Classifying Vertical Wind Speed Profiles for Offshore Wind Resource and Power Assessment

Alexandra St.Pé[1]*, Shelbi Tippett[1], Scott Rabenhorst[2], Ruben Delgado[3]

[1]*University of Maryland, Baltimore County, Baltimore, MD 21250, USA, *Email: astpe@umbc.eu*

[2]*Naval Research Laboratory, Washington D.C., 20375, USA*

[3]*Joint Center for Earth Systems Technology, Baltimore, MD, 21250, USA*

To justify the economic viability of a potential offshore wind energy project, an accurate assessment of the site-specific wind resource, thus expected energy yield, is required prior to wind farm construction. Unfortunately, uncertainties during this assessment exist, due in-part to limited offshore wind measurements throughout a turbine's rotor-layer (~40-200m) and related uncertainties predicting a turbine's available power. To better understand these uncertainties in the Mid-Atlantic USA, Doppler wind lidar and other met-ocean measurements were collected offshore within Maryland's Wind Energy Area from July-August 2013. Given the diversity of vertical wind speed profile (VWP) observations, VWPs are classified based on the goodness-of-fit to several mathematical expressions. Results demonstrate VWP classification is dependent on the temporal and spatial resolution of analysis, however for 10-min VWP types (40-220m), low-level wind maximum are the most frequent (~37%), while only ~17% resemble industry-standard logarithmic-like, power law wind profiles. In addition, VWP variability is related to prevailing wind direction (i.e. offshore fetch), as more unexpected VWPs are found during wind regimes flowing from land to sea, while power-law profiles persist during northeasterly flow. In terms of potential impact on a wind turbine's available power, unexpected VWP types are associated with greater variability in superimposed meteorological features demonstrated to impact turbine performance, therefore the importance of predicting such variability cannot be understated. Finally, the sensitivity of VWP type on several techniques used to estimate a turbine's available power are demonstrated, elucidating how both an overestimate and underestimate of traditional hub-height available power may occur given distinct VWP type and power assessment technique employed; therefore, a possible concern for the offshore wind energy industry in the Mid-Atlantic USA.

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Alexandra St. Pé

Ph.D. Candidate

Geography & Environmental Systems

University of Maryland Baltimore County (UMBC)

Atmospheric Lidar Group:

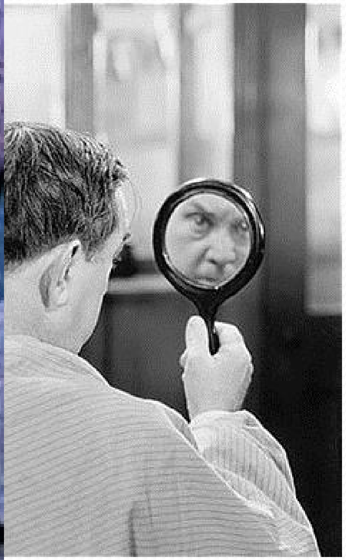
Shelbi Tippett, Scott Rabenhorst, Ruben Delgado

Motivation: Wind Farm Underperformance Bias

- Operational energy yield < expected energy yield

- Early 2000s, **w**
  underperforn
  gains spotligh

- “haircut” phe
  - Investors/le
    correcting e



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Research Focus

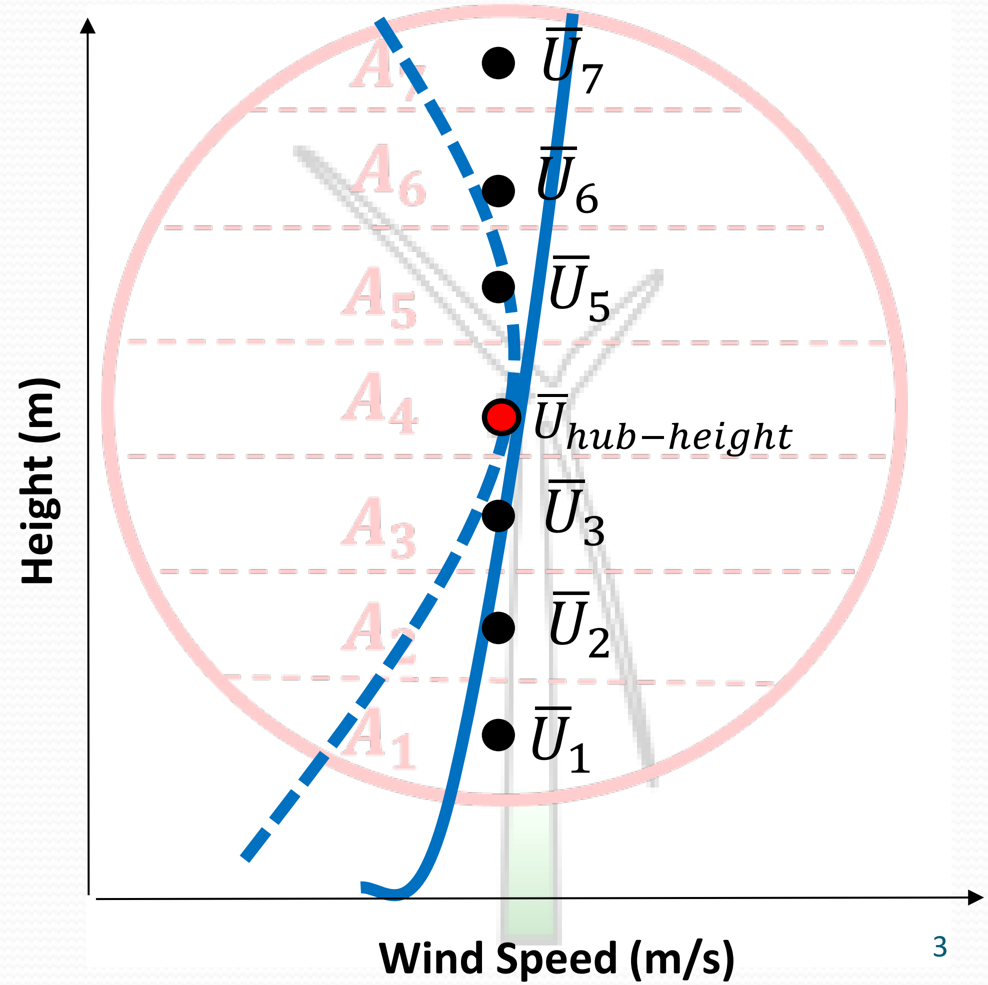
Uncertainty: Turbine Power Curve

$$Power_{Estimate} = 0.5 * \rho * A * \overline{U}^3 * C_p$$

ρ = air density, A= area of rotor layer ,
$\overline{U}$ = hub-height, wind-speed, Cp= power coefficient

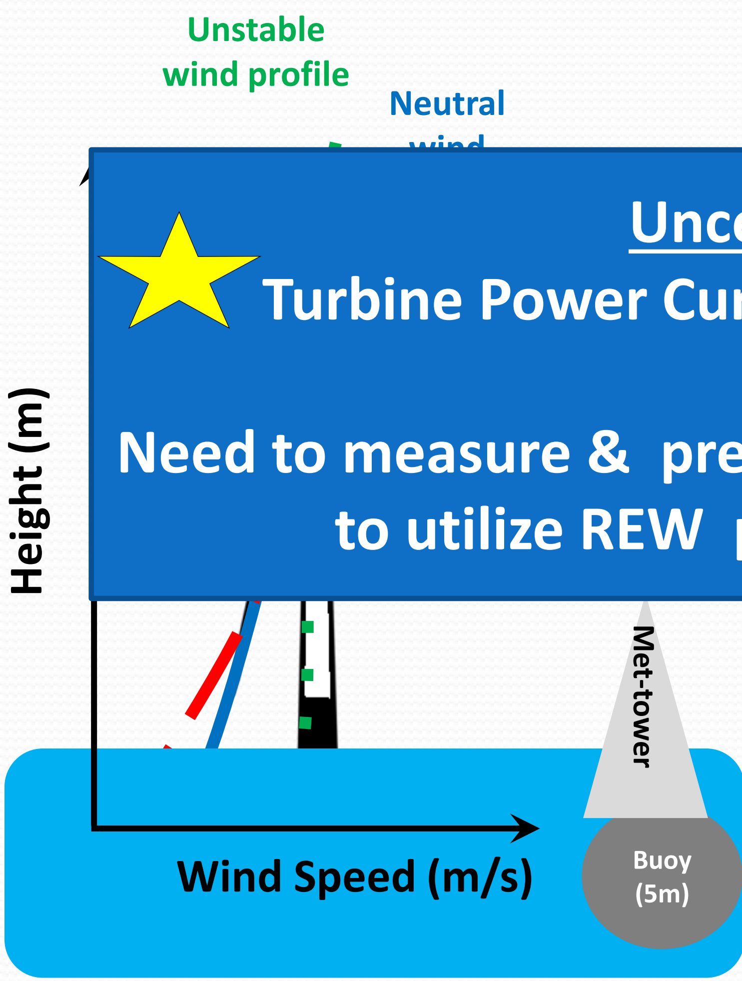
Rotor Equivalent Wind (REW) term introduced to account for wind characteristics throughout a turbine's rotor layer

May reduce uncertainty in turbine's power curve measurements



- Sumner and Masson 2006
- Wagner et al. 2009, 2011
- Choukulkar et al. 2015

Uncertainty: Wind Resource Assessment



Uncertainties:

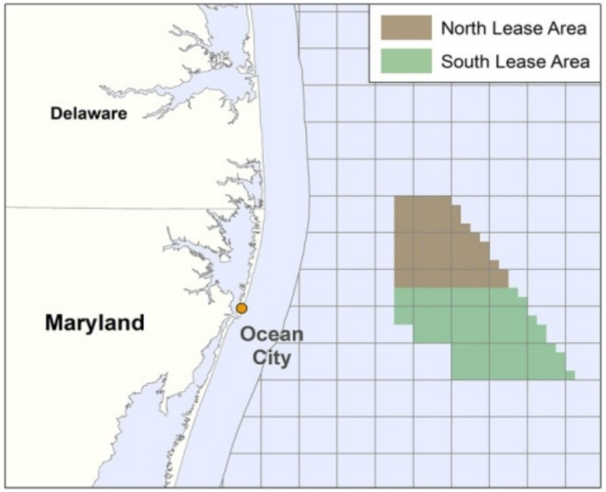
Turbine Power Curve ←→ Wind Resource

Need to measure & predict unexpected VWP shapes to utilize REW power estimate tools

- Severe lack of met-ocean measurements
- …wer …ns, …is
- Atmospheric stability can fluctuate between **neutral** to **unstable** to **stable** conditions, thereby changing the 'shape' of the wind profile

Overview: Maryland Offshore Campaign

- 2013 July-August Offshore Measurements
  - During MEA sponsored Geophysical Survey
  - Leosphere Windcube V2 Offshore
    - Wind speed/direction 40m-220m

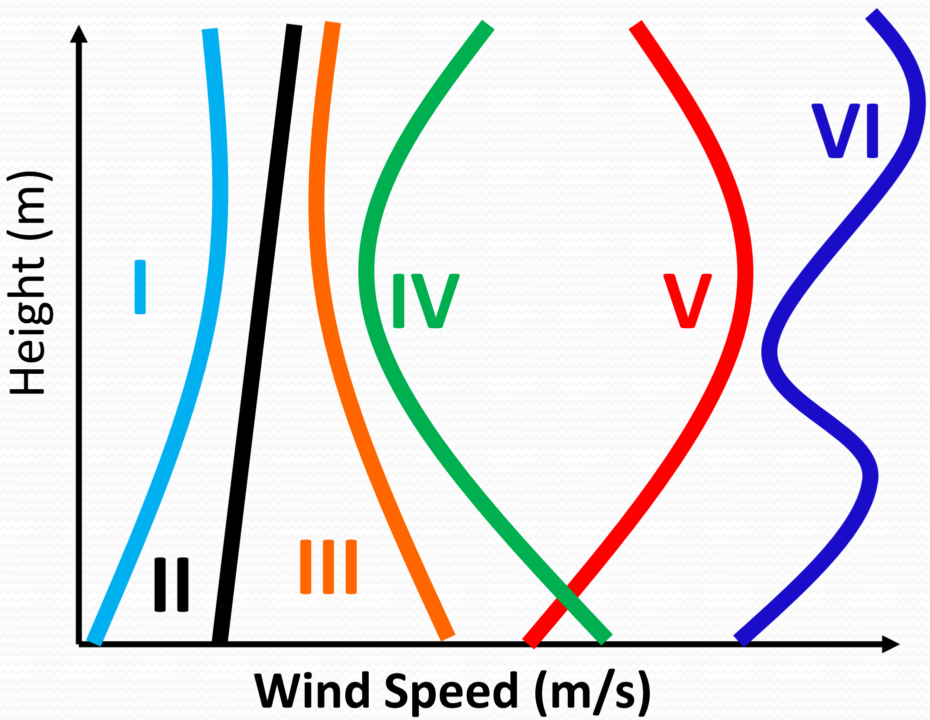


Research Questions:

1. How do measurements compare to traditional wind resource estimates?
2. What is the variability in the *shape* of vertical wind speed profiles (VWPs)?
3. Are there relationships between VWP shape and met conditions?
4. How do available power estimates vary by VWP shape?

Methodology

- Classifying **V**ertical **W**ind **P**rofiles:



Based on goodness of fit:

- Criteria: RSS <=0.10

$$RSS = \sum_{i=1}^{10} \left(u_{fit}(z_i) - u_i\right)^2$$

where *h* is the number of measurement heights, u_{fit} are the fit functions and u_i is the lidar wind speed measurement at height z_i (i=1-*h*).

Type I: Power law Fit (+)
Type II: Linear Fit
Type III: Power law Fit (-)
Type VI: Fourier Fit (2 term)

Based on Max & Min Wind Speed Height:

Type IV: Low-Level Wind Min (LLWMin)
Type V: Low-Level Wind Max (LLWMax)

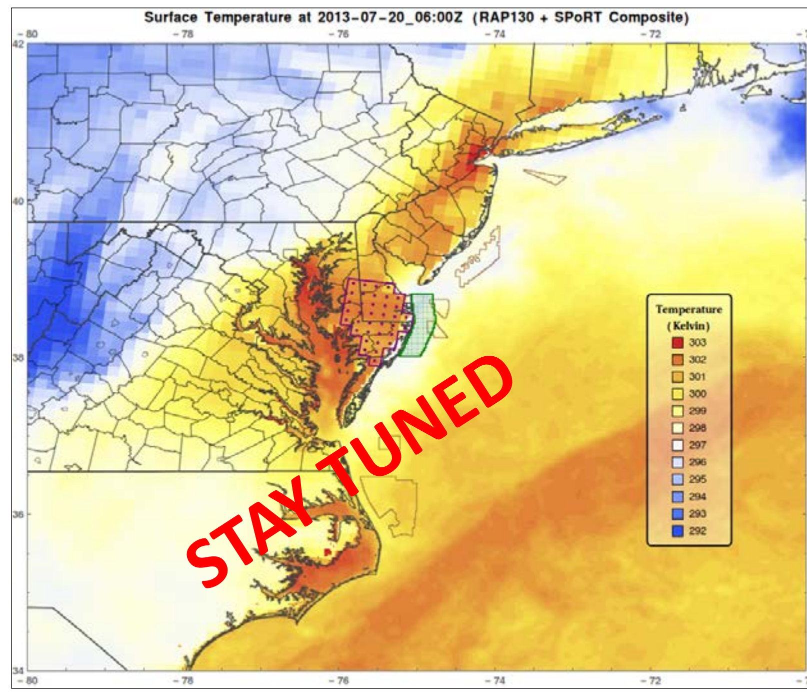
Methodology

- Investigating VWP Type & Local Meteorological Conditions:

July-Aug 2013: Buoy 44009 Analysis

- Air Temperature
- SST
- MSLP
- Wind Speed

July-Aug 2013: Mesoscale Analysis



Methodology

- VWP Type & Turbine Available Power Assessment:

-NREL 5 MW Offshore Wind Reference Turbine

$$\mathbf{P}_W = \mathbf{0.5\rho A}\boxed{\overline{U}^3}\mathbf{C_p}$$

	$\overline{\mathbf{U}}_{100m}$	= Lidar hub-height measurements
Sumner and Masson 2006	$\overline{\mathbf{U}}_{Disk}$	$= \frac{2}{A_t}\int_{H-r}^{H+r} U(z)(r^2 - H^2 + 2Hz - z^2)^{1/2}\,\delta z$ Area averaged wind speed across entire rotor-layer *where* A_t = *total rotor area*, H = 100m *hub height*, r = *rotor radius*, z = *height*, δz = 20
Wagner et al. 2009	$\overline{U}_{\mathbf{TI}}$	$= \sqrt[3]{\frac{1}{A}\sum_i \overline{U_i}^3 * A_i}$ *where* $U_i(z) = \overline{U_i}\,(1 + 3\left(\frac{\sigma_{ui}}{\overline{U_i}}\right)^2)^{1/3}$ Modified $\mathbf{U_{EQ}}$ to account for weighted speed shear & turbulence (TI) *where (i) is specific measurement height*, A_i = weighted area for that rotor-layer slice
Choukulkar et al. 2015	$\overline{U}_{\mathbf{TID}}$	$= \sqrt[3]{\frac{1}{A}\sum_{i=1}^{N} \overline{U_i}^3 [1 + 3\left(\frac{\sigma_{ui}}{\overline{U_i}}\right)^2][1 - \frac{\overline{\theta_i}^2}{2} - \frac{\sigma_{\theta i}^2}{2}]^3 A_i}$ Modified $\mathbf{U_{EQ,TI}}$ to account for direction shear & fluctuations *where* $\overline{\theta}_i$ is the difference of wind direction at a specific height (i) (compared to 100m direction)

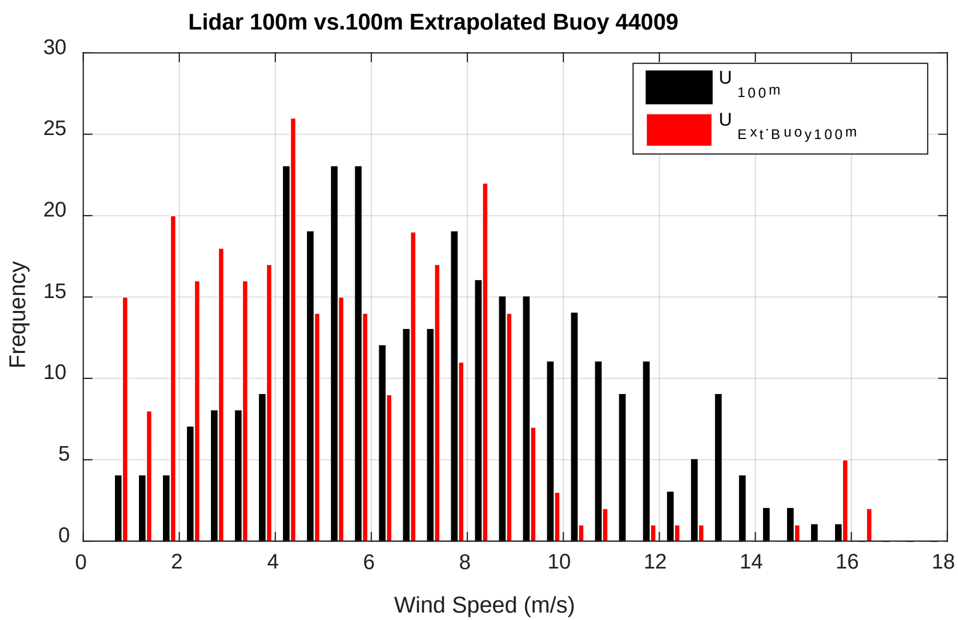
Results: 100m Lidar WS vs. Buoy 44009

- Buoy 44009 **underestimates** wind speed

Power Law Equation:

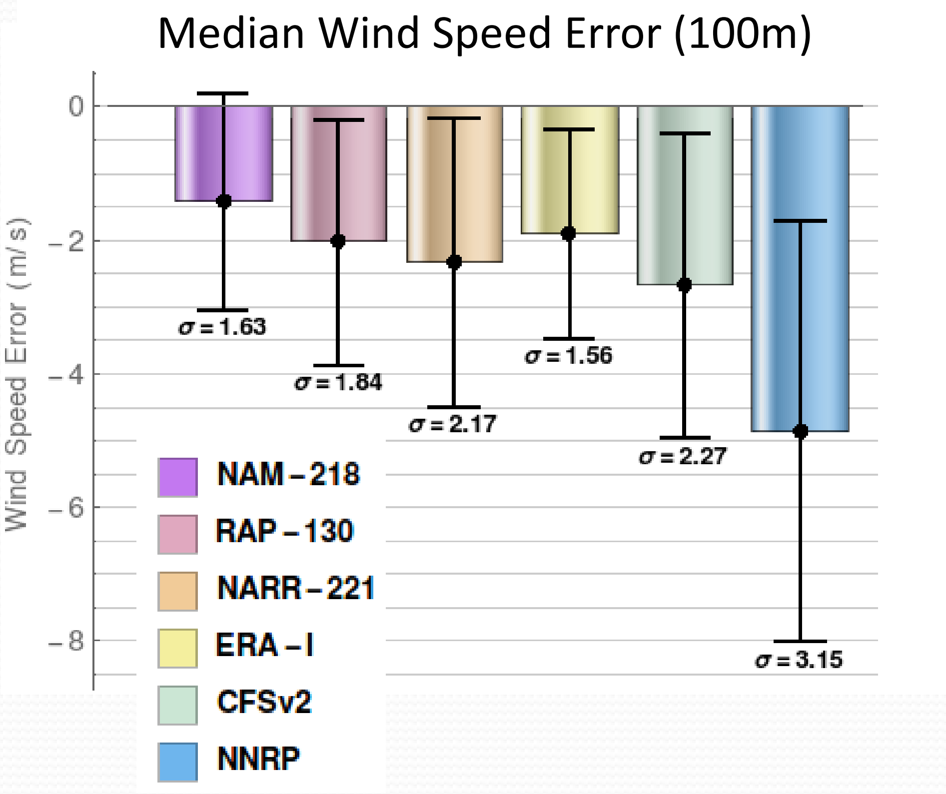
$$\frac{\overline{U}_{100m}}{\overline{U}_{5m}} = \left(\frac{100m}{5m}\right)^{0.11}$$

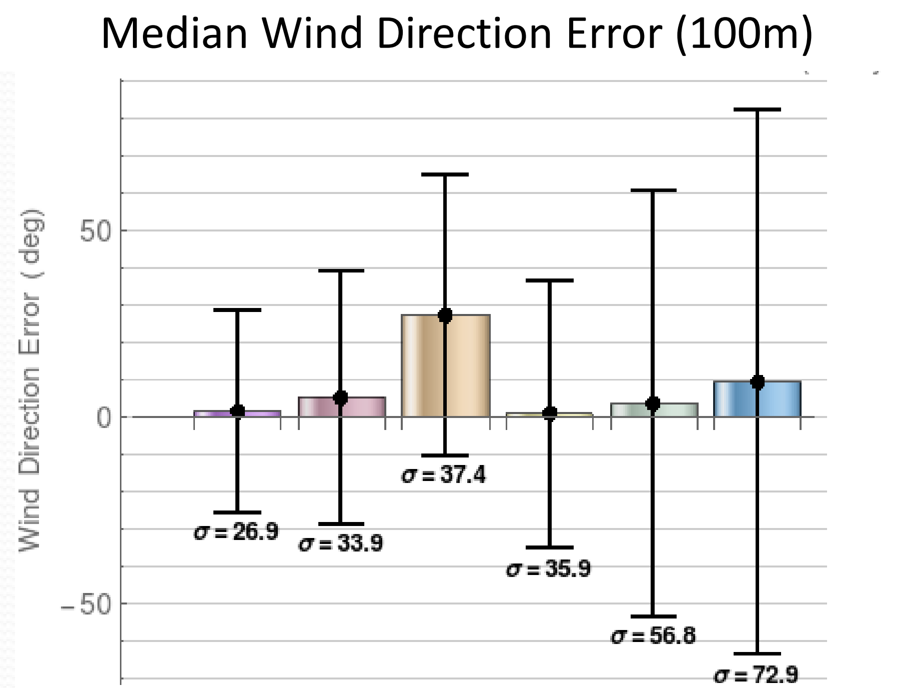
July17-August 30 Average	Median Wind Speed (m/s)
$\overline{U}_{100m}$	7.40 (+/- 3.29)
$\overline{U}_{Ext.Buoy}$	4.73 (+/-3.34)



Results: 100m Lidar WS vs. Model/Reanalysis

- Models' **underestimate** wind speed resource
- Moderate model error in wind direction

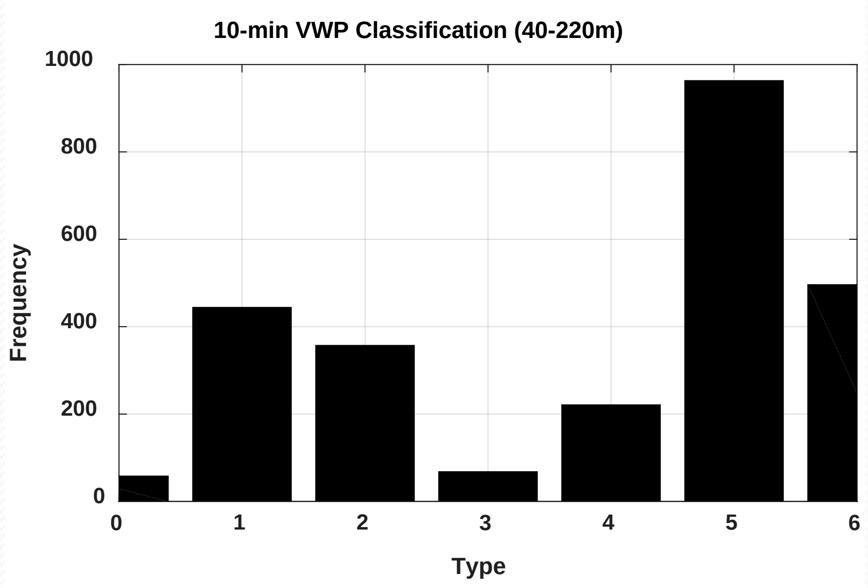




Results: VWP Classification

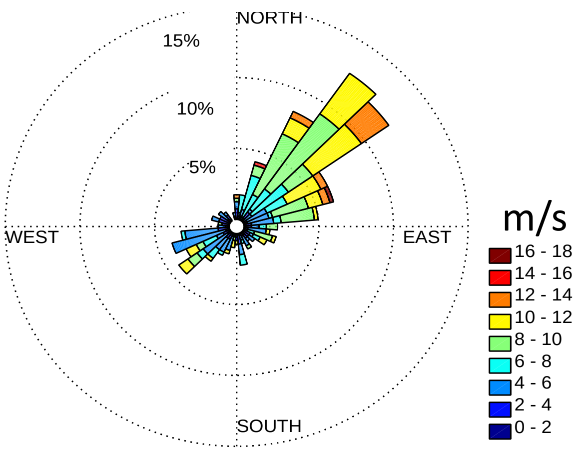
VWP Class	10-Minute Average		Hourly Average	
	% Total (40-160m)	% Total (40-220m)	%Total (40-160m)	%Total (40-220m)
unclassified	0.2%	2.2%	0.4%	2.4%
Type I	31.7%	17.0%	37.8%	21.4%
Type II	14.8%	13.7%	15.1%	14.0%
Type III	6.1%	2.6%	5.3%	3.3%
Type IV	5.8%	8.5%	4.4%	6.8%
Type V	26.8%	36.9%	23.9%	22.1%
Type VI	14.7%	19.0%	13.1%	30.0%

- 40-160m VWP Types (10-min & hourly) → mostly Type I (power law)
- 40-220m VWP Types (10-min & hourly) → mostly Type V & VI

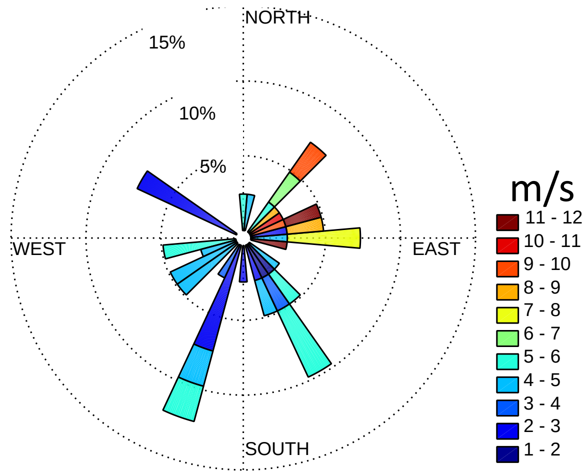


Results: VWP Types & 100m Wind Stats

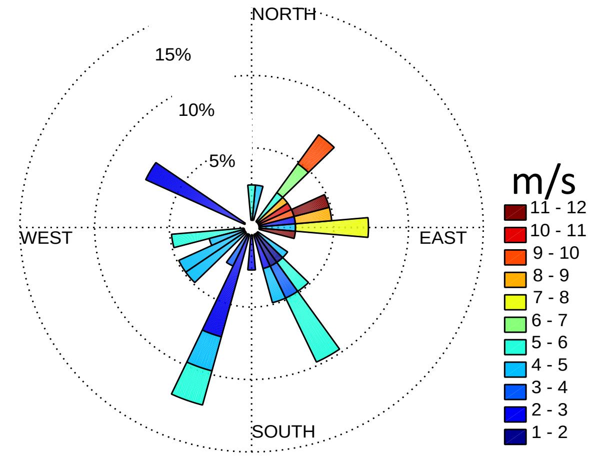
10-Min VWP Type I (100m)



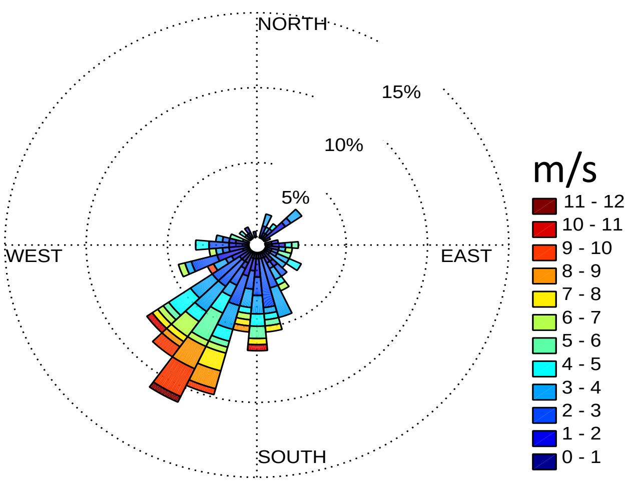
10-Min VWP Type II (100m)



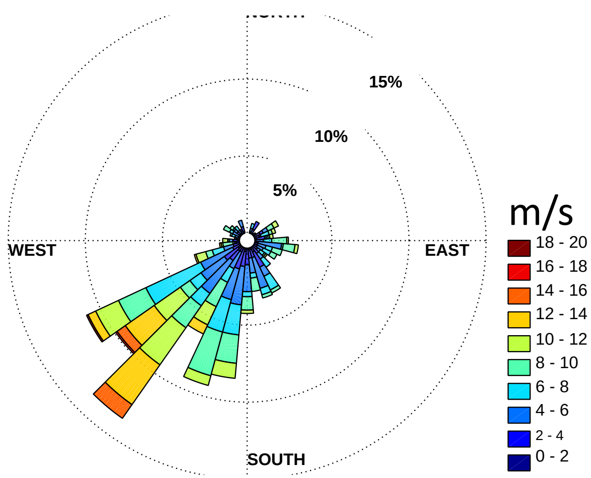
10-Min VWP Type III (100m)



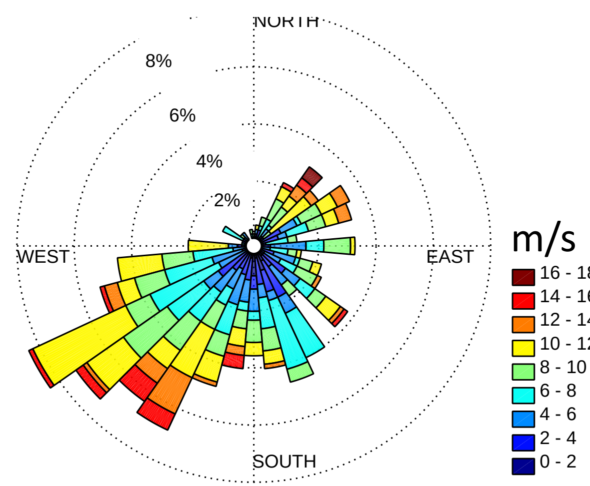
10-Min VWP Type IV (100m)



10-Min VWP Type V (100m)



10-Min VWP Type VI (100m)



Results: VWP Classification & 100m Wind

VWP Type (hourly)	Offshore Windcube V2 100m (Median)	
	Wind Speed (m/s)	Wind Direction (degrees)
I, II, II	6.03 m/s (+/- 3.10)	182.04° (+/- 111.23°)
IV, V, VI	6.98 m/s (+/- 3.36)	233.57° (+/- 80.36°)

- Unexpected VWP Types IV-VI (compared to Types I-III):
  - higher wind speed
  - stronger SW wind component

Results: VWP Classification & Buoy 44009

VWP Type (40/60mins)	Hourly Buoy 44009 (Median)				
	SST (C)	Air T (C)	Air T- SST (C)	MSLP (hPa)	Wind Speed (m/s)
I, II, II	22.95 (+/- 1.32)	22.50 (+/- 1.50)	-0.65 (+/- 0.75)	1015.7 (+/- 2.84)	3.60 (+/- 3.67)
IV, V, VI	23.20 (+/- 1.31)	23.4 (+/- 1.34)	0.10 (+/- 0.61)	1015.3 (+/- 4.86)	3.60 (+/- 2.15)

- Unexpected VWP Types IV-VI (compared to Types I-III):
  - warmer SST
  - warmer air mass
  - higher (stable) Air T- SST values

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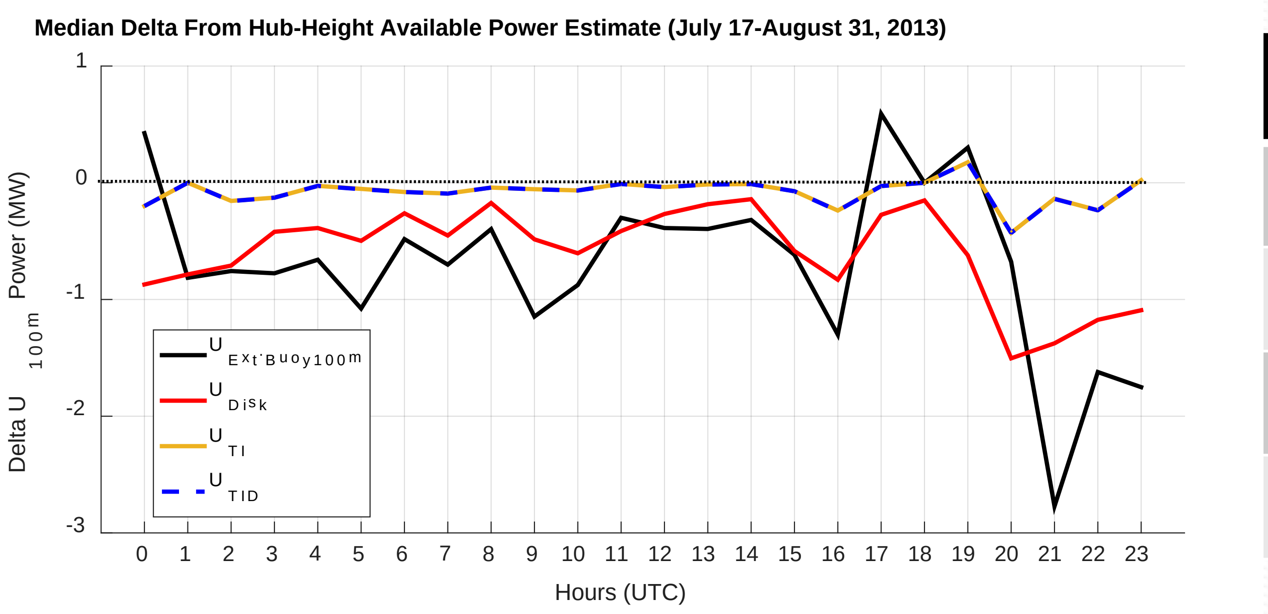
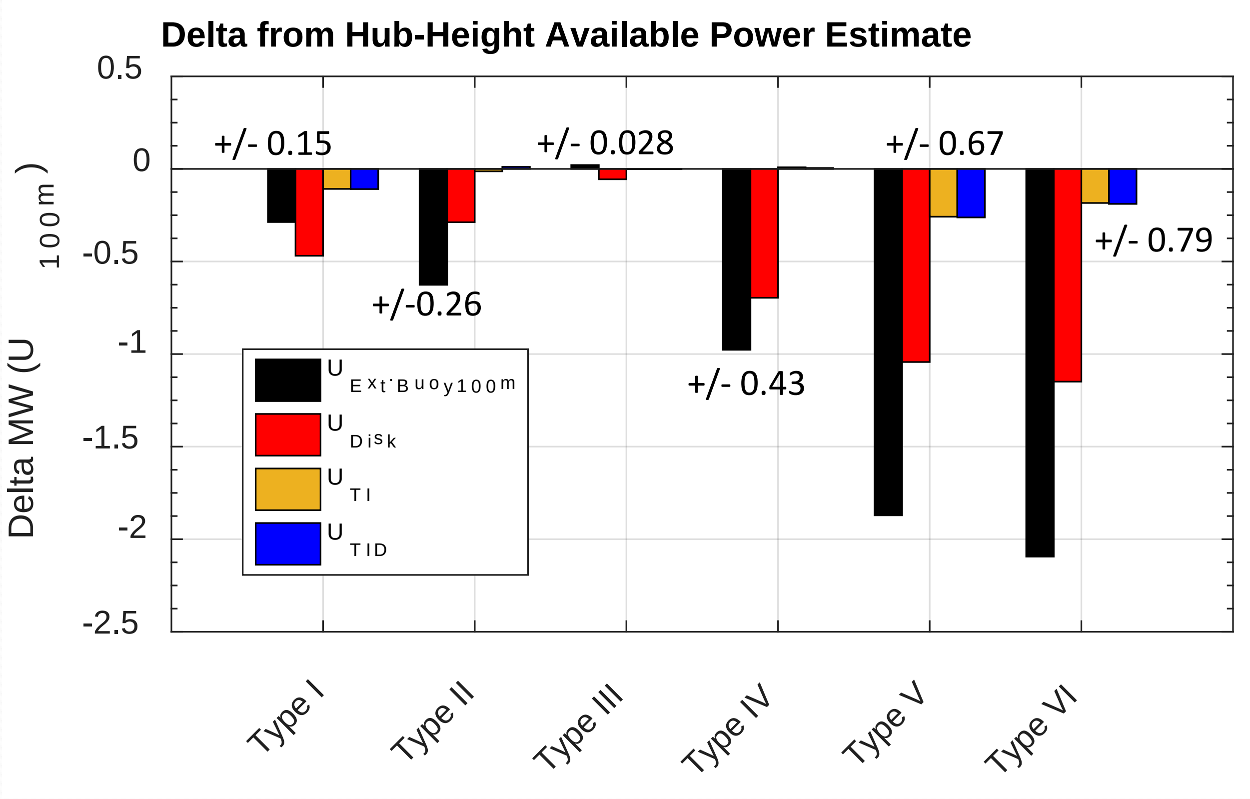
Results: Turbine Available Power Assessment



24hr Median Δ $\overline{U}_{100m}$ (MW)	
$\overline{U}_{\text{Ext.Buoy}100m}$	-1.112
$\overline{U}_{\text{Disk}}$	-0.685
$\overline{U}_{\text{TI}}$	-0.145
$\overline{U}_{\text{TID}}$	-0.147

- On average, hub-height available power higher than other techniques
- Suggests traditional $\overline{U}_{100m}$ estimate may **overestimate** wind resource

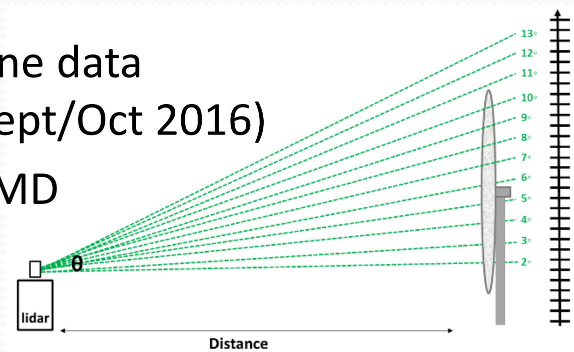
Results: VWP Type & Turbine Available Power

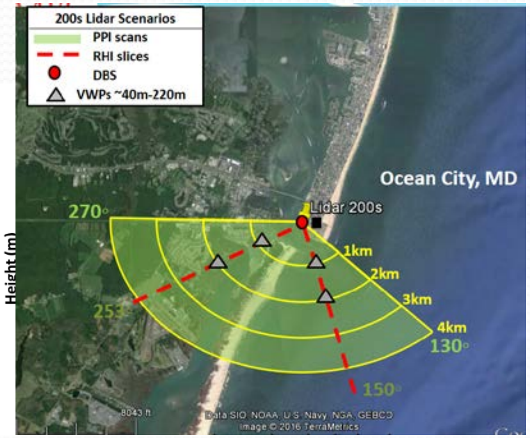


- Unexpected Types IV-VI → greatest Δ from $\overline{U}_{100m}$
- Unexpected Types IV-VI → highest σ between power assessment

Summary/Next Steps

- Unexpected Types IV-VI related to higher hub-height wind speed, SW flow, warmer air mass & stable conditions (sfc)
- Buoy extrapolated wind estimates **underestimates** wind resource ; however hub-height wind power assessment **overestimates** available power (compared to REW)
- Δ between power assessment techniques higher for unexpected VWP Type IV-VI
- Classifying VWPs useful tool for understanding local wind resource & potential impact on turbine available power assessment
- **Next Step:**
  - Similar analysis using **REAL** turbine data (Lewes, DE: VERTEX Campaign Sept/Oct 2016)
  - VWP climatology in Ocean City, MD





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Thank you! Questions?

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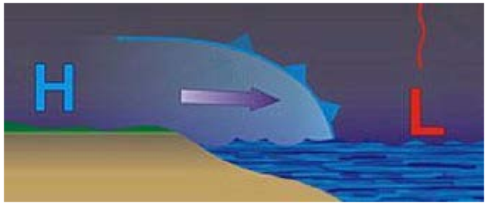
EXTRA

Uncertainty: Offshore Wind Resource

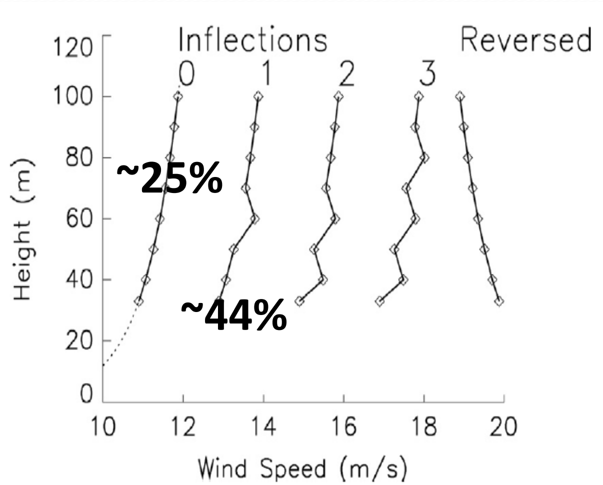
- Coastal atmospheric boundary layer (CABL) may be dynamic, thus VWP shape *may deviate significantly from theory*

Warm Air Flow Over Cooler Water



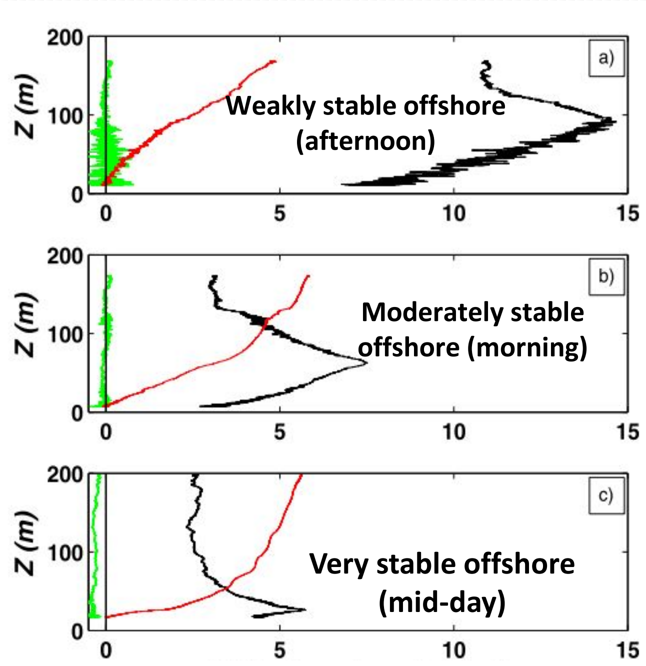
- Can occur ~ 200km offshore (Frank et al. 2000)
- Drives acceleration in surface flow → internal boundary layers → Low-Level Jets

Kettle (2014):



- Classified 10-min average VWP

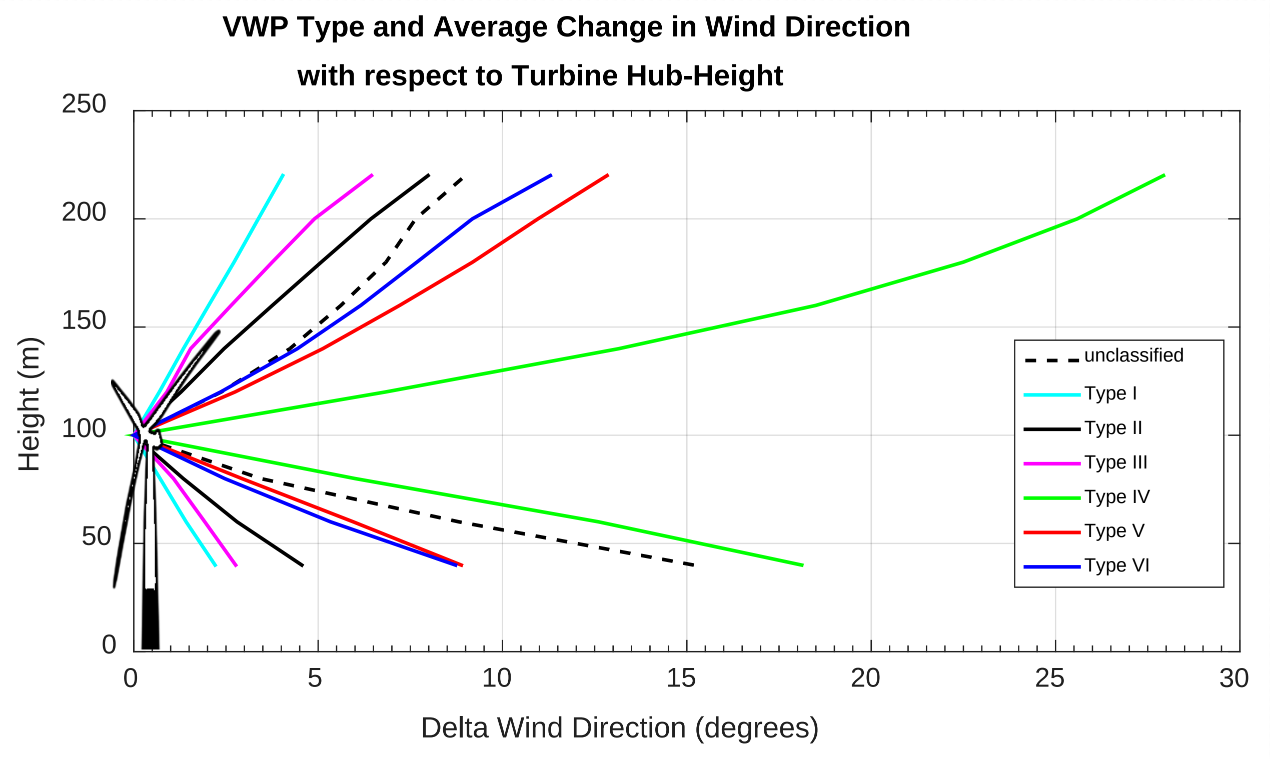
Mahrt et al. (2014):



Need to measure & predict unexpected VWP shapes to utilize REW power estimate tools

Results: VWP Type & Turbine Available Power

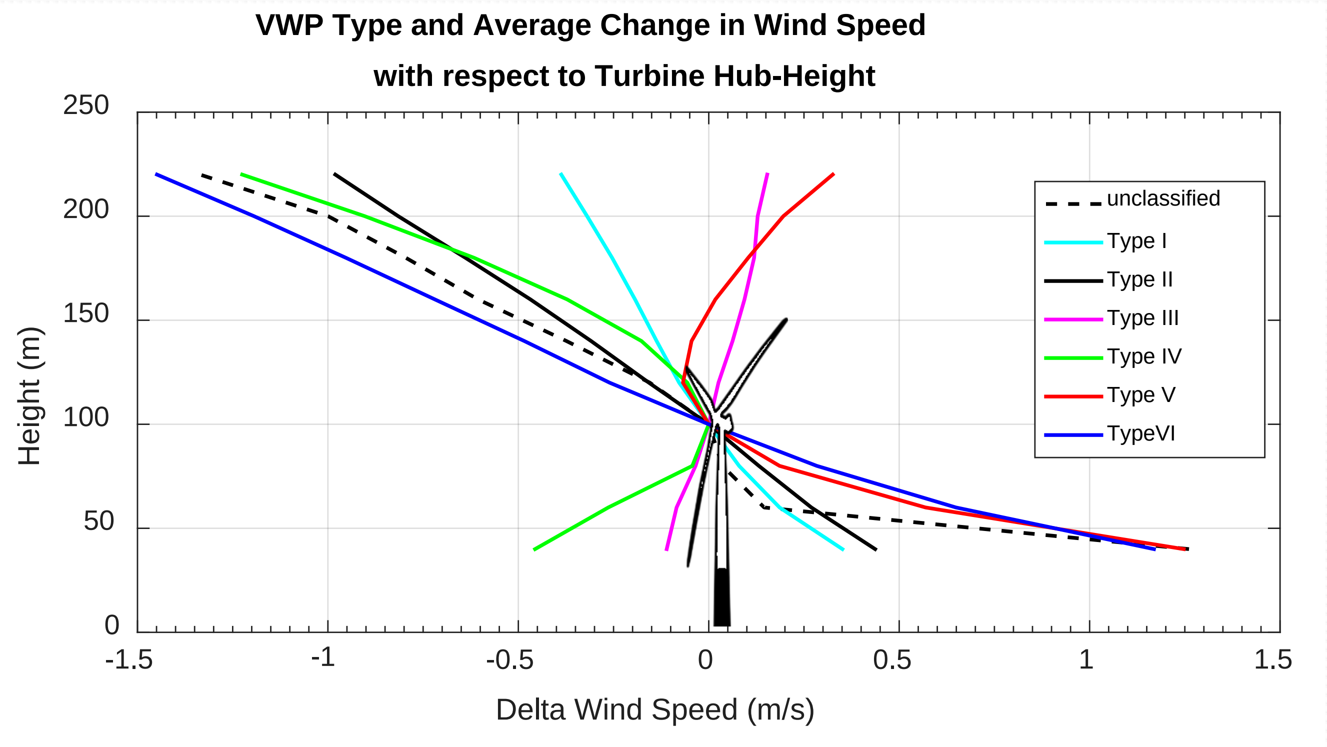
- Type vs. Δ wind direction with respect to turbine hub-height



- Type IV-VI associated with greatest Δ in wind direction throughout rotor-layer

Results: VWP Type & Turbine Available Power

- Type vs. Δ wind direction with respect to turbine hub-height



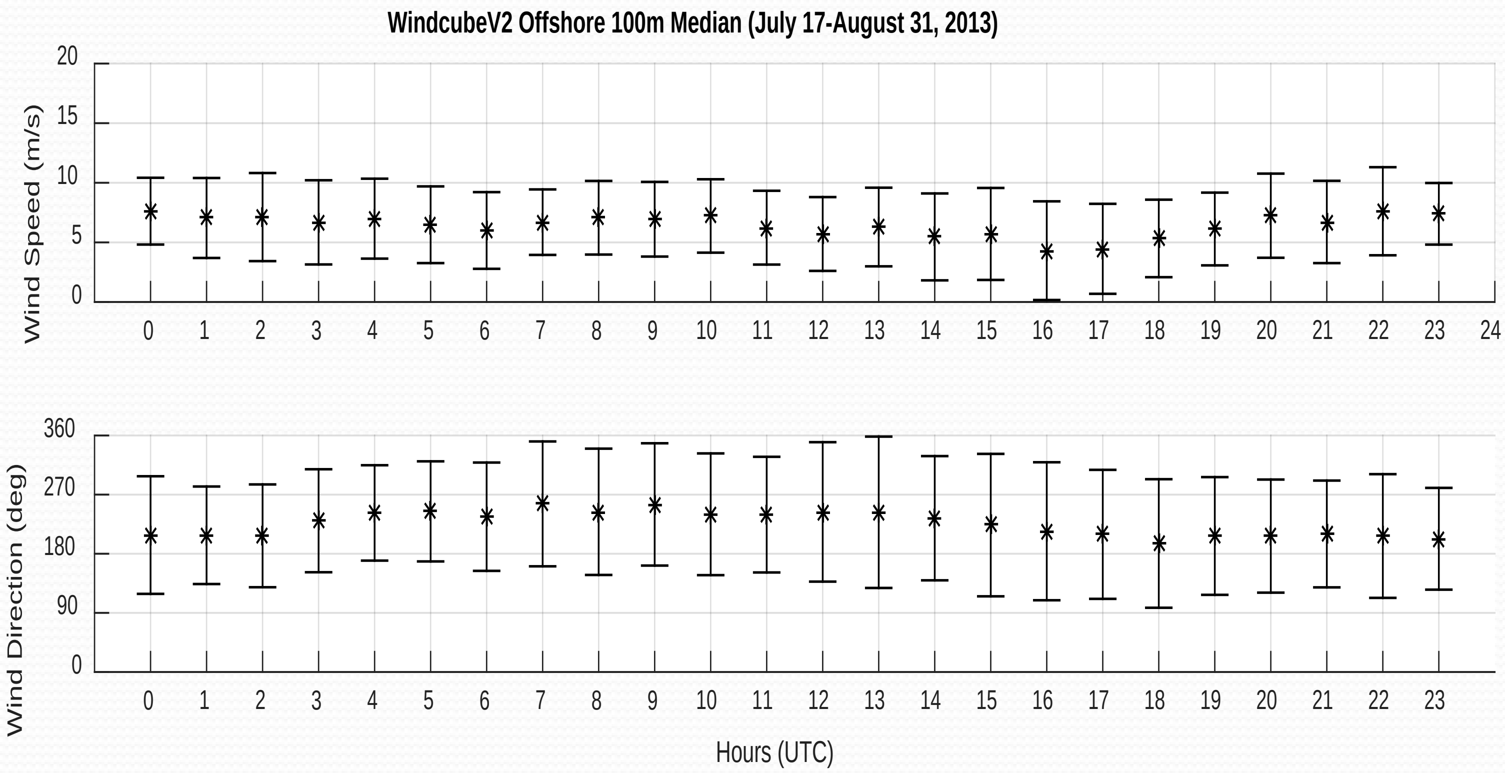
- Type IV-VI associated with greatest Δ in wind speed throughout rotor-layer

Windcube hub-height stats

Type (10-min 40-220m)	Windcube V2 (100m)									
	Wind Speed					**Wind Direction**				
	Mean	**Median**	**σ**	**Max**	**Min**	**Mean**	**Median**	**σ**	**Max**	**Min**
unclassified	10.191	11.156	3.163	14.857	3.124	249.453	240.608	33.611	351.541	122.612
I	6.968	6.788	3.050	17.340	0.632	131.241	68.413	106.513	358.531	0.568
II	6.227	5.794	3.071	16.264	0.372	180.945	206.396	110.577	359.786	0.103
III	4.136	4.136	2.569	11.413	0.497	192.230	213.101	107.671	359.848	4.231
IV	4.388	3.517	2.961	13.752	0.304	227.254	237.391	75.004	359.947	0.522
V	7.737	7.602	3.109	18.5494	0.870	228.623	232.640	73.344	359.650	0.817
VI	7.313	7.091	3.396	16.956	0.751	216.331	231.318	94.058	359.996	1.064

VWP Classification	Fit /Expression	Criteria
Type 0	Unclassified	
Type I	$u_{fit}(z)=u_{hub}(\frac{z}{z_{hub}})^{\alpha_{fit}}$	RSS <= 0.10 α_{fit} = positive (+)
Type II	$f(x) = mx + b$	RSS <= 0.10
Type III	$u_{fit}(z)=u_{hub}(\frac{z}{z_{hub}})^{\alpha_{fit}}$	RSS<=0.10 α_{fit} = negative (-)
Type IV	Low-Level Wind Min (LLWMin) 40m $> Min\_U_z <$ 220m	
Type V	Low-Level Wind Max (LLWMax) 40m $> Max\_U_z <$ 220m	
Type VI	$f(x) = a0 + a1 * cos(x * w)$ $+b1 * sin(x * w) +$ $a2 * cos(2 * x * w) +$ $b2 * sin(2 * x * w)$	RSS <= 0.10

Results: Campaign Average Hub-Height & Buoy 44009 Wind

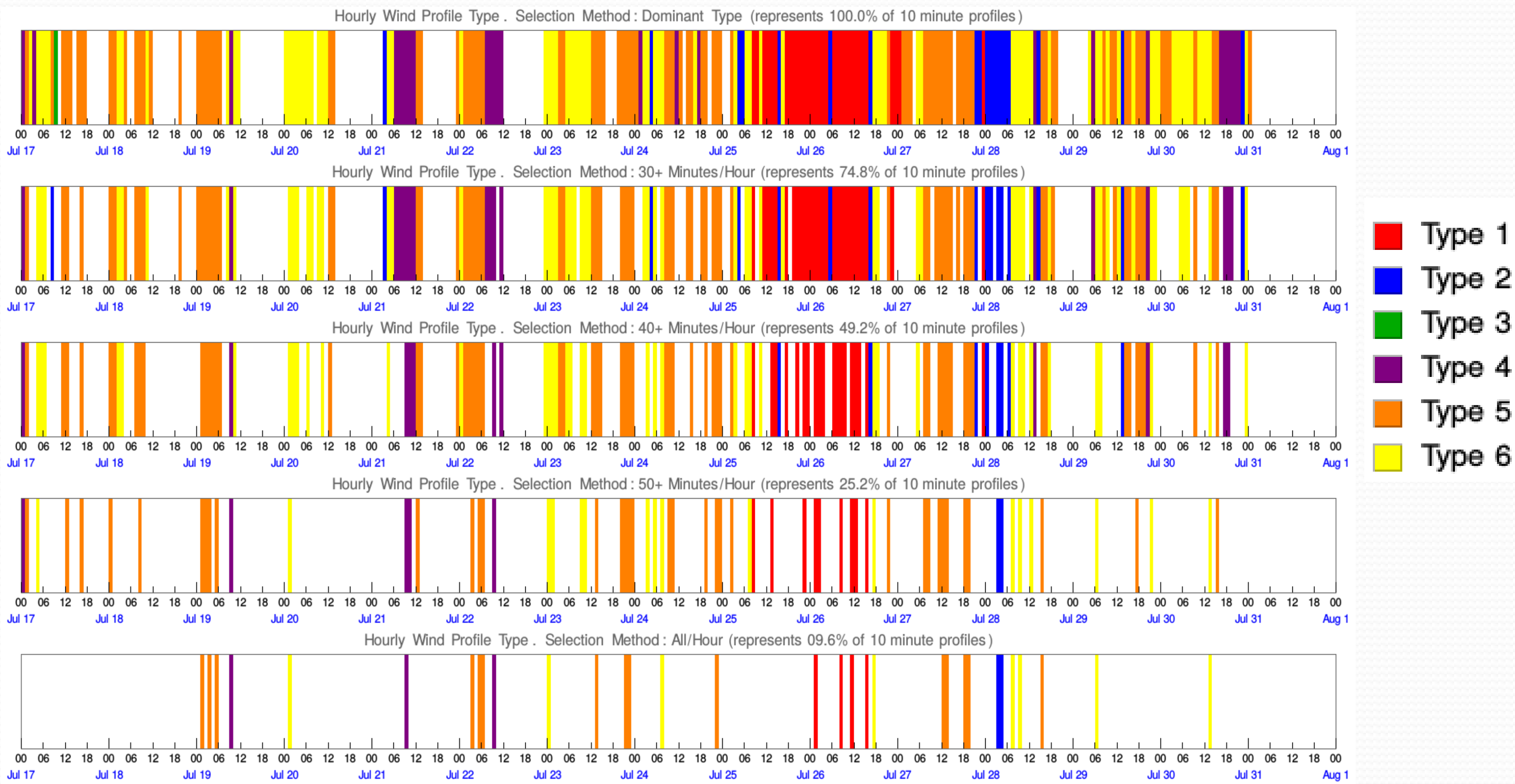


Day: 6AM-8PM Median: 6.34 m/s, 219.53

Night(8PM-6AM) Median: 6.88 m/s, 233.18

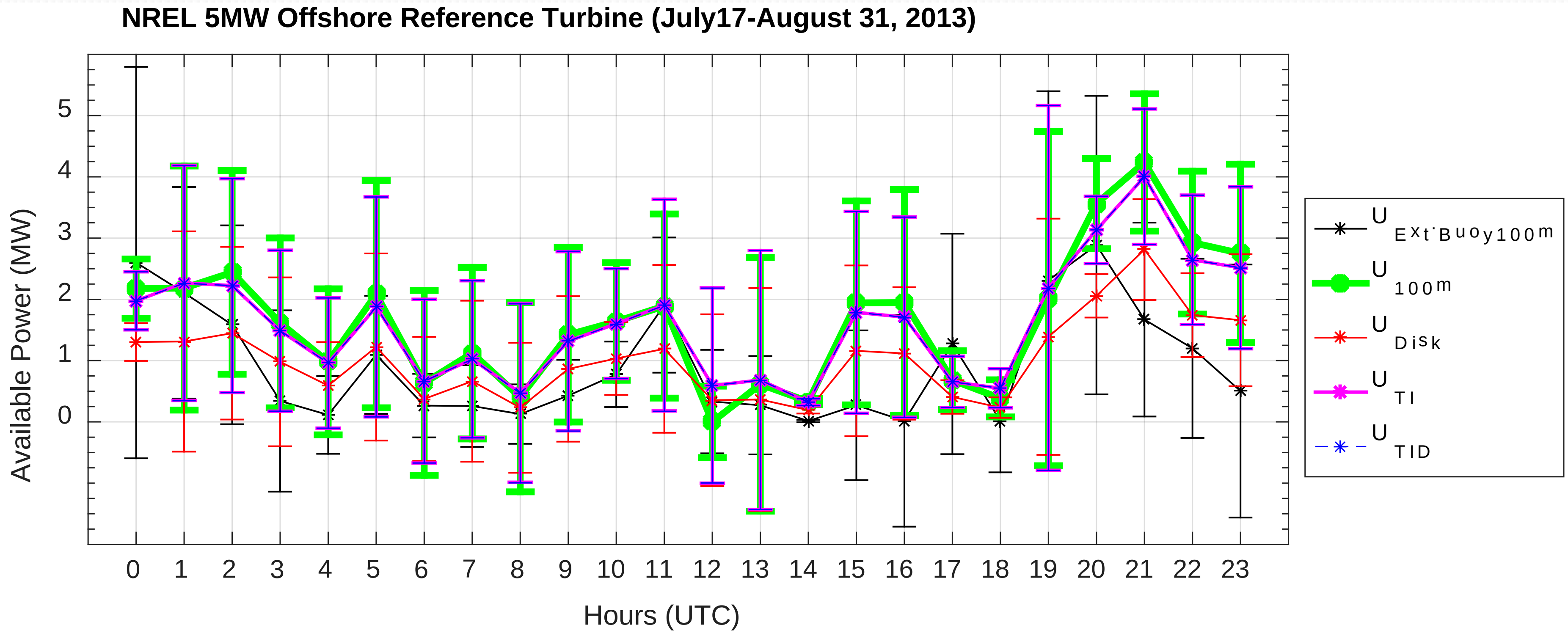
Results: VWP Classification vs. Buoy 44009

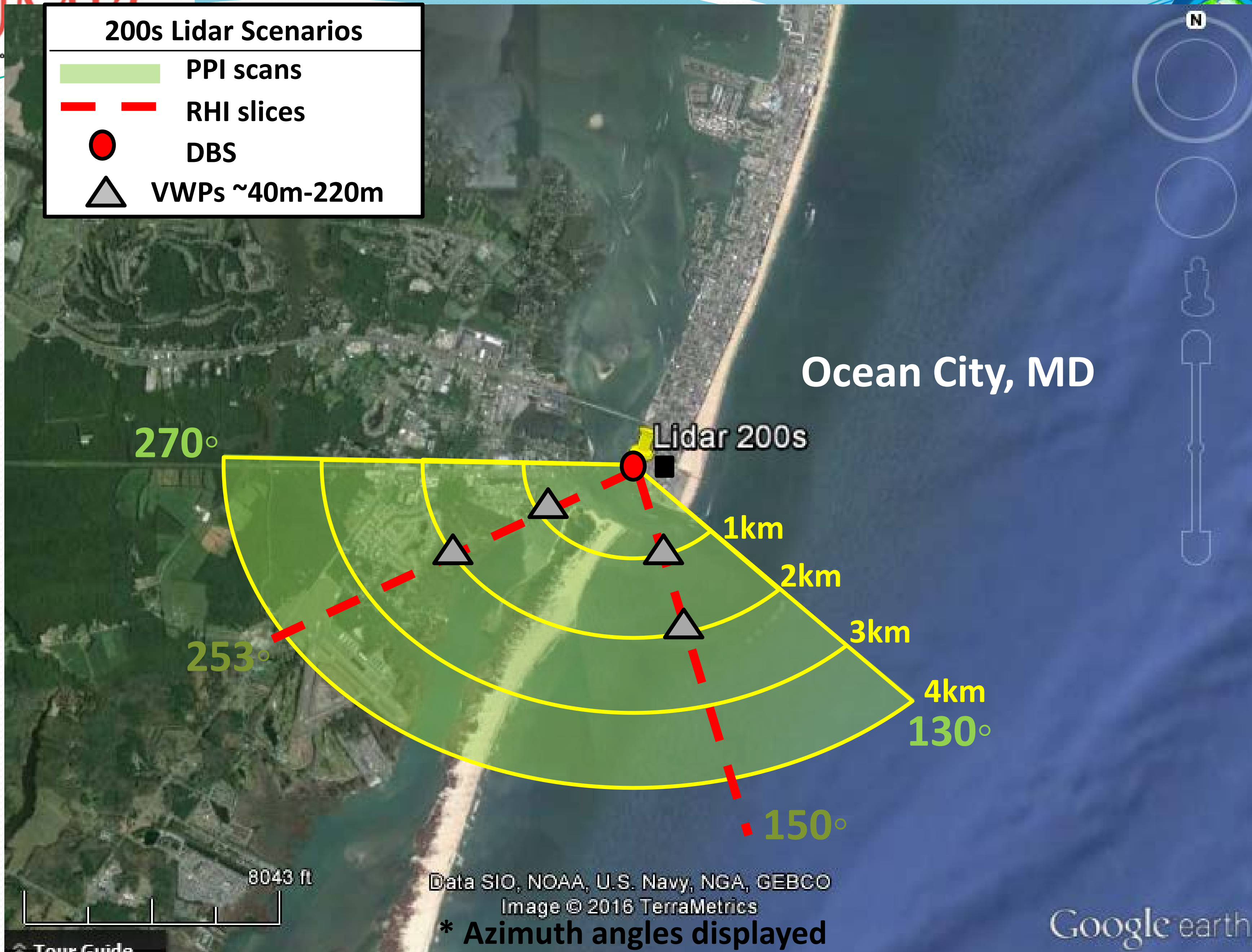
- Criteria for 'dominant' 10-min VWP Type per buoy hour



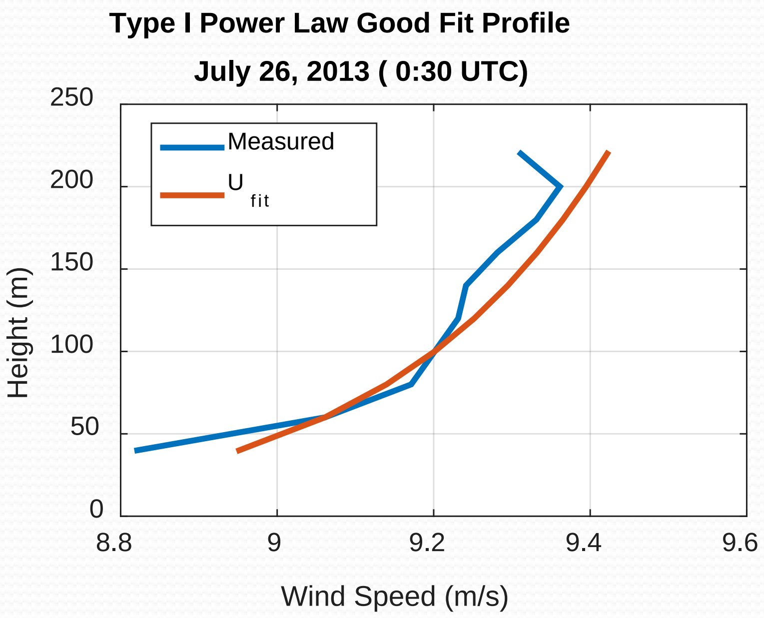
Buoy 44009 vs. VWP Type stats

Type		Median				
		SST (C)	Air T (C)	Air T- SST (C)	MSLP (hPa)	Wind Speed (m/s)
(40min/60min)	unclassified	24.10	24.60	0.50	1014	6.50
	I	23.15	22.50	-0.70	1015.6	4.10
	II	22.50	22.40	-1.100	1015.7	2.30
	III	23.50	22.50	-1	1022	N/A
	IV	23.65	23.25	0	1014.6	0.90
	V	23.10	23.40	0.15	1015.4	4.00
	VI	23.45	23.50	0.05	1015.3	3.10
(hourly)	unclassified	23.30	23.70	0.20	1013.3	3.10
	I	23.20	22.70	-0.50	1015.1	3.40
	II	23.20	23	-0.10	1016.2	2.20
	III	23.30	22.60	-0.70	1017.9	0.65
	IV	23.15	23.05	0.15	1013.9	2.95
	V	23.10	23.20	0.10	1016.6	3.90
	VI	23.10	23	0	1015.2	3

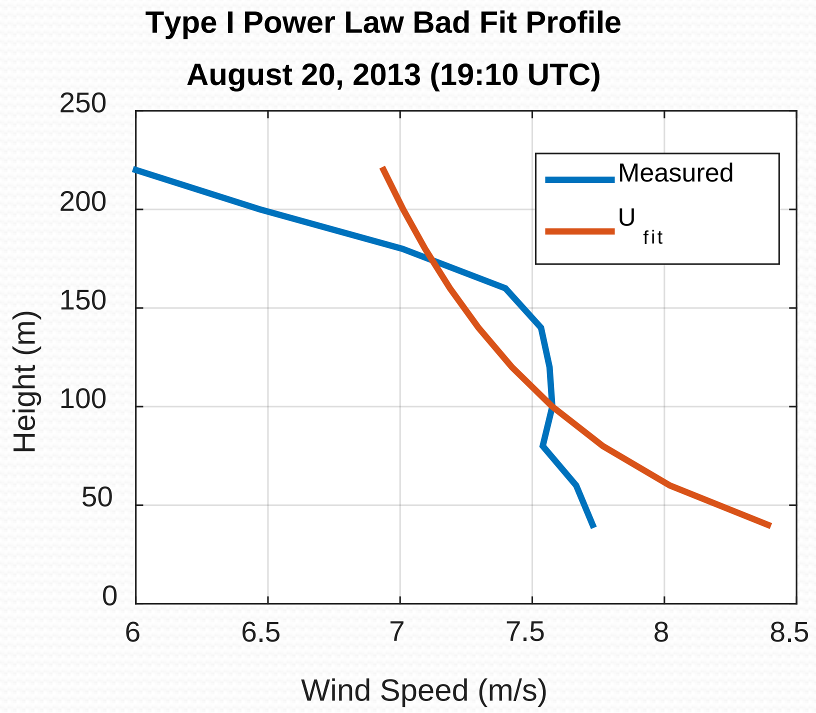

NREL 5MW Offshore Reference Turbine (July17-August 31, 2013)
Available Power (MW)
Hours (UTC)
0
1
2
3
4
5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
U Ext'Buoy100m
U 100m
U Disk
U TI
U TID



* Azimuth angles displayed



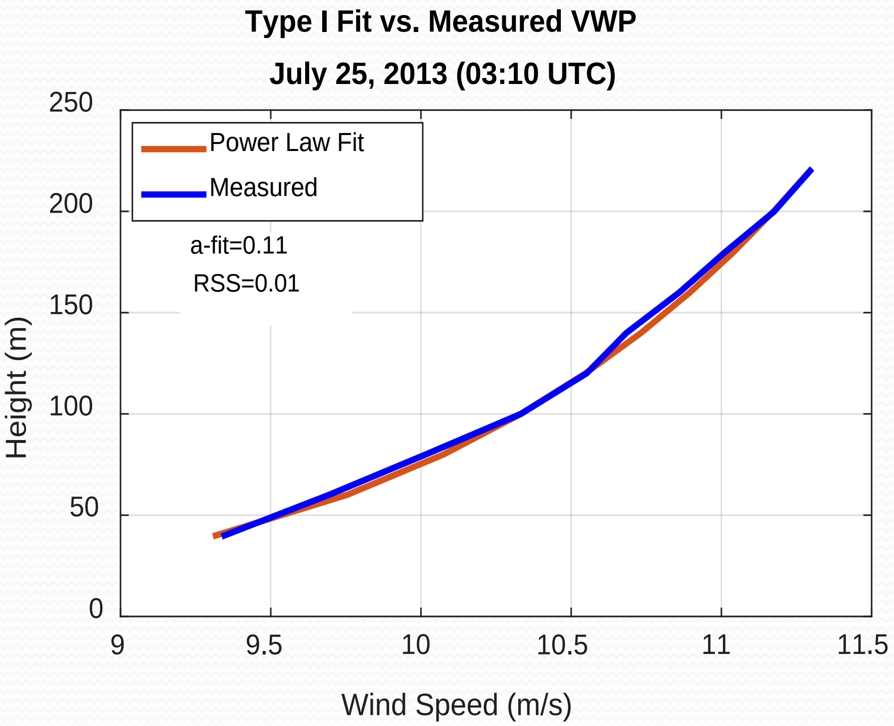
Type I Power Law Good Fit Profile
July 26, 2013 (0:30 UTC)
Measured
U fit
250
200
150
100
50
0
8.8
9
9.2
9.4
9.6
Height (m)
Wind Speed (m/s)

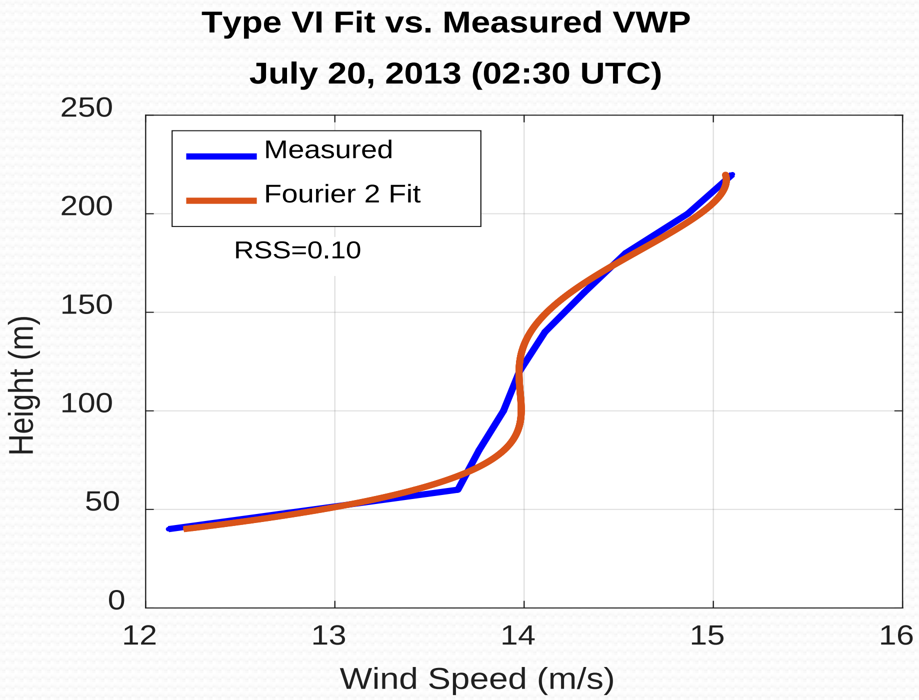


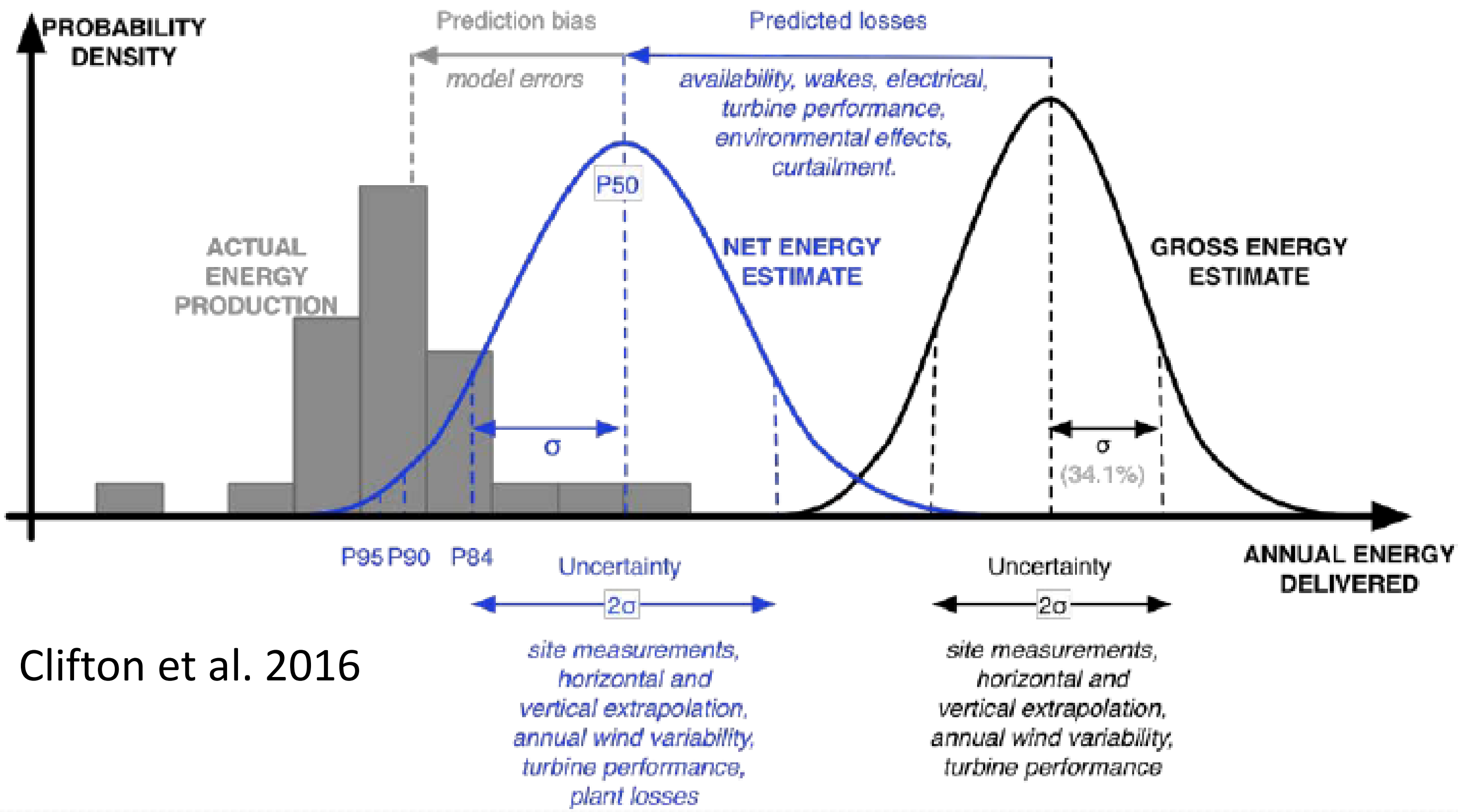
Type I Power Law Bad Fit Profile
August 20, 2013 (19:10 UTC)
Measured
U fit
250
200
150
100
50
0
6
6.5
7
7.5
8
8.5
Height (m)
Wind Speed (m/s)

Results

- Example of 'Good' Fit Using Residual Sum of Squares (RSS) ≤ 0.1







Clifton et al. 2016

Table 1-1. Gross Properties Chosen for the NREL 5-MW Baseline Wind Turbine

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)