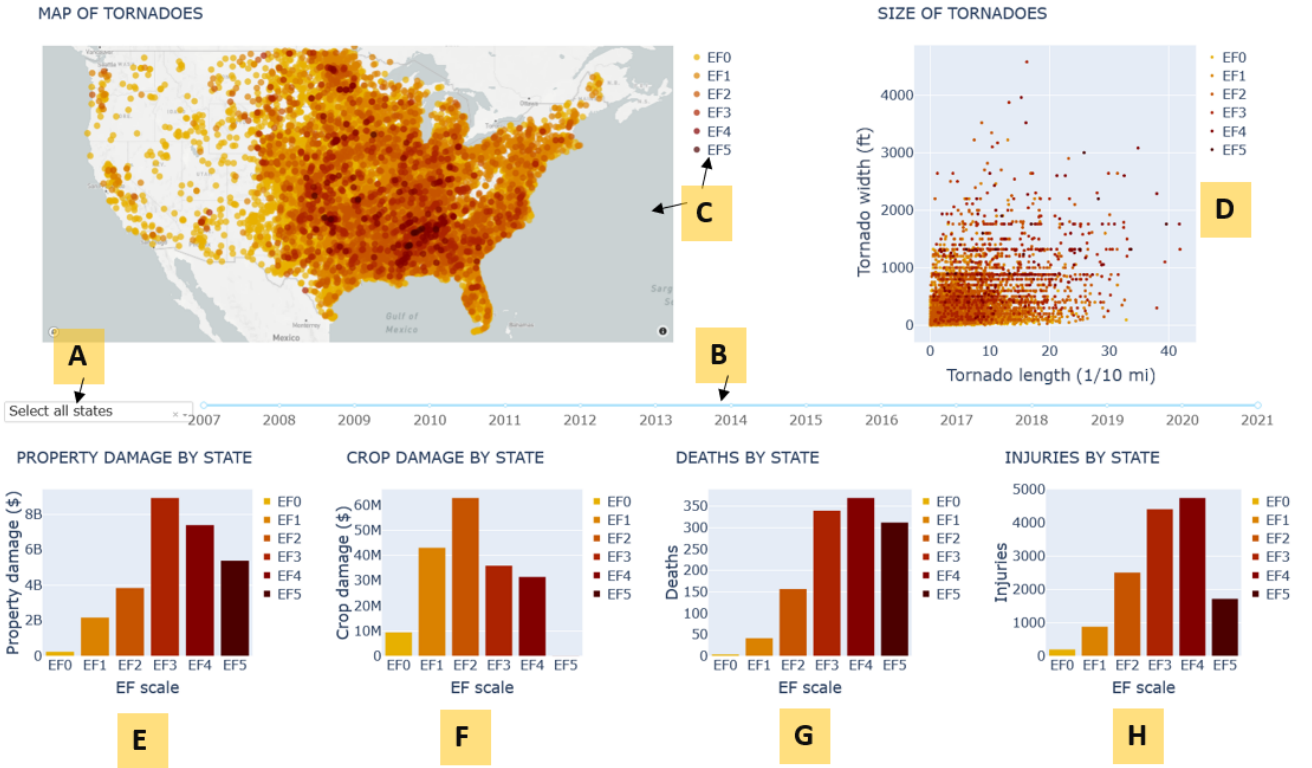

Figure 1: *A screenshot of the interactive dashboard.* ***A*** *is a drop down menu that supports selecting a particular state.* ***B*** *is a time slider to support time-based analyses.* ***C*** *is map of the United States that shows the tornadoes' origin positions (with respect to the chosen year in the time-range slider).* ***D*** *is a scatter plot of each tornado's length and width.* ***E****,* ***F****,* ***G****, and* ***H*** *are bar charts which display the destructive impact of tornadoes with respect to property and crop damage, and the number of deaths and injuries.*

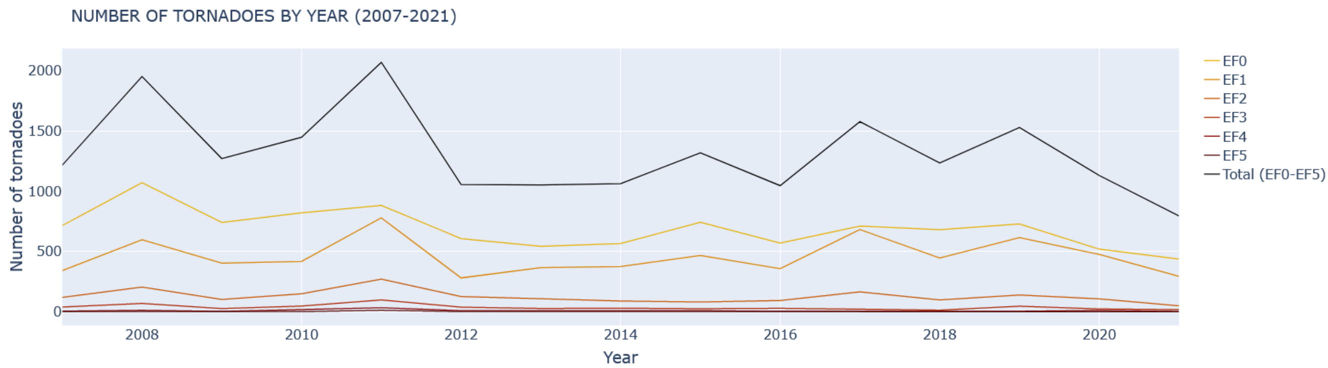

Figure 2: *Time-based development of EF-rated tornadoes from 2007-2021. To allow for a more granular inspection of trends, zooming to months and days is supported.*

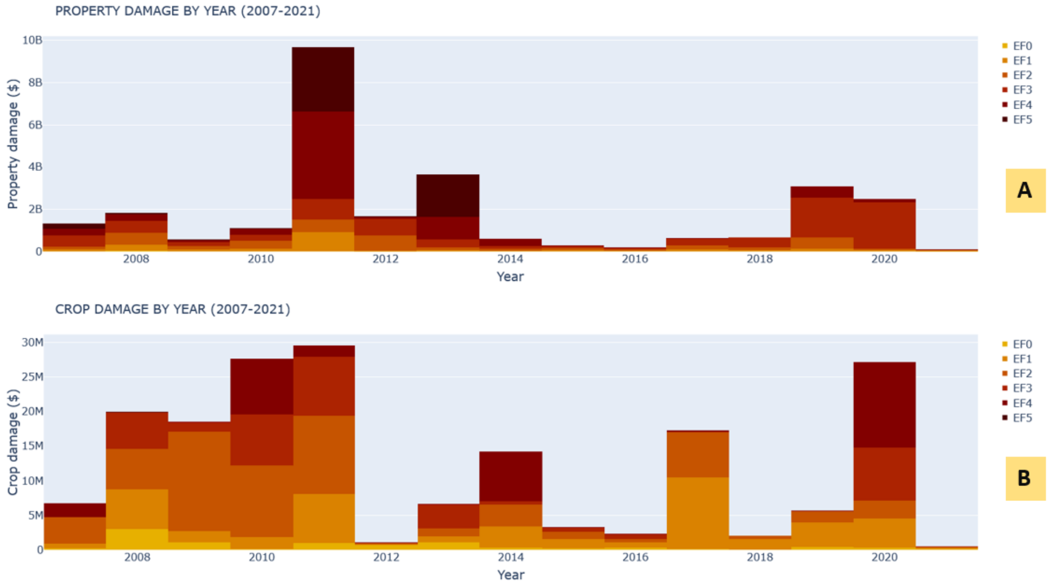

Figure 3: *Analyzing property and crop damage across time.* ***A****: Shows the development of property damage from 2007-2021.* ***B****: Shows the development of crop damage from 2007-2021.*

Figure 4: *Analyzing property and crop damage by state.* ***A****: Shows a bar plot for the amount of property damage tornadoes have caused in US dollars by state over the entire time period.* ***B****: Shows a bar plot for the amount of crop damage tornadoes have caused in US dollars by state over the entire time period.*

stacked bar plots and see information regarding each tornado. All described visual interfaces are linked to support multifaceted visual exploration.

3.3. Interaction

By moving the slider back and forth, a scatter plot (Figure 1C) of tornadoes is displayed on top of the map of the US for a given year. Each dot, colored by their category level (e.g. EF2), shows where a tornado originated. When moving the slider, the other scatter plot (Figure 1D) is updated too, displaying the relationship between the tornado length and width across different tornado categories. Also, the user has the opportunity to look at an individual tornado EF level, for example by clicking on the EF1 tornado-scale button, which will remove the EF1 category from the map and the scatter plot. Lastly, for the map and the scatter plot, a hover feature is provided, in which more detailed information on each tornado is displayed.

The drop down menu (Figure 1A) and the time-range slider provides the user with the opportunity to look closer at each tornado category through four bar plots. The category level is plotted against the summed value of the four attributes: DAMAGE_PROPERTY, DAMAGE_CROPS, DEATHS_DIRECT and INJURIES_DIRECT. This shows the property- and crop damage as well as how many deaths and injuries each tornado category is accountable for. The drop down menu and the time-range slider gives the user the opportunity to see the tornadoes destructive force, either for a single year or for the entire time period. They also provide the opportunity to choose between a single state or all states. Likewise, as for the map and scatter plot, the bar plots also allow to inspect individual tornado categories (by clicking on the categories that the user does not want to view). The bar plots are stacked by each tornadoes destructive contribution, i.e. the amount of damage. This way it is easier to get an insight into which tornado is responsible for the most property damage. Similarly, hovering displays information regarding an individual tornado.

3.4. Usage Scenario

The overview in Figure 3A clearly shows an outlier for the property damage in 2011, which is unusually high compared to the other years. However, the year 2008 had almost the same amount of tornadoes, but the property damage in 2011 was significantly higher than in 2008. Our tool supports investigating such an outlier in further detail. If one displayed the tornadoes for all states in 2011, one could see the distribution of the tornadoes. Figure 5 shows such a display, and it is clear that the southeastern states were hit hard by very destructive tornadoes in 2011, especially if one compares Alabama and Mississippi (see Figures 6 and 7). If we look into Alabama for the year 2011, we can see that its property damage is responsible for at least 3.7 billion US dollars. When comparing to the total property damage of 2011, Alabama is responsible for approximately a third of this damage. The neighbouring state Mississippi faced almost the same amount of tornadoes as Alabama in 2011. However, when comparing the property damage, it is barely a fourth of the property damage from Alabama. On the other hand, when comparing these states with respect to crop damage, Mississippi appears to be hit harder in this regard. More domain specific knowledge would be needed to draw conclusions as to why neighbouring states differ this much in property and crop damage.

4. Discussion

Our visualization tool only shows the destructive impact of tornadoes on a state level. This means that it is not possible to directly link individual tornadoes to damage caused by tornadoes in total. Also, there is no data on how populated these areas are. A different way to visualize the map might have been to use a choropleth map where the various counties show up when the user zooms in on the map. Since there is no local data, other than the latitudes and longitudes to indicate the exact location, it might be more challenging to determine the pattern of damage in one state in regards to the counties. However, our current view makes it easy to see the overall picture, i.e. how damage has increased or decreased over the years in the various states.

There are some limitations to the proposed visualisation tool, such as the lack of information regarding the population, property and crops for each tornado's origin. This makes it difficult to conclude on correlations between the types of structures and crops and the amount of damage caused in each area. In the future, we could take a closer look into other data sets, specifically concerning the damaged areas and possibly include population density, structure of properties, land use and types of crops. A further limitation concerns that we only use the origin location of each tornado. Including the start and end position as the "path" a tornado travels could potentially give us more insight into their behaviour.

Finally, additional layers, e.g., on seasonal weather conditions, topographic features, building types or crop types, would allow for a more sophisticated analysis of the tornado data, and, consequently, improve the capacity to which Tornado Visualizer can support urban planning decision making processes accordingly.

5. Conclusion

We proposed Tornado Visualizer as a means to explore the destructive impact of tornadoes. Our above scenario documents how our tool can be operated to deliver interesting insights. The focus of this paper has been to make a first step towards analyzing the relationship between the EF scale and property damage, crop damage, deaths as well as injuries cause by tornadoes.

We have specifically visualized how the numbers of tornadoes have changed from 2007-2021, as well as how the numbers of each tornado category have evolved. We have also visualized the destruction caused by tornadoes over the above-mentioned time period in relation to property and crop damage. In the future, we aim to evaluate our system with domain experts to seek for further extensions of our concept.

Our visualisation tool is built on historical data and we have not implemented a predictive model. Therefore, a prediction of a tornado's destructive impact is not possible using this tool. In the future, we could develop a machine learning model which might be able to predict a tornado occurrences, behavior and destruction caused.

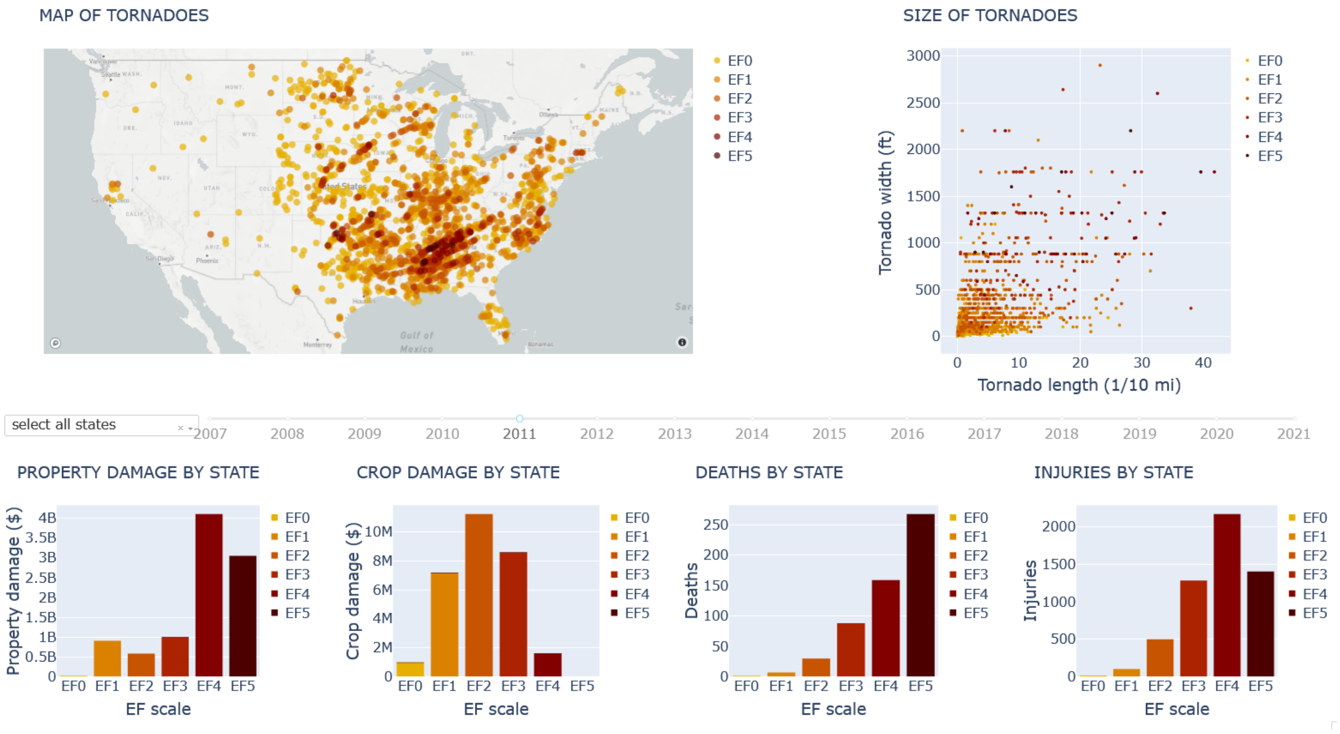

Figure 5: *Analysis of damage caused by tornadoes in 2011.*

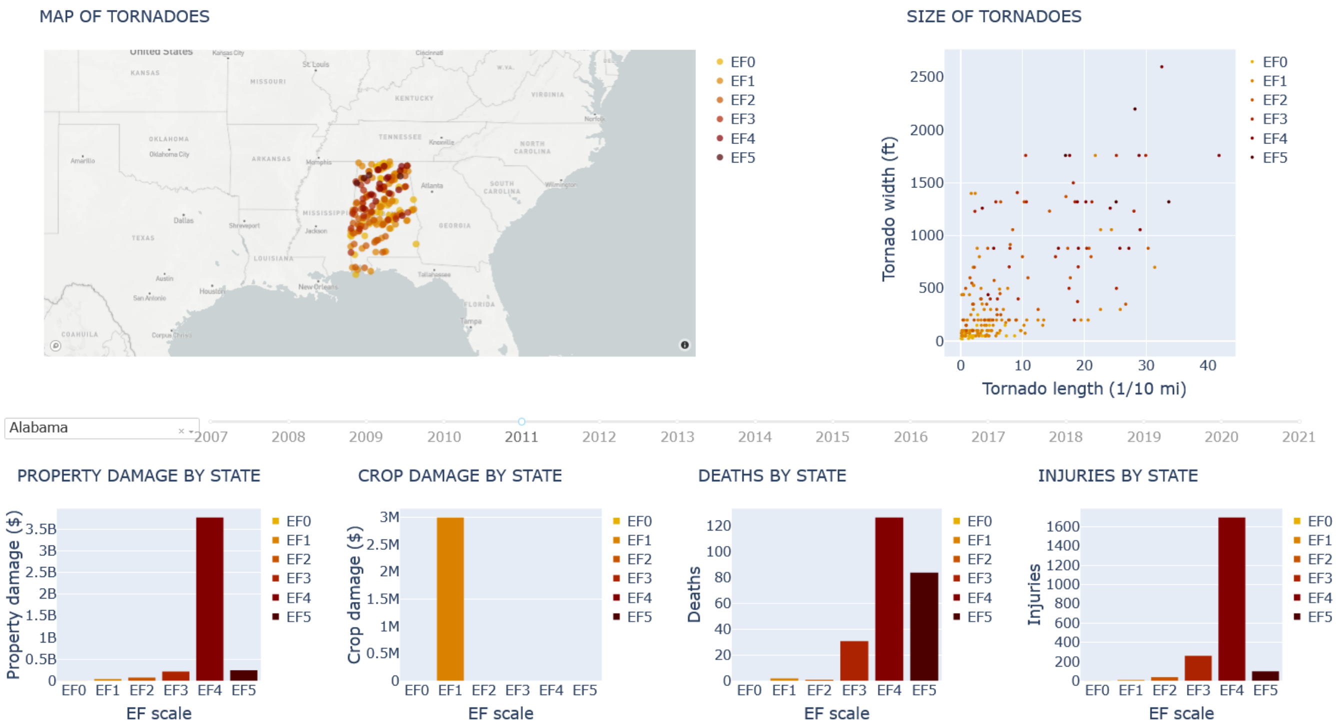

Figure 6: *Analysis of damage caused by tornadoes in Alabama in 2011.*

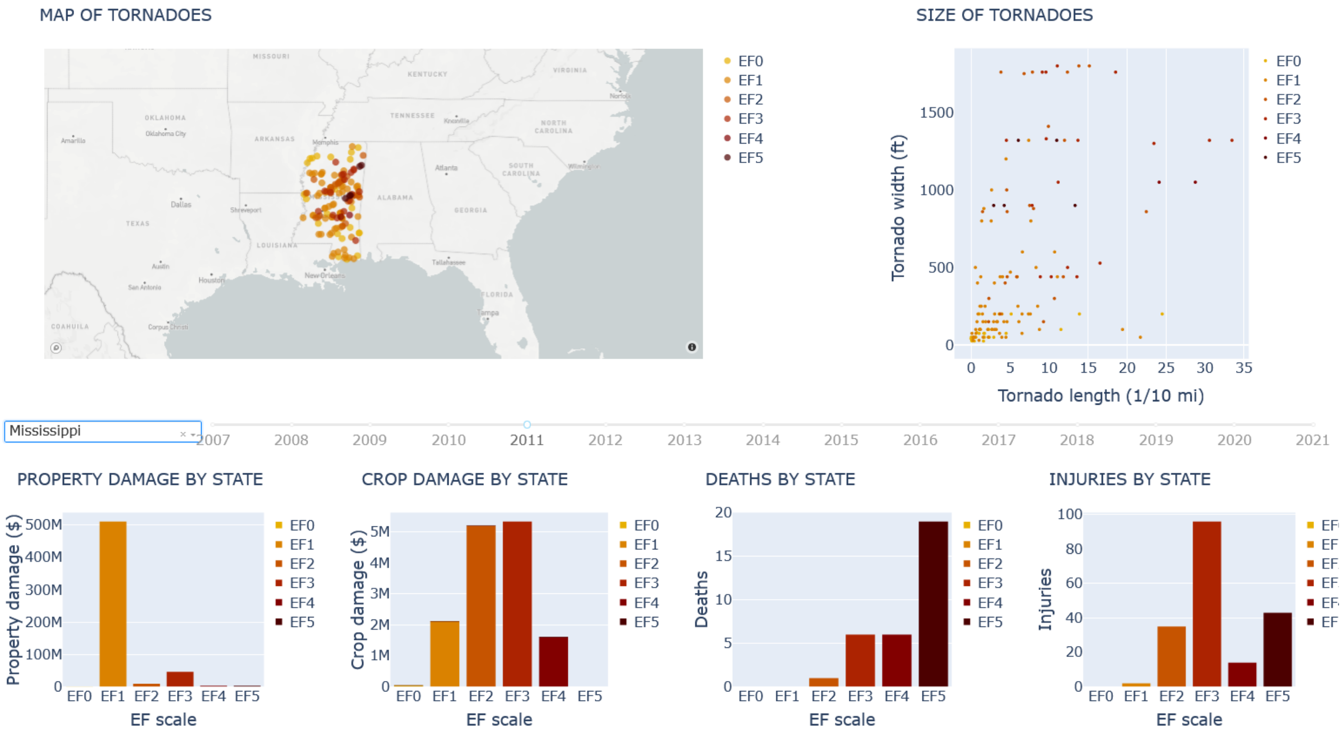

Figure 7: *Analysis of damage caused by tornadoes in Mississippi in 2011.*

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