The Impact Angle of Hurricane Sandy’s New Jersey Landfall

Timothy M. Hall
NASA Goddard Institute for Space Studies
New York, NY

Adam H. Sobel
Department of Applied Physics and Applied Mathematics, Columbia University,
New York, NY.

Formatted

Abstract

Hurricane Sandy's track crossed the New Jersey coastline at an angle closer to perpendicular than any previous hurricane in the historic record. This steep angle was one of many contributing factors to a surge-plus-tide peak-water level that surpassed 4m in parts of New Jersey and New York. The lack of precedent in the historic record makes it difficult to estimate the rate of Sandy-like events using solely historic landfalls. Here we use a stochastic model built on historical hurricane data from the entire North Atlantic to generate a large sample of synthetic hurricane tracks. From this synthetic set we calculate that under long-term average climate conditions a hurricane of Sandy's intensity or greater (category 1+) is expected to make NJ landfall at least as close to perpendicular as Sandy at an average annual rate of only 0.0014 yr^{-1} (95% confidence range 0.0007 to 0.0023); i.e., a return period of 714 yr (95% confidence range 1429 to 435). Thus, either Sandy was an exceedingly rare storm, or our assumption of long-term average climate conditions is erroneous, and Sandy's track was made more likely by climate change in a way that is yet to be fully determined.

1. Introduction

The average trajectory for North Atlantic hurricanes involves a northward, then northeastward motion in mid-latitudes, due to the beta-drift effect and the steering of mid-latitude westerlies. Thus, hurricanes that impact the US eastern seaboard typically do so by skirting up the coast, roughly parallel to the coast. When they make landfall, they typically do so at a grazing impact angle, unless the landfall occurs on promontories, such as Cape Hatteras and Cape Cod.

In Sandy's case, the combination of a blocking high over the western north Atlantic and interaction with an extra-tropical upper-level disturbance (the same one with which Hurricane Sandy eventually merged) led to advection by a highly anomalous easterly flow and the unprecedented track shown in Fig. 1. Our intent here is to estimate the probability of such a track's occurrence in a quasi-stationary climate by statistical modeling of hurricane tracks over the entire North Atlantic.

Sandy appears to have caused record-breaking storm surges in New Jersey and New York. At the Battery in lower Manhattan, for example, the peak surge was 2.81m and the peak water (surge plus tide) was 4.23m above mean sea level (NOAA NCDC; www.ncdc.noaa.gov/sotc/national/2012/10/supplemental/page-7), higher than any recorded by the tide gauge in place since 1920 and comparable to estimates of the surges from the hurricanes of 1788, 1821 and 1893 [*Scileppi and Donnelly*, 2007]. Other peak-water levels in the region were 2.71m at Atlantic City, NJ, 4.0m at Sandy Hook, NJ, and 4.36 on Kings Point, NY.

Storm surge is a function of many factors, including the magnitude and direction of the wind, the storm size, the fetch in space and duration in time over which it exerts stress on the ocean, and the bathymetry. Nearly all these factors were such as to cause strong surge in Sandy. The landfall location led to onshore winds in New Jersey and New York. The track direction put those locations on the right side of the track where the winds are strongest due to superimposition of the storm-relative wind and the motion of the storm. The approach from the open ocean, as opposed to along the coast, meant that the storm was not weakened by interaction with the land surface. The effect of a hurricane's impact angle on surge is complicated and varies widely with coastal geometry [*Irish et al.*, 2008], and the sensitivity of NJ-NY surge to this angle has yet to be determined. Nonetheless, the impact angle was the most anomalous of Sandy's attributes, and the one on which we focus.

2. Methods

Since no hurricane in the historic record has made NJ landfall with an impact angle as near perpendicular as Sandy's, it is difficult to estimate the probability of such a landfall solely using historic landfalls. Instead, we draw in data from the entire North-Atlantic to inform our calculation of the NJ rates. We use a stochastic model of the complete lifecycle of North Atlantic (NA) tropical cyclones (TCs) [*Hall and Jewson*, 2007; *Hall and Yonekura*, 2012] built on historical NA TC data (HURDAT, 1950-2010) [*Javinen et al.*, 1984]. The statistical properties of the synthetic TCs match those of the historic TCs by design. The model is used to generate millions of synthetic TCs, and landfall rates are computed from this synthetic set.

Sandy was declared post-tropical by the National Hurricane Center at landfall, and thus was not a pure TC. This does not compromise our analysis. The HURDAT data on which the model is constructed include the post-tropical phases of storms that started as TCs. Thus, the model accounts for storms such as Sandy.

We simulate 50,000 years at fixed average 1950-2010 values of sea-surface temperature and southern oscillation index, the model's independent variables. The long duration is necessary to get convergence on rates of rare events. We calculate NJ landfall rates from these data, using the coast segments of Fig. 1. The landfalls are filtered according to maximum sustained wind speed just prior to landfall and the angle that the 6-hourly TC increment makes with the NJ coast segment.

3. Results

Fig. 2a shows the 595 simulated TCs that make NJ landfall at hurricane intensity; i.e., with category 1 or greater (CAT1+) maximum sustained winds. Also shown are the 2 historical CAT1+ NJ land-falling storms in the period 1851-2012 for which there are HURDAT data: Hurricane Sandy and the "Vagabond Hurricane" of Sep., 1903. Fig. 2b shows the 124 of these TCs whose coastal impact angle is within 30 degrees of perpendicular. Hurricane Sandy is the sole historical TC satisfying these criteria in the 1851-2012 historical record.

From these TCs we compute CAT1+ NJ landfall rates using successively closer thresholds to perpendicularity as criteria. In this way we build up the annual CAT1+ NJ landfall rate as a function of impact-angle threshold. This function is shown in Fig. 3. NJ CAT1+ landfalls of any angle have a best-estimate annual rate of

0.0119/year, corresponding to a return period (1/rate) of 84 years. Most of these landfalls, however, are at grazing angles, and the rate falls quickly with increasingly perpendicular angle thresholds. For impacts within 30 degrees from perpendicular ($\cos(\theta) = 0.5$ in Fig 3) the best-estimate rate is 0.0026/year, or a return period of 391 years. Sandy made an impact at $\cos(\theta)=0.3$, or 17 degrees from perpendicular. The annual rate of TCs making this or more-perpendicular landfall is only 0.0014 (714 year return period).

In addition to the best estimates shown in Fig 3, we also show 95% confidence bounds obtained from a generalized jackknife uncertainty test. For this test we reconstruct the entire model 100 times, each time dropping out a random 20% of the data years. For each subset model we repeat the simulations and landfall calculations, thereby obtaining 100 estimates of the annual rate as a function of impact angle threshold. The inner 95 of the 100 rates are shown in the figure.

Fig. 4 shows a comparison of modeled and historical landfall counts. Due to the chaotic dynamics of the atmosphere, hurricanes can be thought of as stochastic to some extent. Even if a long-term mean landfall rate is known, the number of landfalls that occur in a finite time varies randomly about the mean. The HURDAT period 1851-2012 is a 162-year window. The annual mean rate for CAT1+ NJ landfalls at any impact angle from the model is 0.0119 (Fig. 3), equivalent to 1.9 landfalls in 162 years. However, there is a wide range of possibility, with considerable magnitude at 0 through 4 landfalls. The historical value of 2 is near the peak of the distribution. The annual landfall number for $\theta < 30$ degrees peaks at 0, but has considerable magnitude at 1, before falling rapidly at higher counts. The historical value of 1 (Sandy) is in the high probability range. In other words, the model is not ruled out by the observations. The model has been found to have realistic landfall characteristics by a variety of other tests, as well [*Hall and Yonekura*, 2012].

4. Discussion

Hurricane Sandy's near perpendicular impact with the NJ coast was exceedingly rare. We have estimated here an annual occurrence rate of only 0.0014/year (714 year return period, 95% confidence range 1429 to 435 years) for landfall by a hurricane of at least Sandy's intensity and at least as perpendicular an impact angle. Because many factors influence storm surge, the rate for surge at least as high as Sandy is likely higher. Historical records suggest that there have been several comparable events in New York City in the last several hundred years [*Scileppi and Donnelly*, 2007]. Numerical simulations estimate that Sandy-level surges on Manhattan occur on average every 400-800 years [*Lin et al*., 2012], somewhat more frequent, but overlapping, our range for Sandy's track.

Our calculations do not explicitly account for long-term climate change. While there has almost certainly been some greenhouse gas-induced warming in the period encompassed by the HURDAT data, the climate was close to pre-industrial for most of the 162-year period, and in any case our model assumes stationary statistics.

It has been argued that decline of arctic sea ice is resulting in greater variability in the jet stream and formation of blocking highs [*Francis and Vavrus*, 2012; *Liu et al*., 2012], which could result in less reliable eastward TC steering and more frequent events like Sandy. The fact that our calculations show Sandy's track to be so rare under long-term average climate conditions lends support to a climate-change influence. On the other hand, the most recent climate model simulations project reductions in blocking frequency in a warmer climate [*Dunn-Sigouin and Son*, 2012]. Global high-resolution models suggest that tropical cyclone frequency will decrease globally, while mean intensity will increase. There is growing consensus that the most intense events will increase in frequency, but there is high uncertainty, especially in individual basins [*Knutson et al*., 2010]. On the other hand, further sea level rise is almost certain, with a meter or more expected in the next century [*Nicholls and Cazenave*, 2010]. This will exacerbate TC-induced flooding even if the storms themselves do not change.

Acknowledements

We thank Prof. Kerry Emanuel for comments on the manuscript. This work was partially supported by a NASA National Climate Assessment award.

References

Dunn-Sigouin, E., and S.-W. Son (2012), Northern hemisphere blocking climatology as simulated by the CMIP5 models, *J. Geophys. Res.,* in press.

Francis, J. A., and S. J. Vavrus, Evidence linking Arctic amplification to extreme weather in mid-latitudes, *Geophys. Res. Lett.*, 39, L06801.

Hall, T. M., and S. Jewson (2007), Statistical modeling of North Atlantic tropical cyclone tracks, *Tellus*, 59A, 486-498.

Hall, T. M., and E. Yonekura (2010), North American hurricane landfall and SST: a statistical model study. *J. Clim*. submitted.

Irish, J. L., D. T. Resio, and J. J. Ratcliff (2008), The influence of storm size on hurricane surge, *J. Phys. Oceanogr.*, 38, 2003-2013.

Javinen, B. R., J. Neumann, and M. A. Davis,(1984), A tropical cyclone data tape for the North Atlantic basin, 1886-1983, contents, limitations, and uses, *NOAA Tech. Memo. NWS NHC 22*.

Knutson, T. R., J. L. McBride, J. Chan, J., K. A. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi (2010), Tropical cyclones and climate change, *Nature Geosci.,* 3, 157-163.

Lin, N., K. A. Emanuel, M. Oppenheimer, and E. Vanmarcke (2012), Physically based assessment of hurricane surge threat under climate change, *Nature Climate Change,* 2, 462-467.

Liu, J. et al. (2012), Impact of declining Arctic sea ice on winter snowfall. *Proc. Natl. Acad. Sci.* 109, 4074-4079.

Nicholls, R. J., and A. Cazenave, A. (2010), Sea level rise and its impact on coastal zones, *Science*, 328, 1517-1520.

Scileppi, E., and J. P. Donnelly (2007), Sedimentary evidence of hurricane strikes in western Long Island, New York, *Geochem. Geophys. Geosys.* Q06011, doi:10.1029/2006GC001463.

Figures

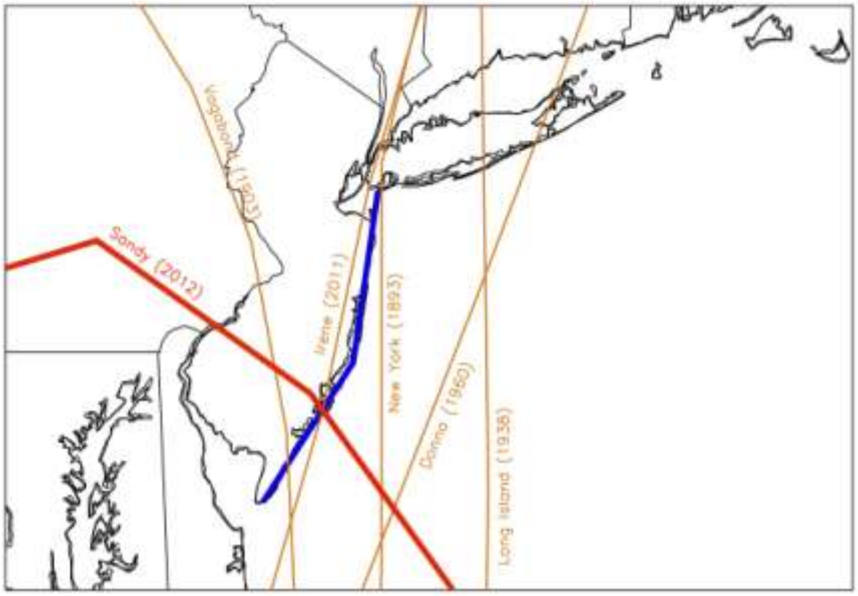

Fig 1: The New Jersey and New York coasts. Shown in blue are the two coastline segments used to define landfalls on NJ. The storm-center track of Hurricane Sandy in 6-hour increments is shown in red. Also shown (orange) are the tracks of 5 other historic hurricanes that affected the region, as labeled: the New York Hurricane of Aug., 1893, the "Vagabond Hurricane" of Sep., 1903, the Long Island Express Hurricane of Sep., 1938, Hurricane Donna of Sep., 1960, and Hurricane Irene of Aug., 2011. Only Sandy and the Vagabond Hurricane crossed our NJ coast segments as CAT1+ hurricanes. (Irene weakened to a tropical storm just prior to NJ landfall.)

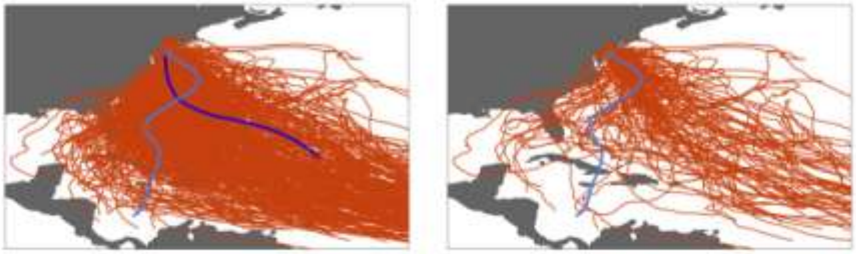

Fig 2: Tropical cyclones (TCs) making landfall on New Jersey. TCs from a 50,000-year neutral climate simulation from the statistical model are shown in red. (a) All TCs making NJ landfall. (b) TCs whose landfalling impact angle is within 30 degrees of perpendicular to the coast segments shown in Fig. 1. The two historical TCs that make NJ landfall in the period 1851-2012 are also shown left: the "Vagabond Hurricane" of Sep., 1903 (dark blue) and Hurricane Sandy (light blue). Only Sandy's impact angle is within 30 degrees of perpendicular.

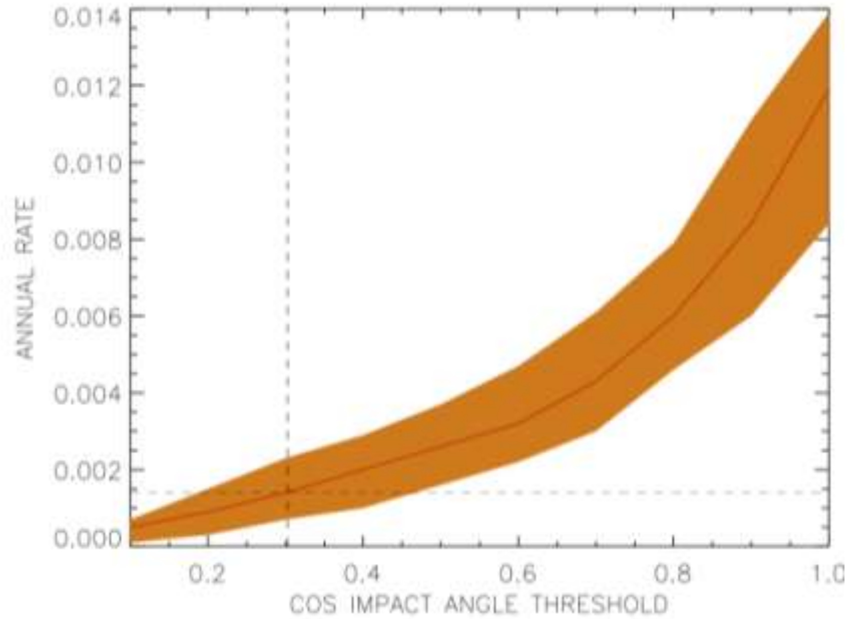

Fig 3: The annual NJ CAT1+ landfall rate as a function of impact angle threshold on the land-falling NJ coast segment. The threshold is expressed as the cos of the angle, θ, from parallel. Thus, at the right ($\cos(\theta)<1$ or $\theta>0$) is the rate for all CAT1+ TCs. On the left is the rate for TCs whose $\cos(\theta)<0.1$ or $\theta>84.3$, that is, within 5.7 degrees from perpendicular. The red line is the best estimate, and the orange region indicates the 95% confidence range from a generalized jackknife uncertainty test. The cross hairs indicate the position of Hurricane Sandy: 17 degrees from perpendicular, corresponding to a best-estimate annual rate of 0.0014, or equivalently a return period of 714 years.

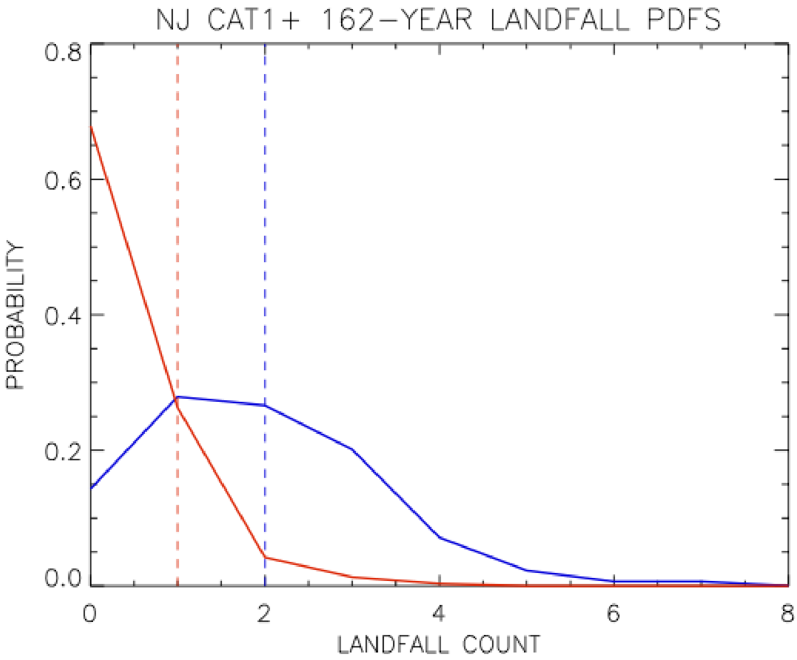

Fig 4: Normalized distributions of NJ CAT1+ landfall counts in 162-year windows from a 50,000-year model simulation. Blue is for all land-falling impact angles, and red is for angles within 30 degrees of perpendicular. The dashed lines at values 2 and 1 indicate the corresponding historical counts that occurred.