P5.2 THE ALONG-SHORE VARIABILITY OF TROPICAL CYCLONE LANDFALLS

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1. INTRODUCTION

The number of Atlantic tropical storms making landfall on the U.S. coast or passing within 100 nm of the coast averaged nearly seven per year over the past 152 years. The frequency of hits and near misses varies over decadal time scales and spatially along the coast. Quantifying the risk associated with U.S. tropical cyclone impacts currently relies on storm statistics derived from about 1000 storms along a 3000 nm coastline. Since relatively few storms influence any particular coastal location, a spatial smoothing function introduced by Ho et al., (1987- referred to as NWS-38) is commonly used. This function introduces into the local storm statistics, storms affecting coastal regions up to 250 nm away. This data pooling may mask true variability in along-shore storm occurrences. On the other hand, the variability seen in the smoothed storm statistics may be an artifact of limited sample size.

This study addresses these issues by examining the relationships between observed coastal landfall frequencies and frequencies of onshore steering flow and anomalous local vertical shear along the coast. Coastal impact frequencies from a much larger set of synthetic storm tracks also shed light on the issue.

2. DATA SETS

Tropical storm and hurricane data from the National Hurricane Center's (NHC's) North Atlantic hurricane database (HURDAT) are used to provide "best track" and intensity data for storms during the period 1851-2002. These data, based on post-season analysis of tropical cyclones, were originally compiled by Jarvinen et al., (1984), and have been extensively updated and revised by Partagas and Diaz (1996) and most recently by Landsea et al., (2003).

Storm positions at 6-hour intervals are used to determine frequencies of coastal landfalls and to provide statistics for the geographic distribution of synthetic storm formation. Storm intensity data, defined by maximum sustained winds at 6-hour intervals provide guidance for synthetic storm duration.

Daily upper air velocity components at 2.5˚ x 2.5˚ resolution are obtained from the NCAR/NCEP reanalysis archives. The data span the region 10N to 50N and 105W to 30W for the years 1948 through 2002. Steering flow is defined by a pressure-weighted average of the wind components over seven adjacent layers between 925 hPa and 250 hPa, and a horizontal inverse-distance weighted average over a 7.5 degree radius, similar to the definition of Chan and Gray (1982). The same vertical and horizontal averaging are applied to the magnitude of the wind shear between adjacent layers to define the environmental shear. These fields are linearly interpolated in space and interpolated in time using cubic splines to provide local steering and shear flow for any storm location at 6-hour intervals.

Following NWS-38, the U.S. coast is divided into three sections:

- The gulf coast, extending from south of Brownsville, TX (mile marker 100) to Cape Sable (mile marker 1400), with an extension crossing Florida Bay to Vaca Key (mile marker 1415),
- The south Atlantic coast, from a keys extension near the Dry Tortugas to Cape Hatteras (near mile marker 2230), and
- The north Atlantic coast, extending from Cape Hatteras to the Maine-Canadian Border.

Following NWS-38, each coast is subdivided into 50-nm segments and smoothed using to an 11-pt tapered filter. Figure 1 illustrates the coast configuration and a portion of reanalysis grid.

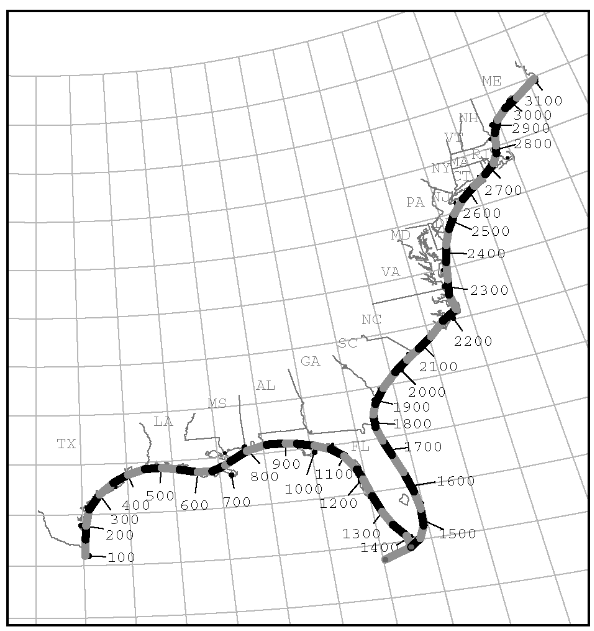

Figure 1. Segmented coast with labeled mile markers

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3. LANDFALLING STORM FREQUENCIES

The along-shore distribution of landfalling tropical cyclones from 1851 to 2002 is shown by the dashed line of Figure 2. Following the procedure of NWS-38, storm counts are smoothed by applying the same 11-pt filter producing the results shown by the thin solid line. The heavy solid line shows the smoothed count of hurricanes only.

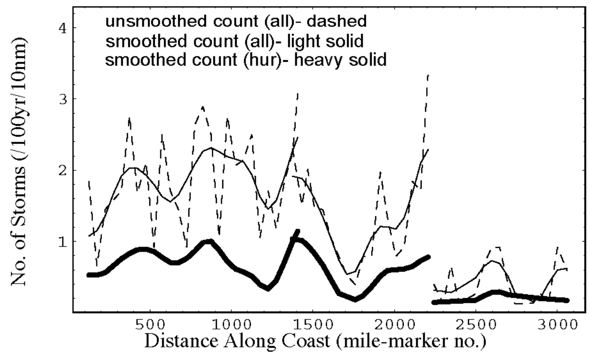

Figure 2. Frequency of landfalling storms from the 152-year HURDAT data set.

Figure 3 shows smoothed storm counts for landfalling storms from the 152-year data set and the 55-year data subset (1948-2002). Counts of all storms are shown by thin lines and counts of hurricanes only are shown by heavy lines. Similarity in the along-shore variability between the longer and shorter data sets in most coastal regions suggests that landfalling storm distribution in the recent 55 years is representative of the longer time period. It is also consistent with the notion that much of the along-shore variability is not a result of statistical sampling. The local minima in the frequency of all landfalling tropical storms near mile markers 650, 1250, and 1700 appear to be robust features of the coastal landfall variability, whereas the local minimum near mile marker 1050 from the 55-year data set is probably not. Maxima near mile markers 300, 850, 1400, and 2200 are also likely to be robust.

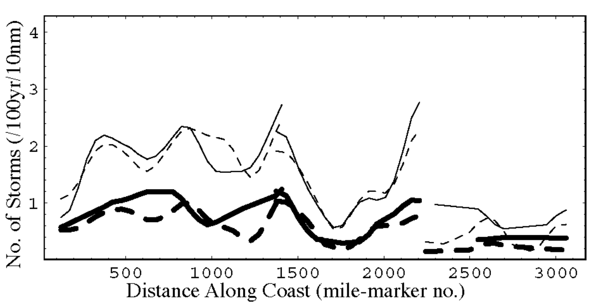

Figure 3. Frequency of landfalling storms (thin) and hurricanes (thick) from the full 152-year data set (dashed) and the recent 55 years of data (solid).

Note that the along-shore variability of landfalling hurricane counts differs markedly among the data sets along the gulf coast (mile markers 500 - 1400). Since roughly half of the entering storms are hurricanes, the sample size is probably small enough to make smoothed counts unreliable due to statistical sampling. The subsequent analysis focuses on all tropical cyclones (tropical storms as well as hurricanes).

4. SIGNIFICANCE OF LANDFALL VARIABILITY

The significance of the along-shore variability in landfalling storm frequency cannot be directly tested using only the storm count data from the 152-year sample. Either a climatologically based explanation consistent with the observed storm counts is required, or a much larger sample size is needed to remove any effects of the statistical sampling. Both methods are explored in the following sections.

4.1 Climatological Considerations

The obvious connection between an onshore steering flow and a landfalling storm implies that coastal regions with a higher incidence on onshore flow may have higher frequencies of landfalling storms. The strength of this relationship may be affected by the vertical shear accompanying the onshore flow. For example, with strongly sheared onshore flow, approaching tropical systems may be considerably weakened before making landfall.

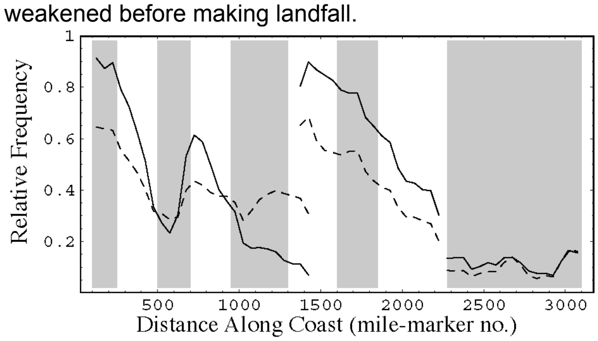

Figure 4. Frequency of onshore flow for all days during the 6-month season (dashed) and Aug-Sep only (solid). Shading indicates positions of minima in the frequency of landfalling tropical cyclones from the 55-yr data set.

Figure 4 shows the along-shore variability of the frequency of onshore steering flow, defined by a 160° coastal approach sector. Results are shown for both the 6-month hurricane season and the more active Aug-Sep period. For reference, the local minima in the smoothed landfalling storm frequency (the thin solid line of Figure 3) are shaded. The low incidence of landfalling storms north of Cape Hatteras and within the coastal sections east of mile markers 500 and 1000 coincide with infrequent onshore steering flow, whereas along the Texas coast and the east coast of Florida north of mile marker 1600, the minima in landfalling frequency appear anticorrelated with the frequency of onshore steering flow. Thus, only a portion of the coastal landfall variability appears directly associated with the frequency of onshore flow.

Daily values of vertical wind shear along the coast were divided into low, moderate, and high shear categories. Low shear is defined as less than 2.5 m/s per 100 hPa. Figure 5 shows the variability of the frequency of occurrence of low shear along the coast.

More frequent landfalling storms, indicated by the white bands, are generally associated with high incidence of low vertical shear. The two landfalling storm frequency minima that are not well explained by the prevailing steering flow (i.e., the Texas coast and Florida's east coast) are correlated with the low incidence of favorable wind shear. Thus a combination of the two factors seem to account for much of the variability in the smoothed coastal distribution of landfalling storm frequency. The steep changes in the frequency of occurrence of both onshore flow and vertical shear imply that the landfall variability along the coast does not arise from small sample size variability.

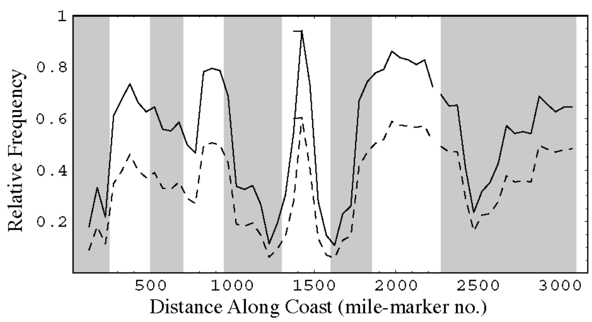

Figure 5. Frequency of low vertical shear for all days during the 6-month season (dashed) and Aug-Sep only (solid). Shaded regions are as in Figure 4.

A very large sample of storms should eliminate the need for along-coast smoothing, producing an accurate distribution of landfalling storms. This motivates the use of a storm track model to generate a large sample.

4.2 Synthetic Storm Climatology

To increase the tropical cyclone sample size, a statistical storm track model is developed using the HURDAT and NCAR/NCEP reanalysis data sets. Preliminary results from this model are discussed here. The idea is to synthesize a large population of storms throughout the hurricane season under the assumption that the precursors of storm formation (e.g., favorable sea surface temperatures, vorticity perturbations) could potentially occur independently of the large-scale steering flow and vertical shear patterns which evolved during the 1948 - 2002 hurricane seasons. The number and location of incipient tropical cyclones are chosen from smoothed distributions of the timing and location of the storms in the HURDAT data set, subject to a maximum permissible wind shear constraint, found from the data sets, of 4 m/s per 100 hPa.

In each 55-year simulation, about 100 storms are allowed to form throughout each six-month season according to Figure 6a. Random initial storm locations are selected from a spatial probability density function (Figure 6b), which evolves daily throughout the season in a manner consistent with the smoothed initial storm positions from the HURDAT database.

Eastward and northward components of storm motion are specified by the local steering flow modified by bias terms. The u- and v- bias terms each consist of a mean and a stochastic component, the latter modeled by a Markov process. The mean bias shows northward and westward displacement of the storm position with respect to the steering flow, consistent with the advective effects of counter-rotating beta gyres (DeMaria, 1985). Parameters for the Markov model are deduced from time series of the track bias relative to the local steering flow.

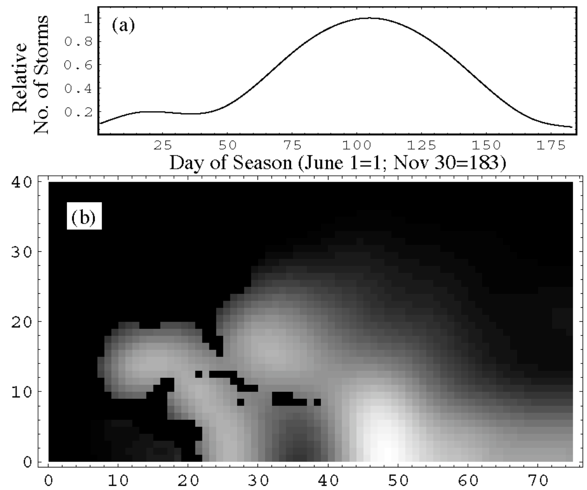

Figure 6. Part a: Relative number of storms formed as a function of day of season. Part b: The seasonal mean spatial probability density function of storm formation

Storm intensity variations are specified from an analysis of the observed storm's maximum sustained wind velocity change over a 6-hour period and the co-located magnitude of the vertical shear. Spatial dependency of the relationship between intensification and vertical shear is not determined because intensification depends on factors not included in the HURDAT or reanalysis data sets. However, the data suggest a memory effect, such that current 6-hour intensification rates are conditioned on previous 6-hour intensification rates, and this varies somewhat with respect to the local vertical wind shear. Parameters of normal distributions of intensification rates conditioned on combinations of wind shear magnitude and previous intensification rates are generated from the data. Random drawings from these distributions provide local intensification rates. The motivation for including storm intensity in the model is to limit the lifetime of storms that do not make landfall.

For landfalling storms, the weakening rates are selected randomly from a normal distribution of landfalling storm's dissipation rates generated from the HURDAT data set. The simulated storm population has lifetimes consistent with the population of observed storms, with a mean of 7-8 days and a standard deviation of 5-6 days.

The model is configured to produce 100 storms each hurricane season for the 55-year period (1948 - 2002). The day-to-day variability of the steering flow and vertical shear is determined from the reanalysis data for this time period. While subsequent work will provide more varied flow conditions using synthetically generated steering and shear flow, evaluating the storm track model's skill requires observed steering flow and wind shear to produce a population of landfalling storms that is comparable with the observed storms.

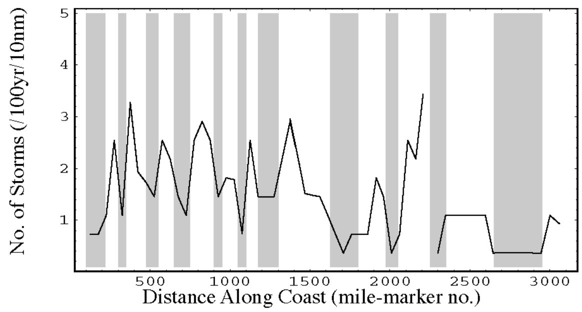

Figure 7. Coastal distribution of landfalling storm count (unsmoothed) from the HURDAT data set for the 55-year period (1948 - 2002). Local minima are shaded.

Synthetic storm counts are shown as unsmoothed along-shore distributions since the large number of landfalling storms should minimize count differences between adjacent 50 nm segments arising from small sample sizes. For reference, Figure 7 shows the observed landfalling storm count from the recent 55-year period in its unsmoothed form. Shaded portions are local minima in the landfalling storm frequency.

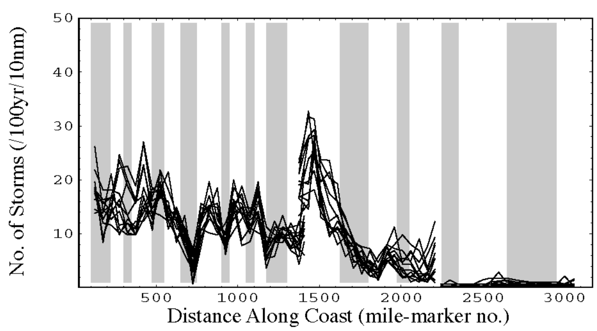

Figure 8. Coastal distribution of landfalling storm count (unsmoothed) from twelve synthetic storm track simulations, each generating about 100 storms per year.

Figure 8 shows coastal landfalling storm counts from twelve simulations producing over 600,000 storms, of which over 17,000 make landfall on the U.S. coast. The shaded regions are identical to those of Figure 7. Individual simulations are presented to emphasize portions of the coast that consistently receive low and high storm counts. For example, the minima near mile markers 700, 900, and 1200-1300 are clearly seen in the observations. These deficits suggest that the smoothing applied in the NWS-38 study masks some of the true along-coast variability in landfall counts. The large deficit at 700 nm reflects the change in coast orientation along southeast Louisiana, and its corresponding change in onshore flow frequency.

There are several large discrepancies between the simulated and observed storm landfall distributions along the coast. The simulations do not produce sufficient landfalls along the northeast coast, do not produce high numbers of landfalls just south of Cape Hatteras, and fail to produce the large landfall counts around 1400 nm. Limited experiments with a modified representation of the track bias do not seem to help. Most storms approaching Cape Hatteras and the northeast coast remain offshore. Refinements in the definition of steering flow, such as making the spatial averaging region dependent on flow direction, are being considered as a possible remedy to this shortcoming.

5. SUMMARY

Observed tropical cyclone landfall frequency varies along the U.S. coast due to a combination of the climatological frequency of occurrences of favorable onshore steering flow and favorable vertical shear. The actual along-shore variability appears greater than that produced when storm counts are smoothed using pooled coastal landfall data from up to 250 nm away. This result stems from high along-shore variability in steering flow and vertical shear.

As currently configured, the storm track model is unable to produce large landfalling storm counts in certain regions, probably due to the simplistic treatment of steering flow. Along the gulf coast, however, where the along-coast landfall variability is large, the model reproduces local frequency minima with considerable skill and confirms the small spatial scale of landfall variability in that region for the period 1948-2002.

6. REFERENCES

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