Classification of Radial Wind Profiles for Gulf of Mexico Tropical Cyclones

Andrew T. Cox
Oceanweather Inc.
Cos Cob, CT, USA

14th International Workshop on Wave Hindcasting and Forecasting
Key West, Florida November 8-13 2015
Overview

1. Approach to the analysis of tropical cyclone winds for ocean response models
2. Model inputs for fitting the radial wind and pressure profile
3. Prior work on storm classification
4. Classification system for radial wind profiles
5. Summary of results
**Approach to the analysis of tropical cyclone winds for ocean response models**

Analysis of tropical cyclone wind and pressure fields applies a GUI interface to the OWI Tropical Planetary Boundary Layer Model.

Available track/intensity, fix data, aircraft reconnaissance, in-situ and satellite data are applied in the determination of model inputs and validation of results.

**Basic steps:**
1. Evaluation of basic storm parameters: track, intensity, speed/direction, environmental conditions
2. Fitting of radial pressure profiles at snapshot times
3. Review 10 m wind output with available validation data
4. Repeat process and impose time continuity in model inputs
OWI Tropical PBL Inputs

Pressure field is prescribed with a Holland profile

\[ P(r) = P_0 + \sum_{i=2}^{n} dP_i e^{-\left(\frac{R_{pi}}{r}\right)^{Bi}} \]

Storm Position – Latitude/Longitude

Storm Motion – Speed/Direction

\( P_0 \) - Central Pressure of Storm

\( R_{pi} \) – Scale Pressure Radius

\( D_{pi} \) – Total Pressure Drop (\( P_{far}-P_0 \))

\( B_i \) – Holland’s B associated with each \( R_{pi} \)

Available from standard sources such as HURDAT but we reexamine these as well

Related to the Radius of Maximum Wind (RMW) expressed as an inner and outer radii

\( P_{far} \) may be derived from synoptic maps or atmospheric model output, however the % associated with each \( R_{pi} \) must be determined

Controls the peakedness of the pressure and resultant wind profile
Specification of a single Rp1/B1 combination can work for many storm wind/pressure profiles, but cannot describe more complex shapes.

Figures to the right depict flight level tangential winds and estimated sea level pressure data (red) measured during Katrina 2005 on Aug-28-2005 12:00 UTC.

Model fits using a single exponential profile (top) and double exponential profile are shown in blue – both result in the same maximum wind and radius of maximum winds but the resultant wind profiles differ greatly.
While application of the double exponential fit can better describe complex wind profiles — including those with two wind maxima like Allen 1980 (right) — it increases the number of model parameters from 3 (Dp1, Rp1 and B1) to 6 (Dp1, Dp2, Rp1, Rp2, B1, B2).

In Joint Probability Method (JPM) or synthetic storm generation the increased number of parameters can lead to a large set of storms to be run, plus statistical relationships applied for Rp1/B1 are even more difficult for the expanded parameter set.

Can this complexity be better described through an analysis of the resultant wind profile rather than in the raw model inputs?

The Gulf of Mexico Meteorological and Oceanographic (GOMOS) hindcast provides over 4,000 profile fits in 396 storms for the period 1900-2011 to evaluate tropical radial wind profiles in the Gulf of Mexico.
Prior Classifications for Profile Shape

Descriptions of the radial wind profile are not new!

- Colon (1963) describes wind profiles as resembling Daisy 1958 (small eye, narrow) or Helene 1958 (large eye, broad)

- Merrill (1984) looked at tropical cyclone size in North Atlantic and North Pacific storms

- Samsury and Rappaport (1991) developed a five class wind profile classification system (figure, right)

- Chen (2010) developed a size index for North Pacific typhoons in which systems were deemed “compact” or “incompact”

The goal of most of the prior work was to relate cyclone size to intensity changes to aid in forecasting
Diagnostic Plots for All Profile Fits

To aid in the development of wind profile classes diagnostic plots of the PBL inputs, measured data, and resultant model fit were produced.

This figure is during Katrina 2005 valid on Aug-29-2005 at 12:00 UTC

Analyzed model data are shown as azimuthally averaged black lines and can be directly compared to azimuthally averaged Aircraft/SFMR dashed lines.

Other data (satellite, recon, in-situ) are not azimuthally averaged and show the variation of the measurements by quadrant of the storm.
Data availability over time for use in tropical wind profile analysis
The “Shelfy” Index

Manual inspection of diagnostic profiles indicated that a classification on just the tropical inputs (Rp 1/2, B 1/2, Dp) would be difficult – a descriptor of the shape of the wind profile was needed

Chen (2010) applied a simple structure parameter $S$ which was the ratio of the tangential wind speed at twice the RMW to the average value. Values of $S < 1$ were deemed “incompact” and $S > 1$ “compact”

This led to the development of $S_{GOM}$ parameter which applied the ratio of RMW and pressure deficit to the average GOM storm (45 mb).
The “Shelfy” Index

A $S_{GOM}$ index of 0.6 was found to be a good threshold between simple profiles and those with shelf or dual radii structure.

Population of GOM snapshots show are near even split of storms 56% below and 44% above.

Nearly all fits with high $S_{GOM}$ (large shelf or dual radii) are from the post 1947 period which indicates the need for in-situ data to fit properly.
Using $S_{GOM}$ and a subset of model inputs, a profile classification system was developed and applied in 4,043 snapshots from GOM storms 1900-2011 in 396 individual storms.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>$S_{GOM}$</th>
<th>Radius Criteria</th>
<th>B Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CSPN</td>
<td>Compact Single Peaked Negligible Shelfiness</td>
<td>$\leq 0.6$</td>
<td>RMW$&lt;24$</td>
<td>$B_1 &gt; 1$</td>
</tr>
<tr>
<td>2 CSPS</td>
<td>Compact Single Peaked Shelfy Outer Core</td>
<td>$&gt; 0.6$</td>
<td>RMW$&lt;24$</td>
<td>-</td>
</tr>
<tr>
<td>3 BSPN</td>
<td>Broad Single Peaked Negligible Shelfiness</td>
<td>$\leq 0.6$</td>
<td>RMW$\geq 24$</td>
<td>-</td>
</tr>
<tr>
<td>4 BSPS</td>
<td>Broad Single Peaked Shelfy Outer Core</td>
<td>$&gt; 0.6$</td>
<td>RMW$\geq 24$</td>
<td>-</td>
</tr>
<tr>
<td>5 MPID</td>
<td>Multi Peaked – Inner Dominant</td>
<td></td>
<td>RMW$<em>{In}$$</em>{Ws}$ $\geq$ RMW$<em>{Out}$$</em>{Ws}$</td>
<td></td>
</tr>
<tr>
<td>6 MPOD</td>
<td>Multi Peaked – Outer Dominant</td>
<td></td>
<td>RMW$<em>{In}$$</em>{Ws}$ $&lt;$ RMW$<em>{Out}$$</em>{Ws}$</td>
<td></td>
</tr>
<tr>
<td>7 SDNP</td>
<td>Shelf Dominant No Peaks</td>
<td></td>
<td>Flat Profile – Manually Determined</td>
<td></td>
</tr>
</tbody>
</table>
**Class #1 CSPN**
Compact Single Peaked Negligible Shelfiness

Class conforms most closely to Colon’s “Daisy” type and S&R’s “Narrow” type

Notable example: Camille 1969

**Class #2 CSPS**
Compact Single Peaked Shelly Outer Core

Stronger (954/945mb) on average than CSPN (980/977 mb)

Notable example: Dennis 2005
Class #3 BSPN
Broad Single Peaked Negligible Shelfiness

Class conforms most closely to Colon’s “Helene” type and S&R’s “Broad” type

Notable example: Georges 1998

Class #4 BSPS
Broad Single Peaked Shelfy Outer Core

The shelfy counter part to BSPN –stronger (956/955mb) on average than BSPN (979/972 mb)

Notable example: Katrina 2005

<table>
<thead>
<tr>
<th>Profile Class</th>
<th>Exponential Fit</th>
<th>Count</th>
<th>Average EyePres (mb)</th>
<th>Average Rad1 (Nm)</th>
<th>Average Rad2 (Nm)</th>
<th>Average Dp%</th>
<th>Average B1</th>
<th>Average B2</th>
<th>Average Pfar</th>
<th>Average Shelf Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (CSPN)</td>
<td>Single</td>
<td>362</td>
<td>980</td>
<td>19</td>
<td>100</td>
<td>1.10</td>
<td>1013</td>
<td>0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>42</td>
<td>977</td>
<td>16</td>
<td>60</td>
<td>1.70</td>
<td>1014</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 (CSPS)</td>
<td>Single</td>
<td>293</td>
<td>954</td>
<td>18</td>
<td>100</td>
<td>1.20</td>
<td>1012</td>
<td>0.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>109</td>
<td>945</td>
<td>16</td>
<td>66</td>
<td>1.80</td>
<td>1013</td>
<td>0.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (BSPN)</td>
<td>Single</td>
<td>384</td>
<td>979</td>
<td>31</td>
<td>100</td>
<td>1.20</td>
<td>1013</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>35</td>
<td>972</td>
<td>32</td>
<td>66</td>
<td>1.50</td>
<td>1012</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 (BSPS)</td>
<td>Single</td>
<td>96</td>
<td>956</td>
<td>33</td>
<td>100</td>
<td>1.20</td>
<td>1013</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>26</td>
<td>955</td>
<td>31</td>
<td>69</td>
<td>1.40</td>
<td>1012</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 (MPID)</td>
<td>Single</td>
<td>42</td>
<td>946</td>
<td>11</td>
<td>85</td>
<td>1.80</td>
<td>1012</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 (MPOD)</td>
<td>Single</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>39</td>
<td>968</td>
<td>15</td>
<td>63</td>
<td>1.10</td>
<td>1012</td>
<td>0.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 (SDNP)</td>
<td>Single</td>
<td>10</td>
<td>988</td>
<td>144</td>
<td>100</td>
<td>1.10</td>
<td>1011</td>
<td>0.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>12</td>
<td>981</td>
<td>25</td>
<td>53</td>
<td>0.70</td>
<td>1010</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Classification of Radial Wind Profiles for Gulf of Mexico Tropical Cyclones
14th International Workshop on Wave Hindcasting and Forecasting
Key West, Florida November 8-13 2015
**Class #5 MPID**
Multi Peaked Inner Dominant

Two wind maxima seen in wind profile – inner maxima stronger, can only be fit using double exponential

Notable example: Allen 1980

**Class #6 MPOD**
Multi Peaked Outer Dominant

Two wind maxima seen in wind profile – outer maxima stronger, can only be fit using double exponential

Notable example: Ike 2008

<table>
<thead>
<tr>
<th>Profile Class</th>
<th>Exponential Fit</th>
<th>Count</th>
<th>Average EyePres (mb)</th>
<th>Average Rad1 (Nm)</th>
<th>Average Rad2 (Nm)</th>
<th>Average Dp%</th>
<th>Average B1</th>
<th>Average B2</th>
<th>Average Pfar</th>
<th>Average Shelf Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (CSPN)</td>
<td>Single</td>
<td>362</td>
<td>980</td>
<td>19</td>
<td>100</td>
<td>1.10</td>
<td>1013</td>
<td>0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>42</td>
<td>977</td>
<td>16</td>
<td>49</td>
<td>58</td>
<td>1.70</td>
<td>1.30</td>
<td>1014</td>
<td>0.50</td>
</tr>
<tr>
<td>2 (CSPS)</td>
<td>Single</td>
<td>293</td>
<td>954</td>
<td>18</td>
<td>100</td>
<td>1.20</td>
<td>1012</td>
<td>0.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>109</td>
<td>945</td>
<td>16</td>
<td>65</td>
<td>66</td>
<td>1.80</td>
<td>1.30</td>
<td>1013</td>
<td>0.77</td>
</tr>
<tr>
<td>3 (BSPN)</td>
<td>Single</td>
<td>384</td>
<td>979</td>
<td>31</td>
<td>100</td>
<td>1.20</td>
<td>1013</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>35</td>
<td>972</td>
<td>32</td>
<td>82</td>
<td>66</td>
<td>1.50</td>
<td>1.50</td>
<td>1012</td>
<td>0.52</td>
</tr>
<tr>
<td>4 (BSPS)</td>
<td>Single</td>
<td>96</td>
<td>956</td>
<td>33</td>
<td>100</td>
<td>1.20</td>
<td>1013</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>26</td>
<td>955</td>
<td>31</td>
<td>96</td>
<td>69</td>
<td>1.40</td>
<td>1.30</td>
<td>1012</td>
<td>0.70</td>
</tr>
<tr>
<td>5 (MPID)</td>
<td>Single</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1012</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>42</td>
<td>946</td>
<td>11</td>
<td>85</td>
<td>63</td>
<td>1.80</td>
<td>1.50</td>
<td>1012</td>
<td>0.94</td>
</tr>
<tr>
<td>6 (MPOD)</td>
<td>Single</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1012</td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>39</td>
<td>968</td>
<td>15</td>
<td>63</td>
<td>50</td>
<td>1.10</td>
<td>1.80</td>
<td>1012</td>
<td>0.94</td>
</tr>
<tr>
<td>7 (SDNP)</td>
<td>Single</td>
<td>10</td>
<td>988</td>
<td>144</td>
<td>100</td>
<td>1.10</td>
<td>1011</td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>12</td>
<td>981</td>
<td>25</td>
<td>100</td>
<td>53</td>
<td>0.70</td>
<td>0.70</td>
<td>1010</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Class #7 SDNP
Shelf Dominant No Peak

Flat wind profile associated with weakest storm class

Notable example: Isaac 2012
Distribution of storm profile classes

Single wind peak Class 1-4 found throughout time period

Double wind peak Classes 5/6 and shelf dominant
Class 7 storms only analyzed when reconnaissance is available
Other relationships explored

- Seasonal dependence on profile class?
- Dependence on other model inputs (Vf)?
- Association with track history/origin of storm in Gulf of Mexico?
- How long does a storm maintain a single profile class? Are there preferences from one class to another?
Synoptic Classification – Notable Results

• Storms which depict a shelf like structure ($S_{gom} >= 0.6$) to the radial wind profile make up 44% of the storm population 1900-2011 and 48% of the population during the aircraft recon period of 1947-2011

• Most “shelby” storms exhibit a single wind maxima in the radial wind profile. Storms with a second radial wind maxima (Class 5/6) make up just 5.6% of the total population

• While “shelby” storms are found in the full 1900-2011 storm population, storms with a second radial wind maxima (Class 5/6) were only analyzed post 1960 – highlighting the need for aircraft recon to diagnose

• Storms which form in the GOM have the highest occurrence (77%) of wind profile classes associated with negligible shelfiness (Class 1 & 3)

• The strongest storms were typically analyzed with a double exponential pressure profile fit in Class 2 (Compact with Shelf, 945mb/16Nmi average central pressure/RMW) and Class 5 (Multiple Peak Inner Dominant, 946mb/11Nmi average central pressure/RMW)

• 58% of storms exhibited multiple wind profile classes while in the GOM. Wind profile classes associated with no shelf (Class 1 CSPN) or negligible shelfiness (Class 3) were the most likely to retain a single wind profile class for the entire GOM lifetime

• On average, storms retained the same wind profile 70-85% of the time for adjacent 6-hourly synoptic snapshots. When the wind profile class does change, some classes exhibit preferences. For instance, Class 5 storms (Multiple Peaks) had zero occurrences of transitioning to a Class 1 (Compact Single) profile.
Summary

Synoptic classification was performed as part of a Research Partnership to Secure Energy for America (RpSea) project 10121-4801-01 - Ultra-Deepwater Synthetic Hurricane Risk Model for Gulf of Mexico


Primary Contractor: Applied Research Associates (Peter Vickery and Lauren Mudd)
Sub-Contractors: Oceanweather Inc. and UCAR (James Done and Greg Holland)

Work is underway on the application of the double exponential fits in a synthetic hurricane generation model

Questions?