Tropical Cyclone Landfall in a Changing Climate: A Statistical Modeling Study

> Timothy Hall NASA Goddard Institute for Space Studies

> > Stephen Jewson Risk Management Solutions

> > > Floyd, 1999, NASA GOES

Evolving hurricane frequency and intensity: Increase in North Atlantic frequency and intensity. Increase in global fraction of most intense storms. No change in global frequency.



Tropical cyclone (TC) intensity depends, in part, upper ocean heat content. Good understanding of mature storms. Poor understanding of genesis.

Focus here on North American landfall of Atlantic TCs:

- What is the risk of hurricane landfall on various regions? How does it vary with climate state?
- Distinction between long-term landfall risk of generic TC and near-term risk of specific TC.
- Traditional approach to estimate landfall risk: analyze past landfall.
- Reasonable if looking over entire NA coast, using all historical data.

Big sampling errors if looking on small, or inactive region and using subsets of historical data in specified climate states.

e.g., US NE: 14 landfalls (any intensity) in 1950--2005. Not enough to partition into climate states.

e.g., No landfalls in SE New England, but clearly non-zero risk.

Statement of "inverse problem:"

Given observations

(historical landfall events, TC tracks, climate indices) estimate underlying landfall rates and their changes.

Tools:

General circulation models? Don't resolve TCs, but help establish climate context.

Statistical models: Various approaches possible.

Statistical track model: stochastic model of TCs from birth to death. Generate many synthetic TCs. Compute landfall rates.

Goal: Build a satisfactory statistical model. Use model to project information from entire basin onto coastlin. (Draw landfall info from TCs in open ocean.) Model (Hall and Jewson, *Tellus*, 2007):

- 1. Annual TC number: sample historical numbers.
- 2. Genesis site: sample pdf of kernels about historical sites.
- 3. Propagation: model latitude-longitude increments

 a. mean increments from averaging "nearby" historical increments.
 b. variance about mean.
 - c. lag-one autocorrelation of anomalies with noise forcing.

$$x_n = x_{n-1} + \Delta x_n \qquad \Delta x_n = \Delta \overline{x}_n + \sigma_n \Delta \widetilde{x}_n \qquad \Delta \widetilde{x}_n = \alpha \Delta \widetilde{x}_{n-1} + \varepsilon$$

4. Death: probability at each location from historical rates.

How to choose length-scales for averaging historical data?

Build model on N-1 years. Forecast Nth year. Vary scales to maximize likelihood of historical data, given probabilistic forecast.

Note: No TC intensity presently modeled.

Genesis site: Sample a PDF comprised of sum of Gaussian kernels centered on each of N historical sites.



Optimizing: maximize likelihood of observed genesis sites in out-of-sample jackknife procedure

•Choose scale L.
•Consider historical genesis site r_j in year n.
•Compute P(r_j) with sum over all sites from years m ≠ n (the likelihood of the observation r_j given the model).
•Sum S = log(P(r_j)) over all sites r_j.
•Vary L to find maximum S.





NOAA HURDAT



Averaging scale for track coefficients optimized by maximizing likelihood of historical tracks.

Means: scale = 300km



optimal

Autocorrelation: analyze historical track anomaly time series. How many lags? Length-scale for computing autocorrelation coefficients?



Treat directions independently.One 6-hour lag sufficient.

Maximize jack-knife out-of-sample likelihood of observations to obtain 900 km averaging scale for autocorrelation coefficients.



Climate-change application: SST increasing due (primarily) to industrial GHG forcing



Condition the construction of track model on being in either 1/3 hottest or 1/3 coldest years (1950-2005).



TC frequency: hot years: 12.8 yr⁻¹ cold years: 8.5 yr⁻¹

Difference is highly significant compared to random sampling of years.

Alone, hot-year frequency increase results in *proportional* and *uniform* landfall-rate increase on NA coast.

But other factors may change: (1) landfall fraction. (2) landfall geographic distribution.

Track model can explore this by hot-cold analysis of model components individually (frequency, genesis site, propagation).

Spatial distribution of genesis: shifts eastward in hot years.





Propagation: curves northward sooner in hot years.



Net: no change in landfall fraction, but change in distribution.

Landfall rates: landfalls per year per 100 km segmented coast



	US NE	US mid-Atl	Florida	US Gulf	Mex Gulf	Yucatan	Full
R_H	0.20	0.39	0.95	1.84	0.52	0.75	4.65
R_C	0.22	0.33	0.71	1.22	0.36	0.31	3.12
Z	-0.2	0.3	0.9	1.1	0.9	2.4	2.1

Florida and Gulf coast: increased landfall. US NE coast: no increased landfall.

Uncertainty: Perform analysis on differences among many random subsets of 56-year period. How significant are hot-cold differences compared to other differences?

Probabilities of at least one, at least two landfalls in 100 km sections



Summary:

Constructed a statistical model of NA tropical cyclone tracks.
Projects information from basin onto coast for landfall estimates.
Condition the model on hot years versus cold years.
Greater landfall in hot years, but not uniform.
Increased risk on Florida and Gulf Coast; no increase for US NE.

Have not included intensity information. Conclusions might be modified if partitioned by intensity (e.g., no overall NE landfall increase, but increase in intense TC fraction). Presently developing statistical intensity model.