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AN IDEALIZED HURRICANE CATASTROPHE MODEL

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Tropical Cyclones are recurring threats to the densely populated US coast. Post-tropical storm Sandy was an example of their devastating effects. US historical damage since 1900 scaled for population, inflation, and individual wealth (Pielke et al 2008) show zero trends. Pareto distributions (e.g., Willoughby 2012a) fitted to the tails seasonally aggregated damage offers some insight. Pareto distribution are power-law approximations to other distributions' tails such that $\Pr\{d \geq D\} = P_o\,(D_o/D)^{\alpha}$, where d is damage, D is cumulative-distribution damage, D_o is the threshold damage corresponding to probability P_o, and α is the Pareto exponent. They can be interpreted as Taylor series approximations to the tails of log-normal distributions (e.g., Katz 2002, Willoughby 2012) that appear to describe hurricane impacts. What is the origin of the distributions' fat tails? Tropical cyclone intensity and size have physical limits. Thus, the prominent tails of the damage distributions must stem from the distributions of assets at risk. It is generally accepted (Ades and Glaeser 1995, Gabiax 1999) that sizes of populated places obey Zipf distributions in which their sizes are inversely proportional to their largest-

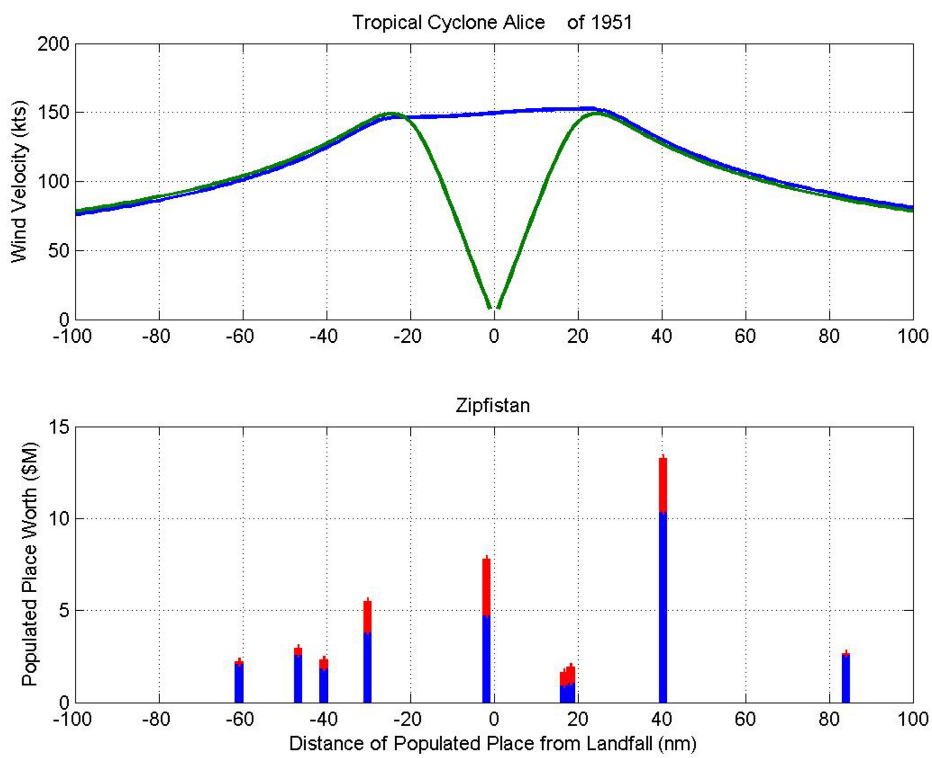

Fig. 1. Upper panel: Radial profile of wind as a function of cross-track distance in virtual cyclone Alice of simulated year 1951 in the Zipfistan model. The black curve is the symmetric Wood-White wind profile, and the blue curve is the profile modified to reflect cyclone motion and the extension of the wind across the front to the eye. Lower panel: Populated places within 100 nm of Alice's landfall. The total height of each bar represents the pre-storm wealth in each populated place. The red portion is the damage; and the blue is the remaining wealth after the storm.

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to-smallest ranking. Zipf distributions are essentially Pareto distributions with unit exponent.

When coastal county population census data (Pielke et al. 2008) is ranked, plotted on a log-log scale and fitted with a Pareto distribution, early census years, such as 1900, produce Pareto exponents close to 1, while 2000 and 2010 have Pareto exponents as large as two. A reason for this discrepancy is that Zipf distributions describe population centers and not necessarily counties. In 1900 each county tended to be dominated by one population center. By the 21st century, counties often contained multiple centers so that the central limit theorem adjusts their distributions toward a normal. We hypothesize that this “Aggregation Effect” is key to understanding how cumulative hurricane damage excedance probabilities with Pareto exponents > 1 arise (Willoughby and Hernandez 2014).

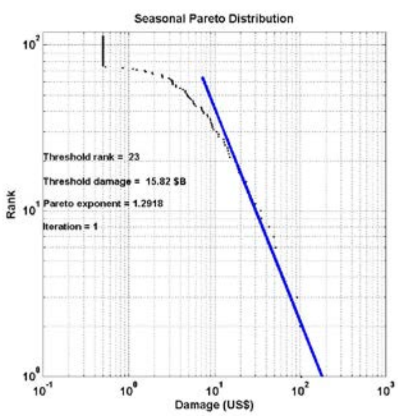

Fig. 2. An example of the Pareto distribution of damage produced by the Ziphistan model.

To test the hypothesis that the Pareto distribution of US damage is inherited from the distribution of the assets at risk, an idealized hurricane catastrophe model was created. It is easily configured to explore different scenarios and test sensitivities. The model is based upon an idealized virtual country (Zipfistan) where assets that scale as populations of locales that obey Zipf distributions are scattered randomly along a straight coastline. Realizations encompass a specified number of seasons, nominally 100. They can be executed either each with a unique Zipfistan demographic or all using a common demographic. Within each season the numbers of hurricane landfalls obey either Poisson or negative binomial distributions. Intensities are uniformly distributed between 33 ms^{-1} and a specified Maximum Potential Intensity (MPI, Emanuel , 1986, 1999), nominally 80 ms^{-1}. Wind profiles obey either Wood-White (Wood et al. 2012) or Holland (2007) parametric models (Fig. 1). Vulnerability curves for populated places follow a sigmoid polynomial curve with specified thresholds of initial damage and total destruction. All specified parameters can be changed from case to case or assigned linear time variations to explore model sensitivities. After each realization, damage is ranked and plotted on log-log scales to be fitted with Pareto distributions (Fig. 2). After minor model tuning, results yielded Pareto exponents that agreed reasonably well with experience for both individual landfalls (α = 1.14) and seasonal aggregates (α = 1.37).

The Zipfistan model is adaptable enough to support a gamut of experiments. Perhaps the most pressing of these is detection of increases in damage as MPI increase on a warming planet (Fig. 3). The standard analysis entails comparing the control and “treatment” experiments by plotting them and testing their median and mean differences with Mann-Whitney, Kolmagorov-Smirnov and Bootstrap tests. A significant preliminary result is that changes from control to treatment cases need to produce in 150-200% changes in damage to produce statistically significant differences between most of the possible comparison pairs in 100-yr simulations (Fig 4).

The model readily adapts to other experiments testing, for example, changes of landfall rates or vulnerability. So far, experimentation has focused on detection of differences between stationary century-long simulations. A more pressing question is detection of trends over decadal time scales. The current model has some unrealistic features inasmuch as it simulates only windstorm losses, but it is straightforward to include effects of storm surge and inland flooding. All of the populated places are assumed to be distributed in one dimension along the coast, but a two-dimensional version that includes distances inland and models inland wind

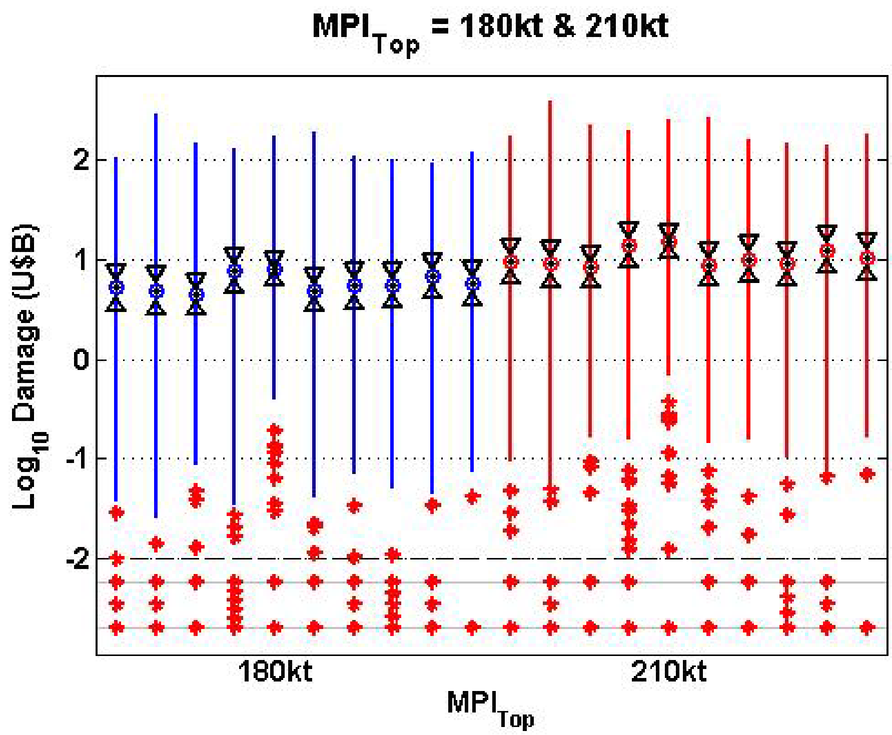

Fig. 3. Box and whisker plots comparing ten, 113 yr Ziphistan realization that have 180 kt MPI (blue) with ten that have 210 kt (red) MPI. The difference in MPI is equivalent to 1½ Saffir-Simpson categories. The ordinate is common log of seasonally aggregated damage in billions of dollars. Corresponding realizations with different MPIs use the same random-number seed so that they are identical apart from different intensity. Of the 100 pairs of comparisons, about ⅔ were significantly different at p = 5% using standard nonparametric tests. When the "treatment" MPI was reduced to 200 kt, only ⅓ of the pairs are significantly different, and when it is 190 kt, about ⅒ were significantly different.

decay is a relatively simple enhancement, as are geographic variations of MPI or landfall frequency.

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