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

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[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 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

[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.

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.

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://tidesandcurrents.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 [Scheleppi 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.

2. Methods

[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 Eisner, 2006], or statistical-dynamical downscaling [Emmanuel, 2006].

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]
makes with the NJ coast segment.

prior to landfall and the angle that the 6 hourly TC increment
south of NJ used to de
falls 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,
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1851. Two of these are labeled: the Vagabond Hurricane of
September 1903, and the Long Island Express Hurricane of
September 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.

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(θ) = 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(θ)
=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.

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
construct 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.

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,
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).

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 1938 Long Island Express hurricane, a category 3 hurricane at Long Island landfall.

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 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, \( \theta \), 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.

**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

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.

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