1.1 THE CLIMATOLOGY OF INLAND WINDS FROM TROPICAL CYCLONES IN THE EASTERN UNITED STATES

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1. Introduction

In the United States, the impacts from tropical cyclones often extend well-inland after these storms make landfall along the coast. For example, after the passage of Hurricane Camille (1969), more than 150 casualties occurred in the state of Virginia, some 1300 km inland from where the storm originally made landfall along the Louisiana coast (Emanuel 2005). According to Rappaport (2000), a large portion of fatalities often occur inland associated with a decaying tropical cyclone's winds (falling trees, collapsed roofs, etc.) and heavy flooding rains. In the 1970s, '80s, and '90s, freshwater floods accounted for 59 percent of the recorded deaths from tropical cyclones (Rappaport 2000), and such floods are often a combination of meteorological and hydrological factors. Moisture from tropical cyclones occasionally merges with eastward-moving continental low pressure systems, producing copious amounts of rainfall inland from the coast. Tropical cyclone-induced flooding has devastated communities located many hundreds of miles from the coast (Gibney 2000). Recent examples of storms that caused significant inland impacts include Hurricane Hugo (wind and rain) in 1989, Hurricane Floyd and Tropical Storm Allison (flooding) in 1999 and 2001, respectively, and Hurricane Fran (wind) in 1996. Each of these storms reveal how the destructive forces of tropical cyclones can impact areas far from the initial landfall point.

Strong winds associated with tropical systems usually diminish quickly once they move ashore, primarily due to the frictional effects of land-based obstructions (topography, forests, urbanized areas) and, thermodynamically through a loss of heat energy from the ocean's surface (Friedman 1975). Emanuel (2005) suggests that the decay rate of a land falling hurricane is rapid; losing half its wind speed value in roughly seven hours, 75% in 15 hours, and nearly 90% after just one day inland. In numerical simulations Tuleya et al. (1984) found that more intense hurricanes decay faster upon landfall than do weaker storms. For these reasons, the primary impact areas of tropical cyclones are generally found along coastal (or near coastal) regions. Most previous studies involving the inland-extent of tropical cyclones have generally focused on their expected or modeled rate of decay post landfall (e.g., Tuleya et al. 1984, Kaplan and DeMaria 1995; Kaplan and DeMaria 2001), while others have focused on recurrence thresholds or probabilities of landfalls along a given portion of the United States coastline (e.g., Bove et al. 1998; Elsner and Bossak 2001; Gray and Klotzbach 2005; Saunders and Lea 2005). Results from Kaplan and DeMaria (1995) showed an idealized scenario for the maximum possible inland wind speed of a decaying tropical cyclone based on both intensity at landfall and forward motion for the Gulf Coast and southeastern United States, and for the New England area (Kaplan and DeMaria 2001). In general, they found that, for inland locations, the effect of storm speed of motion is just as critical as the storm intensity upon landfall, such that a fast moving Category-3 storm on the Saffir-Simpson Scale (Simpson 1974, hereafter referred to as the Saffir-Simpson Hurricane Wind Scale, SSHWS) will have further inland impacts than a slow moving Category-5 storm.

Thus, there is a need to accurately document and understand the inland extent of winds associated with tropical cyclones to enhance public awareness, improve forecasting of hazardous conditions, and in turn save lives. To that end, a comprehensive climatology of the inland extent of tropical cyclone winds over the eastern United States was developed at NOAA's National Climatic Data Center (NCDC). Section 2 describes the data and methods used to construct the climatology, while section 3 discusses the results of the new climatology. The paper concludes with a summary and discussion of the results.

2. Data and Methodology

Historical track data for the North Atlantic was obtained from the International Best Track Archive for Climate Stewardship (IBTrACS, Knapp et al. 2010; Kruk et al. 2009). The IBTrACS dataset is a comprehensive collection of all recorded tropical cyclones worldwide, and the Atlantic basin portion of the record is derived from NOAA's Atlantic Hurricane Database (HURDAT, Jarvinen et al. 1984). In addition,

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the so-called extended best track data was also obtained for the North Atlantic (Demuth et al. 2006). The data for the extended best track begins in 1988 and contains not only the time, position, and intensity of the tropical cyclone at 6-hr intervals, but also the maximum extent of winds (MEW) of a given threshold (34, 50, and 64kt) in four quadrants: northeast, southeast, southwest, and northwest. These wind radii values are the result of operational estimates and became part of the official North Atlantic best track data after 2004.

The first step towards producing an inland tropical cyclone wind impact climatology was to compute the average distance for each MEW threshold (wind radii) using the extended best track dataset. This was done by differentiating those storms which were solely tropical or extra-tropical[1]. Then, for each wind radii and quadrant, a mathematical average was computed and binned by the SSHWS, and included post-tropical storms. This resulted in a matrix of average distances (nm) for each wind radii, SSHWS intensity, and quadrant. However, this matrix was unsuitable for computing the average inland extent of tropical cyclone winds for two reasons. The first reason is that using all data provided in the extended best track dataset produces an average wind radii distance that is comprised of mostly over-water observations and fewer inland observations. Applying this biased result to inland locations would result in inflated frequency counts, owing to the lack of friction at sea producing wider swaths. The second reason is that as Geographic Information System (GIS) software was used to procure results, which includes a "buffering" utility that requires that the tropical cyclones wind swath around a best track point be represented as a "left side" and "right side" only and not in four distinct quadrants. To fit this model, a simple average was computed on the distance estimates specified above.

There are several ways to obtain a frequency distribution for those over land locations which are impacted by tropical cyclone winds. First, a simple count-by-county tabulation can be done where the frequency incrementally increases when a buffered wind swath overlaps any portion of the county. This technique exaggerates (diminishes) the counts for larger (smaller) counties, since large counties are more likely to be affected by a nearby tropical cyclone wind swath. To account for the heterogeneous county size distribution across the eastern United States, an equal-area grid was constructed at resolutions of 5, 15, and 30km. A sensitivity analysis was performed to determine which grid resolution should be used to estimate the inland wind impacts from tropical cyclones (not shown). Interestingly, the sensitivity analysis revealed little change in the maximum frequency count despite the change in grid size. Therefore, in recognizing that the mean absolute distance error in the extended best track dataset is roughly 25km (Demuth et al. 2006), the 30km grid was selected to derive the inland tropical cyclone wind climatology for the eastern United States (Figure 1), and the period of record for this study was set at 1900-2008. While Zandbergen (2009) attempts to normalize county size through the use of a novel "shape index", the application of a 30km grid can be applied in any tropical cyclone-prone basin and altogether eliminates the dependency on counties.

Frequency counts for each 30km grid cell were obtained by executing a custom python script within the Environmental Systems Research Institute (ESRI) ArcInfo Desktop GIS environment. The script was developed to automate the process of selecting best track segments by intensity and buffering them to the left and right for each wind radii. The wind buffers were oriented orthogonal relative to the storm track and rounded edges (versus flat) were incorporated to simulate the circular nature to tropical cyclones. Figure 2 demonstrates this process for a Category-4 hurricane which made landfall along the southeastern Texas Coast in 1932. Figure 2a shows the track of the storm with each segment color coded by storm intensity (SSHWS). Figure 2b overlays the storm's track on the 30 km equal-area grid and shows the aerial extent of the inland impacts if only the center point of the storm track was used. The buffers were then merged and dissolved into a single wind swath with rounded edges (Figure 2c). The resulting inland impact is thus apparent after applying the asymmetrical buffer (Figure 2d). This process was repeated for each storm in the historical best track record from 1900-2008 (i.e., a unique buffer at each MEW threshold was generated for each storm). Once all the buffers were constructed, they were overlaid onto an equal-area grid (Fig. 1) and intrinsic ArcGIS operations (spatial join and join count) were used to determine the cumulative frequency of the 34, 50, and 64kt winds from tropical cyclones. Frequency maps for these thresholds are shown in Figure 3. It is equally important to note that these wind buffers represent the average maximum extent of the winds in each quadrant, and that not all grid cells falling within the corresponding radius will actually receive the indicated winds. Rather, the buffer is simply used as a guide to conservatively estimate the maximum radius of influence from a given tropical cyclone.

3. Results

While the use of frequencies is beneficial in ascertaining how often a particular region was impacted by tropical storm-force or hurricane-force winds, return intervals are often referred to instead. In this regard, rather than acknowledging a single grid cell having 20 "hits" over the course of the 108-year period, or 0.185 storms per year, it is often more meaningful to say that grid cell experiences tropical storm-force winds once every 5.4 years (simply the inverse of the ratio of

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[1] Hereafter, the term post-tropical (PT) will be used instead of extra-tropical as to distinguish between traditional baroclinic mid-latitude cyclones and those which are the transformational result of tropical cyclone decay.

frequency count over the period of interest). In the discussion that follows, return intervals will be used to summarize the historical inland wind climatology.

Figure 3 is an examination of 34 kt winds solely from tropical (and not post-tropical) cyclones (Fig 3a), and all hurricanes with winds greater than 64 kt (Fig 3b). The figure shows that much of the southern Gulf Coast and Eastern Seaboard is regularly affected by 34 kt winds from a tropical cyclone (i.e., one event every 2-5 years), and 64 kt winds from hurricanes once every 3-5 years. The return intervals decrease in the New England area, where tropical storm-force (hurricane-force) winds are experienced once every 6-10 years (11-20 years). The map shows that, in general, warm-core tropical cyclones rarely make it farther north than central Illinois and west of central Ohio.

For those locations that are not color filled, the maps imply that, in the recorded history, these regions have not experienced tropical storm- or hurricane-force winds. However, this does not suggest tropical cyclone winds cannot occur in the future. Again, these maps are a climatological guide for inland wind impacts from tropical cyclones, and a zero percent occurrence does not mean ‘never going to happen’, but that is it ‘highly unlikely’.

To some extent, geography helps explain the heightened exposure of certain regions of the U.S. mainland. Areas that extend out into the Atlantic and Gulf of Mexico are more likely to be affected by North Atlantic and Gulf tropical cyclones. Florida, eastern North Carolina, and Massachusetts are examples of areas that frequently find themselves in the path of tropical storms and hurricanes simply due to the seaward extent of their land area (Gibney 2000).

4. Summary

Tropical cyclones pose a significant threat to life and property along coastal regions of the United States. As these systems move inland and dissipate, they can also pose a threat to life and property, through heavy rains, high winds, and tornadoes. While many studies have focused on the impacts from tropical cyclones on coastal counties of the United States, there was a need for a detailed climatology of the inland penetration of tropical cyclone wind fields.

The NOAA’s NCDC has developed a comprehensive climatology of the inland winds from tropical cyclones for the eastern United States. This was done by using the historical Atlantic basin track data (Jarvinen et al. 1984) in concert with the historical extended best track dataset (Demuth et al. 2006) to comprise an average maximum extent of the winds at 34, 50, and 64 kt thresholds according to storm intensity. A unique storm-relative asymmetrical buffer was generated for each storm and was overlaid on a 30 km equal-area grid using GIS to depict those regions of the eastern United States that have historically been impacted by tropical cyclones.

While the results are shown as return intervals, the focus of this study was to produce a comprehensive climatology of the extent of inland winds from tropical cyclones in the eastern United States. While some locations east of the Rocky Mountains have never experienced such winds, the analysis presented here is purely climatological in nature and no predictive trends or assumptions are provided or inferred. However, for those locations with higher return intervals, knowledge of where tropical storm-force winds or hurricane-force winds have most commonly occurred can better prepare local forecasters, emergency managers, county planners, and others to be even more vigilant to the myriad of threats tropical cyclones pose and recognize that their impacts often extend well inland from the coast.

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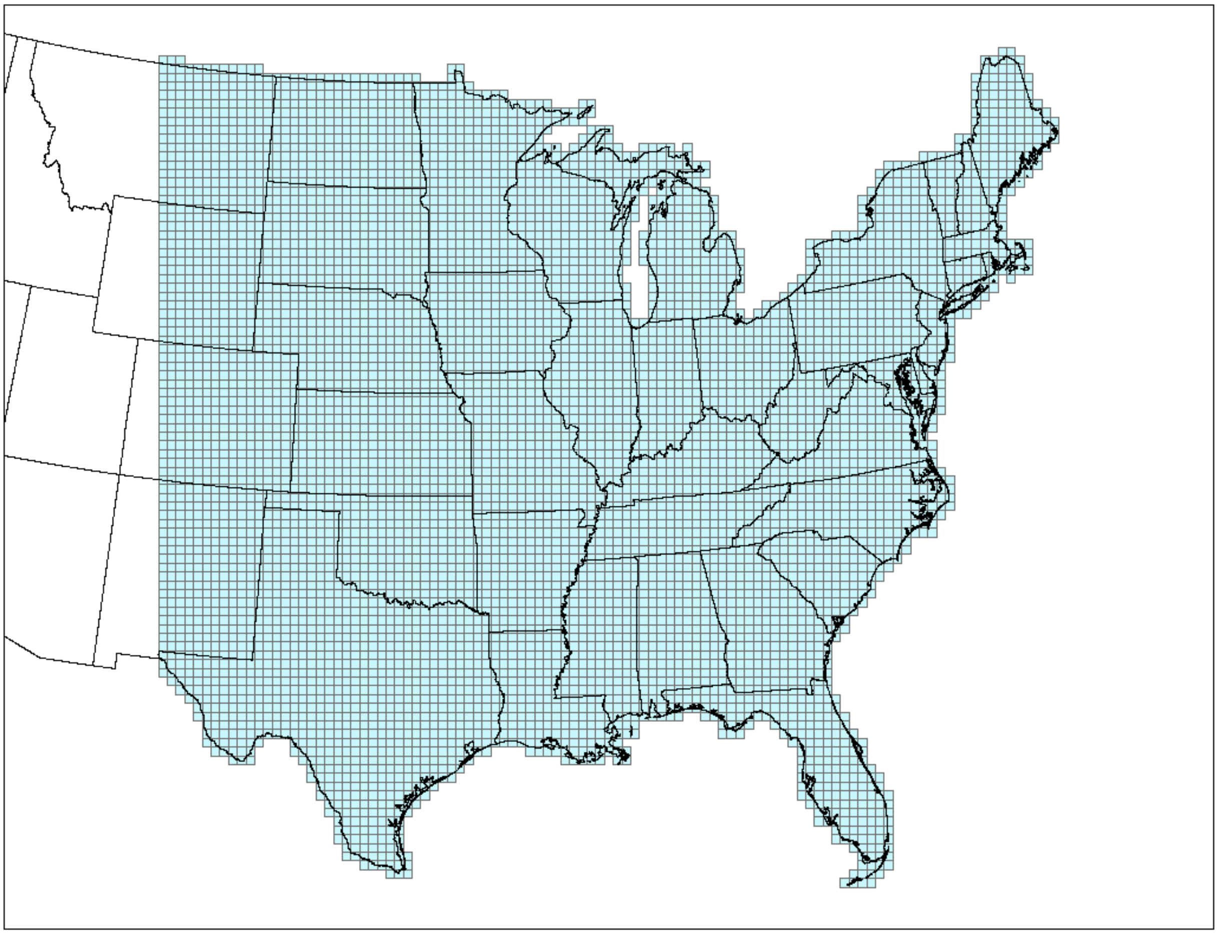

Figure 1. 30km grid used to construct the inland wind climatology.

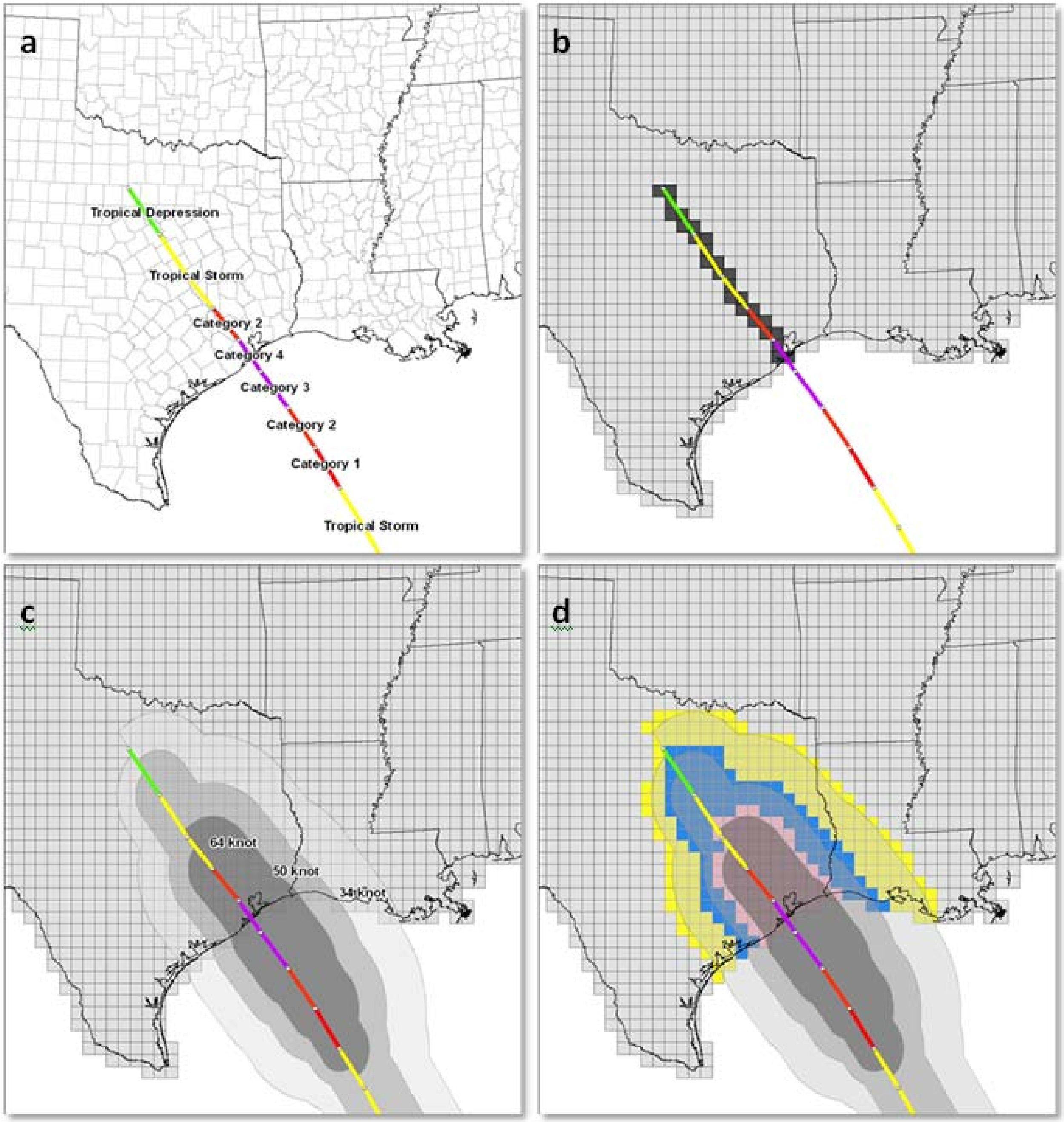

Figure 2 a) a 1932 hurricane making landfall along the Texas coast, b) Grid cells (30 km) intersected with the track, c) the estimated extent of the 34, 50, and 64 kt wind swaths, and d) the resulting inland impact after applying the asymmetrical buffers.

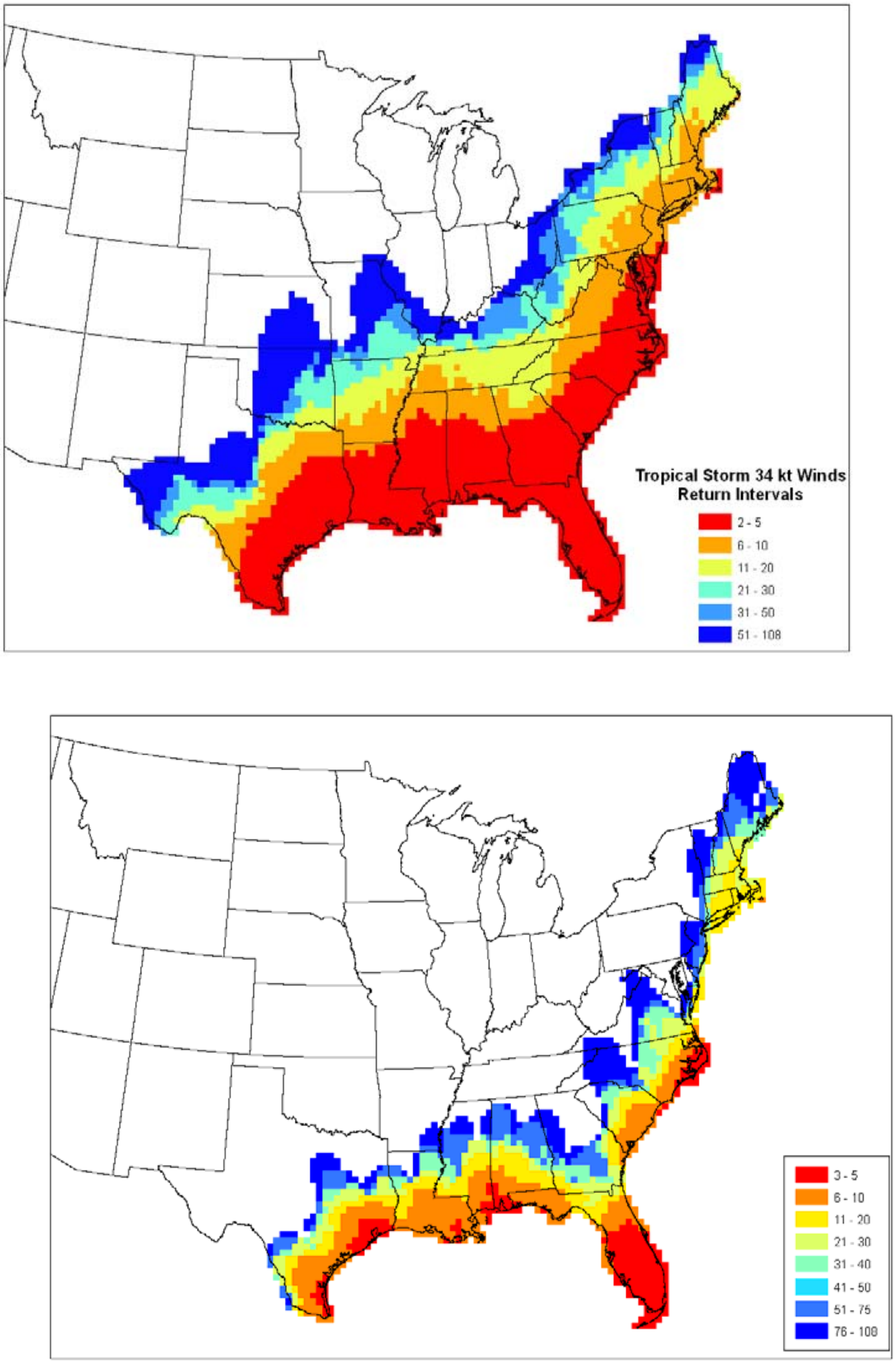

Figure 3. Return intervals, in years, for top) tropical storm force winds greater than 34 kt, and bottom) all hurricane-force winds greater than 64 kt.