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

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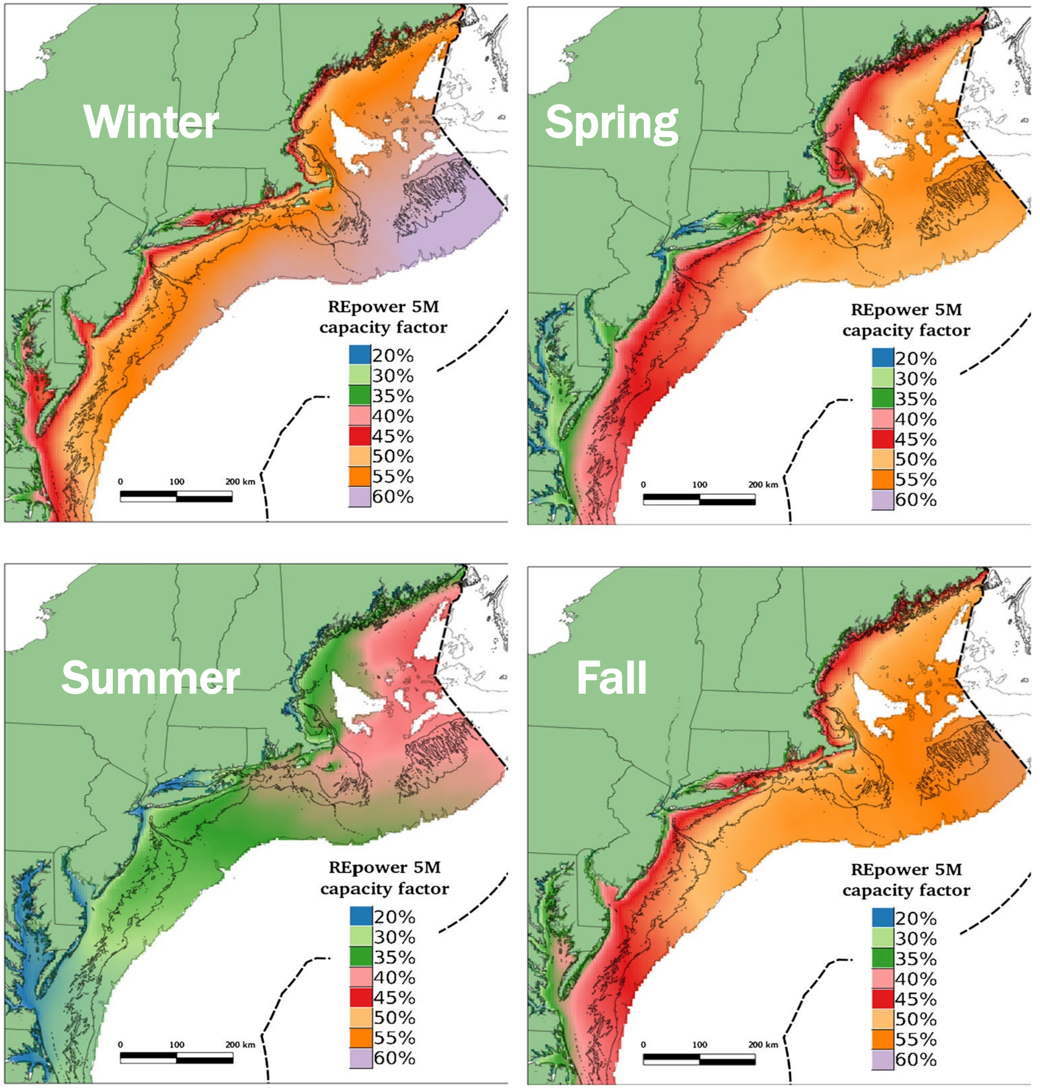
Motivation

- 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

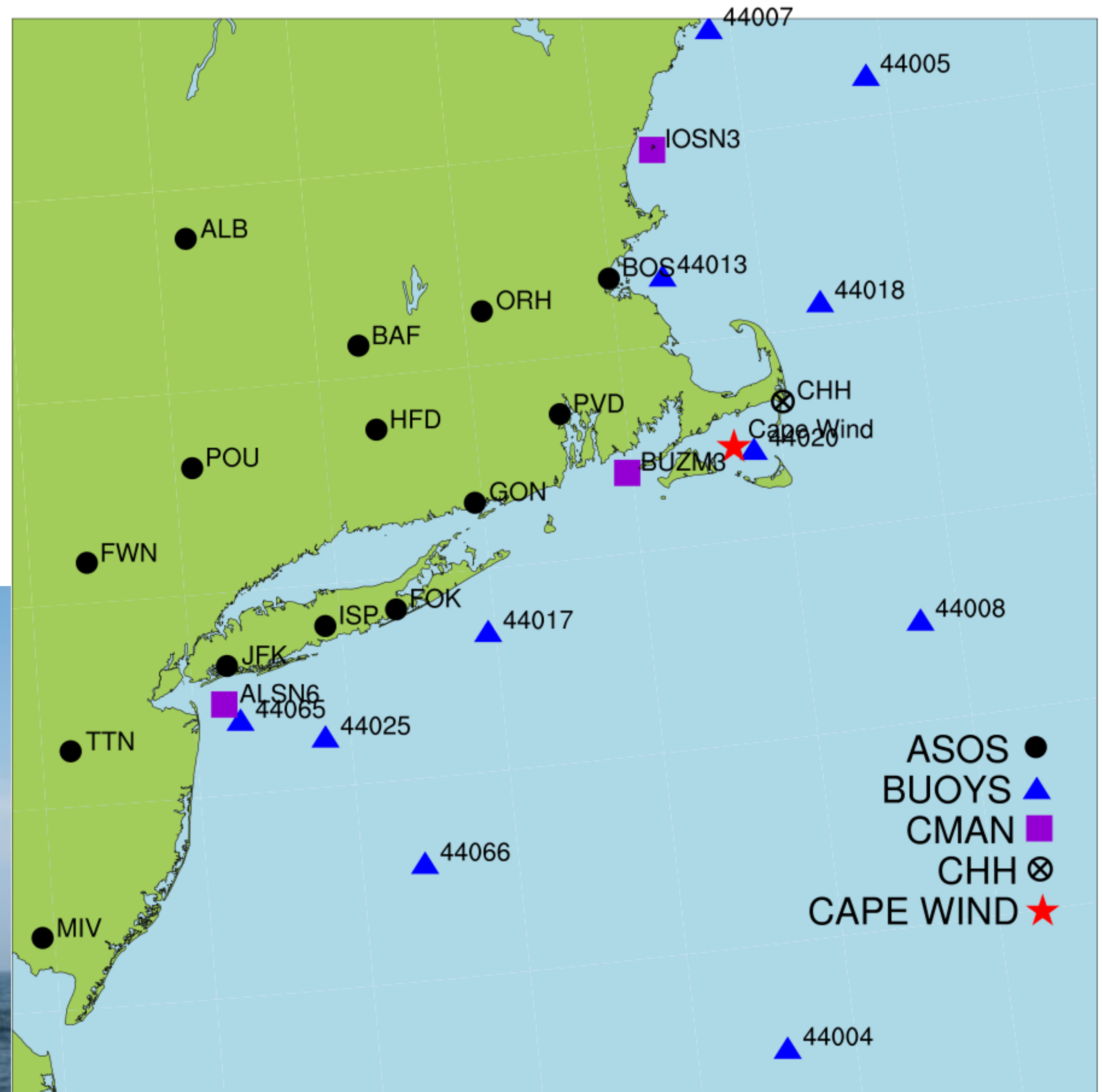
1. What are the systematic errors (biases) of the WRF Planetary Boundary Layer (PBL) schemes in wind speed and temperature in the region, and how do these biases vary diurnally and seasonally?

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?

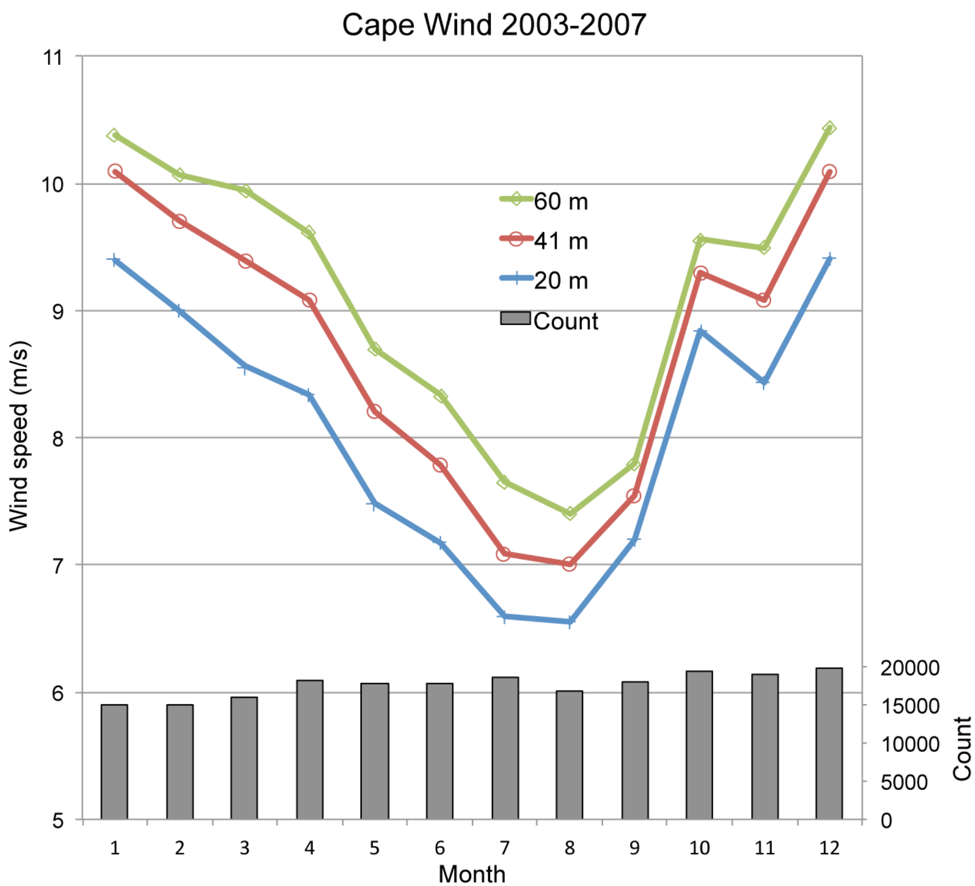
Historical observational datasets: Conventional data

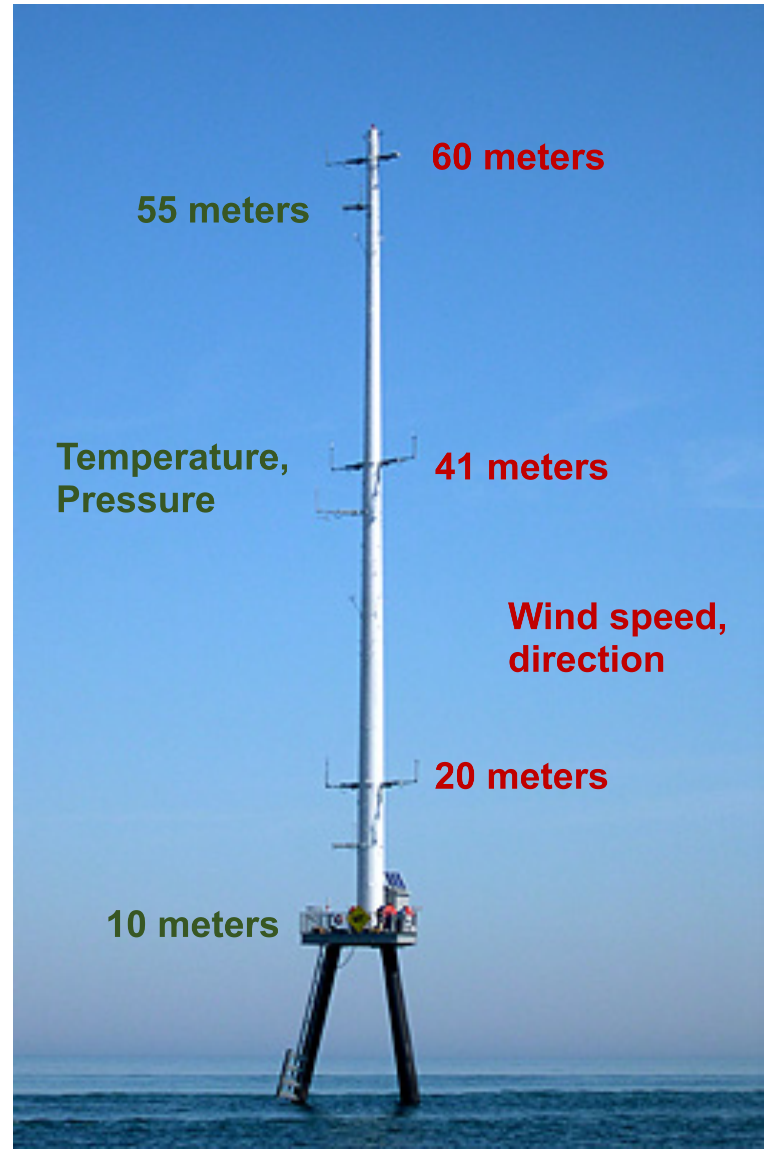
- 11 NDBC Moored Buoys
- 3 NDBC C-MAN Stations
- 14 NWS ASOS Stations



Historical observational datasets: Cape Wind (CW) tower

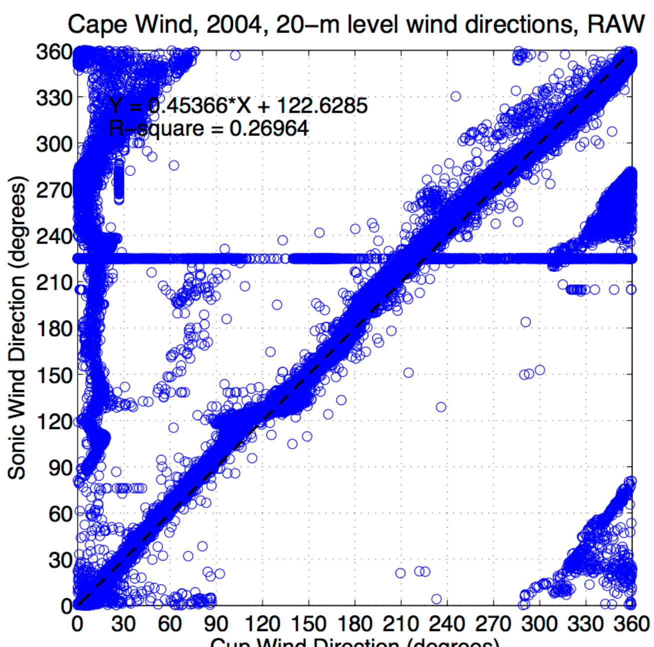
- Multi-level wind and temperature;
- Nine years of data (2003 – 2011, but only 2003 - 2007 complete).

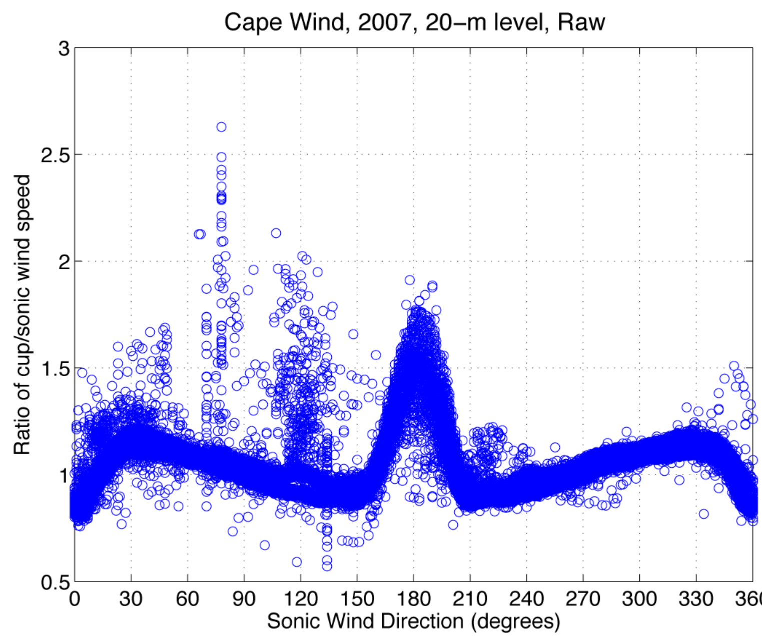




Historical observational datasets: Cape Wind (CW) tower issues

- 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.



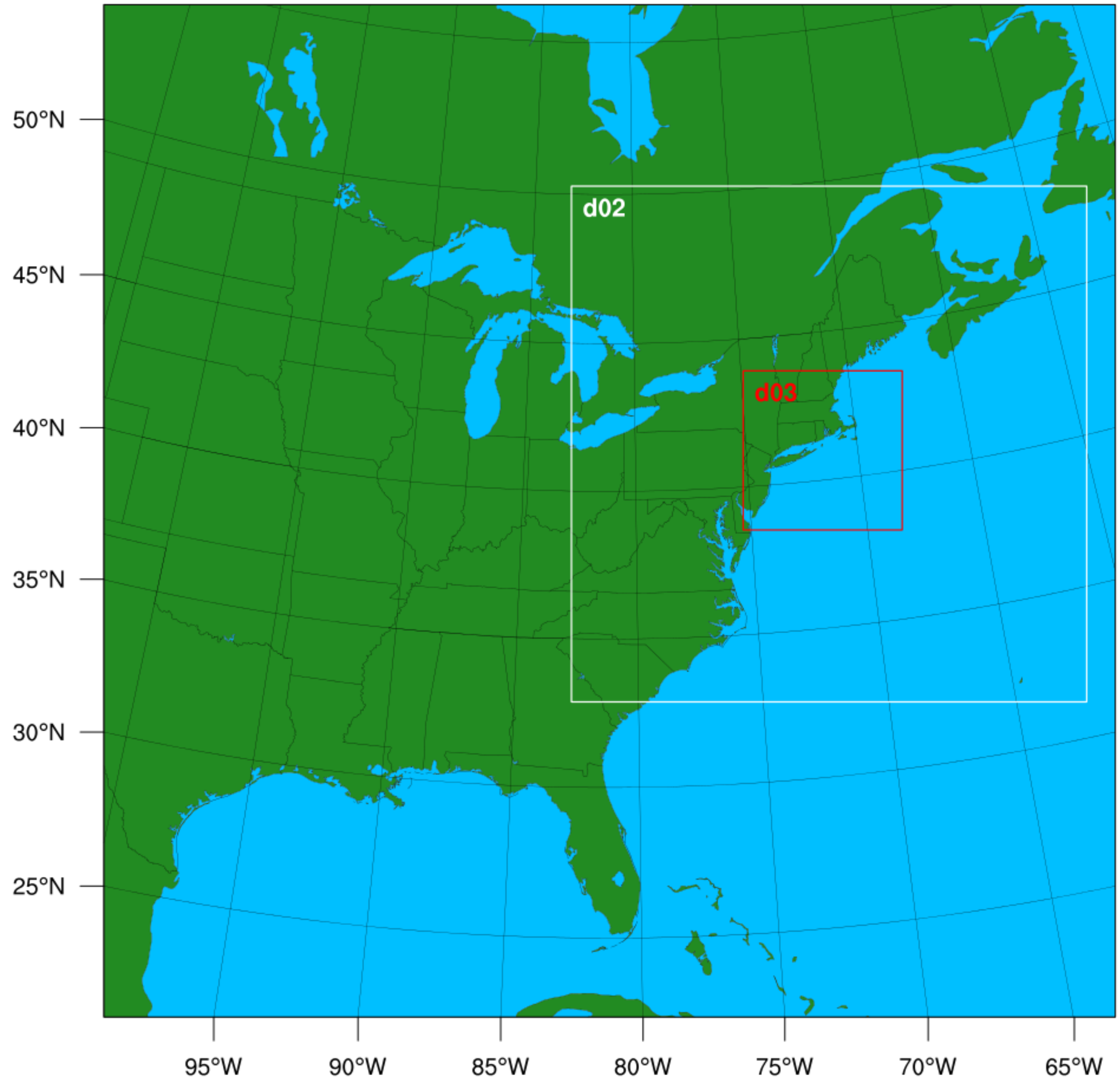


WRF ensemble modeling: Six PBL schemes

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

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.

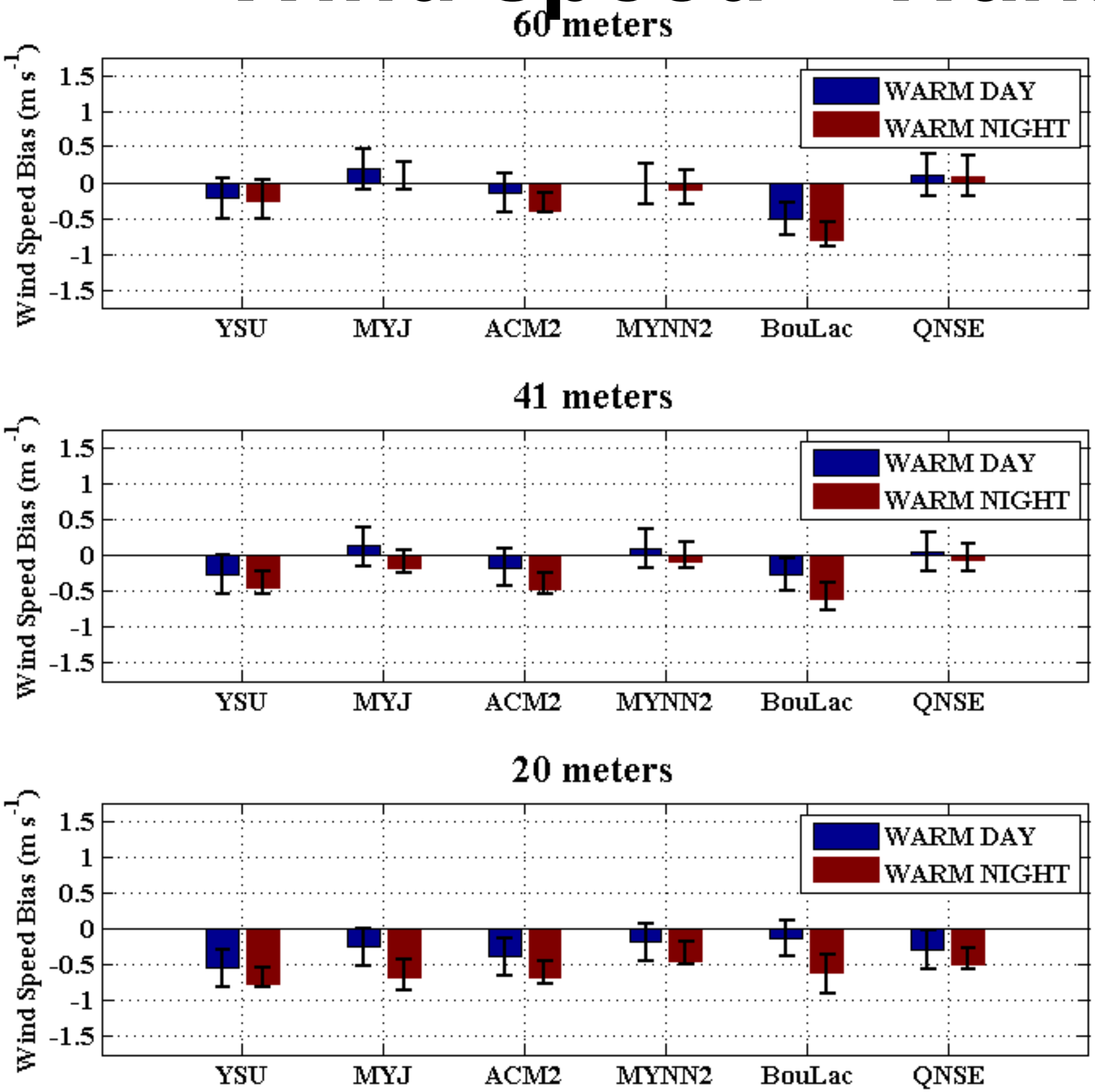


WRF simulation approach for historical study 2003 – 2011

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

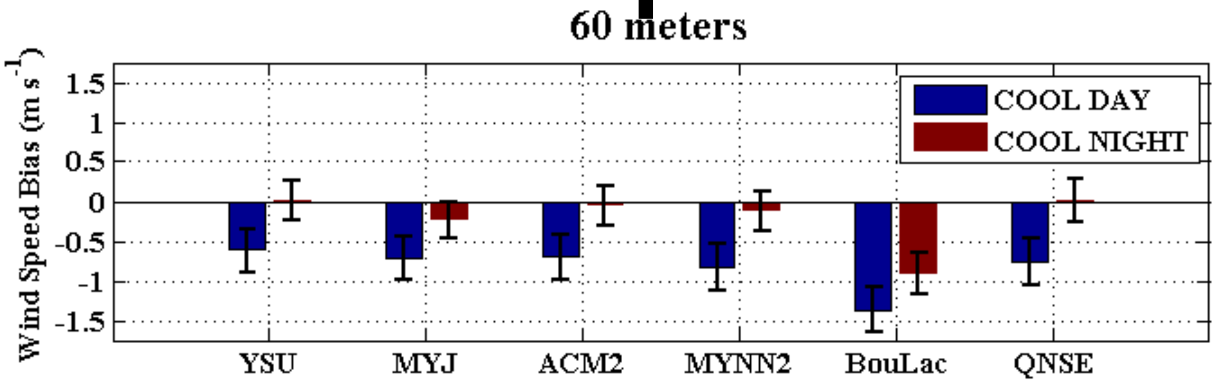
- Equally divided between warm season (April – September) and cool season (October – March);
- Equally divided between 0000 UTC and 1200 UTC model initialization times;
- Verification divided into seasons (warm and cool) as well as diurnal periods:
  - Day (1200 – 2300 UTC);
  - Night (0000 – 1100 UTC).

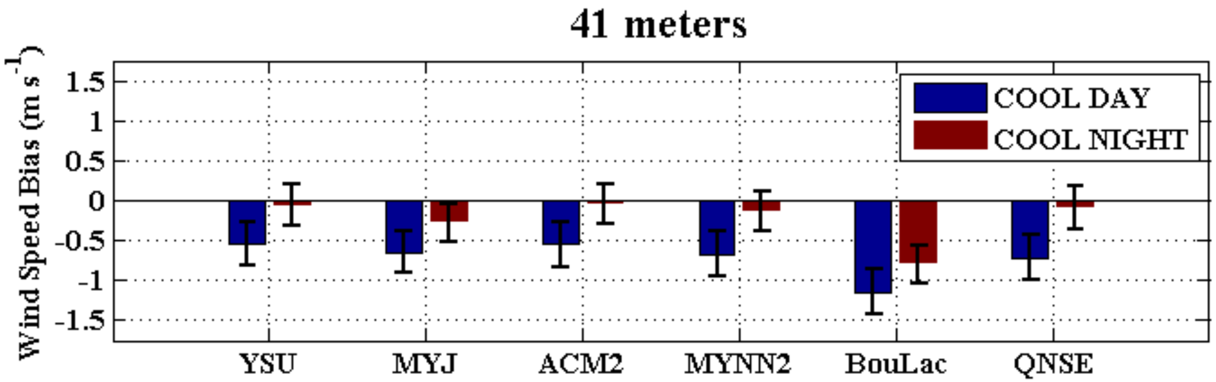
Cape Wind tower mean error: Wind speed – Warm season

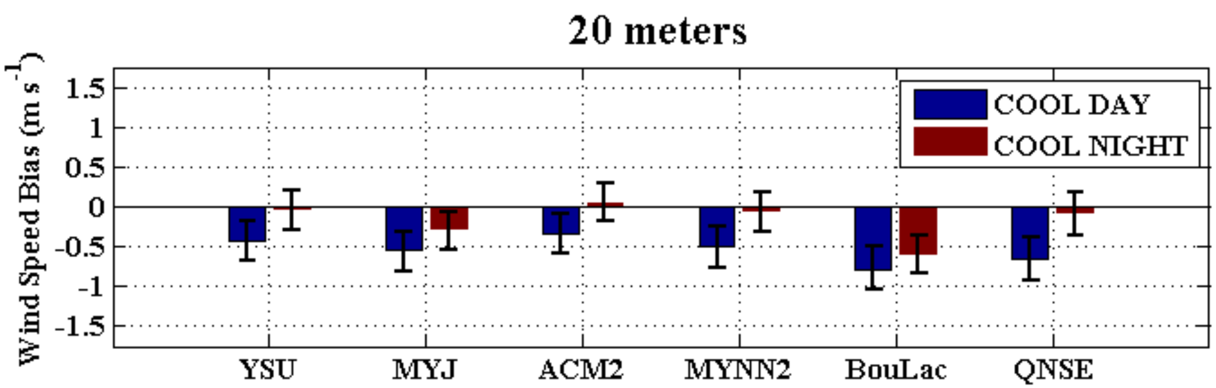


- MYNN2 and QNSE schemes show smallest ME;
- Generally negative ME that decrease in magnitude with height;
- BouLac scheme shows largest ME at 60 m;
- Note: MAE values for all schemes represent 21 – 22% of wind speed magnitude;
- Larger errors at night.

Cape Wind tower mean error: Wind speed – Cool season

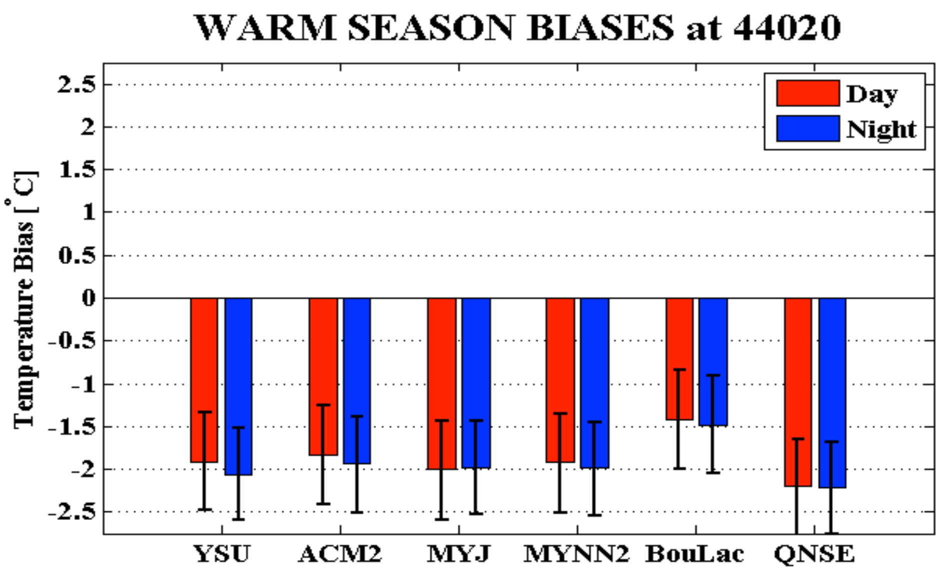


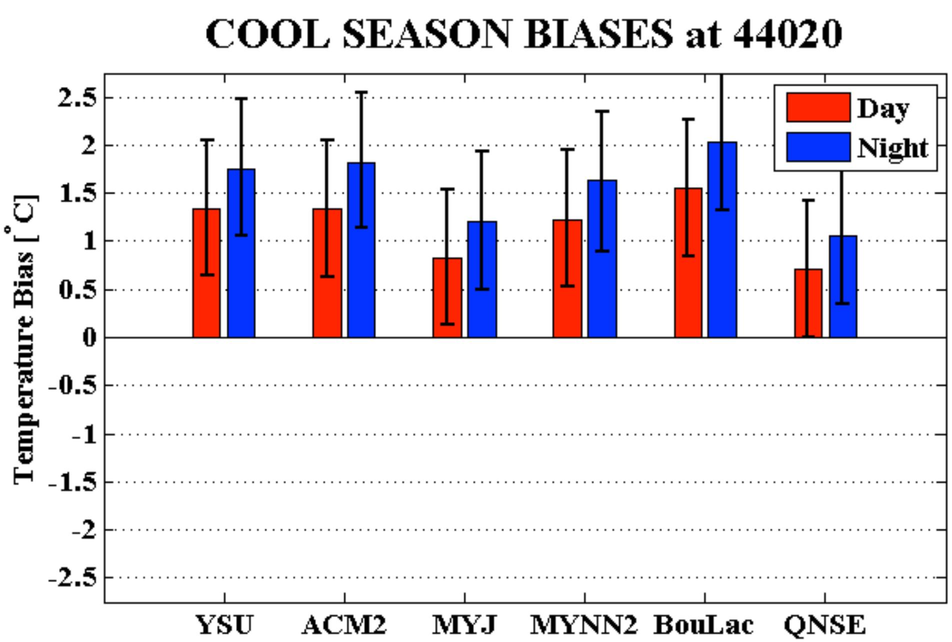




- Generally negative wind speed ME;
- Increase in magnitude with height (opposite of warm season);
- Largest for BouLac scheme;
- Larger errors during day (opposite of warm season).

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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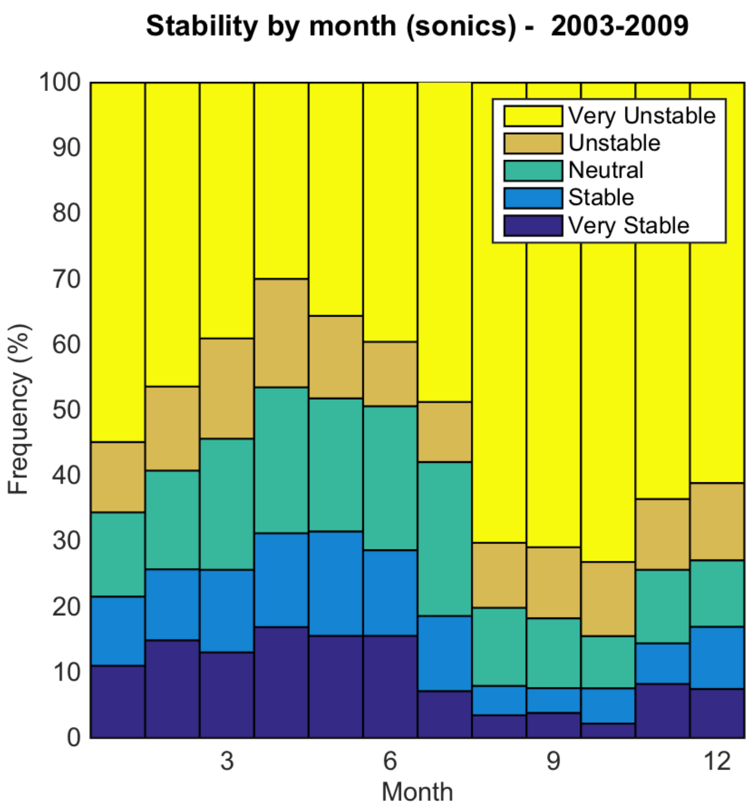
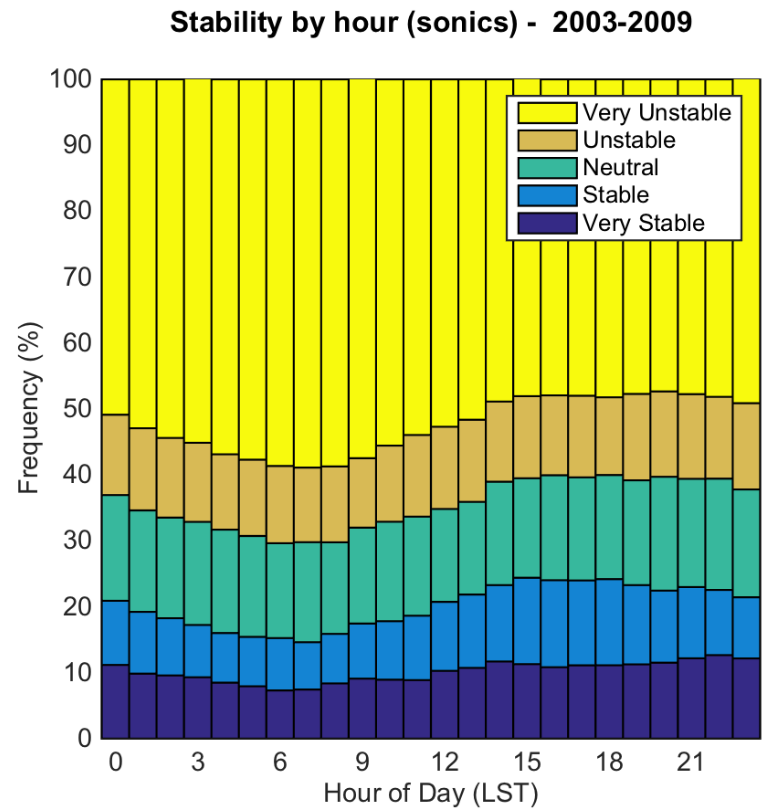
Stability analysis based on historical CW sonic anemometers: unstable conditions dominate

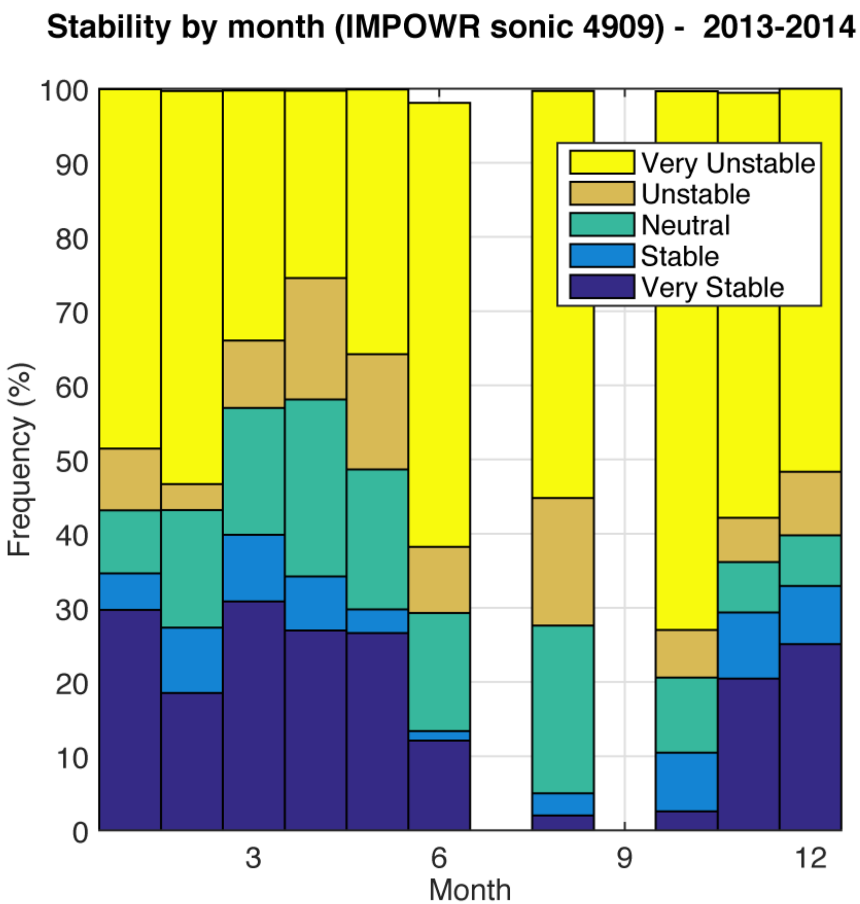


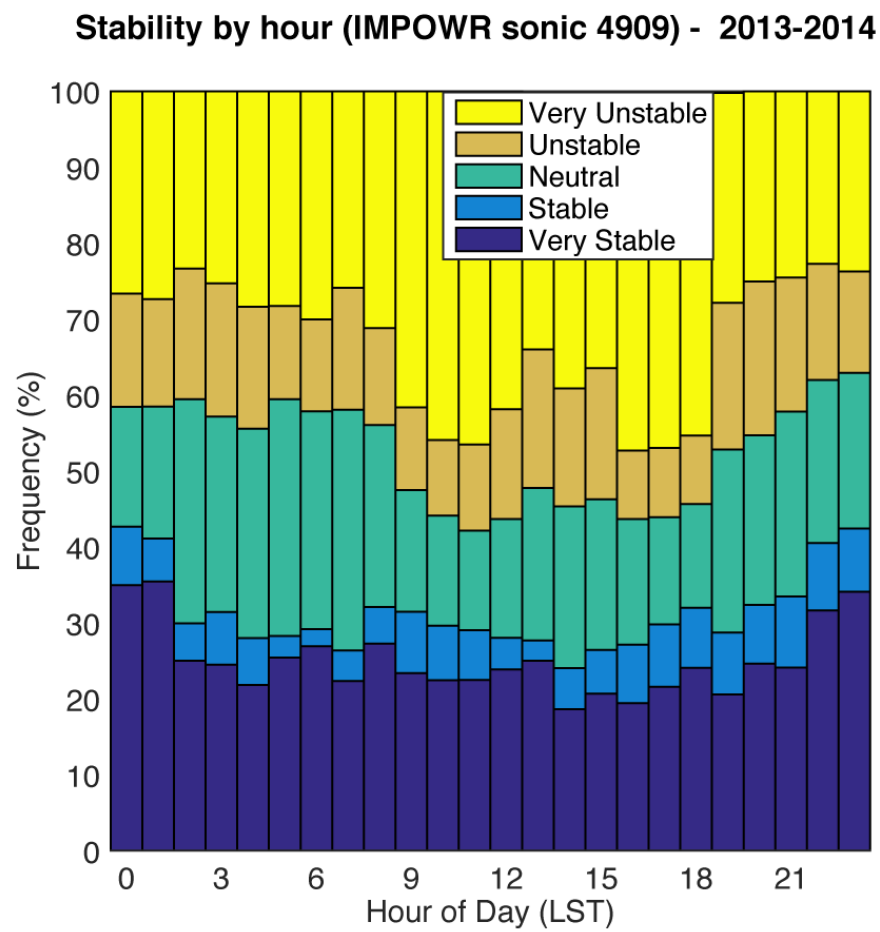


$$L = -\frac{Tu_*^3}{kg\overline{w'\theta'}} = +\frac{Tu_*^2}{kg\theta_*}$$

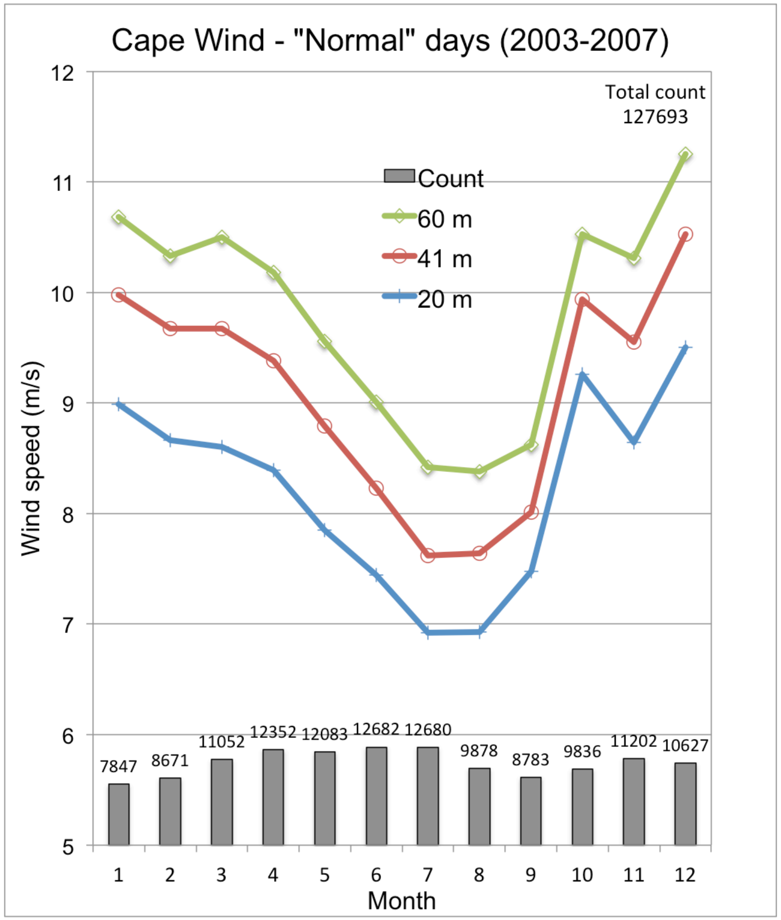
very stable	$0 < L < 200$ m
stable	$200 < L < 1000$ m
near-neutral	$\lvert L \rvert > 1000$ m
unstable	$-1000 < L < -200$ m
very unstable	$-200 < L < 0$ m

IMPOWR sonics consistent with CW sonics: unstable conditions dominate

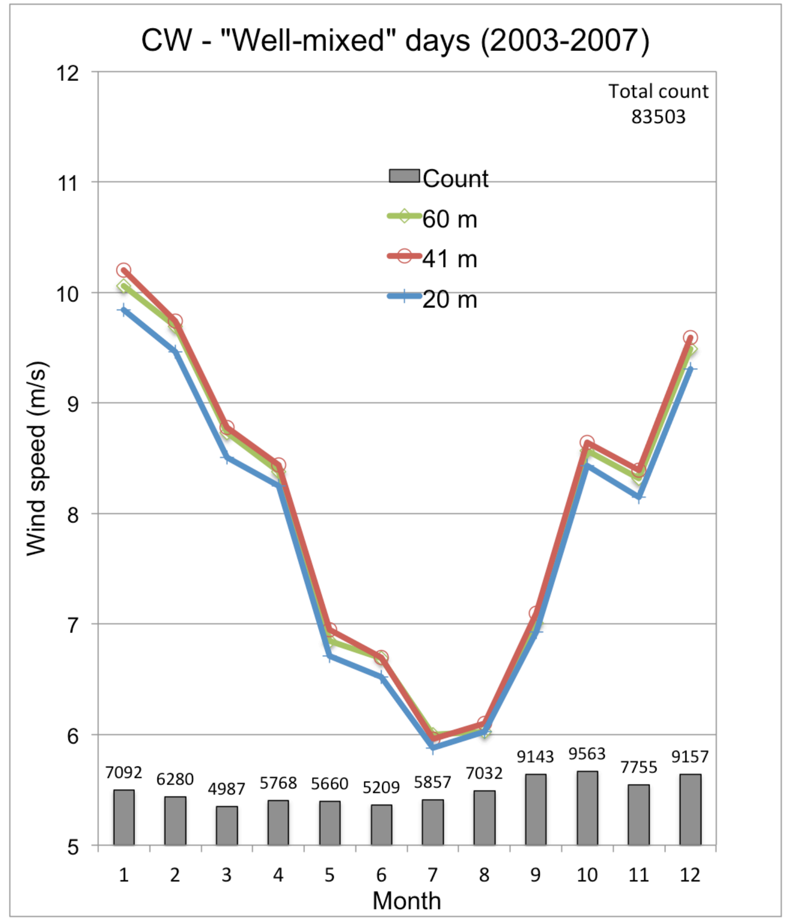




Non-log profiles occur ~40% of the time at CW

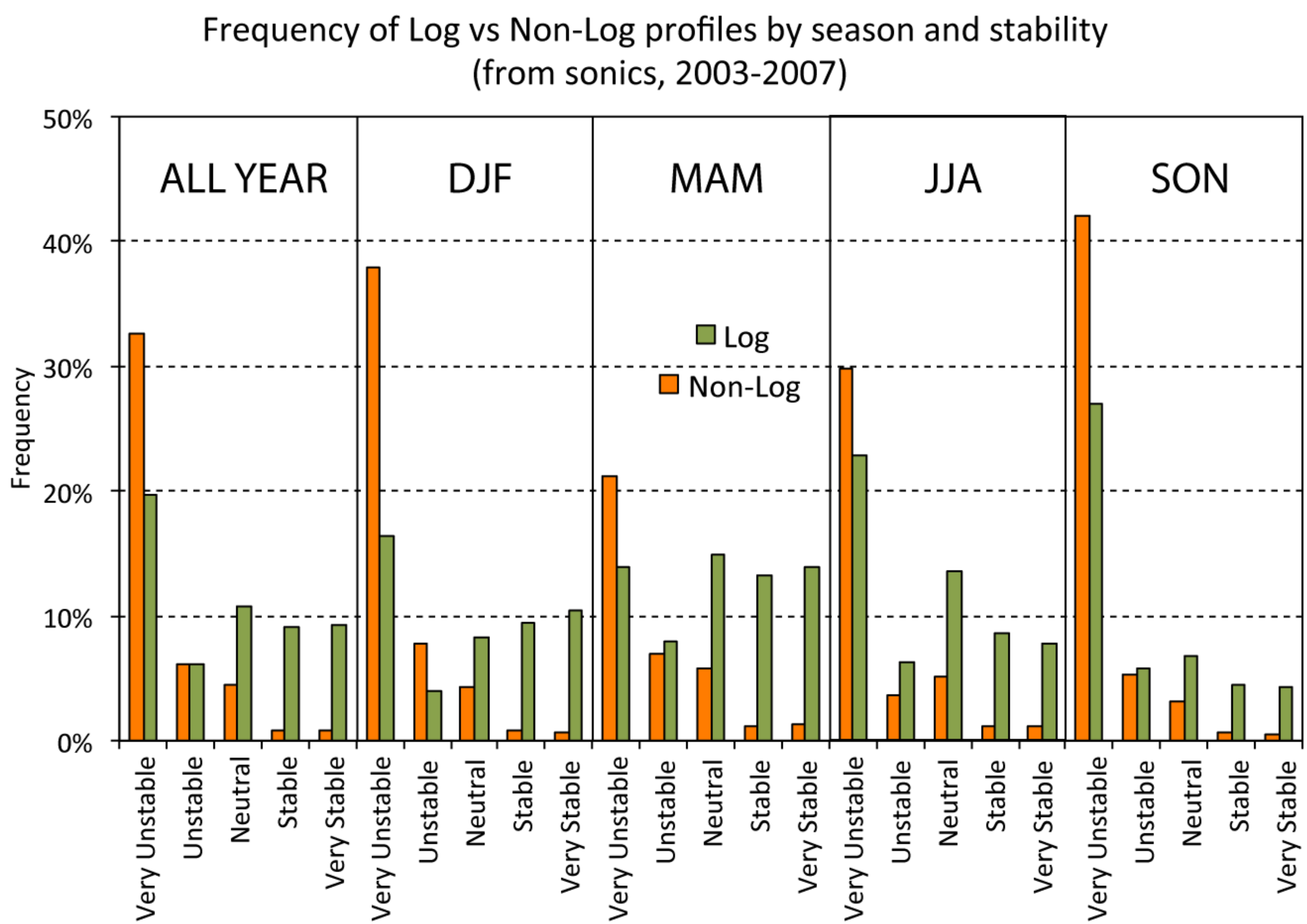


V60>V41>V20



All other 8 cases

Non-log profiles are associated with unstable conditions



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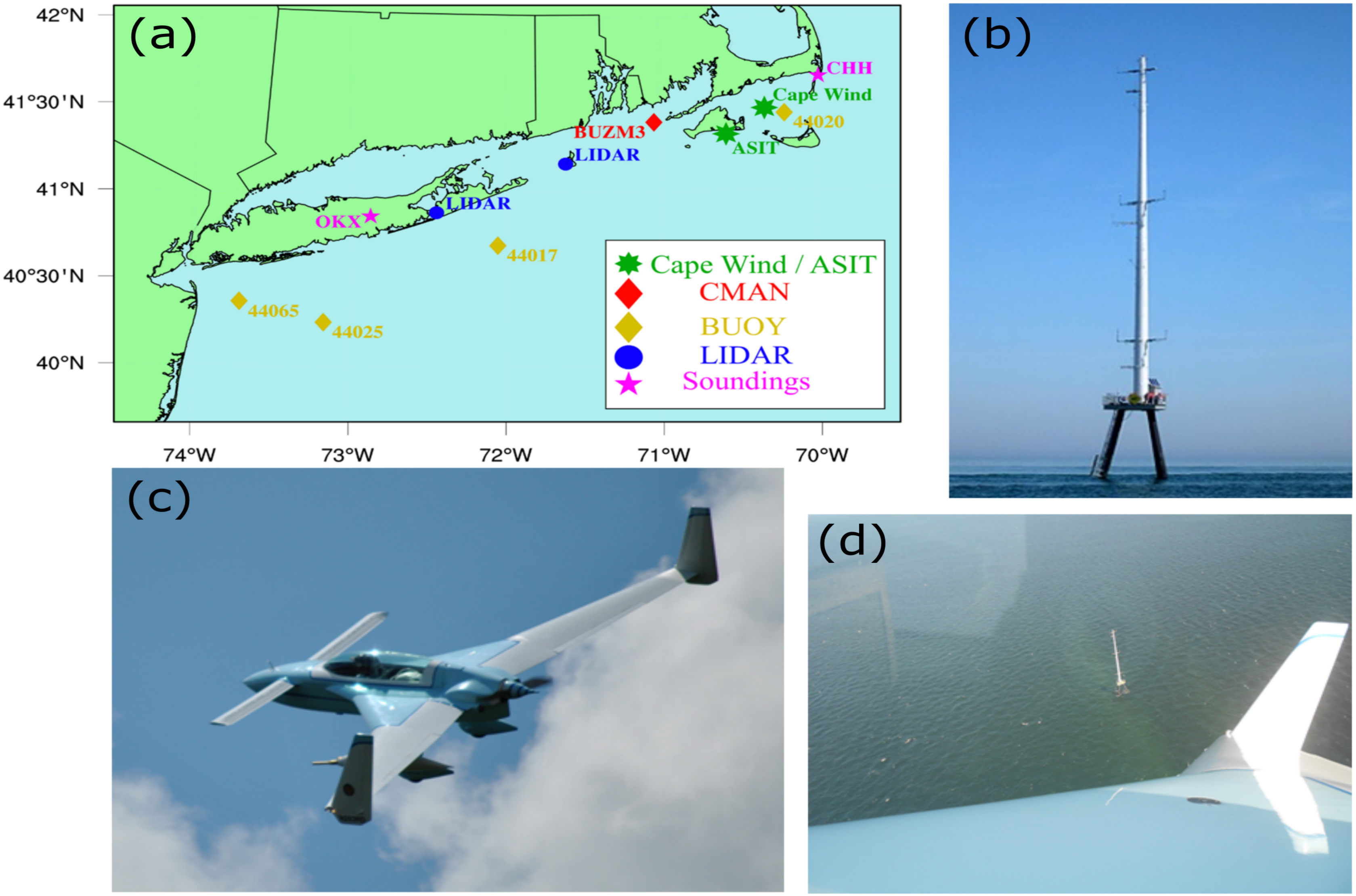
IMPOWR Experiment: Fall 2012 to present



IMPOWR Flights (2012-2014)

Table 1: Flight days for the IMPOWR field experiment

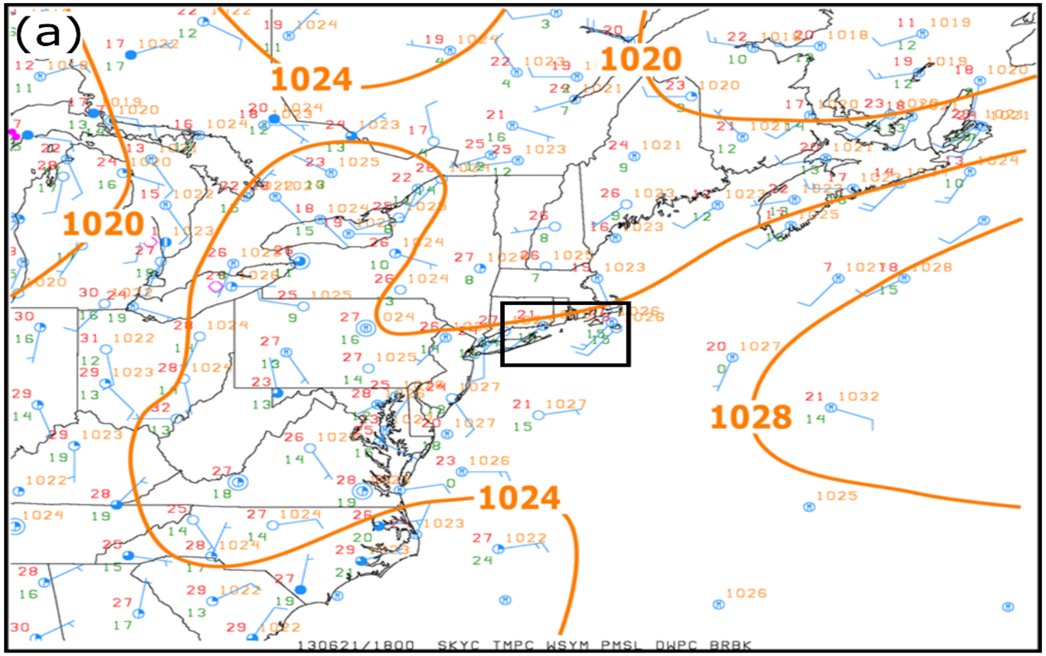
Flight Day	**Weather Conditions**
12 November 2012	Cyclone warm sector with south winds
4 April 2013	Southwest flow around anticyclone
7 April 2013	Stable strong south flow ahead of warm front
9 April 2013	Southwest flow ahead of cold front
4 May 2013	Moderate northeast flow with a subsidence inversion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

AIMMS-20 Instrument

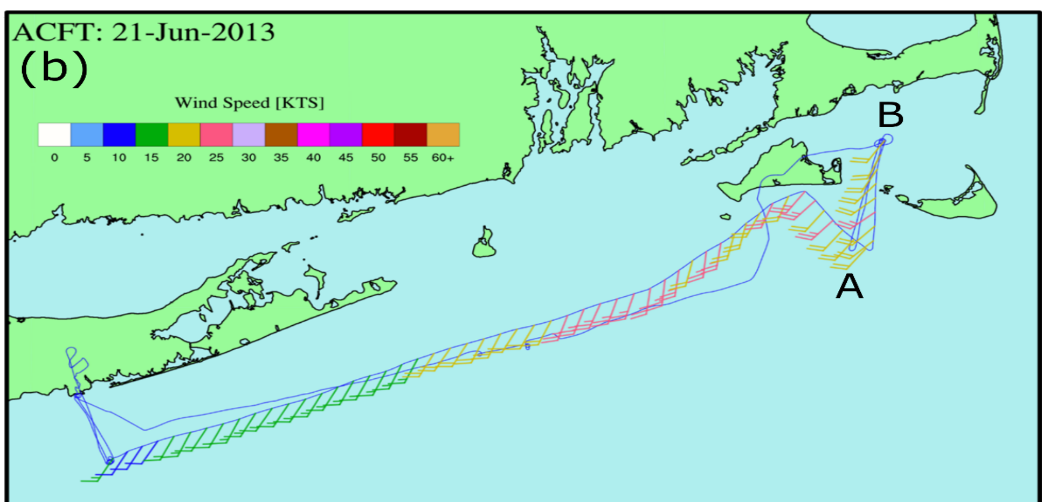
Up to 40 Hz measurements of 3D winds, temperature, pressure and RH

Observations at 1800 UTC 21 June 2013

Surface Analysis



Flight-level winds (kts) 40-50 m ASL



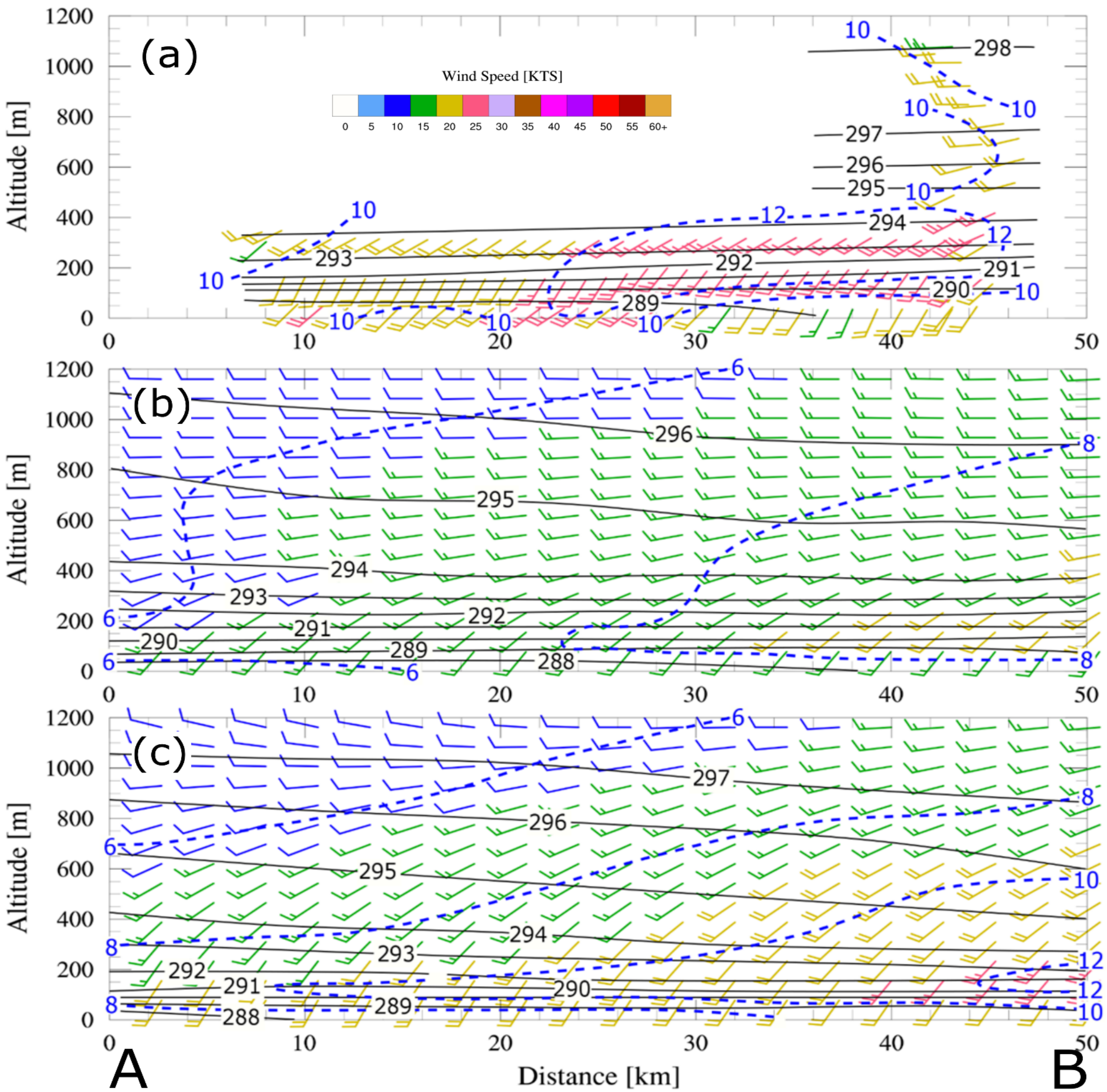
- General SW surface flow around high pressure offshore of New England
- Inland surface temps 26-27C, while 20-21C over water
- Coastally enhanced 40-50 m winds (20-25 kts) towards Nantucket Island

South-North Cross Section Around 1800 UTC 21 June 2013

Flight-level obs

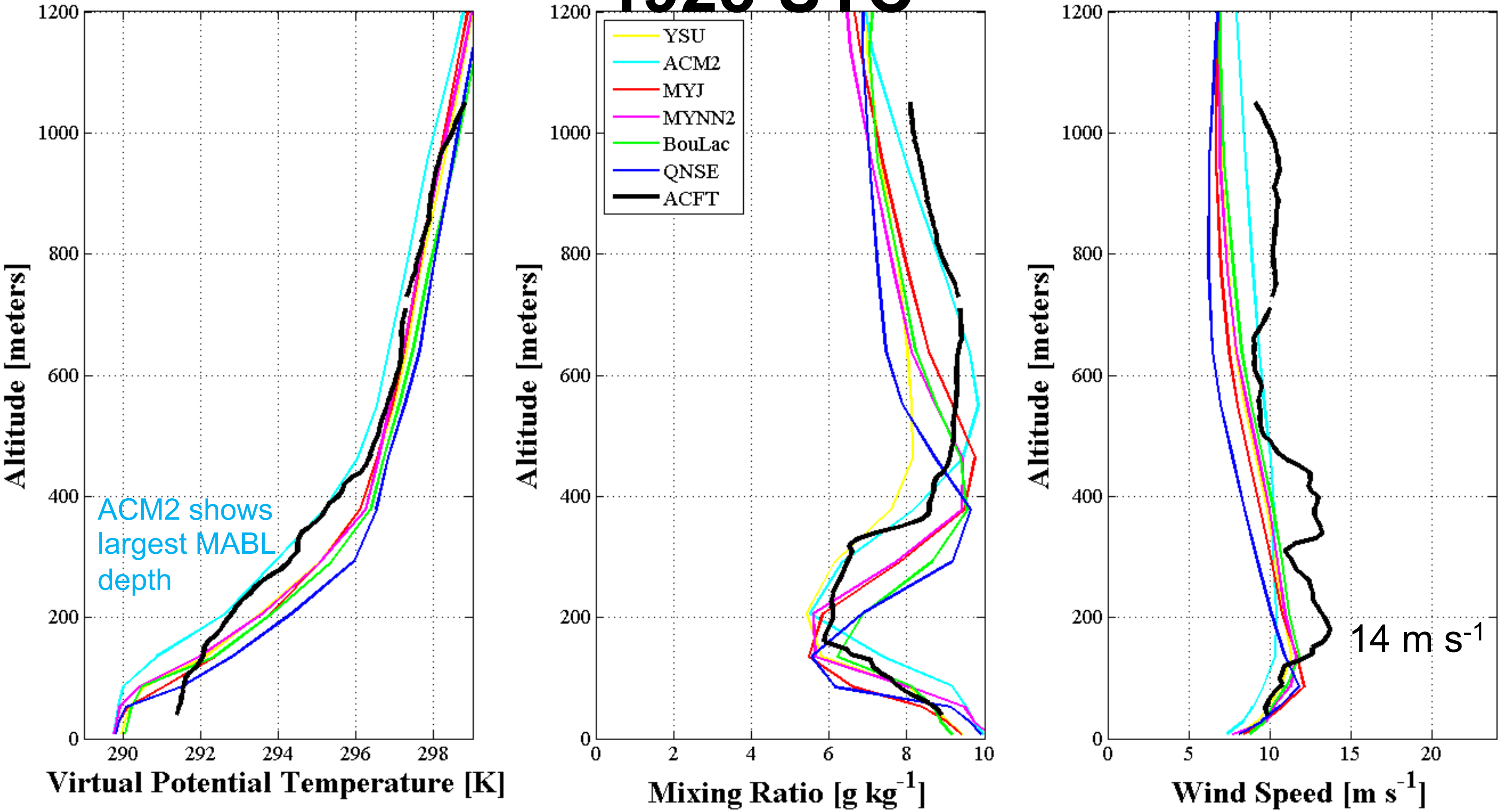
1.33-km WRF (YSU PBL) at 1800 UTC (18-h forecast using RAP IC/BCs)

1.33-km WRF (YSU PBL) at 2100 UTC



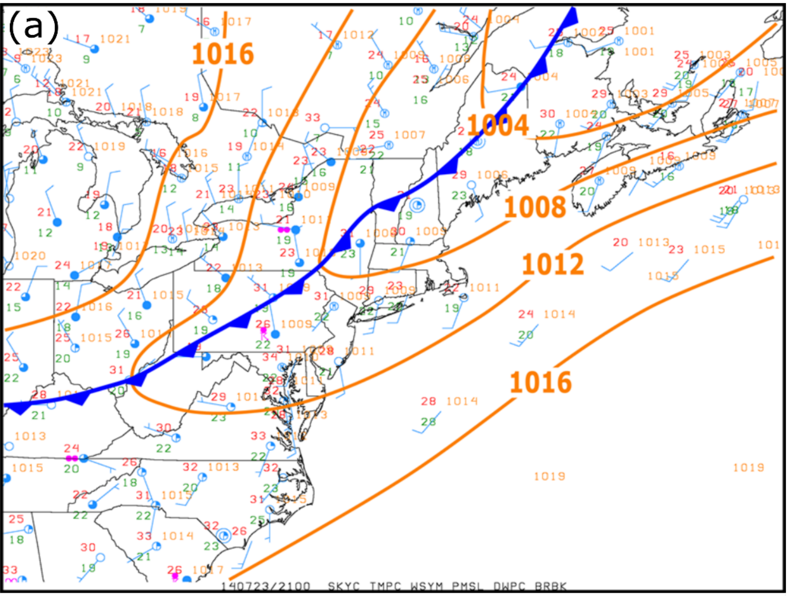
- Observed low-level jet to 25 kts below 400 m
- 1.33-km WRF (YSU PBL) too weak, even a few hours later after more daytime heating.
- WRF marine layer is too shallow near coast.

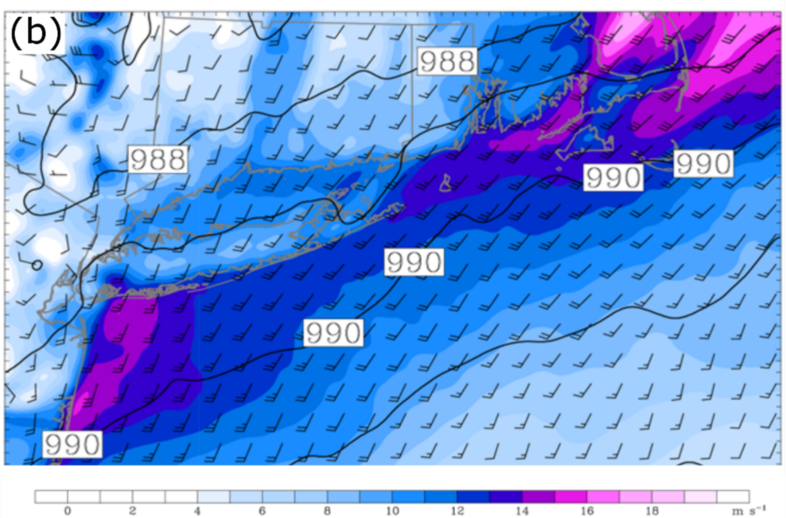
Flight: 1600 – 1900 UTC 21 June 2013
Spiral Around Cape Wind Tower
1925 UTC

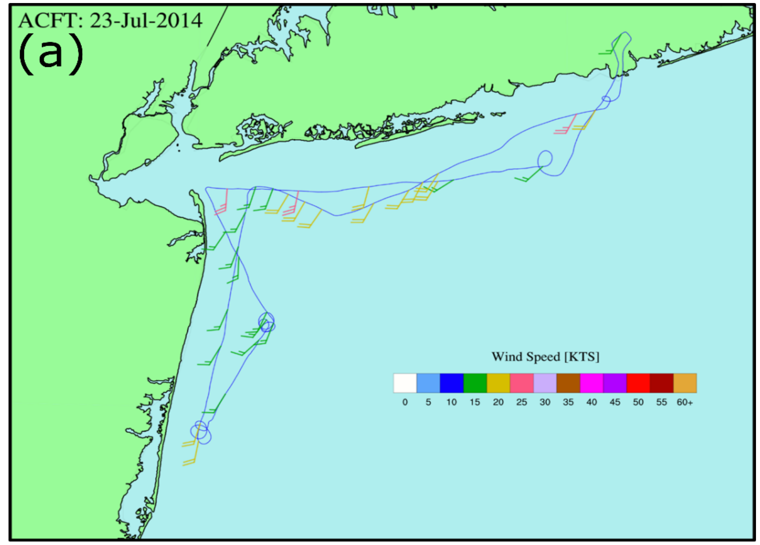


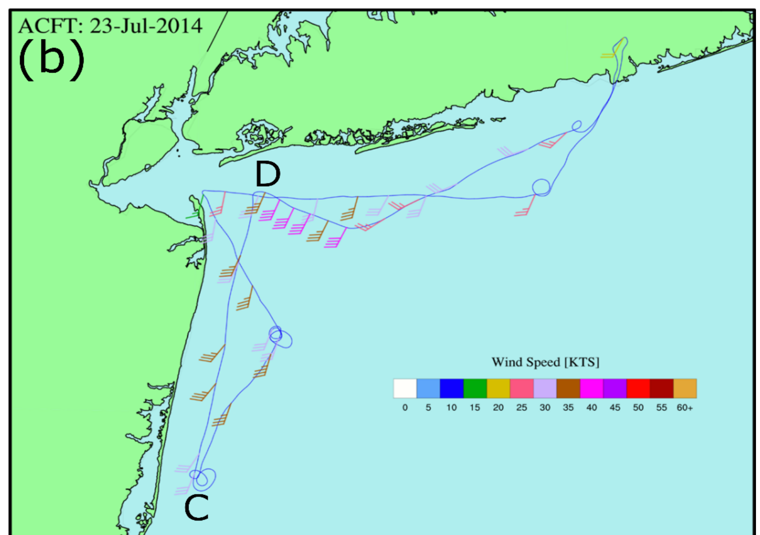
- All schemes exhibit shallower / cooler (1 – 2 °C) MABL than observations
- Lower wind maximum in models (100 m vs. 190 m)
- Schemes underestimate 5-m winds at 44020 (1 – 2 m s^{-1})

New York Bight Jet 1400-1700 UTC and 2000-2200 UTC 23 July 2014







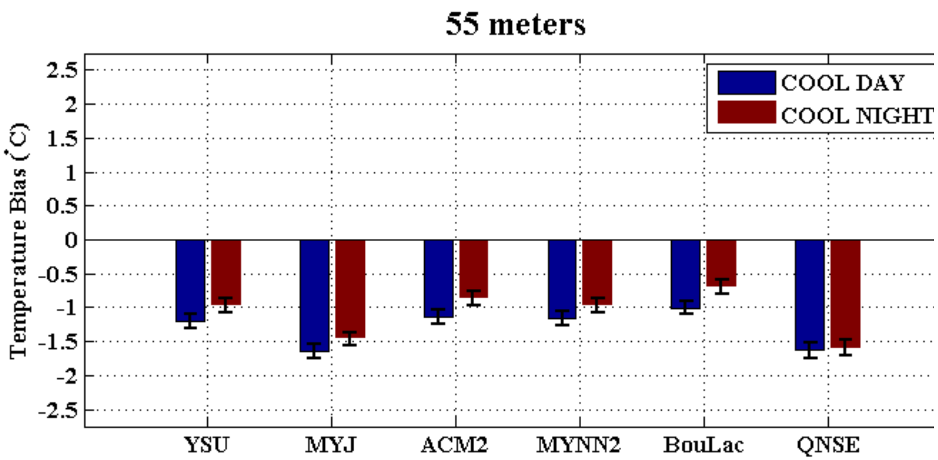


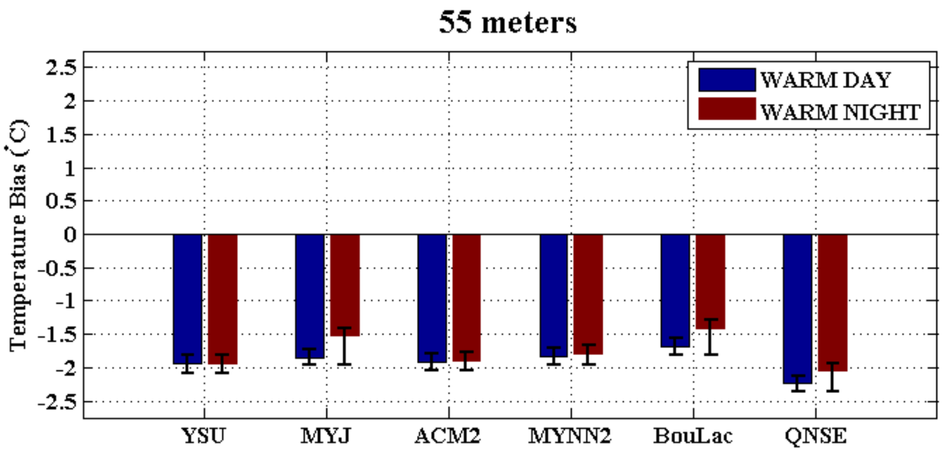
- Observed mid-late AM winds 20-25 kts at 100-225 m
- Jet increases to 35-40 kts by 4-6 PM EDT
- 1.33 WRF (YSU PBL) are 5-10 kts too weak for the jet

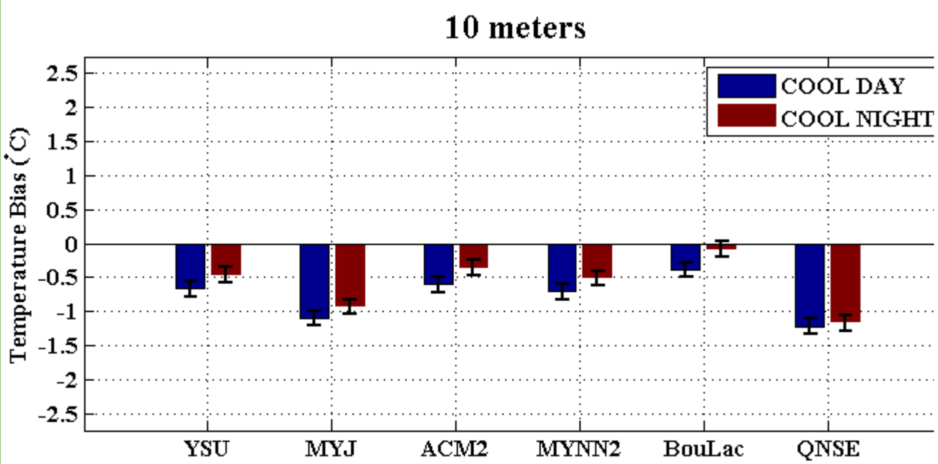
Conclusions

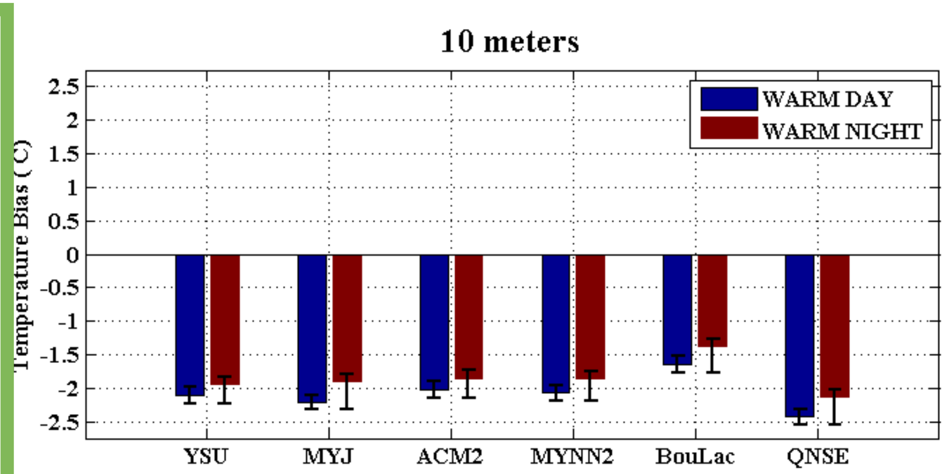
- WRF PBL parameterizations consistently underpredict wind speeds at Cape Wind tower at all levels;
- WRF near surface temperature at Nantucket Sound buoy is too warm during the cool season and too cool during the warm season. This suggests SST bias in Sound (currently testing) or too large surface fluxes (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

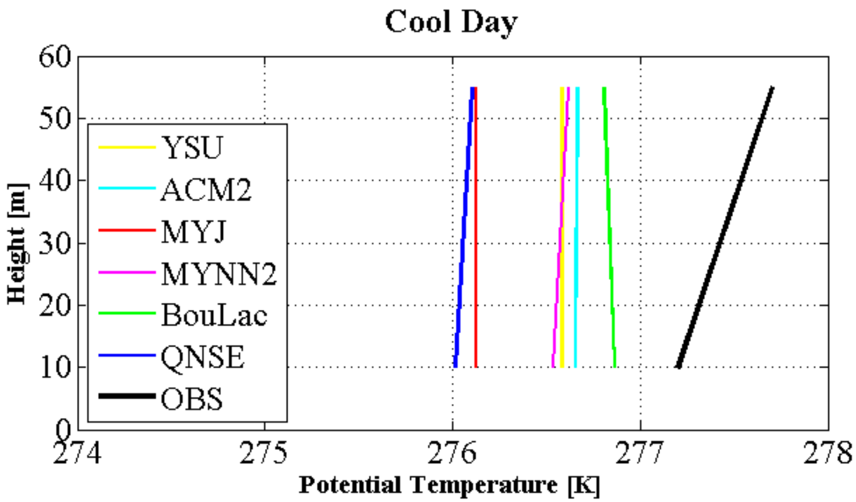


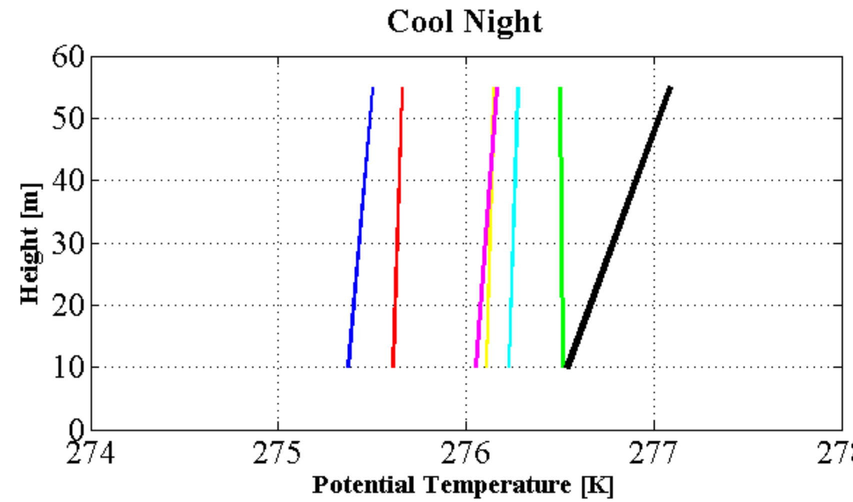


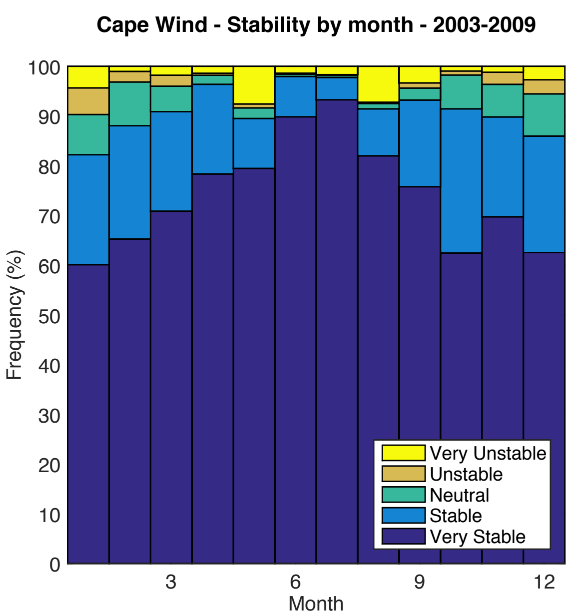




CW temperature sensors are suspicious: 2) Unrealistic stable conditions dominate in cool season (and all year)







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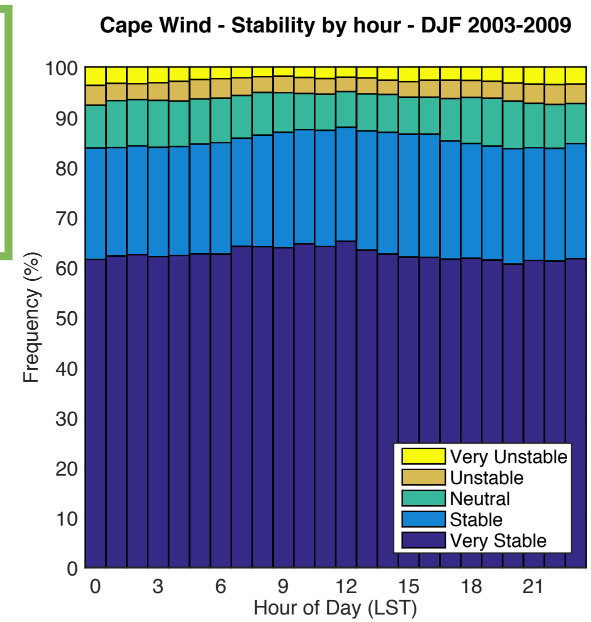

CW temperature sensors are suspicious: 3) Wrong link between stability and shear