On the impact angle of Hurricane Sandy's New Jersey landfall

Timothy M. Hall[1] and Adam H. Sobel[2]

Received 18 February 2013; revised 20 March 2013; accepted 21 March 2013; published 29 May 2013.

[1] Hurricane Sandy's track crossed the New Jersey coastline at an angle closer to perpendicular than any previous hurricane in the historic record, one of the factors contributing to record-setting peak-water levels in parts of New Jersey and New York. To estimate the occurrence rate of Sandy-like tracks, we use a stochastic model built on historical hurricane data from the entire North Atlantic to generate a large sample of synthetic hurricanes. From this synthetic set we calculate that under long-term average climate conditions, a hurricane of Sandy's intensity or greater (category 1+) makes NJ landfall at an angle at least as close to perpendicular as Sandy's at an average annual rate of 0.0014 yr^{-1} (95% confidence range 0.0007 to 0.0023); i.e., a return period of 714 years (95% confidence range 435 to 1429). **Citation:** Hall, T. M., and A. H. Sobel (2013), On the impact angle of Hurricane Sandy's New Jersey landfall, *Geophys. Res. Lett.*, *40*, 2312–2315, doi:10.1002/grl.50395.

1. Introduction

[2] 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 U.S. 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.

[3] In Sandy's case, the combination of a blocking high over the western north Atlantic and interaction with an extratropical 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 Figure 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.

[4] Sandy caused record-breaking storm surges in New Jersey and New York. At the Battery in lower Manhattan, for example, the peak surge was 2.74 m, and the peak water (surge plus tide) was 4.28 m above mean lower low water (NOAA http://tidesandcurrent.noaa.gov), 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 2.71 m at Atlantic City, NJ, and 4.29 m on Kings Point, NY.

[5] 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 normally 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

[6] Because 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 (NA) to inform our calculation of the NJ rates. We use a stochastic model of the complete lifecycle of NA tropical cyclones (TCs) [*Hall and Jewson*, 2007; *Yonekura and Hall*, 2011] 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. In effect data from well beyond the region of interest (e.g., NJ) are used to inform the occurrence on the region, and the model determines objectively the weights to give these additional data [*Hall and Jewson*, 2007]. In this way, coupled with the assumption of statistical stationarity, it is possible to obtain return periods that are much longer than the historical record. Other methods are possible, too; e.g., statistical modeling of local data using the distributions of extreme value theory [*Jagger and Elsner*, 2006], or statistical-dynamical downscaling [*Emanuel*, 2006].

[7] 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.

[8] We simulate 50,000 years at fixed average 1950–2010 values of sea-surface temperature and southern oscillation

[1]NASA Goddard Institute for Space Studies, New York, New York, USA.
[2]Department of Applied Physics and Applied Mathematics and Lamont-Doherty Earth Observatory, Columbia University, New York, New York, USA.

Corresponding author: T. M. Hall, NASA Goddard Institute for Space Studies, New York, NY, USA. (Timothy.M.Hall@nasa.gov)

0094-8276/13/10.1002/grl.50395

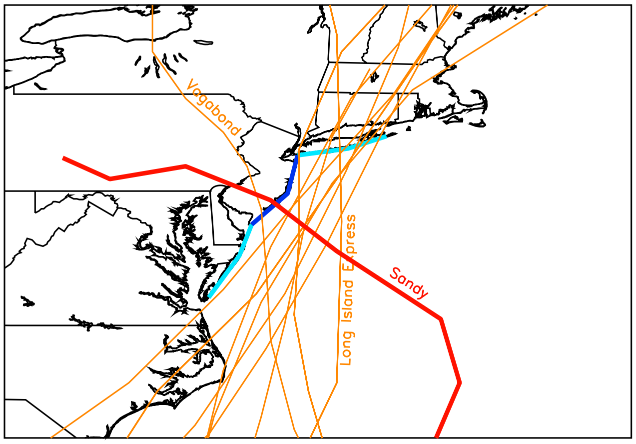

Figure 1. The New Jersey and New York coasts. Shown in dark blue are the two coastline segments used to define landfalls on NJ and in light blue additional segments north and south of NJ used to define a broader coastal region. The storm-center track of Hurricane Sandy in 6 h increments is shown in red. Also shown (orange) are the tracks of the 10 other hurricanes that made landfall on the broader region since 1851. Two of these are labeled: the Vagabond Hurricane of September 1903, and the Long Island Express Hurricane of September 1938. Only Sandy and the Vagabond Hurricane crossed the NJ coast segments. (Irene, 2011, not shown, weakened to a tropical storm just prior to NJ landfall.)

index, the model's independent variables. The long duration is necessary to get convergence on rates of rare events; i.e., the uncertainty due to finite simulation length is small compared to the uncertainty due to the finite historical data used to construct the model, as determined by the jackknife tests discussed below. We calculate NJ landfall rates from these data, using the coast segments of Figure 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

[9] Figure 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 two historical CAT1+ NJ land-falling storms in the period 1851–2012 for which there are HURDAT data: Hurricane Sandy and the "Vagabond Hurricane" of September 1903. Figure 2b shows the 124 of these TCs whose coastal impact angle is within 30° of perpendicular. Hurricane Sandy is the sole historical TC satisfying these criteria in the 1851–2012 historical record.

[10] 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 Figure 3a. A NJ CAT1+ landfall at any angle has a best-estimate annual rate of 0.0119 yr^{-1}, 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. The "Vagabond Hurricane" of 1903, the one historical landfall on NJ other than Sandy, made landfall approximately 50° from perpendicular. For impacts within 30° from perpendicular ($\cos(\theta) = 0.5$ in Figure 3a) 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° from perpendicular. The annual rate of TCs making this or more-perpendicular landfall is only 0.0014 (714 year return period). By comparison, CAT1+ landfalls at least as perpendicular as the Vagabond's impact angle have a rate of 0.006 yr^{-1}, corresponding to a return period of 167 years.

[11] In addition to the best estimates shown in Figure 3a, 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.

[12] To document further sensitivity of our rates, we repeat the analysis, this time using Hurricane Sandy's track in the data set. That is, to the 667 HURDAT TCs 1950–2010 inclusive we add a 668th TC, Sandy, to the set of TCs on which the model's synthetic tracks are built. A new 50,000 year simulation is performed, and NJ landfalls determined. The light blue curve in Figure 3a shows the annual mean rate as a function of impact angle for this simulation. There is a modest increase in all mean rates, and the return period for a Sandy-like impact is reduced from 714 to 625 years. However, this change is well within the uncertainty. The fact that the change is modest is not surprising: even though Sandy's track is highly anomalous,

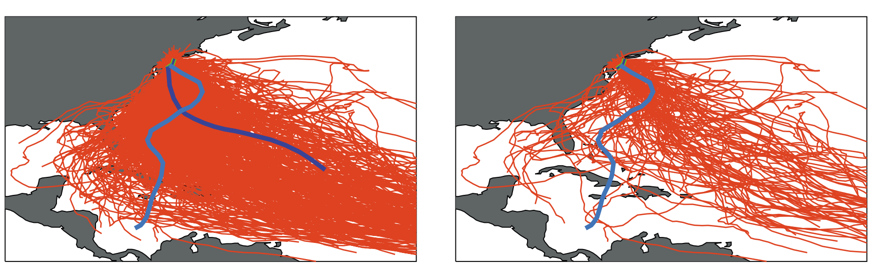

Figure 2. Tropical cyclones (TCs) making landfall on New Jersey. TCs from a 50,000 year neutral climate simulation from the statistical model are shown in red. (a) All TCs making NJ landfall. (b) TCs whose landfalling impact angle is within 30° of perpendicular to the coast segments shown in Figure 1.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

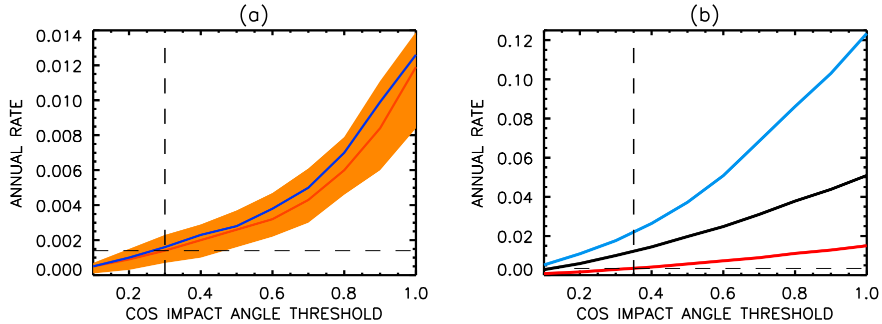

Figure 3. (a) The annual NJ CAT1+ landfall rate as a function of impact angle threshold on the land-falling NJ coast segment. The threshold is expressed as the cos of the angle, θ, from parallel. Thus, at the right ($\cos(\theta)<1$ or $\theta>0$) is the rate for all CAT1+ TCs. On the left is the rate for TCs whose $\cos(\theta)<0.1$ or $\theta>84.3$, that is, within 5.7° from perpendicular. The red line is the best estimate using the model built on HURDAT 1950–2010, 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° from perpendicular, corresponding to a best-estimate annual rate of 0.0014, corresponding to a return period of 714 years. The blue line is the best-estimate curve when Hurricane Sandy's track is added to HURDAT 1950–2010 to build the track model. (b) As in Figure 3a, but now for the larger coastal region illustrated in Figure 1 stretching from the Delmarva peninsula to Long Island. Blue indicates all TC of at least tropical storm status, black CAT1+ and red CAT3+. The cross-hairs indicate the angle dot product (0.35) and rate (0.0034 yr^{-1} or 290 years) of the 1938 Long Island Express hurricane, a category 3 hurricane at Long Island landfall.

it is only one of many TCs that pass within the Gaussian averaging kernel of the track model's local regression, which is objectively optimized to have a 600 km radius (two-sigma).

[13] To set the NJ-landfall rates in context we also compute landfall rates for a larger coastal region, extending further south to the Delmarva peninsula and northeast to Long Island (light blue in Figure 1). Figure 3b shows the CAT1+ landfall rate as a function of impact angle for this region. The rates are much higher at all impact angles, primarily because the "target" is larger. In addition, the near east-west orientation of Long Island makes it more susceptible to a direct hit, as its coast is close to perpendicular to the mean TC track. Also shown in Figure 3b are the curves for two other intensity thresholds: all TCs (CAT0+) and major hurricanes (CAT3+). The rates decline rapidly with intensity at all impact angles. The cross hair in Figure 3b shows The Long Island Express hurricane of 1938, which had CAT3 intensity and an impact angle on Long Island of dot product 0.35. Our best estimate of the return period of a hurricane of at least this intensity and at least this close to perpendicular on the Delmarva-to-Long-Island coast is 290 years, and our best-estimate for CAT1+ landfalls on this broader region at least as close to perpendicular as Sandy is 100 years. We emphasize that the primary feature making Sandy's landfall so rare was the westward motion of the track, resulting in the near perpendicular NJ landfall. Storms making direct hits on Long Island, such as the Long Island Express, can travel less rare northward paths.

[14] Figure 4 shows the simulated probability distribution of the number of NJ landfalls in a 162 year window, the 1851–2012 period of the HURDAT record, along with the actual historical numbers. 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 annual mean rate for CAT1+ NJ landfalls at any impact angle from the model is 0.0119 (Figure 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 Jewson*, 2007; *Yonekura and Hall*, 2011].

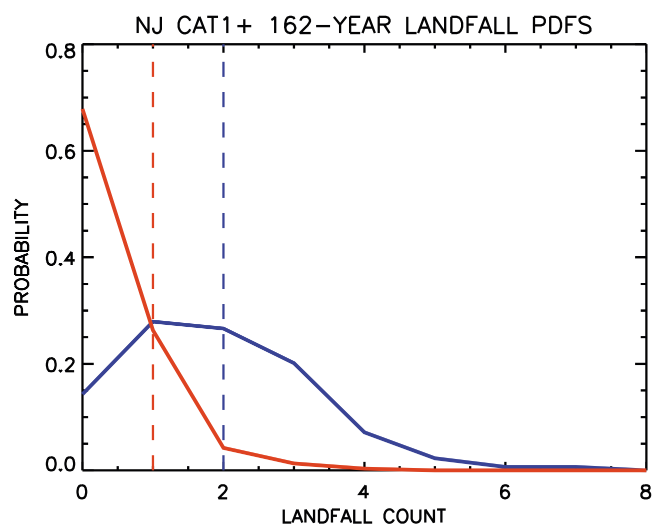

Figure 4. Normalized distributions of NJ CAT1+ landfall counts in 162 year windows from a 50,000 year model simulation. Blue is for all land-falling impact angles, and red is for angles within 30° of perpendicular. The dashed lines at values 2 and 1 indicate the corresponding historical counts that occurred.

4. Discussion

[15] Hurricane Sandy's near perpendicular impact with the NJ coast was exceedingly rare. Our best estimate of the return period is 714 years (95% band 435 to 1429 years) for landfall by a hurricane of at least Sandy's intensity and at least as perpendicular an impact angle, or roughly 600–700 years, given sensitivity to inclusion of Sandy itself in the analysis. This does not directly tell us the return period for a storm surge of Sandy's magnitude, because many factors influence storm surge. Historical records suggest that there have been several events whose surge was comparable to, but arguably still lesser than Sandy's in New York City in the last several hundred years [*Scileppi and Donnelly*, 2007]. Numerical simulations and statistical analysis estimate that Sandy-level surges on Manhattan occur on average every 400–800 years [*Lin et al*., 2012; *Aerts et al*., 2013], somewhat more frequent, but overlapping, our range for Sandy's track.

[16] 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 preindustrial for most of the 162 year period, and in any case our model assumes stationary statistics.

[17] The fact that our calculations show Sandy's track to be so rare under long-term average climate conditions implies either that the New York – New Jersey area simply experienced a very rare event (with climate change playing no significant role), or that a climate-change influence increased the probability of its occurrence. 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 anomalous westward tracks such as Sandy's. On the other hand, the most recent climate model simulations project reductions in blocking frequency in a warmer climate [*Dunn-Sigouin and Son*, 2012], in conflict with the argument for greater jet-stream variability with less sea-ice. Global high-resolution models suggest that tropical cyclone frequency will decrease globally, while mean intensity will increase. There is growing support for the view that the most intense events will increase in frequency, but there is high uncertainty, especially in individual basins [*Knutson et al*., 2010]. The more certain effect of climate change is through further sea level rise, 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.

[18] **Acknowledgments.** We thank Kerry Emanuel for comments on the manuscript, as well as reviewer Chris Fogarty and an anonymous reviewer. This work was supported in part by NOAA grant NA11OAR4310093 and NSF grant AGS 1143959.

[19] The Editor thanks Christopher Fogarty and two anonymous reviewers for their assistance in evaluating this paper.

References

Aerts, J., et al. (2013), Low-probability flood risk modeling for New York City, *Risk Anal.*, *115*, doi:10.1111/risa.12008.
Dunn-Sigouin, E., and S.-W. Son (2012), Northern hemisphere blocking climatology as simulated by the CMIP5 models, *J. Geophys. Res.*, *118*, 1179–1188, doi:10.1002/jgrd.50143.
Emanuel, K. (2006), Climate and tropical cyclone activity: A new model downscaling approach. *J. Climate*, *19*, 4797–4802.
Francis, J. A., and S. J. Vavrus (2012), Evidence linking Arctic amplification to extreme weather in mid-latitudes, *Geophys. Res. Lett.*, *39*, L06801, doi:10.1029/2012GL051000.
Hall, T. M., and S. Jewson (2007), Statistical modeling of North Atlantic tropical cyclone tracks, *Tellus*, *59A*, 486–498.
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.
Jagger, T. H., and J. B. Elsner (2006), Climatology models for extreme hurricane winds near the United States, *J. Climate*, *19*, 3220–3236.
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., et al. (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, *Nat. Clim. 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 (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.
Yonekura, E., and T. M. Hall (2011), A statistical model of tropical cyclone tracks in the western North Pacific with ENSO-dependent cyclogenesis, *J. Appl. Meteor. Climatol.*, *50*, 1725–1739.