Re-analysis of Tropical Storm and Hurricane Probabilities of Occurrence for Coastal Areas of the United States, Canada, and Bermuda for 1851 to 2017

Richard C. Daniels, GSP, Washington State Department of Transportation, danhriel@wsdot.wa.gov

BACKGROUND
In 1996-1997 the U.S. Global Change Research Program sponsored the creation of several data sets to document past and present climate conditions, among these was an analysis of "Storm Occurrences and other Climate Phenomena Affecting Coastal Zone." (NDP-035, 1991). These data sets served as primary data sources for a climate assessment performed by the intergovernmental Panel on Climate Change. The "Storm Occurrences" dataset included a tropical cyclone probability of occurrence analysis for 1 by 1 degree cells for the Atlantic Hurricane Basin based on data from 1851 to 1989 for the United States, Canada, and Bermuda (Brindfels and Daniels 1991).

METHODS
In this study, tropical cyclone probabilities of occurrence for 1 by 1 degree cells for the Gulf of Mexico and Atlantic seaboard were recalculated using the National Hurricane Center's (NHC) North Atlantic Hurricane Database, version 2. NDP-035 extended the tropical cyclone record 66 years back in time to 1851 and extended the record forward to 2017 -giving us 167 years of record. I compared the new data set with the old for the 1899-1989 reference period to determine if there was a statistically significant change to the calculated probabilities of Hurricanes and Tropical/Subtropical Storms. Hurricane probabilities were recalculated for three 55-year periods (1851-1905, 1906-1962, 1963-2017) and a trend analysis conducted.

HURDAT-2 Track and Intensity Modifications
Geographical positions of storms in HURDAT-2 are estimated to the nearest 0.1 degree at six hour intervals. Positional uncertainty is larger than this implied, with the position accuracy in the open ocean often being <=50 km (i.e., approximately the size of a 1 by 1 degree grid cell). Location accuracy is better, with an uncertainty of <=21 km. Below are examples for the period 1899 and 1899 of the changes made to the original tropical cyclone record (Neumann et al. 1999). These changes were made by NOAA's Atlantic Oceanographic and Meteorological Laboratory from 2002-2014 during their tropical cyclone reanalysis project(s). Small track changes were normally on the order 0.1 to 0.2 degrees, which for positions at latitudes of longitude (<=10 degrees) will result in large alterations to the track.

2. Neumann et al. (1999) originally storm #28 - Assessment as Category 2 hurricane at landfall in Florida; this was signed from tropical storm at landfall status.
3. Neumann et al. (1999) originally storm #2. Based on Partagas and Diaz (1996) reassessing. The original HURDAT-2 record plotted some positions of this storm in Florida to account for relatively weak winds along the coast despite storm status.
4. Neumann et al. (1999) originally storm #17 - Large alterations to the track, hurricane offshore transition delayed, as per Partagas and Diaz's (1996) repositioning.
9. New tropical storm/reposition added near Bermuda moving from 30N, 79W to 34N, 66 W.

1899
1. Neumann et al. (1999) storm #1. No change.
2. Neumann et al. (1999) storm #2. Changing the start date of the storm, thus extending the track backwards.
3. Neumann et al. (1999) storm #3. No change in track, higher winds at landfall.
4. Neumann et al. (1999) storm #4. Changing the start date of the storm, thus extending the track backwards.
5. Neumann et al. (1999) storm #5. Large alterations to the track, and transition to a subtropical storm off Nova Scotia.
7. Neumann et al. (1999) storm #7. Changing the start date of the storm, thus extending the track backwards into the Caribbean.

For the 91-year reference period (1899 to 1989) on the Atlantic basin 92 new named storms were added to the record, these new events and modifications to existing storms were tallied for the coastal areas for the

Hurricane Track Analysis
Hurricanes 1899-1989
Hurricanes 1990-2017
Hurricanes 1851-2017

Hurricane T-Score for NDP-035 vs. HURDAT-2
Hurricane R2 for NDP-035 vs. HURDAT-2

RESULTS
For the 1899-1989 reference period a R2 of 0.75 was found for Hurricane (mean difference = 14%) and an R2 of 0.75 for Tropical/Subtropical Storms (24% 25% was found). The populations for the two data sets are NOT significantly different at the 99% confidence interval. Differences in probabilities seen when the two datasets are mapped and compared are directly attributable to modifications in the source data resulting from NOAAs Atlantic Oceanographic and Meteorological Laboratorys 2002-2014 tropical cyclone reanalysis project(s).

Combining Tropical and Subtropical Storms
Subtropical Storms are the low pressure systems that have characteristics of both tropical and extratropical cyclones. In NDP-035 and this study Subtropical Storms were combined with Tropical Storms for the probability of occurrence analysis. These types of storms—maximum sustained surface winds at least 17.5 m/s but less than 33 m/s and (2) they cause similar coastal erosion impacts at landfall (i.e., swell, storm surge, heavy rain, etc.).

Table 1. Tropical/Subtropical Storm Correlation Analysis

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Mean Difference (%)</th>
<th>Standard Deviation (%)</th>
<th>Regression</th>
<th>Geographically Weighted Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurricanes 1899-1989</td>
<td>2.7</td>
<td>3.6</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Hurricanes 1990-2017</td>
<td>2.1</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Hurricanes 1851-2017</td>
<td>2.3</td>
<td>3.4</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
</tbody>
</table>

Table 2. Hurricane Correlation Analysis

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Mean Difference (%)</th>
<th>Standard Deviation (%)</th>
<th>Regression</th>
<th>Geographically Weighted Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurricanes 1899-1989</td>
<td>2.2</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Hurricanes 1990-2017</td>
<td>2.3</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Hurricanes 1851-2017</td>
<td>2.6</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
</tbody>
</table>

Table 3. Hurricane Trend Analysis

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Mean Difference (%)</th>
<th>Standard Deviation (%)</th>
<th>Regression</th>
<th>Geographically Weighted Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurricanes 1899-1989</td>
<td>2.3</td>
<td>3.4</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Hurricanes 1990-2017</td>
<td>2.5</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Hurricanes 1851-2017</td>
<td>2.5</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
</tbody>
</table>

Table 4. Tropical/Subtropical Storm Trend Analysis

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Mean Difference (%)</th>
<th>Standard Deviation (%)</th>
<th>Regression</th>
<th>Geographically Weighted Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical/Subtropical Storms 1899-1989</td>
<td>2.3</td>
<td>3.4</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Tropical/Subtropical Storms 1990-2017</td>
<td>2.5</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
<tr>
<td>Tropical/Subtropical Storms 1851-2017</td>
<td>2.5</td>
<td>3.5</td>
<td>Not Different</td>
<td>Not Different</td>
</tr>
</tbody>
</table>

Using the HURDAT-2 data three 55-year hurricane periods were created. The correlation between these periods was found to be relatively low (=0.44) with no significant trend identified. On the U.S. Gulf and East coast hurricane activity did increase by 0.8% from the 1899-1940 to 1941-1982 and by 3.9% from 1983-1992 to 2017. This 3.1% increase is to move the change that would be expected when the additional storms added to the record by the tropical cyclone reanalysis project(s) are considered.


In 1990-1997 the U.S. Global Change Research Program sponsored the creation of several data sets to document past and current climate conditions; among these was an analysis of “Storm Occurrences and other Climate Phenomena Affecting Coastal Zones” (1991). These data sets served as primary data source for several climate assessments sponsored by the Intergovernmental Panel on Climate Change. The “Storm Occurrences” dataset included a tropical cyclone probability of occurrence analysis for 1 by 1 degree latitude, longitude cells for the Atlantic Hurricane Basin based on data from 1899 to 1989 for the United States, Canada, and Bermuda.

In this study, tropical cyclone probabilities of occurrence for 1 by 1 degree cells for the Gulf of Mexico and Atlantic seaboard were recalculated using on the National Hurricane Center’s (NHC’s) North Atlantic Hurricane Database, version 2. HURDAT-2 extended the tropical cyclone record 48 years back in time to 1851 and extended the record forward to 2017 giving us 167 years of record. I compared the new data set with the old to determine if there was a statistically significant change to the calculated probabilities of tropical cyclones. Hurricane probabilities were calculated for three 55-year periods (1851-1906, 1907-1962, 1963-2017) and the original reference period and a trend analysis conducted.

For the reference period a R2 of 0.76 (mean difference +1.4%) for hurricanes and a R2 of 0.71 (+2.24%) for tropical storms/subtropical storms was found. The populations for these two data sets were NOT significantly different at the 99% confidence interval. Any visible variation in frequencies between the two data sets were NOT directly attributable to modifications in the source data resulting from NOAA’s Atlantic Oceanographic and Meteorological Laboratory’s 2002-2014 tropical cyclone reanalysis project(s). For the three 55-year hurricane periods a weak correlation was found (<0.44). On the Gulf and East coast hurricane activity increased by 0.8% from the 1851-1906 to 1907-1962 and by 0.9% from 1907-1962 to 1963-2017. These probability increases are not statistically significant.
### Statistical Analysis for NDP-035 vs. HURDAT-2 Derived Probabilities

Degrees of Freedom is number of samples – 1.

DF = 238 for Tropical/Subtropical Storms; DF = 200 for Hurricanes

<table>
<thead>
<tr>
<th>DF</th>
<th>A = 0.2</th>
<th>0.10</th>
<th>0.05</th>
<th>0.02</th>
<th>0.01</th>
<th>0.002</th>
<th>0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>∞</td>
<td>t₀ = 1.282</td>
<td>1.645</td>
<td><strong>1.960</strong></td>
<td>2.326</td>
<td>2.576</td>
<td>3.091</td>
<td>3.291</td>
</tr>
<tr>
<td>120</td>
<td>1.289</td>
<td>1.658</td>
<td><strong>1.980</strong></td>
<td>2.358</td>
<td>2.617</td>
<td>3.160</td>
<td>3.373</td>
</tr>
</tbody>
</table>

If the p-value is greater than the alpha level, at the chosen level of significance, we cannot conclude that there is a difference between means.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical/Subtropical Storms 1899-1989 NDP-035</td>
<td>Mean Difference 1.35% Standard Deviation 3.0% t-score 7.33; R² 0.77 Not Different</td>
<td>Mean Difference 2.24% Standard Deviation 3.35% t-score 10.47; R² 0.71 Not Different</td>
<td>Mean Difference 0.2% Standard Deviation 6.0% t-score 0.53; R² 0.26 Different</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurricanes 1899-1989 NDP-035</td>
<td>Mean Difference 0.80% Standard Deviation 2.4% t-score 4.85; R² 0.71 Not Different</td>
<td>Mean Difference 1.4% Standard Deviation 2.32% t-score 9.31; R² 0.76 Not Different</td>
<td>Mean Difference -0.3% Standard Deviation 5.6% t-score -0.65; R² 0.21 Different</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1851-1906</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Difference 0.8% Standard Deviation 6.0% R² 0.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1907-1962</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Difference 0.9% Standard Deviation 4.9% R² 0.27</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
HURDAT-2 Track and Intensity Modifications

Below are examples of the changes made to the original tropical cyclone record (i.e., HURDAT, version 1) for the period 1899-1902. These changes were made by NOAA’s Atlantic Oceanographic and Meteorological Laboratory from 2002-2014 during their tropical cyclone reanalysis project(s). A complete list of changes and corrections made in HURDAT-2 is available from: https://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html.

1899

2. Neumann et al. (1999) originally storm #1. Assessment as Category 2 hurricane at landfall in Florida, this is an upgraded from tropical storm at landfall status.
3. Neumann et al. (1999) originally storm # 2. Reposition the hurricane slightly offshore of Florida to account for relatively weak winds along the coast despite having a strong hurricane offshore. Partagas and Diaz made reasonable though large alterations to the track shown in
4. Neumann et al. (1999) originally storm # 3. No change, reasonable small alterations to the track.
9. Add new tropical storm/depression near Bermuda at 34N, 66 W to 30N, 79W

1900

2. Neumann et al. (1999) storm #2. Changing the start date of the storm, thus extend the track ‘backwards’.
3. Neumann et al. (1999) storm #3. No Change in track, higher winds at landfall.
4. Neumann et al. (1999) storm #4. Changing the start date of the storm, thus extend the track ‘backwards’.
5. Neumann et al. (1999) storm #5. Large alterations to the track in the Gulf of Mexico.
8. Neumann et al. (1999) storm #7. Changing the start date of the storm, thus extend the track ‘backwards’ into the Caribbean.

1901

1. Neumann et al. (1999) storm #1. Large alterations to the track and intensity, delay transition to tropical storm status.
2. Neumann et al. (1999) storm #2. Large alterations to the track, faster transition to tropical storm status with landfall near Galveston, Texas.
6. Newly documented Hurricane near 19N 31W to 20N 37W from newspaper accounts, the Historical Weather Map series, and the COADS ship database.
7. Neumann et al. (1999) storm #5. Large alterations to the track and intensity reduced to category 1.
8. Neumann et al. (1999) storm #6. No change to track, intensity increased to hurricane near Cuba.
9. Neumann et al. (1999) storm #7. No change to track or intensity.
12. Add new tropical storm.
13. Neumann et al. (1999) storm #10. No change to track, upgrade the storm to a hurricane.

1902

1. Neumann et al. (1999) storm #1. Large alterations to the track and intensity.
2. Neumann et al. (1999) storm #2. Large alterations to the track and intensity reduced to tropical storm and landfall in Texas.
4. Neumann et al. (1999) storm #4. Large alterations to the track and intensity, landfall in Mexico as tropical depression.
8. Neumann et al. (1999) storm #8. No change in track, landfall southeast Florida, reduced to hurricane category 1 at landfall.
11. Neumann et al. (1999) storm #11. No change
13. Neumann et al. (1999) storm #13. Changed track and reduce maximum strength to Tropical Storm then extratropical as it approached Norfolk, Virginia.