The IMPOWR (Improving the Mapping and Prediction of Offshore Wind Resources) project: Evaluation of WRF PBL Schemes

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Motivation

- Extraordinary offshore wind resource with seasonal variability;
- Current offshore wind maps were constructed using limited/no observations at turbine hub height;
- No information on the uncertainty of offshore wind maps is available;
- **GOAL:** Provide a comprehensive Planetary Boundary Layer (PBL) verification over southern New England coastal waters, as well as some possible improvements to the PBL parameterizations using ensemble modeling.

Modeled seasonal daytime offshore wind resource at 90 m as capacity factor of 5MW REpower (Dvorak et al. 2012)
Research Questions

1. What are the systematic errors (biases) of the WRF Planetary Boundary Layer (PBL) schemes in wind speed and temperature in the region, and how do these biases vary diurnally and seasonally?

2. What is the climatology of the observed low-level stability (around 20-m) diurnally and seasonally?

3. How well does WRF simulate low-level jet and stability structures observed using field data over coastal southern New England?
Historical observational datasets: Conventional data

- 11 NDBC Moored Buoys
- 3 NDBC C-MAN Stations
- 14 NWS ASOS Stations
Historical observational datasets: Cape Wind (CW) tower

- Multi-level wind and temperature;
Historical observational datasets: Cape Wind (CW) tower issues

- Original plan to instrument upper arms of tower with new instruments was not safe;
- IMPOWR instruments only added on platform (10 m);
- Lots of data quality issues.
# WRF ensemble modeling: Six PBL schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Turbulence Closure Order</th>
<th>Surface Layer Scheme</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>YSU</td>
<td>1.0</td>
<td>MM5</td>
<td>Non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer</td>
</tr>
<tr>
<td>ACM2</td>
<td>1.0</td>
<td>MM5</td>
<td>Asymmetric Convective Model with non-local upward mixing and local downward mixing</td>
</tr>
<tr>
<td>BouLac</td>
<td>1.5</td>
<td>MM5</td>
<td>Designed for use with BEP (Building Environment Parameterization) urban model</td>
</tr>
<tr>
<td>MYJ</td>
<td>1.5</td>
<td>MYJ</td>
<td>One-dimensional prognostic turbulent kinetic energy scheme with local vertical mixing</td>
</tr>
<tr>
<td>QNSE</td>
<td>1.5</td>
<td>QNSE</td>
<td>A TKE-prediction option that uses a new theory for stably stratified regions</td>
</tr>
<tr>
<td>MYNN2.5</td>
<td>1.5</td>
<td>MM5</td>
<td>Predicts sub-grid TKE terms</td>
</tr>
</tbody>
</table>
WRF ensemble modeling: Setup

- WRF v. 3.4.1;
- 30-hour simulations;
- 38 vertical levels;
- NARR analyses as IC/BCs;
- 0.5 RTG SST;
- Verification used 4-km domain;
- First 6 forecast hours discarded as model spin-up time.
WRF simulation approach for historical study 2003 – 2011

90 model simulation dates randomly and uniformly distributed between 2003 – 2011:

• Equally divided between warm season (April – September) and cool season (October – March);

• Equally divided between 0000 UTC and 1200 UTC model initialization times;

• Verification divided into seasons (warm and cool) as well as diurnal periods:
  – Day (1200 – 2300 UTC);
  – Night (0000 – 1100 UTC).
Cape Wind tower mean error: Wind speed – Warm season

- MYNN2 and QNSE schemes show smallest ME;
- Generally negative ME that decrease in magnitude with height;
- BouLac scheme shows largest ME at 60 m;
- Note: MAE values for all schemes represent 21 – 22% of wind speed magnitude;
- Larger errors at night.
Cape Wind tower mean error: Wind speed – Cool season

- Generally negative wind speed ME;
- Increase in magnitude with height (opposite of warm season);
- Largest for BouLac scheme;
- Larger errors during day (opposite of warm season).
Buoy 44020 5-m mean temperature error

- Surface cool bias during the warm season;
- Surface warm bias during the cool season;
- Possible explanations:
  - surface heat fluxes are too large in the WRF (not likely, explained later);
  - SST issue (testing undergoing);
- What about atmospheric stability?
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Stability analysis based on historical CW sonic anemometers: unstable conditions dominate

\[ L = - \frac{T u^3_*}{k g w' \theta'} = + \frac{T u^2_*}{k g \theta_*} \]

very stable \( 0 < L < 200 \) m
stable \( 200 < L < 1000 \) m
near-neutral \( |L| > 1000 \) m
unstable \( -1000 < L < -200 \) m
very unstable \( -200 < L < 0 \) m
IMPOWR sonics consistent with CW sonics: unstable conditions dominate
Non-log profiles occur ~40% of the time at CW

V60>V41>V20

All other 8 cases
Non-log profiles are associated with unstable conditions

Frequency of Log vs Non-Log profiles by season and stability
(from sonics, 2003-2007)
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IMPOWR Experiment: Fall 2012 to present
## IMPOWR Flights (2012-2014)

Table 1: Flight days for the IMPOWR field experiment

<table>
<thead>
<tr>
<th>Flight Day</th>
<th>Weather Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 November 2012</td>
<td>Cyclone warm sector with south winds</td>
</tr>
<tr>
<td>4 April 2013</td>
<td>Southwest flow around anticyclone</td>
</tr>
<tr>
<td>7 April 2013</td>
<td>Stable strong south flow ahead of warm front</td>
</tr>
<tr>
<td>9 April 2013</td>
<td>Southwest flow ahead of cold front</td>
</tr>
<tr>
<td>4 May 2013</td>
<td>Moderate northeast flow with a subsidence inversion at top of PBL</td>
</tr>
<tr>
<td>10 May 2013</td>
<td>Southwest flow with coastal sea breezes</td>
</tr>
<tr>
<td>16 May 2013</td>
<td>Southwest flow with coastal jet</td>
</tr>
<tr>
<td>20 June 2013</td>
<td>Coastal jet with westerly flow aloft</td>
</tr>
<tr>
<td>21 June 2013</td>
<td>Coastal jet with westerly flow aloft</td>
</tr>
<tr>
<td>23 June 2013</td>
<td>Coastal jet with southwesterly flow aloft</td>
</tr>
<tr>
<td>24 June 2013</td>
<td>Weak NY Bight jet event</td>
</tr>
<tr>
<td>28 September 2013</td>
<td>Northeasterly flow around anticyclone</td>
</tr>
<tr>
<td>2 October 2013</td>
<td>Weak westerly flow</td>
</tr>
<tr>
<td>12 May 2014</td>
<td>Southwest flow with coastal jet</td>
</tr>
<tr>
<td>22 July 2014</td>
<td>New York Bight Jet</td>
</tr>
<tr>
<td>23 July 2014 (Flight 1)</td>
<td>New York Bight Jet (before jet)</td>
</tr>
<tr>
<td>23 July 2014 (Flight 2)</td>
<td>New York Bight Jet (after jet)</td>
</tr>
<tr>
<td>31 July 2014</td>
<td>Southwest flow with coastal jet</td>
</tr>
<tr>
<td>11 November 2014</td>
<td>Cold NW flow over warmer coastal waters</td>
</tr>
</tbody>
</table>

**AIMMS-20 Instrument**

Up to 40 Hz measurements of 3D winds, temperature, pressure and RH
Observations at 1800 UTC 21 June 2013

Surface Analysis

- General SW surface flow around high pressure offshore of New England
- Inland surface temps 26-27°C, while 20-21°C over water
- Coastally enhanced 40-50 m winds (20-25 kts) towards Nantucket Island

Flight-level winds (kts)
40-50 m ASL
South-North Cross Section Around 1800 UTC 21 June 2013

Flight-level obs

1.33-km WRF (YSU PBL) at 1800 UTC
(18-h forecast using RAP IC/BCs)

1.33-km WRF (YSU PBL) at 2100 UTC

- Observed low-level jet to 25 kts below 400 m
- 1.33-km WRF (YSU PBL) too weak, even a few hours later after more daytime heating.
- WRF marine layer is too shallow near coast.
Flight: 1600 – 1900 UTC 21 June 2013
Spiral Around Cape Wind Tower
1925 UTC

- All schemes exhibit shallower / cooler (1 – 2 °C) MABL than observations
- Lower wind maximum in models (100 m vs. 190 m)
- Schemes underestimate 5-m winds at 44020 (1 – 2 m s\(^{-1}\))

- Observed mid-late AM winds 20-25 kts at 100-225 m
- Jet increases to 35-40 kts by 4-6 PM EDT
- 1.33 WRF (YSU PBL) are 5-10 kts too weak for the jet
Conclusions

• WRF PBL parameterizations consistently underpredict wind speeds at Cape Wind tower at all levels;
• WRF near surface temperature at Nantucket Sound buoy is too warm during the cool season and too cool during the warm season. This suggests SST bias in Sound (currently testing) or too large surface fluxes (inconsistent with next findings);
• Atmospheric stability at Cape Wind is predominantly unstable based on Monin-Obukhov length from sonic anemometer at 20 m (thus strong mixing and little shear);
• IMPOWR observations suggest that:
  – WRF diurnally-forced low-level jets are too weak during the warm season.
  – WRF too cool near surface;
  – PBL is too shallow near coast (e.g., not enough mixing);
• Location too complex to verify PBL parameterizations.
CW temperature sensors are suspicious:
1) Inconsistent T errors in cool season
CW temperature sensors are suspicious:
2) Unrealistic stable conditions dominate in cool season (and all year)

\[ L = -\frac{T_u^3}{kgw'\theta'} = +\frac{T_u^2}{kg\theta^*} \]

- very stable: \(0 < L < 200\) m
- stable: \(200 < L < 1000\) m
- near-neutral: \(|L| > 1000\) m
- unstable: \(-1000 < L < -200\) m
- very unstable: \(-200 < L < 0\) m
CW temperature sensors are suspicious:
3) Wrong link between stability and shear