Assessing exposure to Atlantic Basin tropical storms in United States counties

Joshua Ferreri[a], Meilin Yan[a], Mohammad Z. Al-Hamdan[b], William L. Crosson[b], Seth Guikema[c], Roger D. Peng[d], G. Brooke Anderson[*,a]

[a] *Department of Environmental and Radiological Health Sciences, Lake Street, Fort Collins, CO, Zip*

[b] *Universities Space Research Association, Street, Huntsville, AL, Zip*

[c] *Department, Street, City, State, Zip*

[d] *Department of Biostatistics, Street, Baltimore, MD, Zip*

Abstract

There are many important applications for having county-level estimates of exposure to tropical storms over many years. For example, ... Current approaches include ... but have the following limitations ... .

Here, we present open source software we have developed to explore county-level exposure to tropical storms in United States counties between 1988 and 2011. Further, we explore the differences in exposure classification when using different metrics (e.g., wind speed, rainfall, distance).

```r
library(hurricaneexposure)
```

Introduction

What it means to assess county-level tropical storm exposure.

Why it's important to measure TS exposure for counties. Current hurricane exposure assignments are often nonspecific and may lead to missclassification of exposure at the county-level (Grabich et al. 2016). Researchers have found heterogeneity in exposure assignments of counties in assessing multiple classification methods, both within and accross storms (i.e., storm dependent) (Grabich et al. 2016). Such missclassification can have important public health and economic implications.

Studies have begun to assess county-level hurricane exposure using large historical datasets (Zandbergen 2009) ... making the `hurricaneexposure` package a powerful tool in future exposure analysis.

Currently, it seems that most hurricane track mapping capabilities are restricted to geographical information system software. The introduction of this package expands the mapping potential of hurricane tracks and therefore the assessment of hurricane exposure and impacts to R.

Examples of using TS exposure estimates for multiple storms. (Zandbergen 2009) developed an exposure factor based on location (longitude and latitude), county shape, county size, and distance from the coast. The study assumed symmetrical activity of storm related factors,(Zandbergen 2009) which does not accurately represent storm characteristics once landfall has been made.(Kruk et al. 2010, Halverson (2015))

[*]Corresponding Author

Email addresses: `joshua.m.ferreri@gmail.com` (Joshua Ferreri), `alice@example.com` (Meilin Yan), `alice@example.com` (Mohammad Z. Al-Hamdan), `alice@example.com` (William L. Crosson), `alice@example.com` (Seth Guikema), `alice@example.com` (Roger D. Peng), `brooke.anderson@colostate.edu` (G. Brooke Anderson)

Examples of other datasets at the county level. If exposure to tropical storms over multiple storms and years can be assessed, these exposure datasets can be joined with other time series to explore the impacts of tropical storms. For example, daily counts of human health outcomes in environmental epidemiology studies are often available aggregated at the county level, and such data has often been paired with time series of environmental exposures (e.g., air pollution, temperature) to determine associated risks.

Data and Methods

Distance-based exposure. We collected "best tracks" data on hurricane tracks for Atlantic basin storms between 1988 and 2014 from the extended best tracks database. This dataset is based on a poststorm assessment of each storm conducted by the United States National Hurricane Center (NHC) and incorporates data from a variety of sources, including satellite data and, when available, aircraft reconnaisance data (Landsea and Franklin 2013). This data gives time stamps for each observation in Coordinated Universal Time (UTC; also known as Zulu Time, sometimes indicated by "Z").

These data typically give measurements of storm center location at 6-hour intervals, at synoptic times (i.e., 6:00 am, 12:00 pm, 6:00 pm, and 12:00 am UTC); some landfalling storms have an additional observation at the time of landfall (Landsea and Franklin 2013). These positions are given to within 0.1 degrees latitude / longitude at these synoptic times (Landsea and Franklin 2013). We interpolated these location values to every 15 minutes during the period when the storm was active, using a linear interpolation between each measured point.

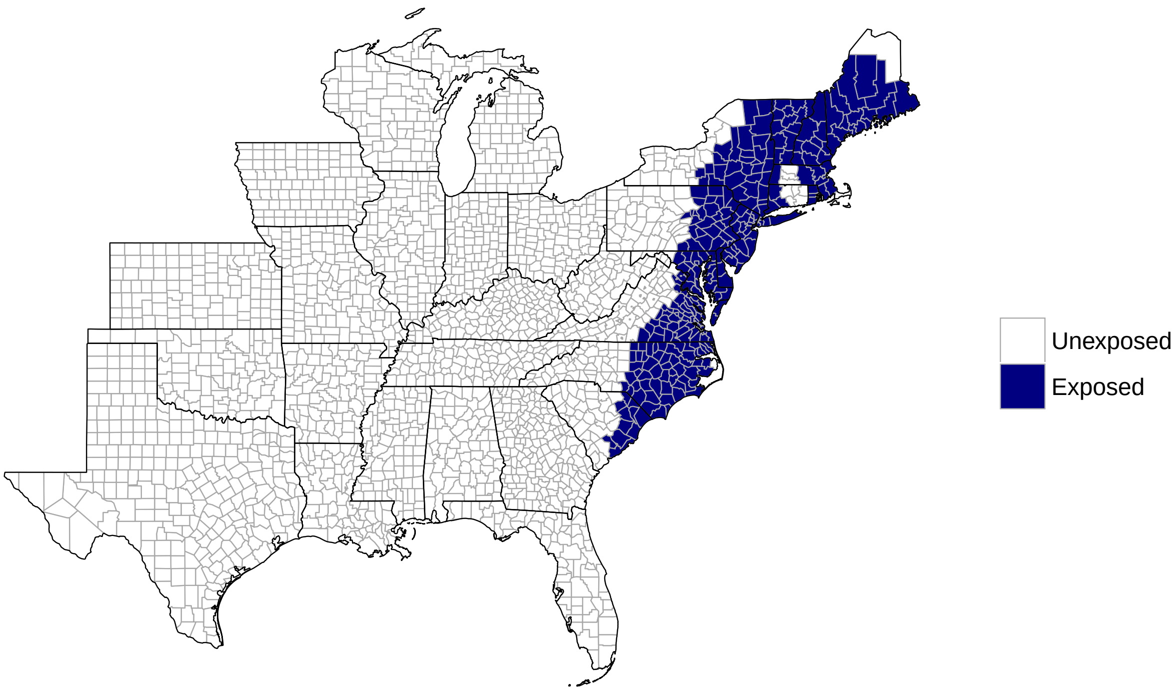
We calculated the distance between each county's center and each of the 15-minute-interval estimates of a storm's location. To do this, we used the Great Circle method to calculate the distance between pairs of latitude and longitude coordinates, using the R package `sp`. For each county, we used the population mean center, based on the U.S. Census's 2010 Decennial Census, as the center location of the county. From these distance calculations, we identified the date-time and distance between the storm track and the county center at the 15-minute interval when the storm was closest to the county center. We used the `countytimezones` R package to convert each date-time of the closest storm approach for a county to the county's local time zone and identified the local date when the storm was closest to the county. This "closest date" was used to pair the distance estimates with rainfall estimates.

Rain-based exposure. Given its high resolution and consistancy with rain gage values, (Villarini et al. 2011) recommends the use of Stage IV precipitation data for the analysis of rainfall distribution in landfalling tropical cyclones. However, the Stage IV dataset only provides data since 2001 (Lin and Mitchell 2005) and is therefore inadequate for use in this analysis.

NLDAS does not provide information on precipitation over the ocean, preventing its use in assessing the develpment of the storm prior to landfall (Villarini et al. 2011). This point is moot for this analysis.

Wind-based exposure. These wind models use estimates of maximum wind speed from the best tracks dataset. These maximum wind speed estimates in the best tracks dataset are rounded to 5-knot intervals and is the maximum 1-minute-average windspeed at 10 meters above the ground (Landsea and Franklin 2013). This windspeed is typically determined using the Dvorak technique to estimate windspeed from satellite measurements, although data from aircraft reconnaisance in also sometimes incorporated in the estimate (Levinson et al. 2010).

Results



Discussion

Distance-based exposure. There are some sources of uncertainty for storm locations from the best track hurricane data. These include ...

However, these best tracks should be fairly reliable for more recent years of storms, as we use here. Many of the uncertainties related to storm positions in best track data are more of a concern for the years before ... (e.g., pre-19[xx]).

While there are often several different "best tracks" datasets, from different sources [?– weather services?] for other ocean basins, the "best tracks" data from ..., which is the basis of the tracks we use here, are the undisputed primary source of tropical storm track data for the Atlantic basin.

There are a number of limitations to using distance to assess exposure to tropical storms. Tropical storms vary in size and intensity, and a measure of distance from the storm track will not incorporate these differences and so could mis-classify exposure both in terms of generating false positives (counties close to the storm track of very mild or small-radius storms) and false negatives (e.g., during very large or intense storms).

There is some uncertainty in the position estimates from the best tracks hurricane dataset, since the estimation of storm position for best tracks data involes a poststorm subjective smoothing and integration of many different types of data (Landsea and Franklin 2013). In a survey of researchers who perform the poststorm data aggregation to create the best tracks datasets, uncertainty in the center position of a US landfalling storm in the "best tracks" dataset was estimated at approximately 8 nautical miles for major hurricanes, 11 nautical miles for Category 1 and 2 hurricanes, and 15 nautical miles for tropical storms (Landsea and Franklin 2013). Uncertainty in estimates of a storm's position also varies by time of day, with more certain estimates during daylight than during the night (Landsea and Franklin 2013).

Currently, distance parameters involved with assessing risk of a particular storm have been rather arbitrary, contributing to the necessity in understanding how such parameters influence a county's exposure status. In assessing the risk of a given storm based on distance, recent studies have defined the distance from the storm track affected by a given storm differently. (Czajkowski, Simmons, and Sutter 2011) assessed county-level risk and exposure based on a three-tierd definition, with primary counties being those closest to the storm track on either side, secondary counties being adjacent to primary coutnies, and tertiary counties adjacent to secondary counties. Such a defenition resulted in an exposure defenition based on an average distance radius of 120 km on either side of the storm track (Czajkowski, Simmons, and Sutter 2011). Such a distance is slightly greater than that commonly used by public health departments (i.e., 100 km) (Czajkowski, Simmons, and Sutter 2011). In other cases, distance has been defined on the basis of maximum sustained wind speeds and their decay, with exposure defined as those counties exposed to wind speeds greater than or equal to tropical storm strength (39–73 miles per hour) (Zandbergen 2009) and may not provide an accurate respresentation of the communities exposed to a given storm (e.g., a large number of inland counties are likely underrepresented under this definition).

In a study assessing the association between hurricanes and undesireable birth outcomes, researchers found that results were not sensitive to the omission of residences 100 km from the storm path, and that results varied insignificantly from 30-75 km (Currie and Rossin-Slater 2013).

Rain-based exposure. It can be very difficult to reliably measure rain during extreme rain events, including tropical storms. For example, a heavy rain can wash away [?] rain monitors [?]. It can also be very hard to measure rain during heavy wind, as the rain does not fall straight into the monitor [?].

Some of the other possible sources for estimating rain during tropical storms include . . . [Stage IV, TMPA, NEXRAD]

The estimated rainfall amounts from our data are likely underestimates. This data source, however, should be internally consistent and so useful for comparing across different storms when all exposure estimates are based on this rain data.

Rainfall estimates are likely underestimates for a few reasons. First, they are based on averaging hourly measurements to a daily mean estimate. This averaging would smooth over shorter periods of very extreme rainfall. Further, this data is averaged over multiple grid points within each county and so would not fully reflect very extreme local precipitation (although this might be less of a concern for classifying exposure to a large-scale storm system, like a tropical storm, compared to more fine-scale storms). Finally, this NLDAS data provides a re-analysis that incorporates measured rainfall, using models, etc., to incorporate that observed data into a spatially and temporally continuous dataset of rainfall. However, during extreme storms, the problems with measuring rainfall using [rain monitors] would propogate into the NLDAS data, so although NLDAS would prevent missing values during the storm if monitors are not able to provide data, if monitors are out, rainfall estimates from NLDAS will be based more on models than on observations. More on NLDAS bias low here (Villarini et al. 2011). Such bias, though unimportant in our analysis, may play a larger role in the extrapolation to other studies or exposure analysese where the precipitation cutoffs used here may provide a threshold that results in the missclassification of less affected counties as exposed.

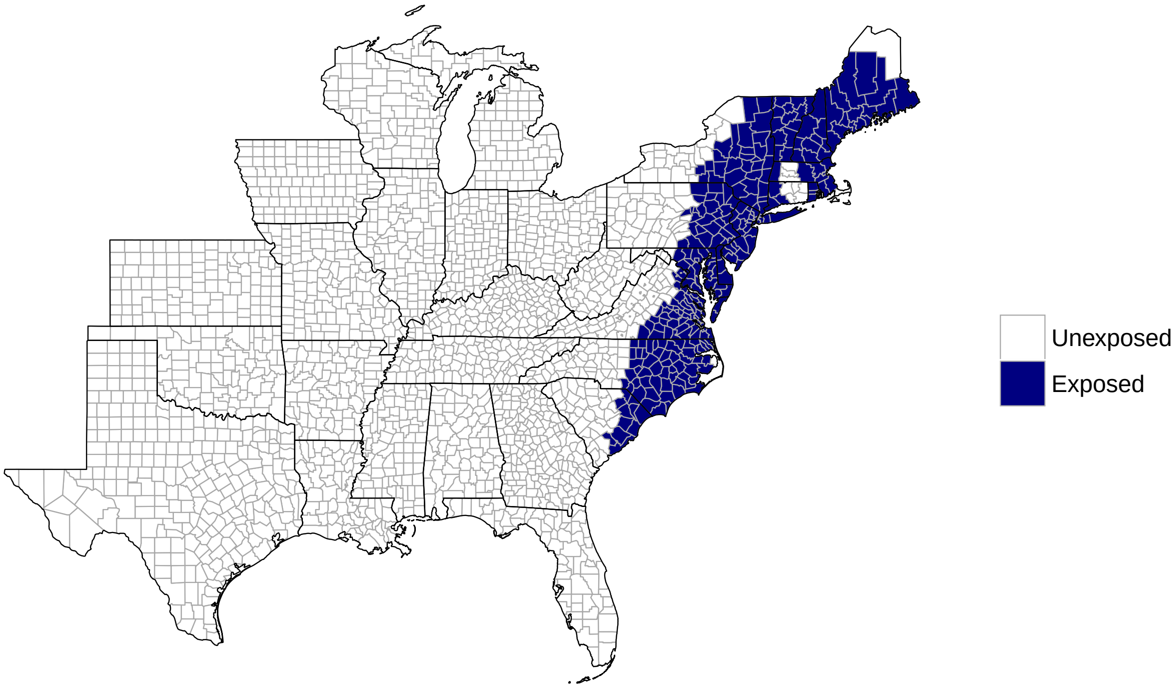
Exposure classification based on rainfall has some advantages. For example, it allows the identification of exposed counties that are inland, rather than coastal, but that were affected by heavy rainfall during the storm. Often, storm-related deaths are associated with inland flooding. In fact, over half of the hurricane-related fatalities from 1970 to 1999 were a result of freshwater flooding, accounting for the vast majority of deaths in inland counties (**???**). In another analysis, researchers found that 79% of freshwater-drowning fatalities occured in inland counties,(Czajkowski, Simmons, and Sutter 2011) further stressing the importance of rainfall in hurricane risk analysis. Storms can produce a lot of rain especially in certain topographies, like near mountains, so counties that are well inland can sometimes experience more extreme rain that other counties at similar distances from the storm's track.

In comparison to the storm track, the areas of extreme rain and extreme wind can vary. For example, storms undergoing an extratropical transition can bring heavy rains to the left of the storm's center track, while extreme winds are more common to the right of the track (Halverson 2015, Grabich et al. (2016)). In contrast, storm that interact with a downstream ridge tend to bring heavy rains to the right of the storm's center track (Atallah, Bosart, and Aiyyer 2007).

Some storms can be of lower intensity (i.e., on the Saffir-Simpson scale) yet bring dangerous rainfall, including well inland of the storm's landfall. For example, storms including Floyd in 1999, Gaston in 2004, Irene in 2011, and

Lee in 2011, have had severe inland impacts, often through extreme rainfall, as post-tropical storms (Halverson 2015). This rainfall can be particularly severe in the Appalachians (Halverson 2015). Further, heavier rainfall is more common for storms moving at slower forward speeds (Chang, Yang, and Kuo 2013). Storms with a slower forward speed and larger rainfall area contribute to a longer duration of rainfall, and therefore an increased chance of flood-related damage (Rezapour and Baldock 2014).

For example,



Wind-based exposure. Wind suffers from similar challenges for measuring during tropical storms. In particular, the strong winds of tropical storms can break or blow away the anemometers used to measure wind speed.

Here, we used wind speed models, rather than observed wind speed, to estimate exposure to tropical storms based on winds.

A variety of other wind speed models exist besides the one used here. In particular, there are options for wind speed models as far as …

There is some uncertainty in the maximum wind speed values estimated at each synoptic time for each storm. For US landfalling storms, the estimate of storm intensity in the best tracks dataset is estimated to have an uncertainty of around 8 knots for tropical storms, 10 knots for Category 1 and 2 hurricanes, and 13 knots for major hurricanes (Landsea and Franklin 2013). Since the wind model used here uses these best tracks maximum wind speeds as an input, this uncertaintly would propogate into our estimates of windspeed within each county for each storm.

A recent study suggests that nearly all states east of the Rocky Mountains have experienced wind exposure associated with either tropical or post-tropical storms (Kruk et al. 2010).

Example uses of exposure datasets.

Table including various exposure papers and the parameters used.

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