Predicting hurricane regional landfall rates: comparing local and basin-wide track model approaches

Tim Hall, GISS*
and
Stephen Jewson
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Abstract
We compare two methods for making predictions of the climatological distribution of the number of hurricanes making landfall along short sections of the North American coastline. The first method uses local data, and the second method uses a basin-wide track model. Using cross-validation we show that the basin-wide track model gives better predictions for almost all parts of the coastline. This is the first time such a comparison has been made, and is the first rigorous justification for the use of basin-wide track models for predicting hurricane landfall rates and hurricane risk.

1 Introduction
There is considerable interest in trying to predict the number of hurricanes that might make landfall on different parts of the North American coastline in future years. Such predictions are needed, for example, by insurance companies, to set insurance rates, and local government, to set building codes. There are various questions that need to be considered when making these predictions, such as:

• how is climate change affecting hurricane activity?
• which parts of the historical data are relevant to current and future hurricane activity?
• what methods give the most accurate predictions of future landfall activity?

Addressing these questions in detail is a challenging undertaking, and the science of predicting hurricane landfall rates is still in its infancy. Before trying to answer all these questions, it is important to understand individual parts of the problem, and the pros and cons of methodologies that one might use.

In this article we focus on an important basic question: if we wish to estimate hurricane landfalling rates for a small section of the coastline, is it better to make that estimate using local data, or using a basin-wide track model? Using local data is the simplest and most obvious thing to do. For instance, to predict the number of hurricanes making landfall in Texas, one might fit a distribution to the number of hurricanes hitting Texas in the historical record. However, this method may not make the best use of available historical data, since it ignores all the data for hurricanes that don't hit Texas, and this data might contain useful additional information that could improve the estimates. This reasoning has been one of the factors that has motivated the development of basin-wide hurricane track simulation models, and these models are commonly used by the various entities that need to understand hurricane risk. However, in spite of there being a number of publications describing how one might build such a model (such as Chu and Wang (1995), Darling (1991), Drayton (2000), Emanuel et al. (2005), James and Mason (2005), Rumpf et al. (2006), Velez et al. (2005), Vickery et al. (2000), our own work described in Hall and Jewson (2005), and others), we are not aware of any serious attempt to evaluate whether such models really work as a method for estimating regional landfall rates. The purpose of this paper, therefore, is to ask that question: can basin-wide track models give better predictions of landfall rates than local estimates? To simplify matters, we ask this question in the context of an assumption that the climate was stationary for the period 1950-2003. This is clearly not correct, as there have been well documented interdecadal-timescale fluctuations in the numbers of hurricanes during this period (see, for example, Goldenberg et al. (2001)). However, making this assumption wouldn’t seem to benefit either

*Correspondence address: Email: tmh1@columbia.edu
the local or the basin-wide track model methods we are comparing, and it makes the question of how to compare the two classes of model more tractable.

What is the likely outcome of this comparison between the local and basin-wide track model methods? On the one hand, the basin-wide models use much more data to predict local landfall rates: this is one of the main reasons for building such models, as mentioned above. This might make them more accurate than the local methods. On the other hand, no basin-wide model is likely to be perfect, and all are likely to have biases relative to the real statistical behaviour of hurricanes. If these biases are large, this could easily overwhelm the benefits of using more data. Which of the local and basin-wide track model methods is better therefore depends on a trade-off between these two effects. We suspect that for very large regions of coastline (for instance, for the entire North American coastline) the use of local data is likely to be relatively more successful. On the other hand, for small sections of coastline, especially those with low hurricane landfall rates, the use of basin-wide track models might be more successful, since the benefit of using surrounding data is likely to be greater.

Prima facie making a fair comparison between local methods and track models would seem to be difficult: what is the standard against which these two methods should be compared? This problem, is, however, solved relatively easily using cross-validation. In other words, we split the data, build the models on one part of the data, and compare the ability of the models to predict the other part. We use the best possible version of this approach, which is the leave-one-out jack-knife. Since we are testing the ability to predict a distribution, and not just a single value, we need to use a probabilistic scoring system. We choose what we think is the most sensible generic probabilistic score, which is the out-of-sample expected log-likelihood. This score is the obvious extension of Fisher’s log-likelihood (Fisher, 1912) to out-of-sample testing. It has been used by a number of authors such as [Dowe et al. (1996), Roulston and Smith (2002) and Jewson and Penzer (2006)].

2 Methods

Our goal is to compare local and track model methods for estimating hurricane landfall rates. In particular, we will compare the local methods described in Hall and Jewson (2006) with the track model of Hall and Jewson (2005). Both types of model will be used for predicting the climatological distribution of the number of hurricanes making landfall on each of 39 segments of the North American coastline. These segments don’t overlap, and together they form an approximation for the whole North American coast from the Yucatan peninsula in Mexico, to Canada.

2.1 Local methods

Our local method for predicting hurricane landfall rates comes from Hall and Jewson (2006): it takes the historical data for the number of hurricanes crossing the coastline segment, and fits a poisson distribution using Bayesian statistical methods. The method integrates over all possible poisson distributions, which results in a form of the negative binomial distribution. The main result in Hall and Jewson (2006) is that this Bayesian method works better than the obvious classical method of fitting just a single best-fit poisson distribution. The improvement gained by using the Bayesian method is largest when the number of historical landfalls in the segment is zero or very small.

2.2 Track model methods

The track model we use to predict landfall rates is described in a series of six short articles (the sixth of which is Hall and Jewson (2005)). It takes historical data for historical hurricane genesis, tracks and analysis, and builds a statistical model that can simulate an arbitrary number of future hurricanes. The genesis model is poisson, and hence the distribution of numbers of hurricanes crossing coastal segments in the model is also poisson. As described in the papers cited above, we took particular care to build the model in a such a way that it is not overfitted, and so it should stand a good chance of making accurate predictions of landfalling rates. We note, however, that the model is noticeably imperfect, and that landfall rates for certain parts of the coastline are clearly wrong (see figure 7 in Hall and Jewson (2005)). We are working on eliminating such biases from the model, but for now we test the model as is, warts and all.
2.3 Comparison

We compare these two models using leave-one-out cross-validation, using the out-of-sample expected log-likelihood as the merit function, as follows.

- We approximate the North American coastline using 39 straight line segments. We consider these segments one at a time.
- We loop over the 54 years of historical hurricane data from 1950 to 2003 (this data is all taken from the 2004 version of HURDAT \cite{Jarvinen:1984}).
- We miss out each year in turn
  - Using the remaining years, we fit both models. For the local model, fitting consists of simply estimating the model parameters using the historical landfalling data for that segment. For the track model, fitting consists of estimating the smoothing length-scales in each part of the model using the entire historical hurricane database. In fact, the smoothing lengthscales turn out not to change when we miss out single years of data, since they are only calculated at a fairly low resolution, and all 54 fitted track models have the same smoothing lengthscales.
  - For each model, we then make a prediction of the number of hurricanes making landfall in the year missed out, for the segment of interest. For the local models, the prediction is simply the fitted distribution. For the track model, the prediction is based on counting storms in a 500 year simulation from the model, and fitting a poisson distribution (using the same Bayesian method as used for the local model). The simulations do not use any information from the year being predicted.
  - We then compare the predictions for each year with the actual number of hurricanes in each year. We do this by evaluating the predicted distribution function at the observed number of storms, which gives a single probability density value.
  - We take the log of this probability density and create an average of the 54 log scores to give an overall score for each model for each segment.
  - We repeat this whole exercise for each of our 39 segments.

This gives us a single score for each model for each segment. We can then compare these scores between the two models.

3 Results

The results of this score comparison are shown in figure \ref{fig:results}. The left panel shows the definitions of the coastal segments used in the comparison. The right panel shows the expected log-likelihood score for the basin-wide model minus the score for the local model. Positive values indicate that the basin-wide model is giving more accurate predictions than the local model.

We see that the track model wins this comparison for 34 of the 39 coastal segments. One can ask whether this could happen by chance, if the two models were in fact equally good. Using a statistical test based on the binomial distribution, it turns out that this would be extremely unlikely to happen by chance. As a result we can conclude that the track model is genuinely better (using this score) than the local method, on average over all the segments, but not for every segment individually.

It is interesting to compare these results with the results shown in figure 7 in \citet{Hall:2005}, which shows an in-sample comparison between landfall rates from the track model and landfall rates from the local model. For four of the five gates where the track model loses in the current study, we can see that problems with the track model already show up in these in-sample comparisons. For instance, in \citet{Hall:2005} the track model gives lower landfall rates than the local method would predict between B and C, between E and F, and between F and G, and the current study shows that this is probably because the track model is wrong in those regions. The track model gives higher landfall rates than the local method between G and H, and again, the current study shows that that is probably because the track model is wrong. On the other hand, the track model gives lower rates than the local method between H and I, but the current study suggests that the track model is actually more accurate for this part of the coastline: one might say that this implies that the region between H and I has been unlucky during this 54 year period, and experienced more hurricanes than it would do on average. Similarly at
point E the track model gives higher rates than the local method, but the current study suggests again that the track model is more accurate for this location. In this case one might say that point E has been lucky over the last 54 years, and experienced fewer hurricanes than it would be expected to on average.

4 Discussion

Regional landfalling rates for hurricanes are often estimated either using local methods, that count the number of hurricanes that have hit a region in the historical record, or using track model methods, that count the number of hurricanes that hit that region in statistical simulations. However, in spite of considerable effort to develop a number of different track models (see citations to 9 different models in the introduction) there has never been any rigorous attempt to compare the two types of method (or indeed, to compare the track models with each other). One might hope that the track models will do better since they use more data than the local methods, but whether they really do perform better or not depends on the size of the (inevitable) errors in the track models, and can’t be guessed in advance: it is purely a matter for statistical testing. To be an honest comparison such testing can only be performed using cross-validation, since in-sample testing favours over-fitted models with many parameters. This point is particularly important because track-models are all based on a very large number of fitted parameters. We perform such a test for the first time, by comparing local methods based on Bayesian statistics from Hall and Jewson (2006) with the track model of Hall and Jewson (2005). We find that the track model gives a better estimate of the climatological distribution of the number of hurricanes making landfall for 34 out of 39 coastal gates. We consider this result to be a major milestone in the development of methods for predicting rates of landfalling hurricanes: for the very first time we have shown that track models can give more accurate predictions than local methods. This is, on its own, a justification for the whole enterprise of trying to build track models. We do emphasize, however, that we have not shown that all track models necessarily work better than the local method, but only the particular track model that we have tested.

This result opens up a number of directions for future study, such as:

- would the same track model also work better than local methods for larger coastline segments? Up to what limit?
- would the same track model also work better for the prediction of intense storms?
- could the performance of the track model be further improved, to the extent that it would beat the local method for all 39 coastal segments?
- could other track models, such as the 8 other models cited in the introduction, also beat the local methods?
- of all the published track models, which is the best in terms of landfall rate predictions?

We plan to look at all these questions in due course.

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Figure 1: The left hand panel shows the eastern coastline of North America, with letters as reference points. The right panel shows the difference in predictive performance of the two models we have tested, for hurricane landfall rates along this coastline. Positive values indicate that the basin-wide track model works better, while negative values indicate that the local model works better. We see that the basin-wide track model wins for 34 of the 39 segments.