Opportunities and challenges for the use of NOAA Storm Events database for societal impacts research

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Abstract

Severe weather events currently cause tens of thousands of deaths per year in the United States and cost trillions of dollars in damaged property and economic loss. These weather events and their impacts are tracked and recorded by several organizations such as the National Weather Service (NWS), the National Oceanic and Atmospheric Administration (NOAA), and the Federal Emergency Management Agency (FEMA). This disaster data is used by scientists in several fields of study (economics, epidemiology, atmospheric science, agriculture, etc.) to examine how weather events impact human life and how we can reduce or avoid these impacts. However, storing disaster data faces unique challenges because of the quickly evolving nature of recording processes and weather technology. These challenges pose concerns regarding biases and errors in disaster data. This paper investigates the presence of mechanisms that could lead to biases in the NOAA Storm Events database. This database contains information on storms, significant weather phenomena, rare or unusual weather, and other significant meteorological events across the United States. We use the noaastormevents package in R to examine evidence of bias within the Storm Events weather data and propose ways to avoid errors while using this data in future studies. This examination reveals five major categories of bias present in the Storm Events data set that are common in weather data. These five categories include hazard bias, temporal bias, threshold bias, accounting bias, and geographic bias. We suggest that these biases result from various factors including structural changes over time, reporting errors, inherent bias, and others. Outlining these factors and understanding their impacts will help scientists use large amounts of data appropriately and portray new findings accurately.

Introduction

Severe weather events currently cause extensive monetary loss, property and crop damage, interruptions in commerce, and human injury and fatality. Since 1980, the US has experienced 273 weather and climate disasters that each left over $1 billion in damages (Environmental Information, n.d.). In total, these events cost the US over $1.790 trillion and caused 14,223 deaths (Environmental Information, n.d.).

Scientists expect the impacts of weather events to worsen over time as a result of climate change. For example, the increasing presence of greenhouse gases in the atmosphere leads to increasing annual and extreme temperatures. Extreme temperatures lead to a wide range of health complications. Extreme heat can lead to heat cramps, heat exhaustion, heatstroke, and hyperthermia, while extreme cold leads to hypothermia and frostbite (Crimmins and L. Ziska 2016). Extreme temperatures also exacerbate health conditions related to cardiovascular disease, respiratory disease, cerebrovascular disease, and diabetes (Crimmins and L. Ziska 2016). The continually increasing extreme temperatures will increase the number of temperature related illnesses and deaths in the US per year.

Climate change is also projected to increase the number and severity of extreme natural disasters. In specific, scientists expect the number of naturally occurring wildfires to increase (Crimmins and L. Ziska 2016). Wildfires emit particulate matter and ozone precursors which decrease air quality. Low air quality harms the human respiratory and cardiovascular systems and decreases overall well being and productivity. Other natural disasters threaten physical and mental health resulting from "damage to property, destruction of assets, loss of infrastructure and public services, social and economic impacts, environmental degradation, and other factors" (Crimmins and L. Ziska 2016).

The current impacts of disasters combined with the anticipated increases in their severity and occurrence make it critical that we understand the patterns and scale of weather hazards. Continued disaster data collection and research will improve scientists' ability to predict these events and avoid such large fallout and loss.

Several organizations currently collect disaster data in the US including the National Weather Service, NCEI, and FEMA. Using this disaster data is common in interdisciplinary research because natural hazards impact several fields of study: economics, epidemiology, atmospheric science, agriculture, etc.

The American Meteorological Society has published various papers analyzing fatalities associated with weather events (Terti et al. 2017, Ashley and Mote (2005), Ashley and Black (2008), Gensini and Ashley (2010)).

Ashley and Black examined the cause, spatial distributions, and fatalities caused by nonconvective high-wind events in the US from 1980 to 2005. This study found that fatalities associated with nonconvective high-wind events often occur in boats or vehicles. These fatalities are most likely to occur on the West Coast or Northeast as a result of extratropical cyclones. These areas of the US have large forests and bodies of water with high population densities that are opportune to being highly affected by high winds (Ashley and Black 2008). Keeping these vulnerabilities in mind, the study outlines possible improvements to high wind warning systems in the areas. These improvements aim to protect people most likely to be injured or killed by nonconvective high-wind events.

Ashley and Mote conducted a similar study examining derecho events in the US from 1986 to 2003 (Ashley and Mote 2005). Derechoes are often overlooked when examining impactful weather events. However, this study revealed how they actually produce damage comparable to tornadoes and hurricanes. Derechoes caused 153 fatalities and over 2,600 injuries over the 18 year span of this study. They were also responsible for as much or more monetary loss than some hurricane and tornado events over the time span. Their study helps to draw attention to this type of weather event in hopes to advance derecho risk assessments.

Both of these studies, in part, used data from the National Oceanic & Atmospheric Administration (NOAA) Storm Events database to conduct research. This database currently contains information on 48 different storms, significant weather phenomena, rare/unusual weather, and other significant meteorological events across the United States. NOAA has been recording weather information since 1950 and storing it csv files for each year. NOAA has changed its recording strategies several times from only recording tornado events starting in 1950 to its current 48 event types. Following these changes, they have reformatted and standardized events types without changing any specific values or details ("Storm Events Database," n.d.).

[TK: do these next two paragraphs go into too much detail for the introduction?]

> The database assigns each weather phenomenon with a location, date, event type, event ID, episode ID, property damage estimate, crop damage estimate, county name, state, event narrative, and episode narrative.
>
> The US National Weather Service (NWS) collects weather data for NOAA from storm trackers, federal agencies, the media, the public, and several other sources. The NWS then uses this data to create the NOAA Storm Events database that is released as a monthly publication.

This data allows scientists to examine how weather events impact human life and how we can reduce or avoid these impacts. However, storing disaster data does not go without limitations. This is because the process of recording disaster data and the technology we use to do it are constantly evolving. These factors make it incumbent that scientists understand the biases and limitations in weather datasets to use large amounts of data appropriately and portray new findings accurately.

Gall et al. wrote a paper covering six major biases associated with major disaster databases used in the US (Gall, Borden, and Cutter 2009). In our paper, we will focus on the NOAA Storm Events database and investigate the presence of mechanisms that could lead to these major biases in the data. We used the noaastormevents package in R to dissect these issues and examine evidence of bias in several hazard types.

[TK: Should I include this next paragraph in the intro somewhere at the end?]

Though the NOAA Storm Events database is quite extensive, several biases affect its data.These biases fall under five major categories which are common in weather data. These include hazard bias, temporal bias, threshold bias, accounting bias, and geographic bias. These biases result from various factors including structural changes over time, reporting errors, inherent bias, and others.

Hazard Bias

A hazard is something that has the potential to cause damage. It is a threat that can severely disrupt society's workings. A hazard's potential to cause harm is compounded by human factors and human activity. Human factors include culture, gender, race, socioeconomic status and political structure, while human activity includes land development, urbanization, emergency preparedness, response plans, etc. [cutter1996responses]. These factors can influence the actual potential for harm, the perceived potential for harm, and the ability to respond if a disaster does occur.

The terms risk and disaster are two other concepts that tie into the defintion of a hazard. Risk is the probability of a hazard occurring and actually causing harm. A disaster is the occurence of a hazard that creates a large impact on a group of people or peoples.

For example, a shark swimming in the ocean is a hazard that has potential to cause damage. However, the risk of this hazard causing a person harm varies depending on the person's location relative to the shark. This hazard would become a disaster if the shark attacked the swimmer.

Susan Cutter has done extensive research on hazards and has spent much time defining these different terms. In her work, she states that hazards include the probability of an event occuring (risk), the impact, and the contextual/socioeconomic elements surrounding it. Other scientific authors have similar thoughts on the term hazard and believe it is important to include human culpability (McEntire and others 2005).

In the context of this paper, we use the term hazard to refer to all of the possible major storm event types that can be entered in the NOAA Storm Events database. We use the term disaster to refer to a reported occurence of a specific hazard. NOAA Storm Events currently records 55 different event types that are listed in the NWS instruction manual (NWS, n.d.). Most of these event types correlate to one type of hazard bbut some of them correlate to different intensitions of the same type of hazard. Some examples of this include the event type "Strong Wind" versus "High Wind" or "Cold/Wind Chill" versus "Extreme Cold/Wind Chill". In these instances, the hazard would be wind or wind chill while the intensities are strong, high, cold, or extreme cold.

For 2019, the database reported 51 total events of 55 different event types. The most frequent type of events reported were Thunderstorm Wind, which had over twice as many reports as the second most frequent, Hail. Hail, in turn, had almost twice as many events reported as the next most common few—Flood, Flash Flood, and Winter Weather. The least common reported events included Volcanic Ashfall, Sleet, Dense Smoke, Sneakerwave, Seiche, and Marine Tropical Depression.

[TK: include plot of event types in 2019]

NOAA further characterizes its data by categorizing large storms as episodes which contain several individual events. NOAA assigns the disaster with one episode ID and its associated events with event IDs. Further details of the episode and events are recorded under the event narrative and episode narrative. The NWS instruction describes this in terms of a swath of events occuring along a path from Point A to Point B during Time C to Time D (NWS, n.d.). Events belonging to the same episode cannot be more than five calendar days apart to ensure they all resulted from one meteorological episode. This categorization helps to ensure that a single storm is not interpreted as a series of unrelated events. An example of this would be a hurricane given one episode ID, and the rain, wind, floods, etc. associated with that hurricane given event IDs that fall under that episode.

To showcase this idea, for the episodes with the most events in 2019, the following graph shows the number of events reported for the episode. This figure demonstrates how one large weather episode can include several other events types. For example, Episode 133801 in this figure indicates several reports of flood, debris flow, strong winds, high wind, and hail. All of these different event types occurred as a result of one large storm labelled episode 133801. This unique episode ID helps related events from getting double counted as separate entities.

[TK: include plot and add in names of episode in paragraph rather than numbers]

In some cases, events falling under one episode are the same type of hazard just at different intensities, as described above. In these circumstances, the collection of events may be recorded in only one county/zone but will showcase the spatial range and and varying intensity of the event. This is likely why we see the events with different intensities of the same hazard clustered together (in one county/zone?) in the database, like heat/excessive heat and cold/extreme cold.

In other cases, a larger synoptic weather system might bring a variety of different hazards leading to several different recorded event types (e.g., thunderstorm wind and hail, which cluster together). In these cases, there may be several counties/zones in the affected area that report more than one event for the episode.

[TK: I think I am struggling with these concepts TK: potentially add in map of events over different counties vs one county]

The following plot shows a cluster analysis to group events that are more likely to occur together within an episode. We removed event types with less that 50 listings in 2019. The figure shows that there are certain event types which are very commonly reported together such as high wind and strong wind or heat and excessive heat. These types of events are likely to be reported together becuase they are likely to occur at the same time. It is important to keep these trends in mind as there may be overlap or uncertainty in how to categorize what happened during an episode.

[TK: include cluster analysis plot]

hazard bias by probability and quality/quantity

probability of an event being recorded in the database if it happens The NOAA Storm Events documentation records the standards that should be used when deciding whether or not to include a disaster report. In general, the documentation states that the Storm Events database seeks to record rare, unsual, recording breaking, or highly impactful weather events. However, this standard varies by event type. For example, the documentation states that all Tornado events should be recorded, regardless of if it had any impact like injury, fatality, damage (NWS, n.d.).

[TK: note to self: so basically we should word this as some sort of disclaimer that if you are going to be using this data for a study you should keep in mind what your focus is; is it to examine all events in a meteorological sense? or just to see human imapcts? because then you should refer to this table or to the NWS documentation to make sure that the database is capturing what you are trying to examine][TK: include table that lists all events and if they recorded based on impact, or on intenstiy]

Recorded based on impacts, noteworthiness, or public interest:

- astronomical low tide
- avalanche

- coastal flood
- dense fog
- dense smoke
- dust devil
- dust storm
- flash flood: “A life-threatening, rapid rise of water into a normally dry area beginning within minutes to multiple hours of the causative event (e.g., intense rainfall, dam failure, ice jam).” Doesn’t have to cause a fatality, but needs to happen somewhere where it could, it sounds like. There is also this note: “To maintain the most reliable data set it is important to separate low-impact flooding from

flash flooding. Low-impact flooding should not be considered a Flash Flood event; rather it should be considered a Flood event. Low-impact flooding does not pose a significant threat to life or property in the same way a Flash Flood does."

- flood
- freezing fog
- funnel cloud
- freezing fog
- funnel cloud
- heavy rain
- high surf
- lakeshore flood
- lightning
- marine dense fog
- marine hail
- marine heavy freezing spray
- marine high wind
- marine hurricane/typhoon
- maring lightning
- marine strong wind
- marine thunderstorm wind
- marine tropical depression
- marine tropical storm
- rip currents
- seiche
- sneaker wave
- storm surge/time
- strong wind
- thunderstorm wind
- tsunami
- volcanic ash
- wildfire
- winter weather

Recorded based on intensity (or having happened at all)

The probability that an event is recorded might differ by event type. Certain hazard types are underreported which leads to an undercounting in the database.

Drought hazards exemplify this issue; they are notoriously underreported because there is a lack of physical damage and it is hard to quantify spatial and monetary losses (Gall, Borden, and Cutter 2009).

There are several types of avalanches including slab, loose snow, icefall, cornice fall, glide, and slush [encyclopedia]. Many of these types can occur naturally due to a variety of envrionmental conditions or can be triggered by human activity. NOAA documentation states that avalanches should only be recorded if human fatality or injury occurs. This insinuates that the NOAA Storm Events database does not seek to record every instance of an avalanche occuring. This should be kept in mind if using Storm Events to examine avalanche events. [TK: ask CIRA if they have more info about avalanches if we are going to use this example]

On the other hand, hurricanes or tornadoes that pass through large cities will cause high amounts of physical damage and fatalities. This would attract the attention of insurance companies and produce clear records of damages.

quality and quantity of information provided for a recorded event For example, you might get much more reliable estimates of damage for certain types of events than others, or longer and more helpful descriptions.

The US government has certain programs that focus on specific hazards more than others. For example, the

NWS is obliged to provide monetary loss estimates for any flood event even if the damage assessment is a 'guesstimate' (Gall, Borden, and Cutter 2009).

[For some types of reporting, the *episode* gets the narrative, but not separate narratives for each event, while for some events (like tornadoes), each *event* might get a narrative. Also, for fatalities and injuries, it sounds like the estimates are given at the *episode level* for forecast zone-based events but then at the *event level* for county-based events.]

> "2.9.1 Episode Narrative. Generate an episode with a narrative; otherwise individual events cannot be entered into the Storm Data software. An episode narrative describes the entire episode in a general fashion, and briefly describes the synoptic meteorology associated with the episode. Information in the episode narrative can be very useful for researchers and other users of Storm Data. This narrative does not need to be long or elaborate, rather make it brief and informative. An example would be "A strong cold front passed through the Washington, D.C. area, triggering several instances of damaging thunderstorm winds and large, baseball-size hail." "To ensure events being logged in a single episode are part of the same synoptic meteorological system, events within the same episode may begin no more than five (5) calendar days apart. This will enable the Storm Data preparer to properly document events that double back into a specific region or events that are very slow moving. Examples include Hurricane and Winter Storm events." (NWS, n.d.)

[Here are more quotes from that section that I might want to weave in:

> The episode narrative will appear in the Storm Data publication after all events contained within the episode. The episode narrative does not appear in the examples shown in Appendix A, which is reserved for only event narratives. Additionally, a brief summary of fatalities and injuries should be part of the episode narrative for zone-based events.
>
> 2.9.2 Event Narrative. Detailed information pertaining specifically to the event and not the overall episode will appear in an event narrative. The event narrative describes the significance or impact of an event within an episode. An event narrative is required for all Tornado events, all Thunderstorm Wind events, and all Lightning events, whether over land or marine zones.
> This narrative will appear immediately below the header-strip in the publication and should contain descriptive information about the times, locations, and severity of destruction of property, trees, crops, power lines, roads, bridges, etc. Additionally, a brief summary of fatalities and injuries should be part of the event narrative for county-based and marine zone-based events.
> For Thunderstorm Wind events with estimated gusts, use sentences such as "Several trees were toppled by powerful downburst gusts."]

[BA: This could be a place for us to talk about how some events are reported by county versus some by forecast zone, and then we could talk about how this could lead to differences across hazard types in the granularity of information reported (including the spatial scale in which the info is reported).]

The NOAA Storm Events database also uses forecast zones as another unit of aggregation. Forecast zones are created as subsets of counties for more specific location data. Specific types of events are typically either always reported for a county (`CZTYPE` of "C") or always reported for a forecast zone (`CZTYPE` of "Z") (see table below)**. Events typically reported by county include floods, tornado-like events, and a few other events often related to thunderstorms. Events typically reported by forecast zone include severe winter weather, extreme heat, events related to the water or coast, and a few others ("High Wind", "Dense Fog", "Strong Wind", "Wildfire", "Dust Storm", "Dense Smoke").

This demonstrates the difficulty of narrowing down where exactly certain events occured. It is important to keep in mind that some events might be very localized (for example, a flash flood, or even storm surge that's only near the coast of the county), but the county-level reporting of the event means that the whole county gets classified as experiencing or not experiencing the event.

[TK: These two paragraphs come from the geographic bias section in the outline]

Related to this idea, I think that some event types include latitude and longitude locations (even starting and ending points), while some do not include more detailed location information beyond the area they're reported for (county or forecast zone). This would be another case of where there's a different amount of information available for different types of hazards listed in the database, and we could use our data to show that (it might also be listed in the NOAA manual which events lat/long should be reported for).

Another point on this idea of different amount/quality of information on different hazards might be that some hazards are recorded based on clear ways to measure intensity (for example, using a well-defined scale, as is done for tornadoes with the Fujita scale), while others don't. The NOAA guidebook might have some details on this in terms of telling people to use specific scales to report some types of events.

hazard bias by who reported event

There's variation in who reports different types of events in this database.

and we can illustrate that with the table of number of events reported by source of event report as well as the figure with the numbers of reported events by source.

We could add some discussion for these different sources on calibration, agreement across reports (e.g., across monitoring equipment for an automated weather station system, versus across people for volunteer reports), and likelihood of "catching" an event based on source (for example, an automated system would probably "see" any event that happens at the spot the monitor's located, while an event that's usually reported by people would miss anything that happens when a person isn't around or can't see it (e.g., at night, in a sparsely populated area).

We might want to make a comparison on how the number of reported events for an event type is associated with the proportion of events reported by an automated system (e.g., Mesonet, ASOS, AWOS, River/Stream Gage) versus by media or a person (e.g., media, 911 call center, Storm Chaser, Amateur Radio, Public). It looks like some of our very rare events (Sneakerwave, for example) are only reported by sources like broadcast media, fire department/rescue, and newspaper.

hazard bias by standards for when different events are recorded

I think every tornado is reported, but for some event types, it's only reported if it causes deaths, injuries, or damages.

We could look through that manual to find some more examples, and perhaps compare the frequencies reported in Storm Events to how common events are based on climatological-type studies.

For example, we could try to find a source that says how often you'd really expect Sneakerwaves and Sleet to happen, and then see if there's something in the reporting standards for Storm Events that is making it so we only see a few in the database. By contrast, I'm guessing that the standards for reporting might be more open for the events that show up a lot, like Thunderstorm Wind and Hail.

detection technology differences

ne may be that the detection technology level may differ by hazard—we may have a better process for ID-ing cases of one hazard/event type compared to another (this is a similar idea to how changes in technology over time might lead to temporal bias). I wonder if some of our rare events (Sneakerwave, Seiche, Sleet) might be examples of spots where we don't have great technology yet to detect them (or not a large enough network of monitors even if we do have the technology)?

implications

For example, would it only be an issue when comparing frequencies of different types of events? Could it lead to confounding in a single-hazard study that's looking at disaster impacts? It would certainly result in undercounts of certain types of hazards, if you're trying to characterize how frequently a type of hazard tends to happen. Would there be implications from information bias, particularly measurement error? (We could save this paragraph to draft for after we've drafted the rest of this section, and just put in a placeholder for now.)

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