Novelties for the offshore wind profile

WindSim user meeting 2019

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Introduction: The WindRes project

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Aim of the project

Develop a tool providing information on wind resource for a targeted site using wind observations from space

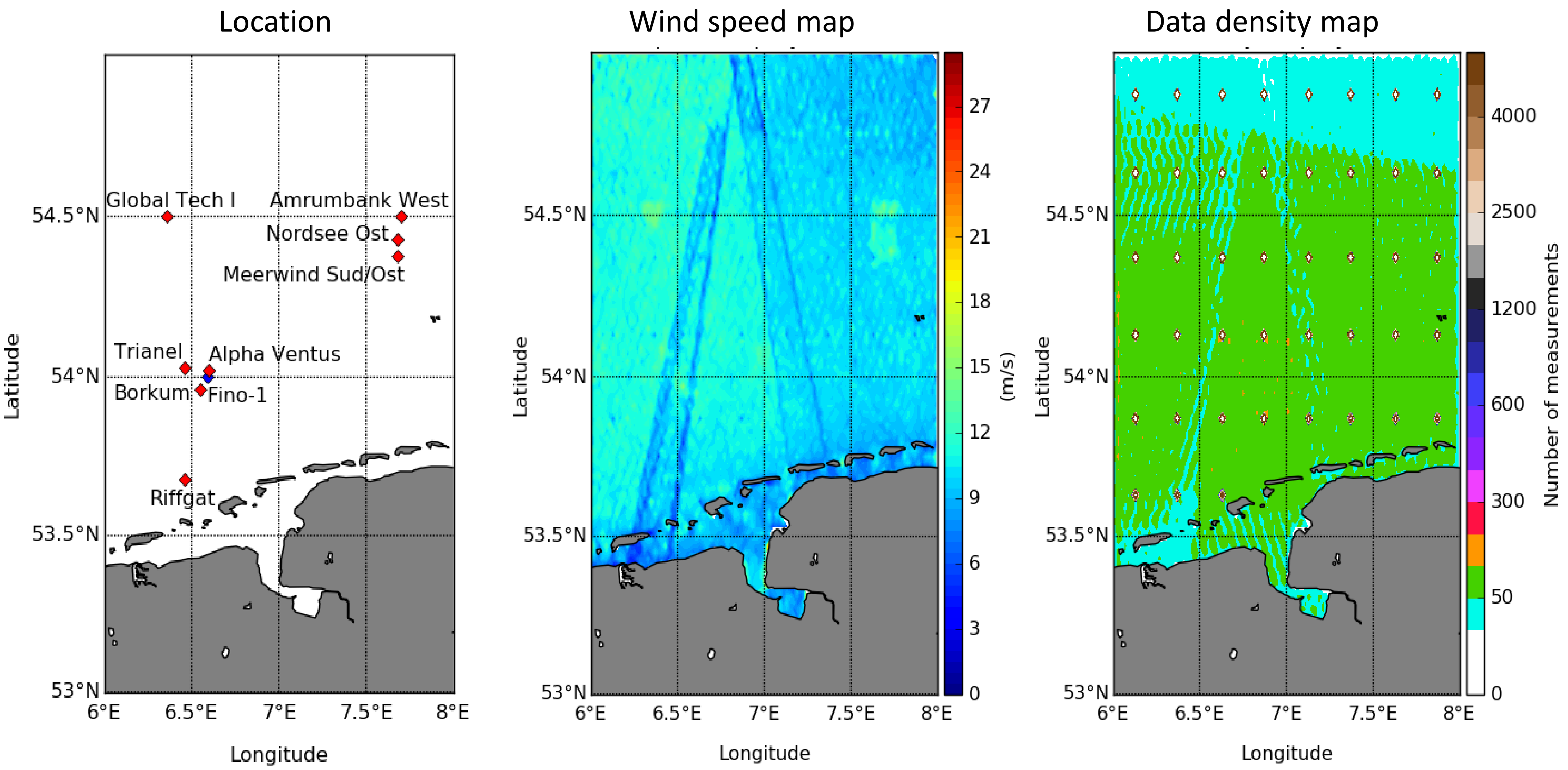
Key challenges

Translate NORSEWInD research into commercial, operational tools.

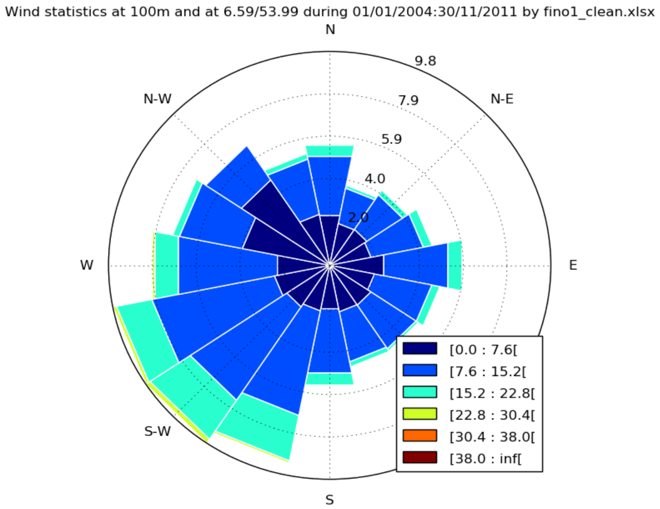
Develop key applications for offshore renewable energy industry and demonstrate its impact.

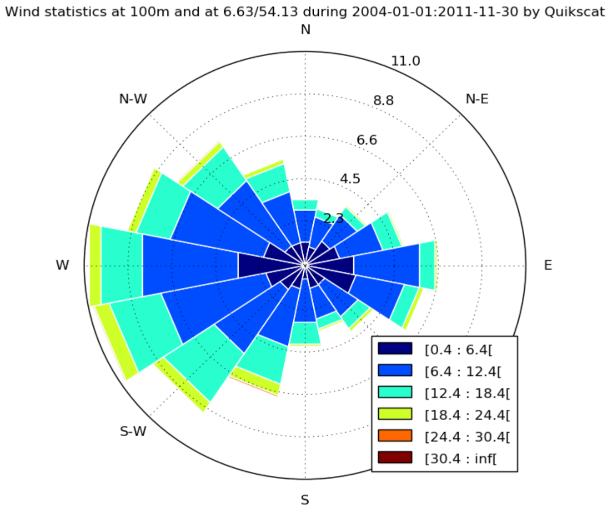
Demonstrate opportunities offered by satellite services within energy sector.

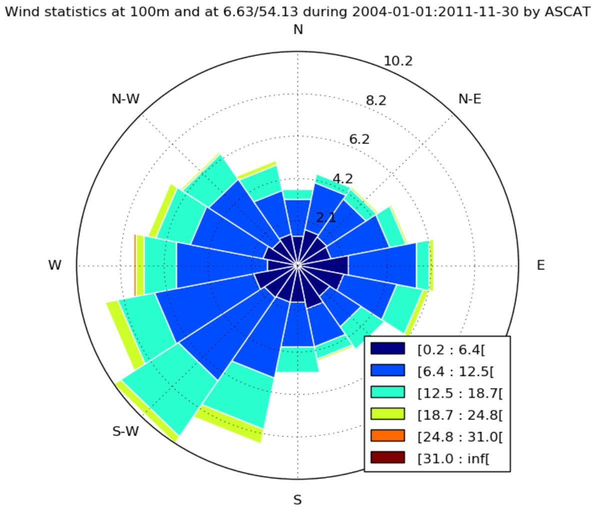
Introduction: The WindRes project

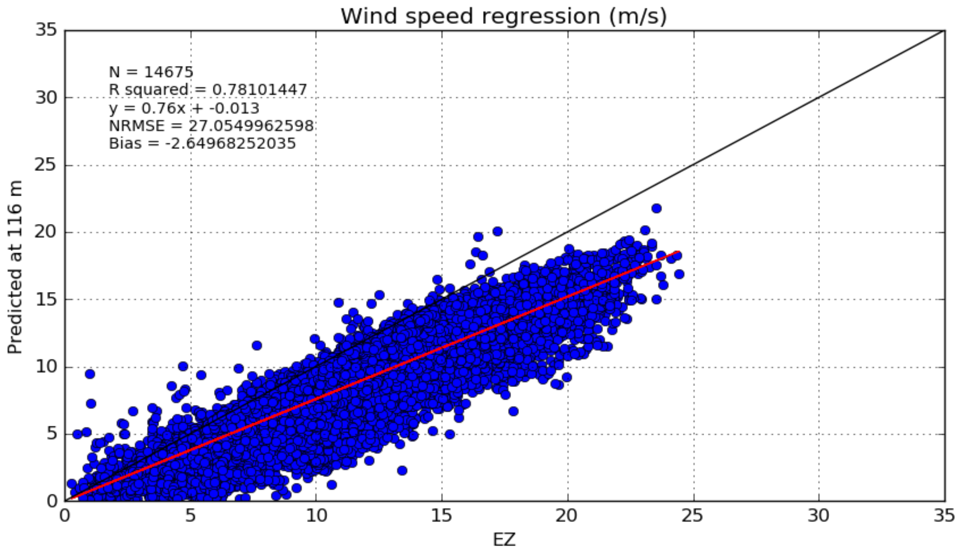


Introduction: The WindRes project









Open source code available on GitHub:

https://github.com/SatelliteApplicationsCatapult/WindRes

Introduction: The WindRes project

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Difficulties

- Time between measurements
- Vertical extrapolation of wind speed
- Coastal areas
- Truncation of wind speed distribution
- Low accuracy for low and high winds
- Criteria for image processing

Influences

- Weather (rain, water column)
- Marine atmospheric boundary layer
- Surface waves
- Internal waves
- Currents
- Bathymetry
- Surface slicks

Opportunities for the wind sector

- Use of satellite data as historical data during the MCP method (planning stage)
- GNSS-Reflectometry for real time measurements (construction & operation stages)

Introduction: Vertical extrapolation

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$$U(z) = \frac{U_*}{k}\left[\ln\left(\frac{z}{z_0}\right) + \Psi_s(z/L_s)\right] \qquad z \gg z_0$$

Rewritten equation

$$U(z) = \frac{U_*}{k}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\right]$$

Neutral winds at 10 m over the sea

$$\boxed{U(z) = \frac{U_*}{k}\left[\ln\left(\frac{z}{z_0}\right)\right]}$$

2 measurements at
different heights required

$$\cancel{U(z) = U(z_r)\left[\frac{\ln(z/z_0)}{\ln(z_r/z_0)}\right]}$$

Charnock's equation

$$\boxed{z_0 = \alpha_c \frac{U_*^2}{g}}$$

z_0
U_*

U: *wind speed*
U$_*$: *friction velocity*
k: *von Karman constant*
z: *height*
z$_0$: *surface roughness length*
Ψ : *atmospheric stability correction*
L$_s$: *Obukhov length*
α$_c$: *Charnock's parameter*
g: *gravitational acceleration*

Introduction: Locations

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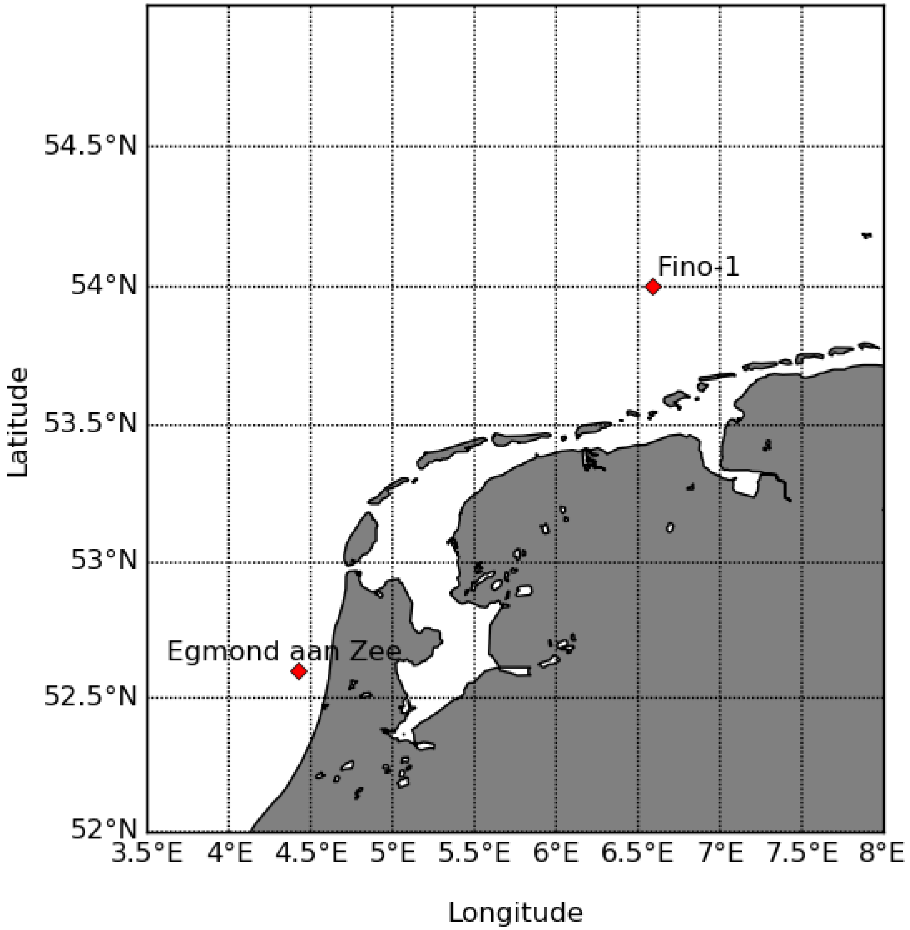
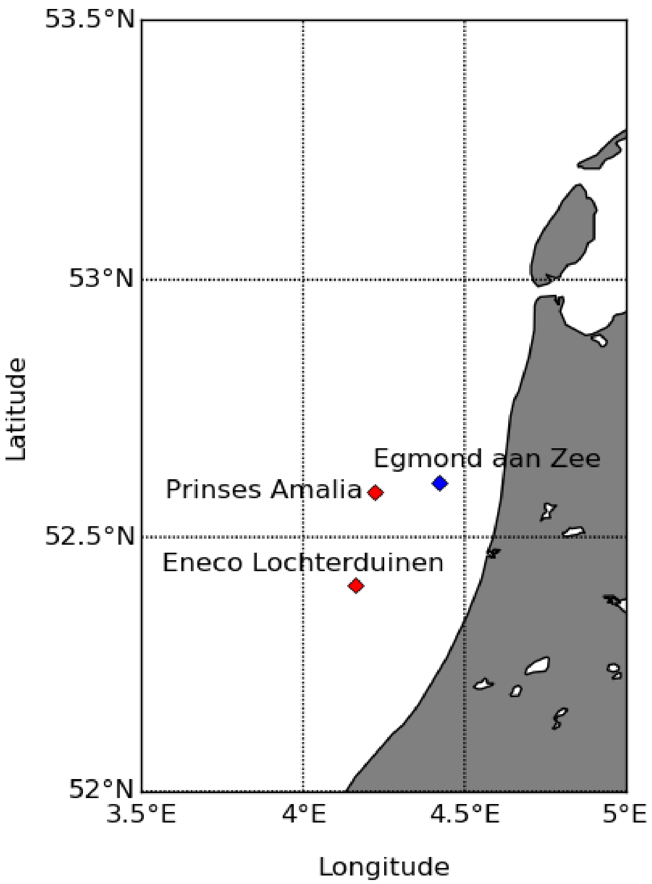
Insitu data composed by two meteorological masts in the North Sea, Fino-1 & Egmond aan Zee.

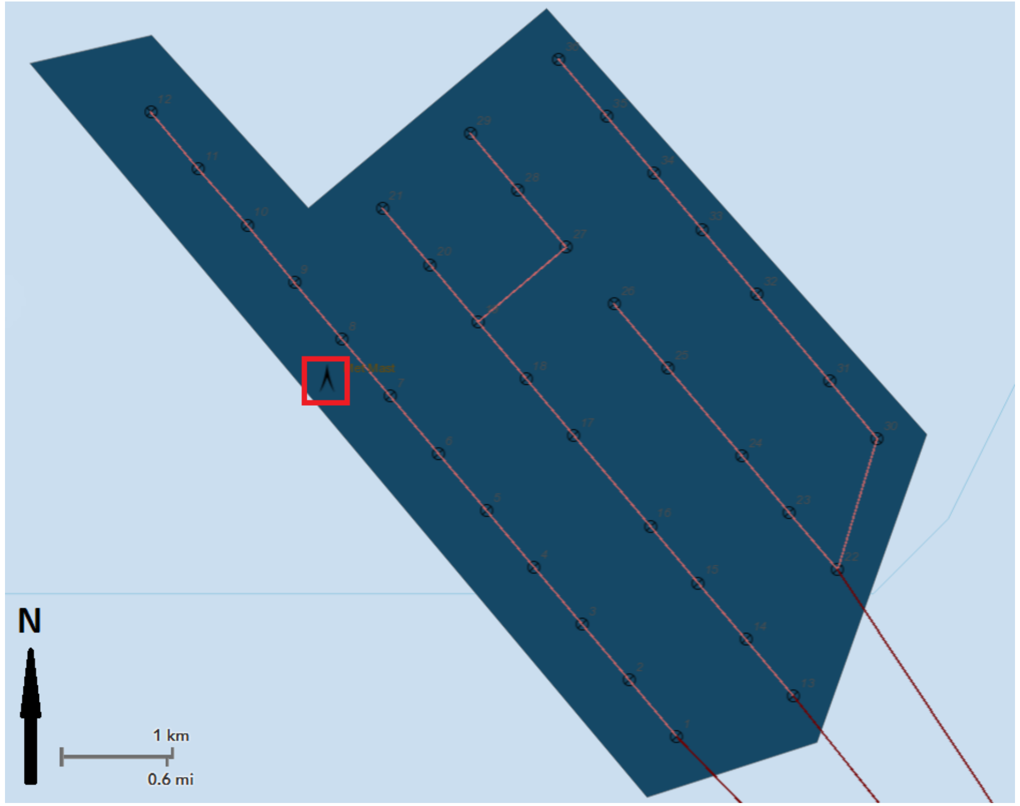
	Fino-1	Egmond
Distance to shore	40 km	14.5 km
Depth	30 m	16.5 m
From	1/1/04	1/7/05
To	30/11/11	31/12/08
Highest anemometer	90 m	116 m



Introduction: Locations

Egmond aan Zee





Source: www.4coffshore.com

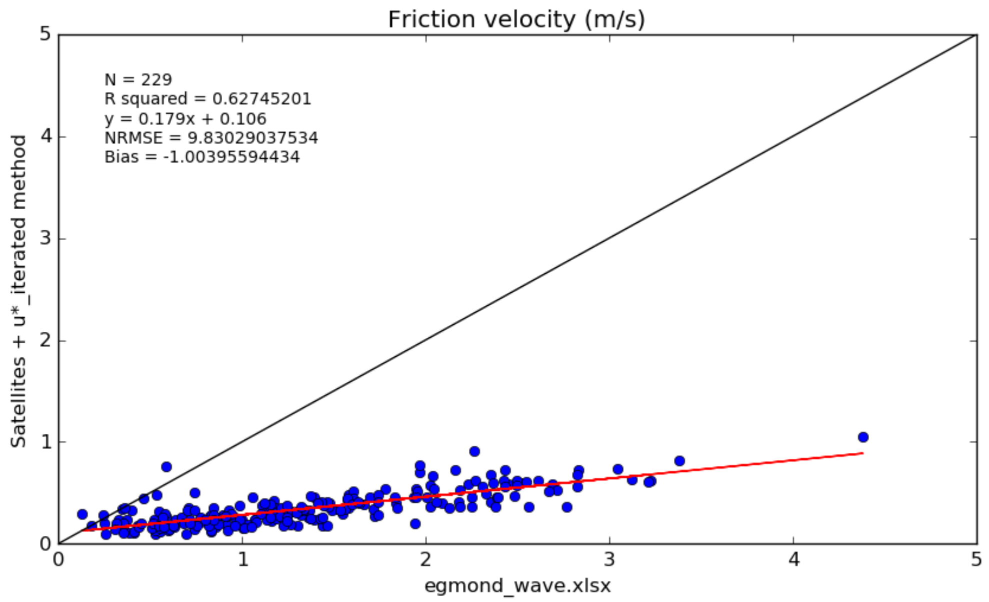
Review of z_0 methods: Constant α_c

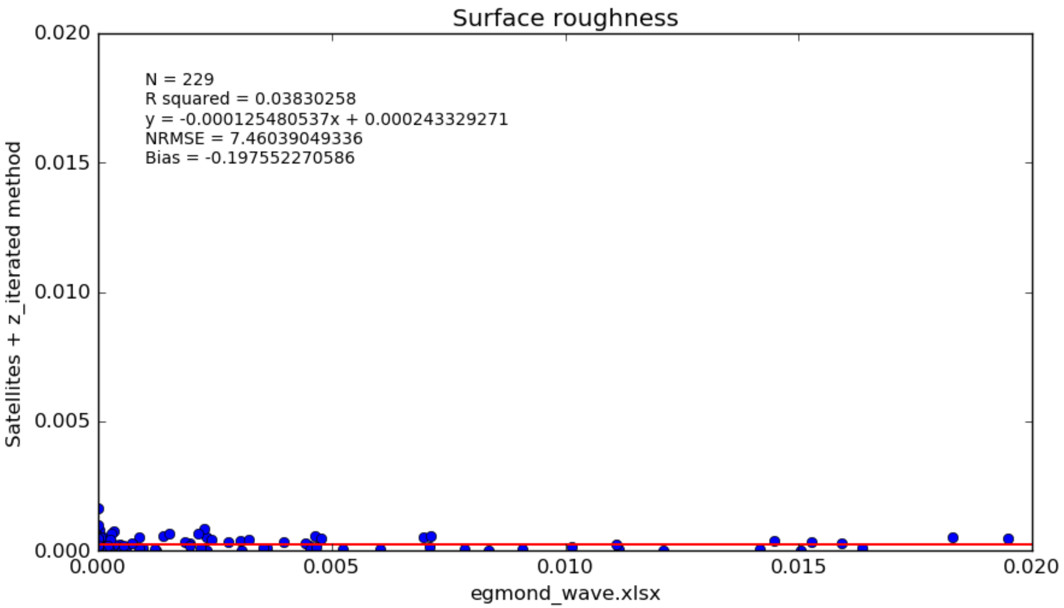
$$U(z) = \frac{U_*}{k}\left[\ln\left(\frac{z}{z_0}\right)\right]$$

+

$$z_0 = \alpha_c \frac{U_*^2}{g}$$

1. **Constant Charnock's parameter, α_c= 0.0144**
2. **Calculate U* and z_0 at 10 m**
3. **Calculate U when z is the hub height**





Review of z_0 methods: Wave age expressions

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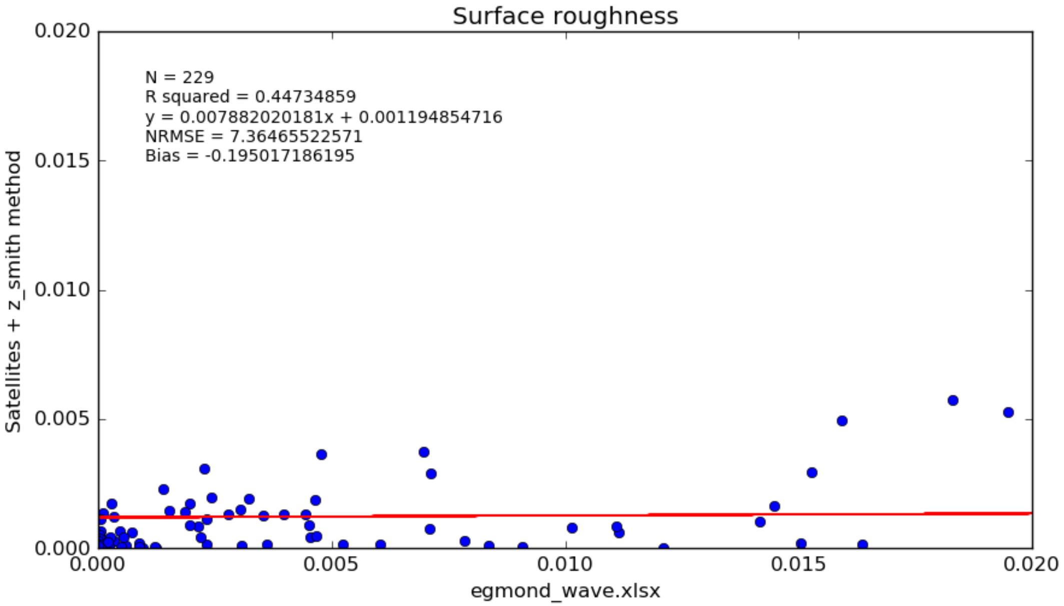
***c_p**: phase speed of the wave*

***c_p/u_*** : wave age*

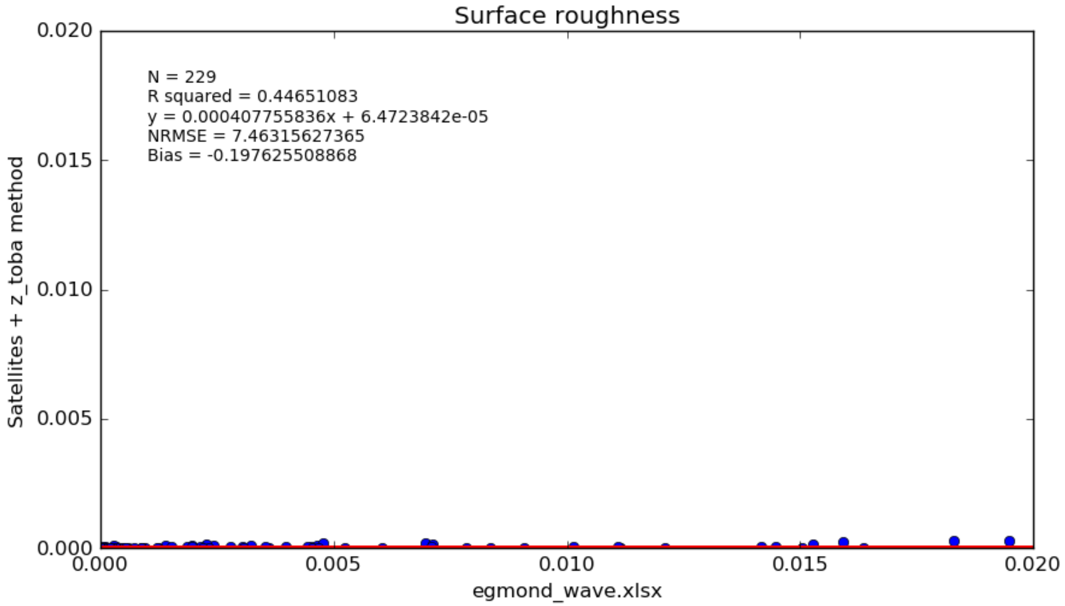
Smith

$$\alpha_c = 0.48(u_*/c_p)$$



Toba

$$\alpha_c = 0.025(u_*/c_p)$$



Review of z_0 methods: Wave age expressions

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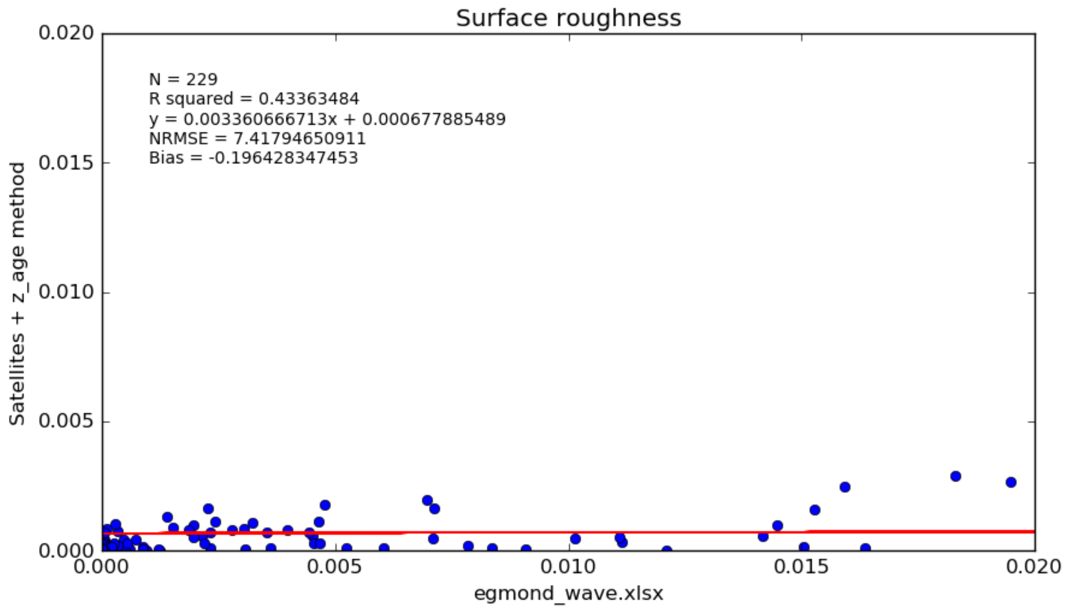
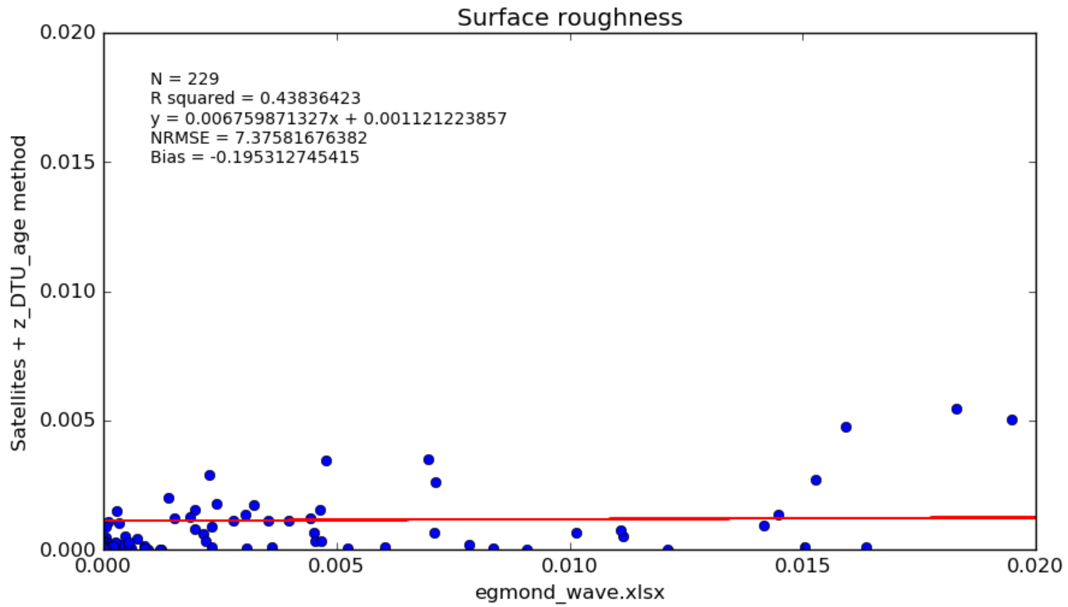
Edson

$$\alpha_c = 0.114\left(\frac{u_*}{c_p}\right)^{0.622}$$



Astrup

$$\alpha_c = 1.89\left(\frac{u_*}{c_p}\right)^{1.59} \times \left[1 + 47.165\left(\frac{u_*}{c_p}\right)^{2.59} + 11.791\left(\frac{u_*}{c_p}\right)^{4.59}\right]^{-1}$$



Review of z_0 methods: Wind speed expressions

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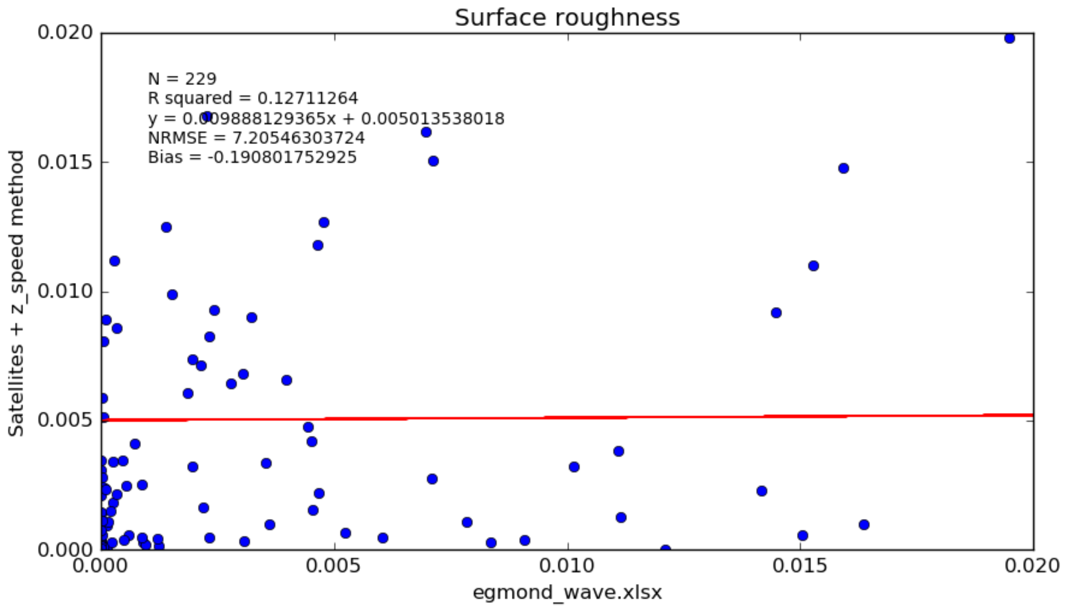
Edson

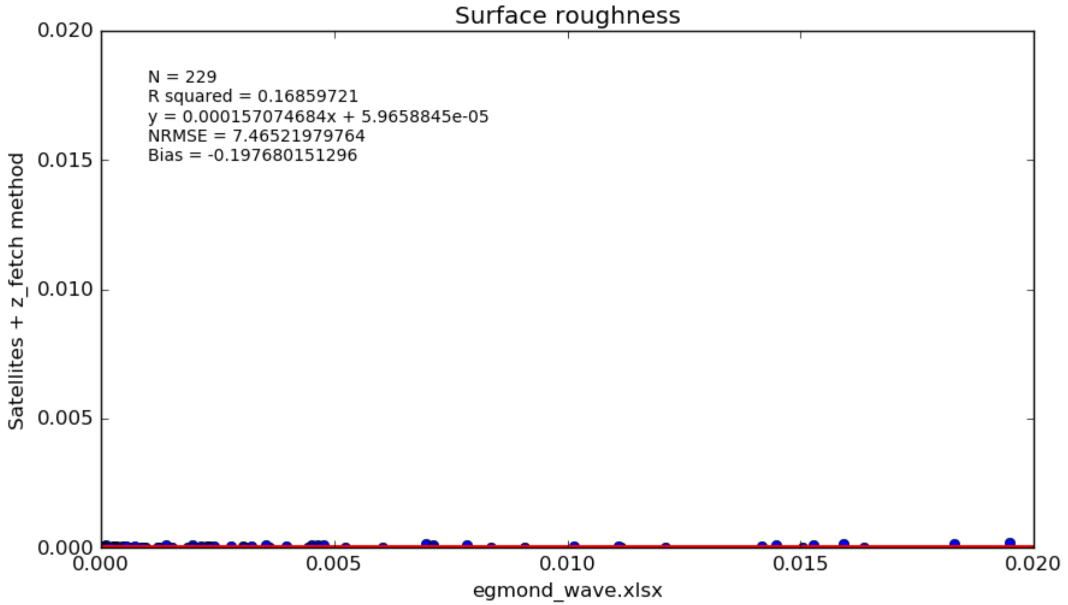
$$\alpha_c = 0.017U_{10N} - 0.005$$



Astrup

$$\frac{u_*}{c_p} = \frac{3.5}{2\pi} \times \left(\frac{(U_{10})^2}{x \times g}\right)^{1/3}$$

$\boldsymbol{x}$: *fetch*



Review of z_0 methods: Wave slope expressions

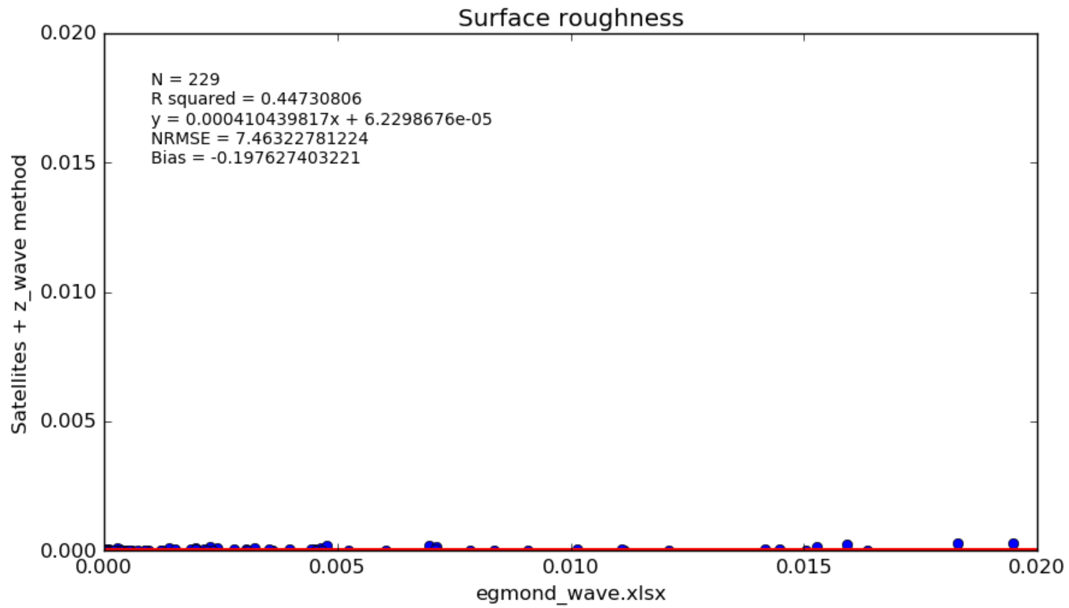
***H_s* : significant wave height**

***L_p* : wave length**

***H_s/L_p* : wave slope**

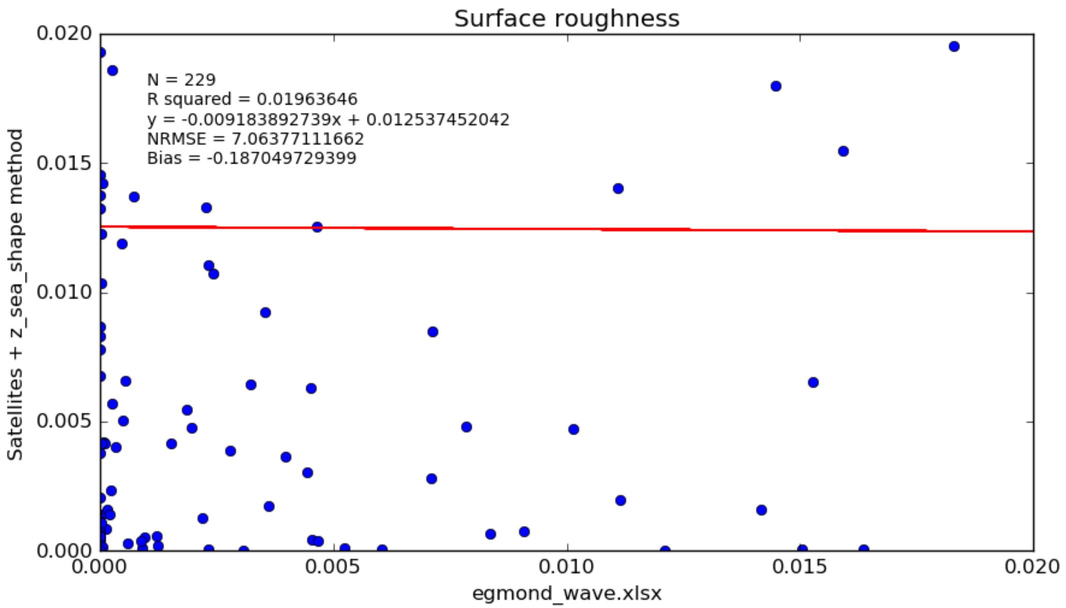
Edson

$$\alpha_c = 0.09 H_s \left(\frac{2\pi}{L_p}\right)$$

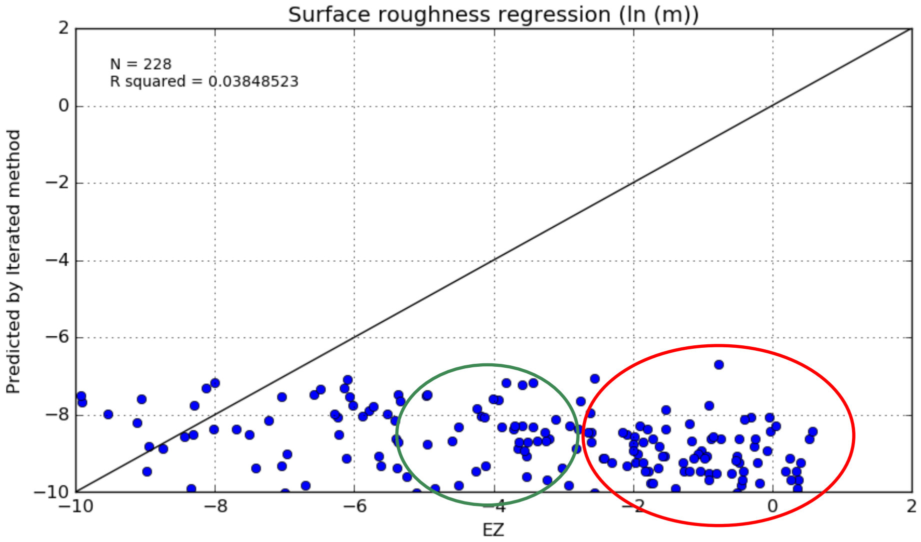


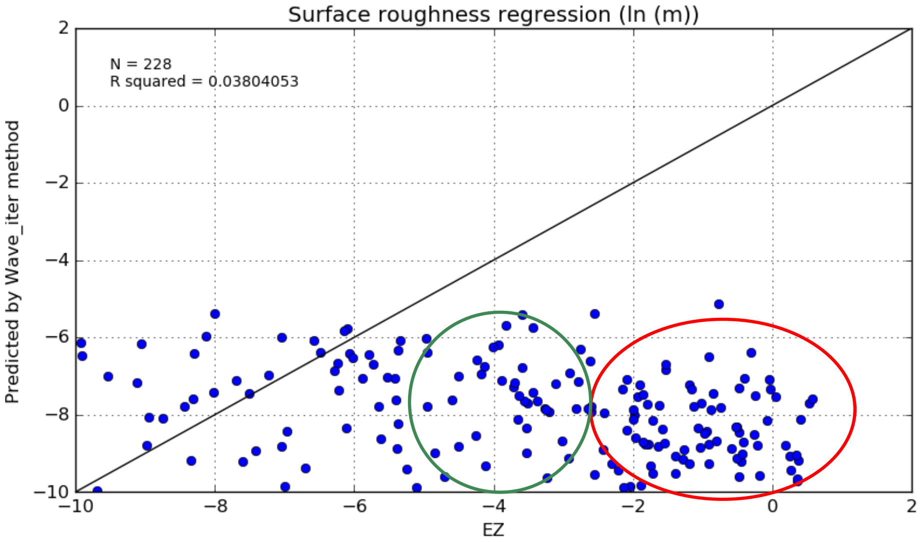
Taylor

$$\frac{z_0}{H_s} = 1200\left(H_s/L_p\right)^{4.5}$$



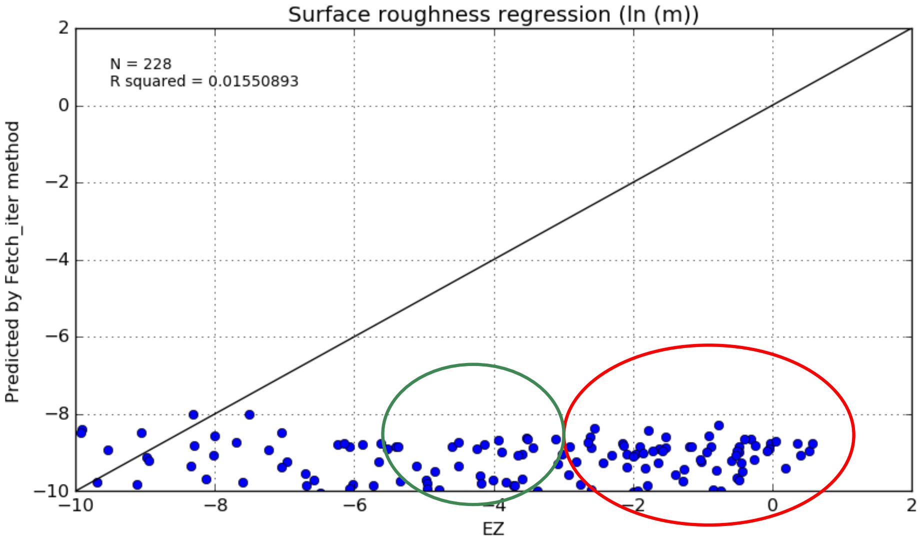
Review of z_0 methods: **Log scale**

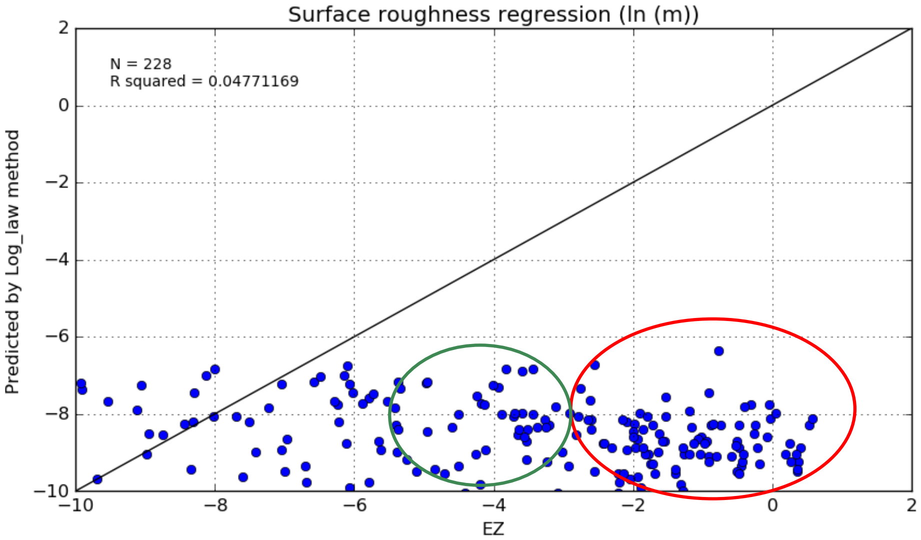




Offshore z_0
~ $10^{-3} - 10^{-5}$

!!!

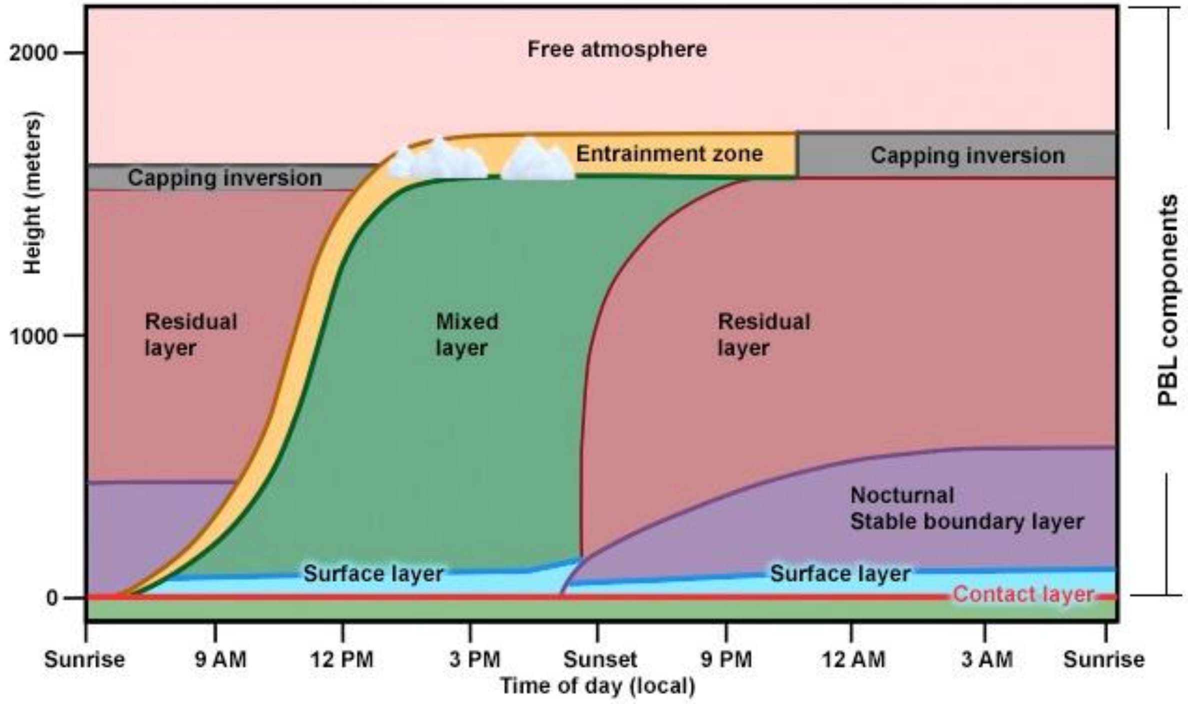




On offshore high z_0 values

Possible Reasons

- Instrumental errors (anemometers, vanes, datalogger,…)
- Physical phenomena (wind shear, eddies, low-level jets)
- Atmospheric stability (heat flux or turbulence)
- Wake effect (WT's nearby or other obstacles)
- Incomplete physical law (log law and/or z_0 model)



Source: MetEd UCAR

On offshore high z_0 values: **Instruments**

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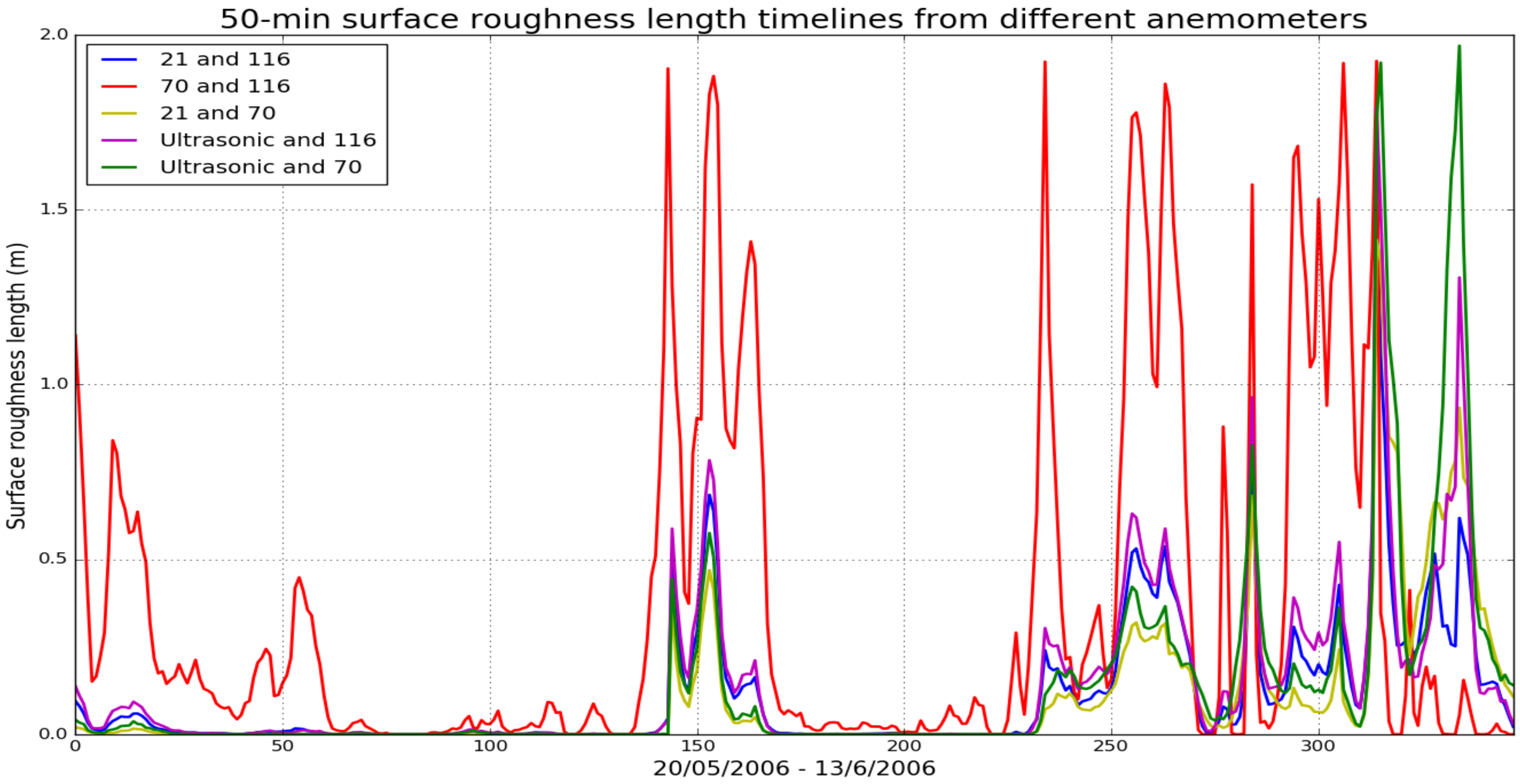
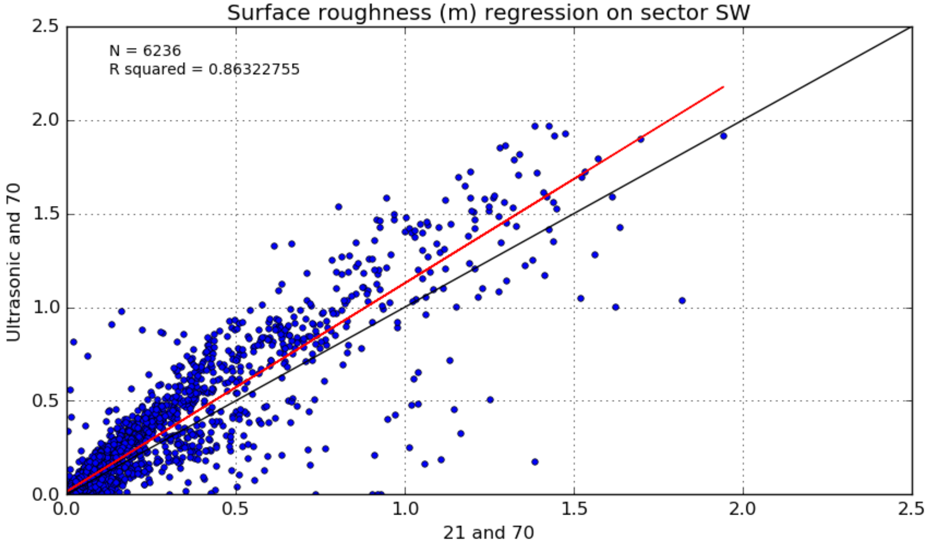


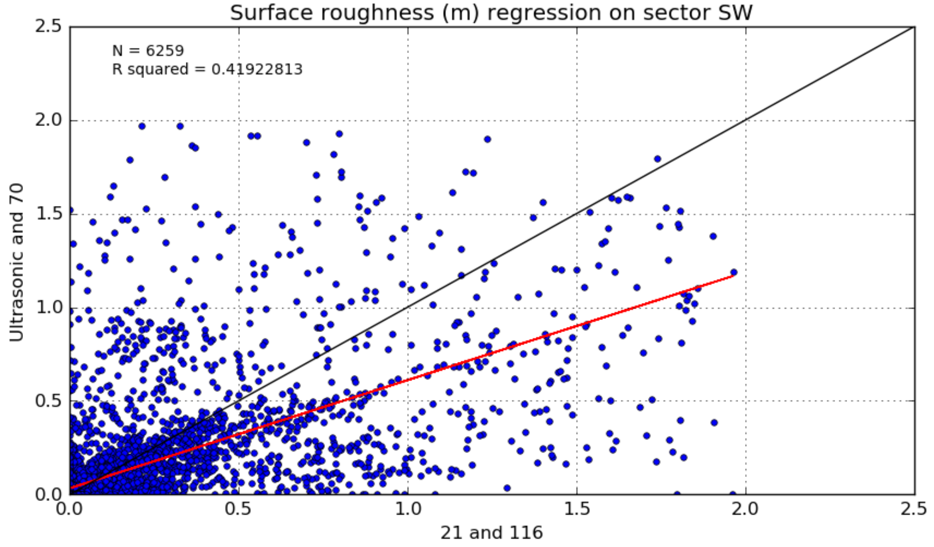
$$U(z) = U\,(z_r)\left[\frac{\ln(z/z_0)}{\ln(z_r/z_0)}\right]$$

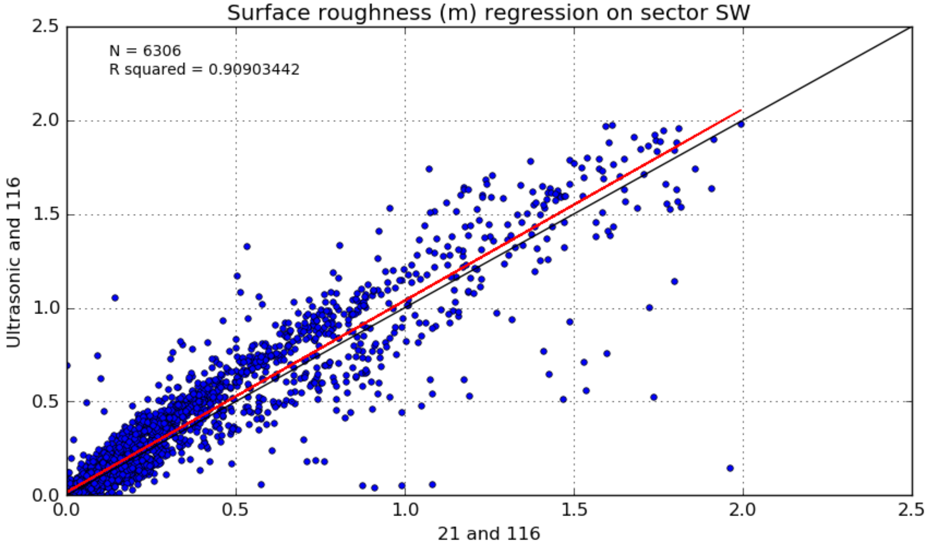
Egmond aan Zee:

Cup anemometers at 21, 70, 116 meters
Sonic anemometer at 21 meters

On offshore high z_0 values: Instruments







It seems to be certain disagreement between anemometers at 70 and 116 metres. However, high z_0 was always found

On offshore high z_0 values: **Phenomena**

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Gusts, eddies and wind shear can be significant for periods of 10 minutes or less. Hence, 50 minutes periods were used.

Low-level jets use to be larger in time than eddies. These could be represented as an inverted wind profile, lower wind speed at high heights than low heights. In these cases, the z_0 cannot be mathematically calculated by the logarithmic law; and then these situations were filtered out.

On offshore high z_0 values: **Stability**

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$$\Theta_v = \Theta(1 + 0.61r)$$

$$L_s = -\frac{u_*^3 \Theta_v}{\kappa g \overline{w'\Theta'_v}}$$

Θ *: Potential temperature*

Θ_v *:Virtual potential temperature*

w' *: vertical speed*

$\overline{w'\Theta'_v}$ *: Heat flux*

		$\overline{\Theta_v}$ profile (K)	$\overline{w'\Theta'_v}$ ($ms^{-1}K$)	z/L_s	L_s (m)	$1/L_s$ (m^{-1})
Stable		$\overline{\Theta_{v1}} < \overline{\Theta_{v2}}$	< 0	> 0	≤ 200	≥ 0.005
Neutral	**Near neutral/stable**	$\overline{\Theta_{v1}} \cong \overline{\Theta_{v2}}$ If there is no convection	≅ 0	≅ 0	200 ≤ L ≤ 500	0.002 < 1/L < 0.005
	Neutral				|L|≥500	0.002 ≥ 1/L ≥ -0.002
	Near neutral/unstable				-500 ≥ L ≥ -200	-0.005 ≤ 1/L ≤ -0.002
Unstable		$\overline{\Theta_{v1}} > \overline{\Theta_{v2}}$	> 0	< 0	≥ -200	≤ -0.005

On offshore high z_0 values: **Stability**

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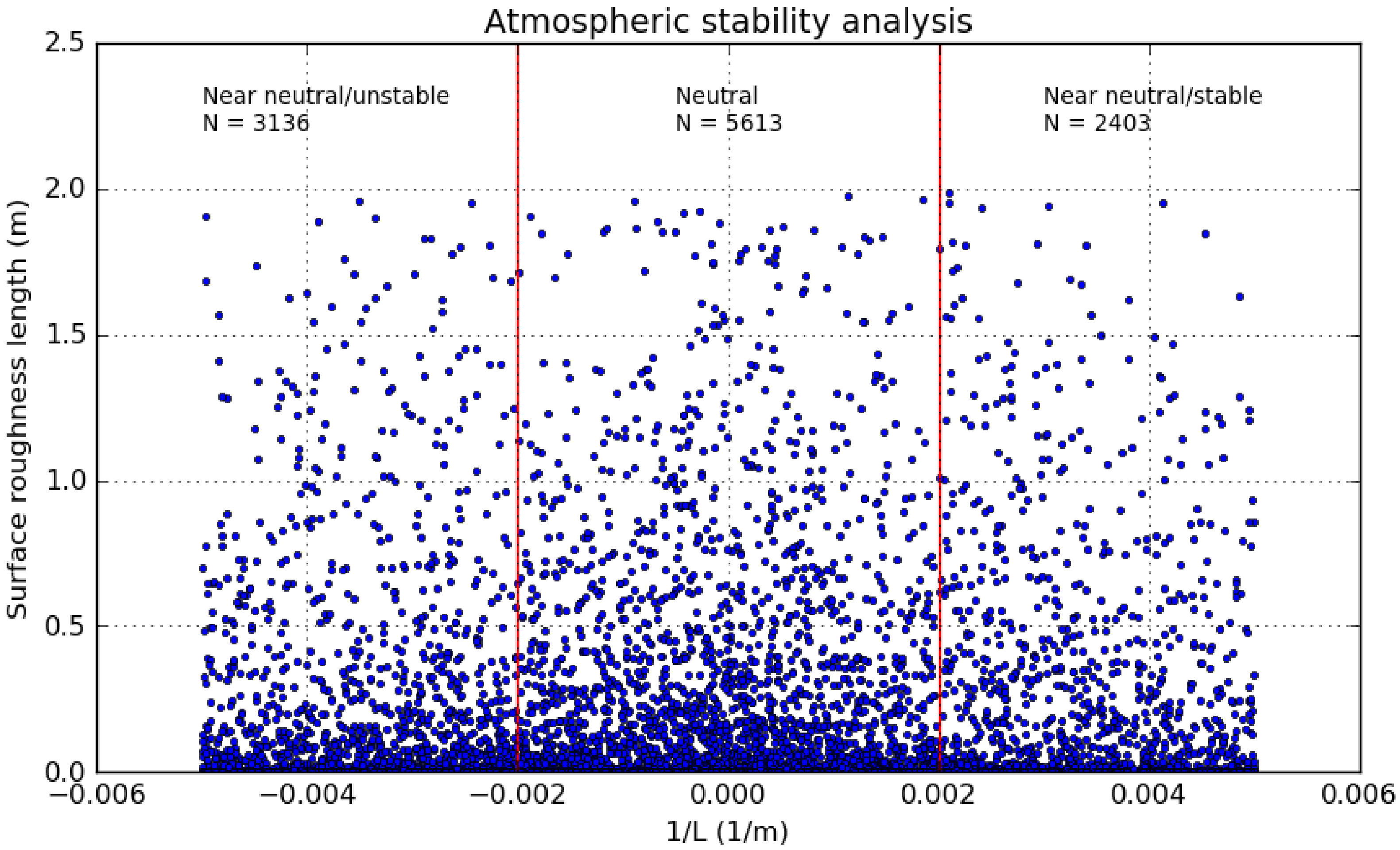
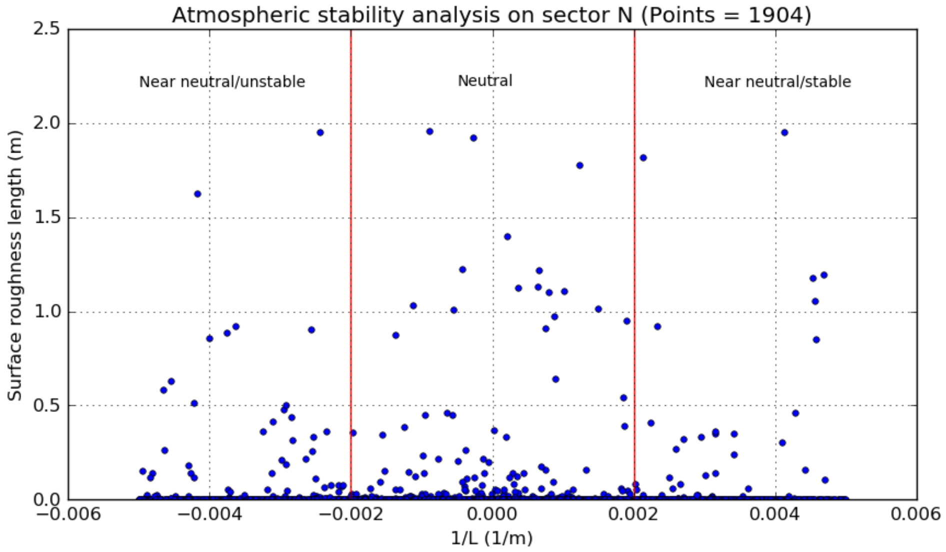
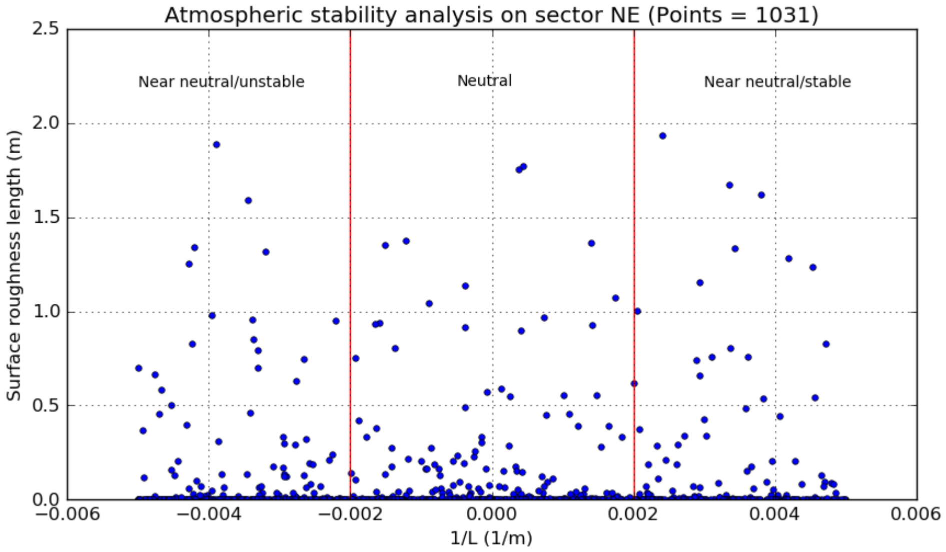
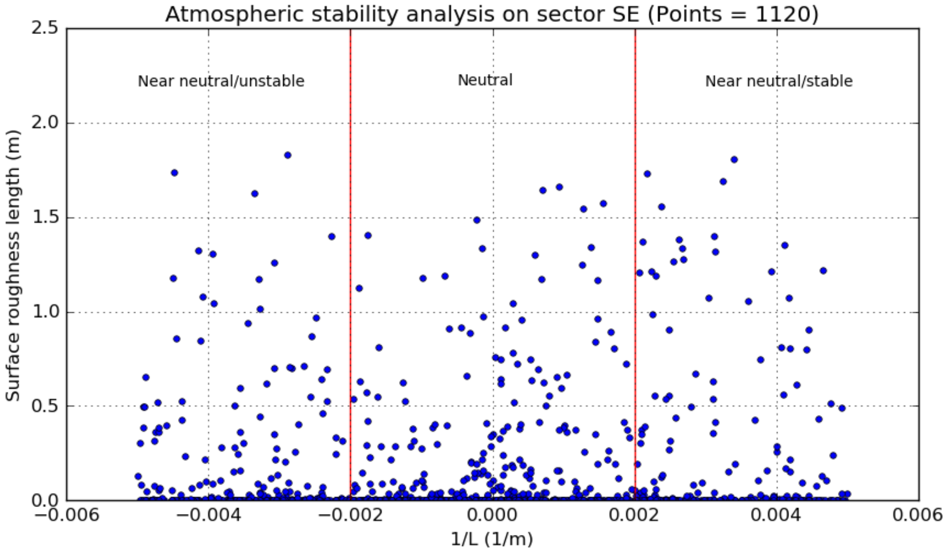


On offshore high z_0 values: **Wake effect**

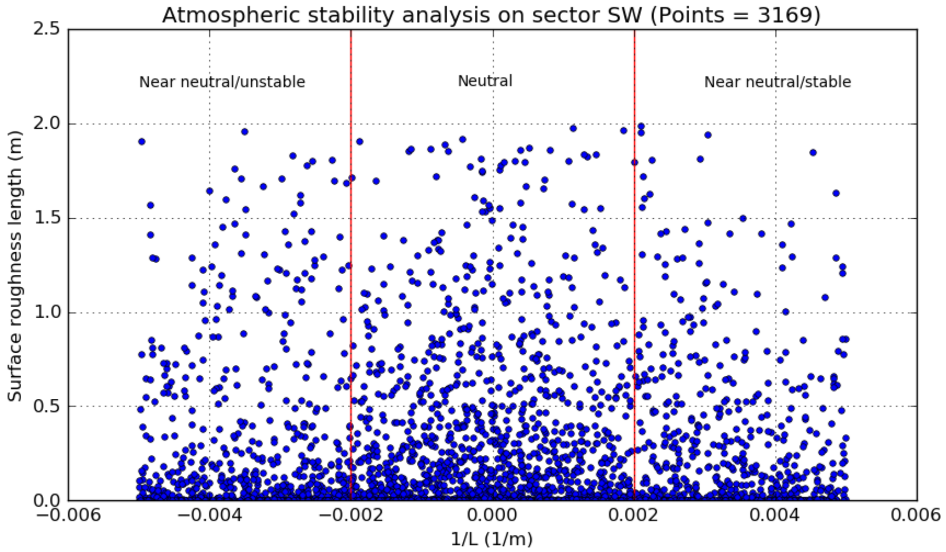


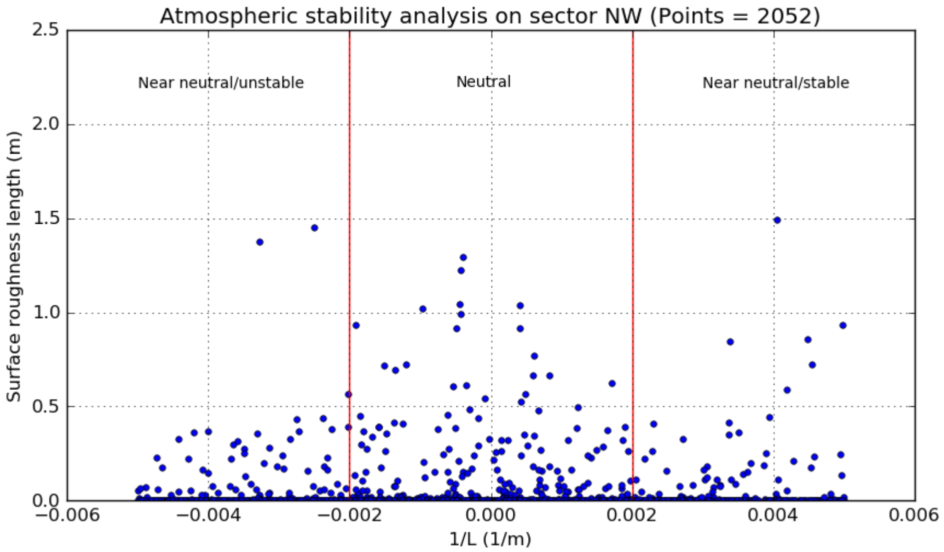


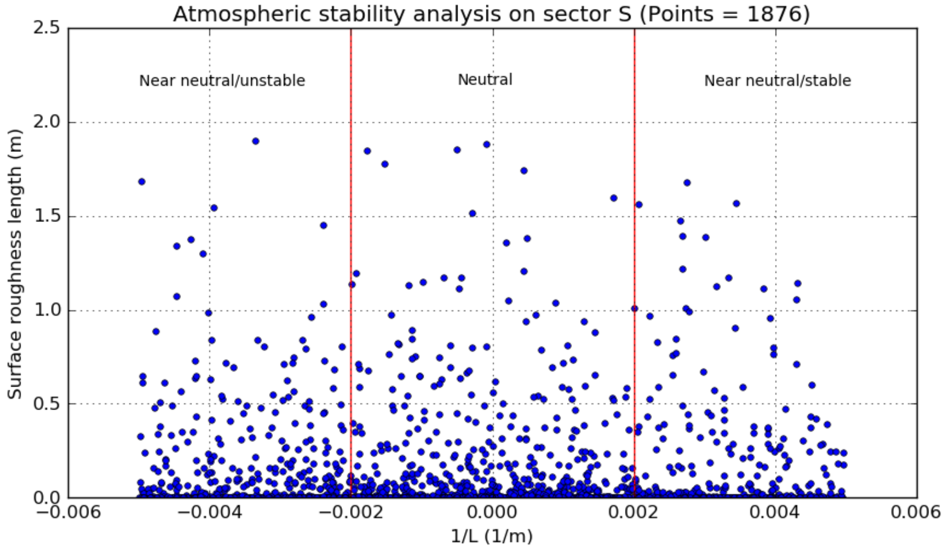


Analyses of surface roughness length under different stability conditions for the 3 sectors under a possible wake effect from wind turbines.

On offshore high z_0 values: **Wake effect**

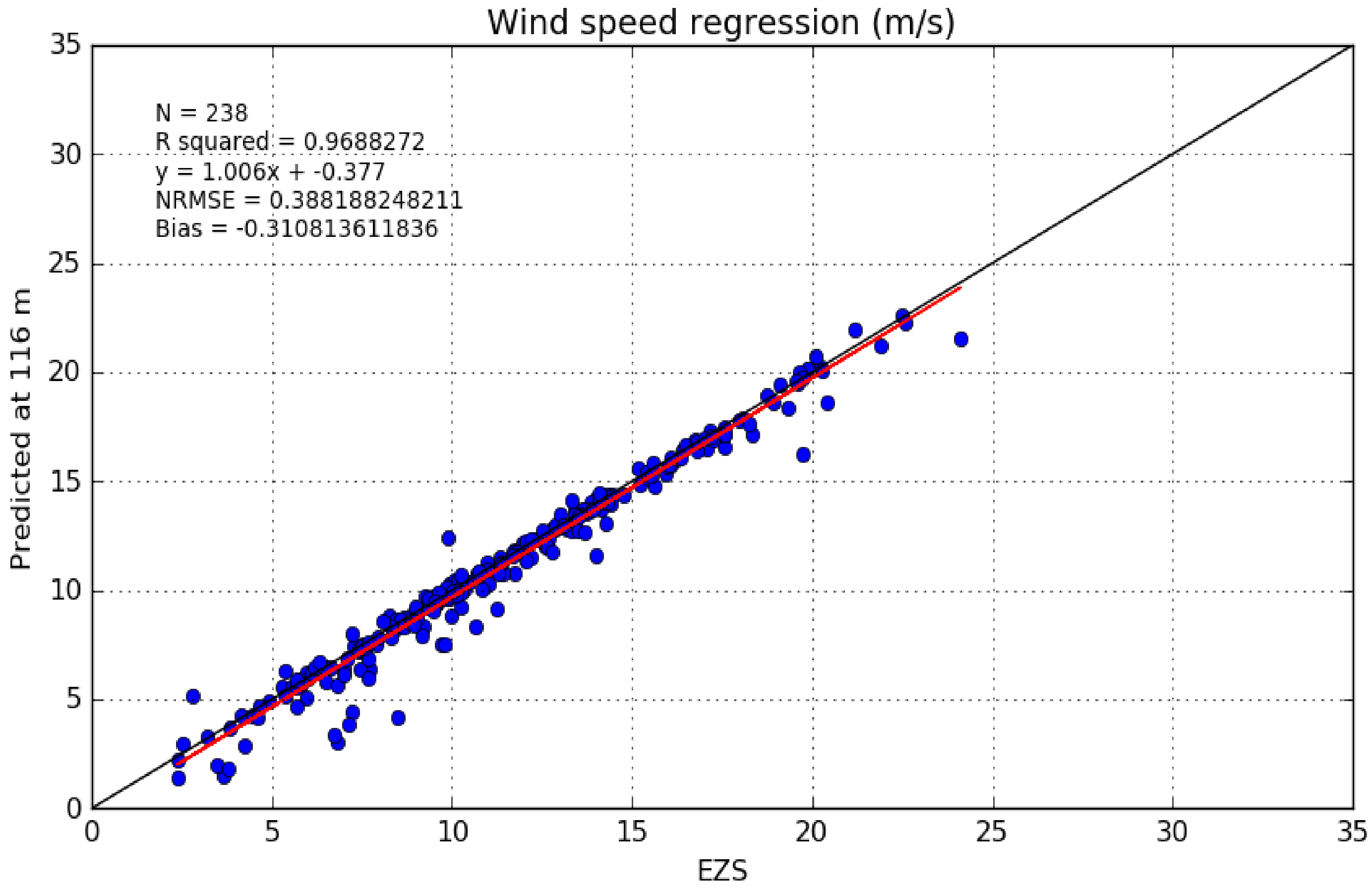






Analyses of surface roughness length under different stability conditions for the 3 assumed wake-free sectors.

On offshore high z_0 values: **Log law**



$$U(z) = U\ (z_r)\left[\frac{\ln(z/z_0)}{\ln(z_r/z_0)}\right] \Rightarrow z_0$$

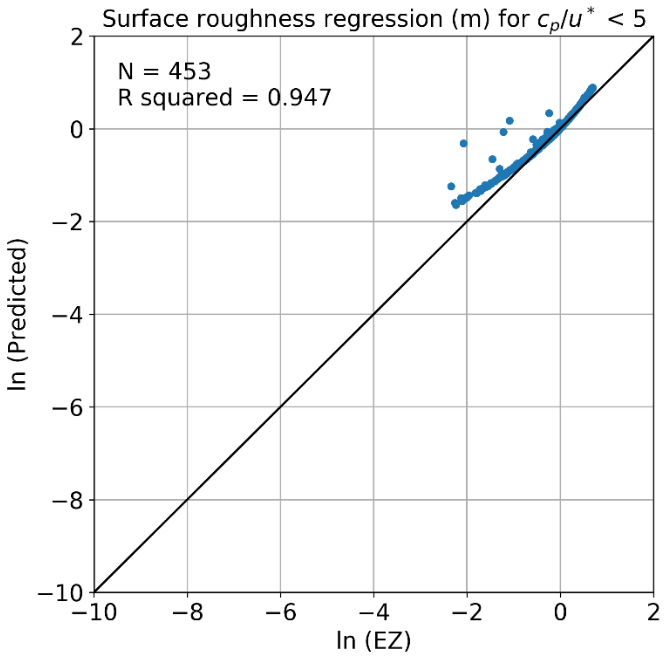
+

$$u_* = \frac{\kappa(U_2 - U_1)}{\ln(z_2/z_1)} \Rightarrow u_*$$

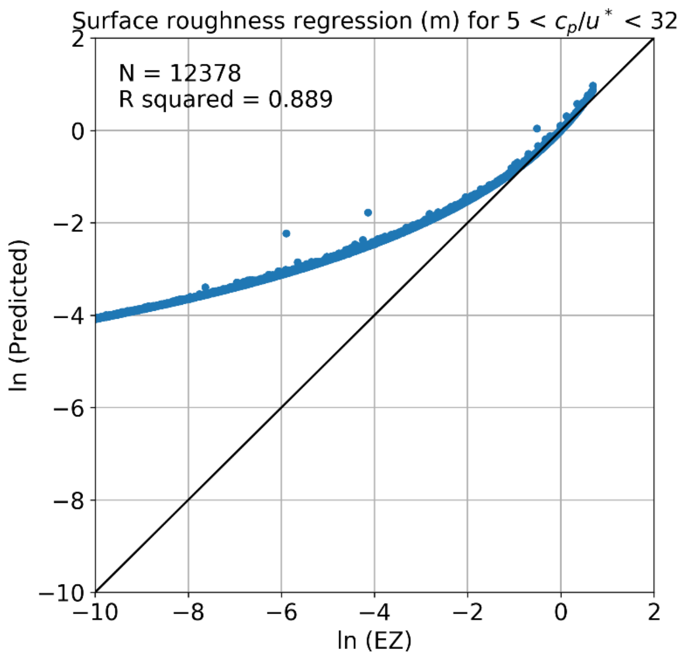
$$U(z) = \frac{U_*}{k}\left[\ln\left(\frac{z}{z_0}\right)\right]$$

$$\Rightarrow U_{116}$$

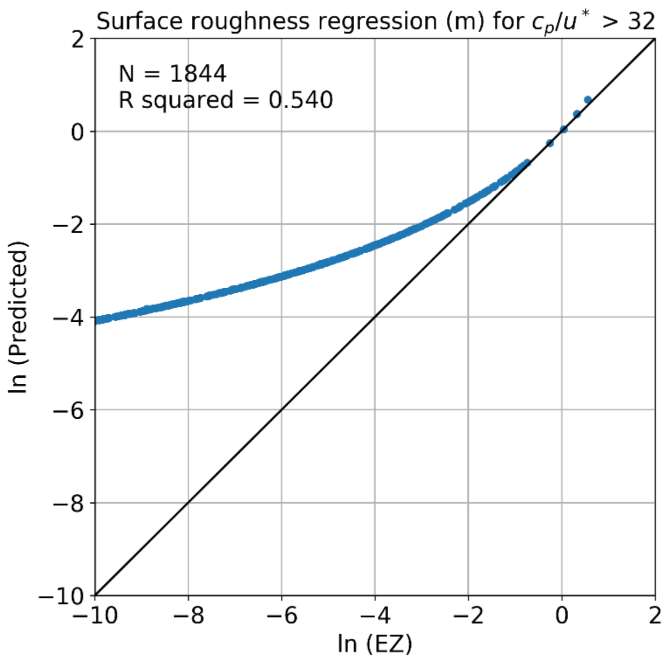
On offshore high z_0 values: **Sensibility analysis**



Calm seas



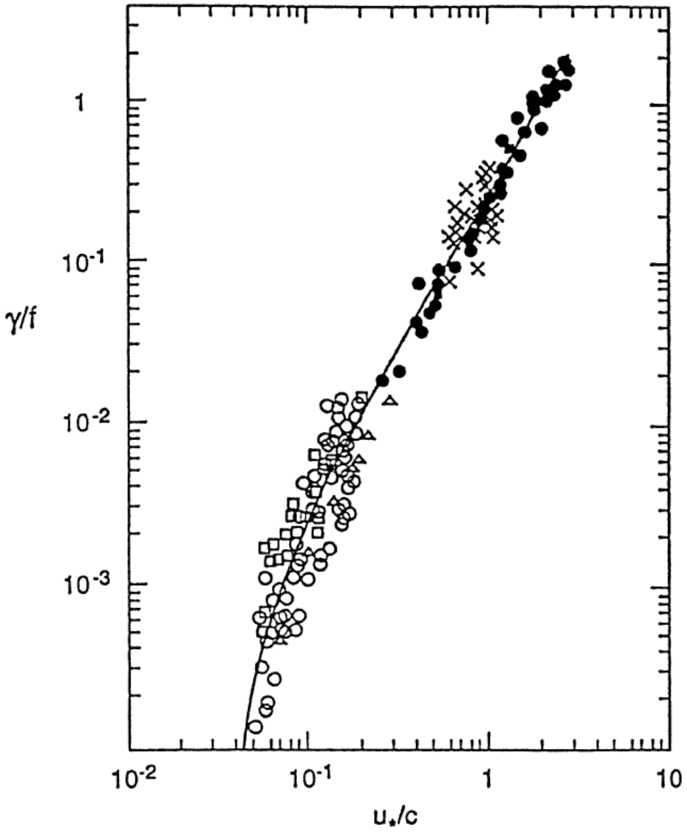
Growing seas



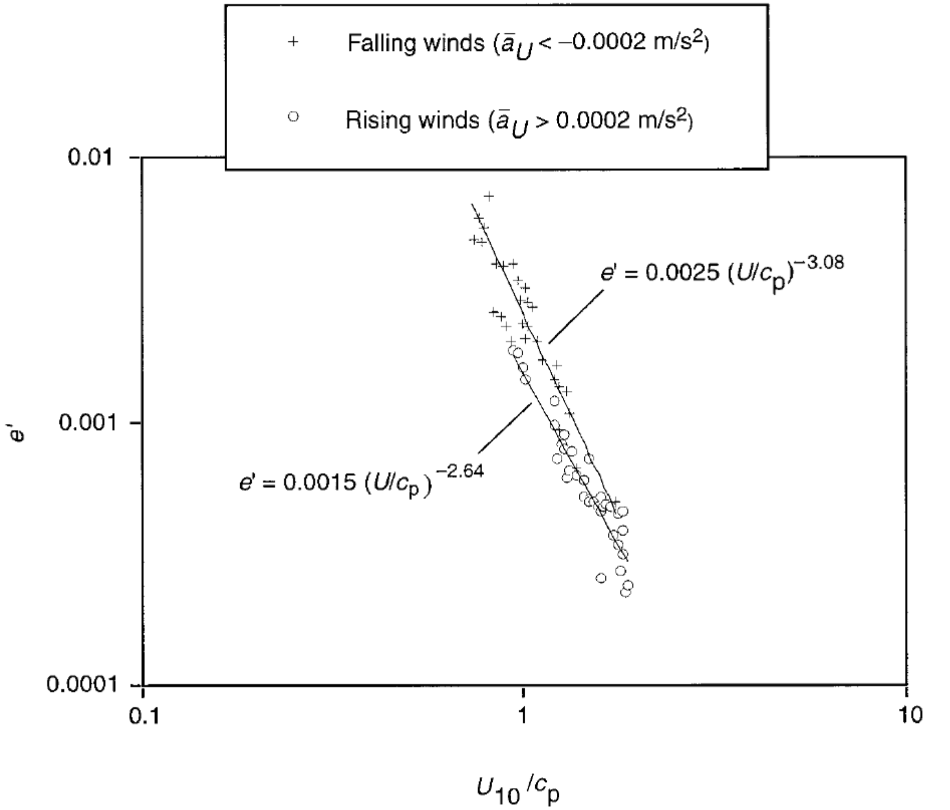
Decaying seas

The younger the wave the rougher the sea

On offshore high z_0 values: Kinetic energy exchange



Observed non-dimensional wind wave growth rates (vertical axe) against the inverse wave age (horizontal axe). Open circles and squares are field data, others are laboratory data. γ represents the non-dimensional wind input growth rate, f is the wave frequency, and c is the phase speed. Source: Komen et al., 1994.



Non-dimensional wind energy (e’) in falling and rising wind conditions against the inverse wave age. Source: J.L. Hanson, O.M. Phillips, 1999.

New formulation: **Lettau's equation**

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C_d *: Drag coefficient*

h* *: effective obstacle height*

s *: silhouette or cross-section area*

n *: number of obstacles*

A *: area of the domain*

θ *: angle between wind and wave direction*

$$z_0 = C_d h^* s(n/A)$$ Onshore

$$z_0 = \frac{u_*^2}{U_{10}^2} \frac{H_s^2}{L_p} |\cos\theta|$$ Offshore

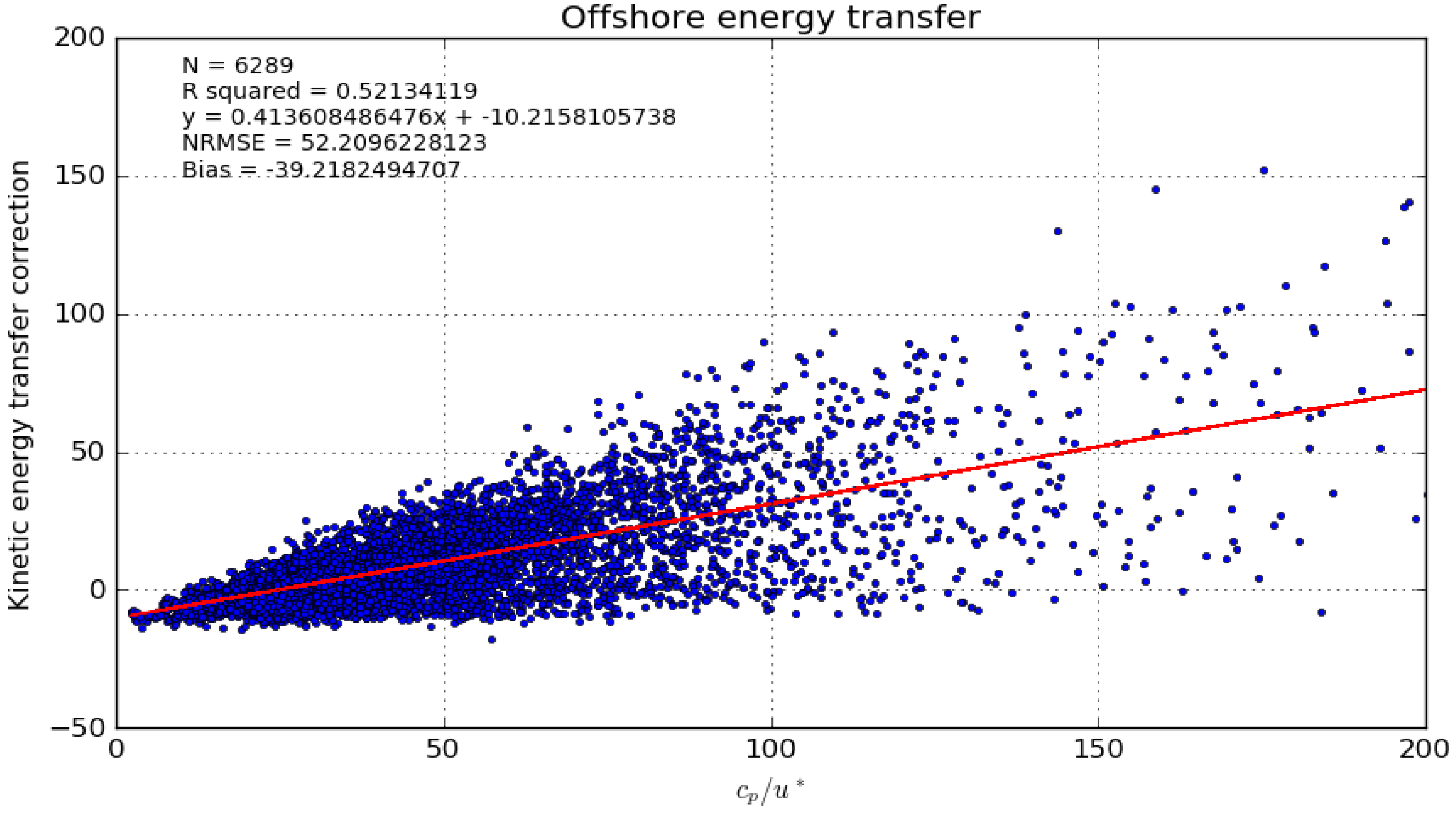
Assuming deep seas in absence of white capping and breaking waves

New formulation still agrees with the direct proportionality between z_0 and u_* found by Charnock in 1952

New formulation: Offshore log law

$$U(z) = \left(\frac{u_*}{\kappa}\right)\left[\ln\left(\frac{z}{z_0}\right) + \Psi_s\left(\frac{z}{L_s}\right) + \varepsilon_k\left(\frac{c_p}{u_*}\right)\right]$$

Kinetic energy transfer correction between ocean and atmosphere (KETC)

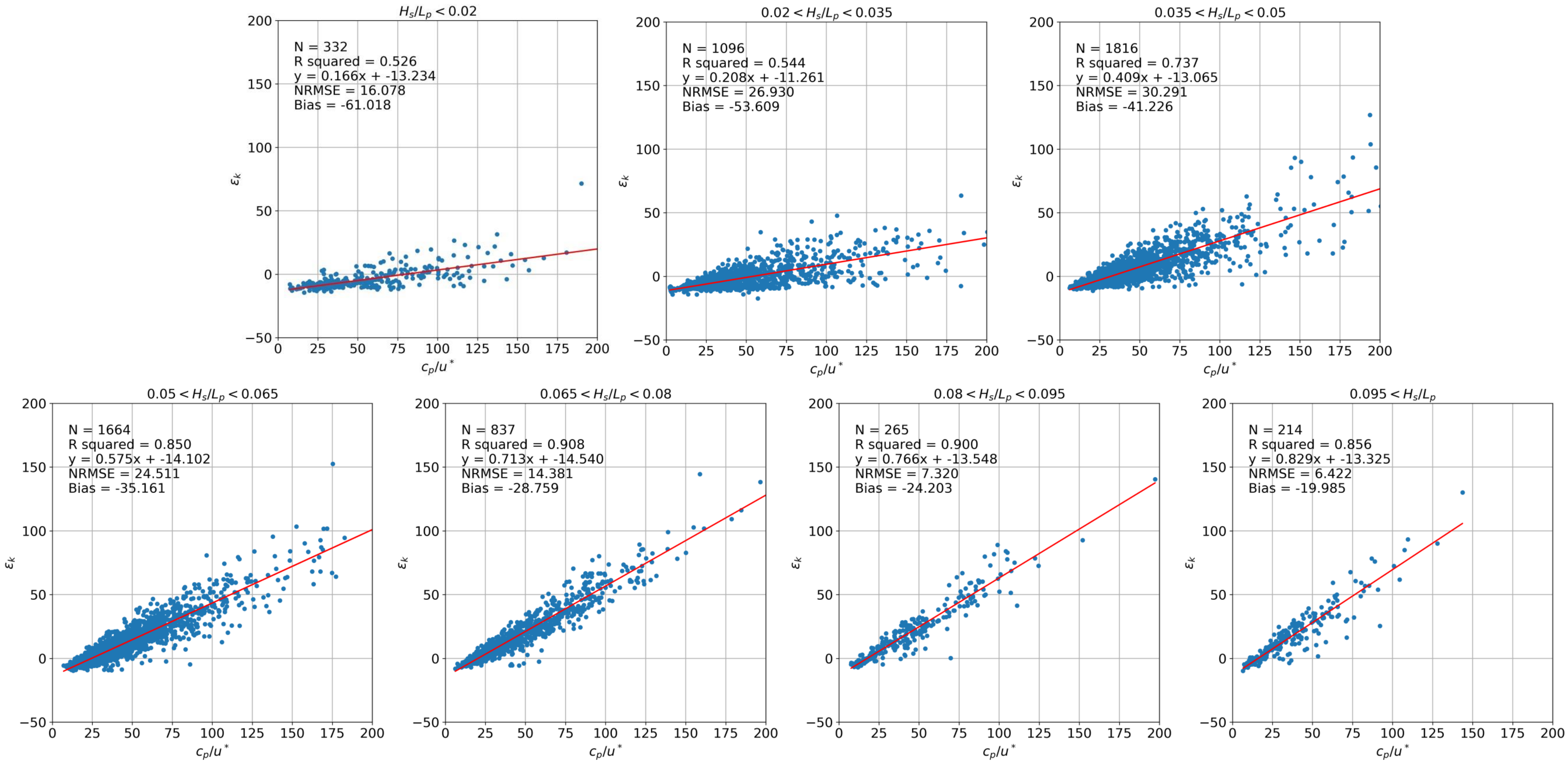


$$y = 0.414\,\frac{c_p}{u^*} - 10.216$$

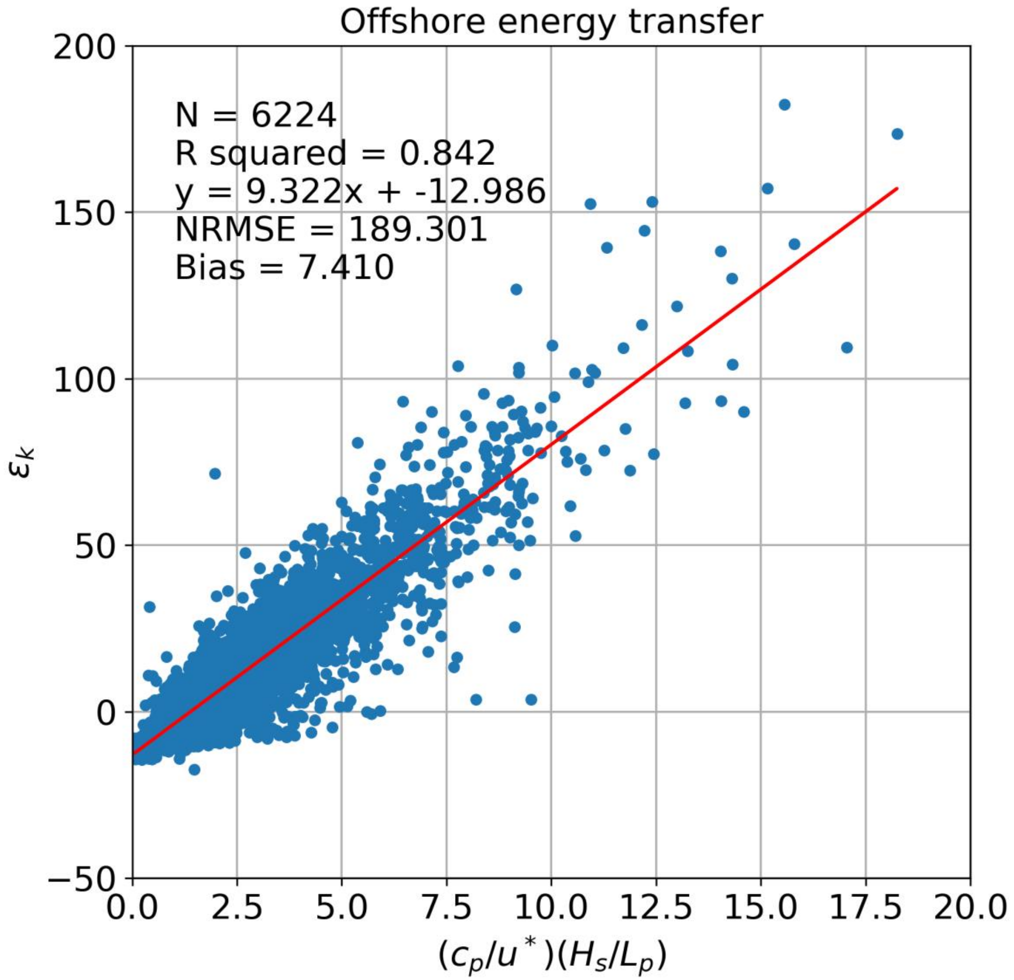
KETC	c_p/u^*	Sea type
< 0	< 24.68	Growing
≈ 0	= 24.68	Fully developed
> 0	> 24.68	Decaying

This wave age for fully developed seas agrees with literature where fully developed seas are meant to be found between 22 – 35 $\frac{c_p}{u^*}$

New formulation: Offshore log law



New formulation: Offshore log law



$$U(z) = \left(\frac{u_*}{\kappa}\right)\left[\ln\left(\frac{z}{z_0}\right) + \Psi_s\left(\frac{z}{L_s}\right) + \varepsilon_k\left(\frac{c_p}{u_*}, \frac{H_s}{L_p}\right)\right]$$

When z = 21 metres

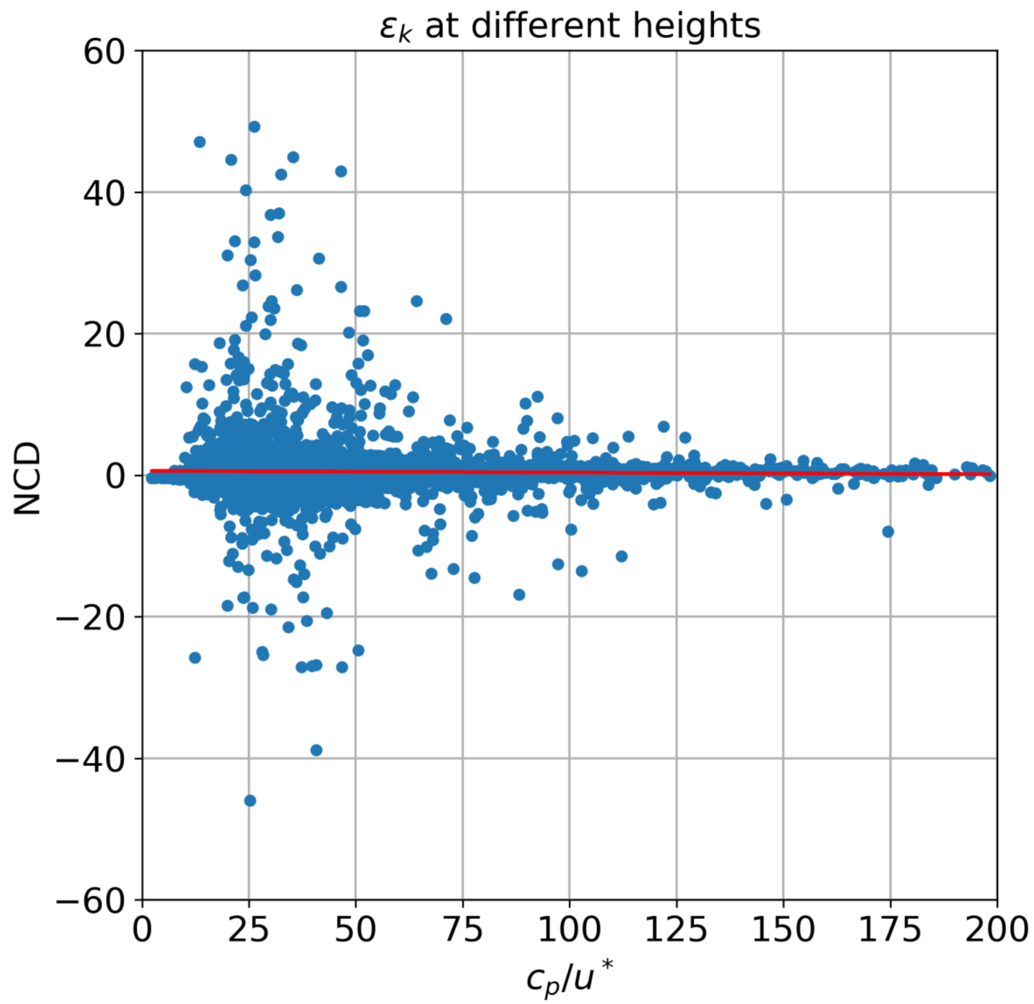
New formulation: Offshore log law

KETC at different heights

$$NCD = \frac{(KETC_{70} - KETC_{21}) + (KETC_{116} - KETC_{21}) + (KETC_{116} - KETC_{70})}{(KETC_{21} + KETC_{70} + KETC_{116})/3}$$

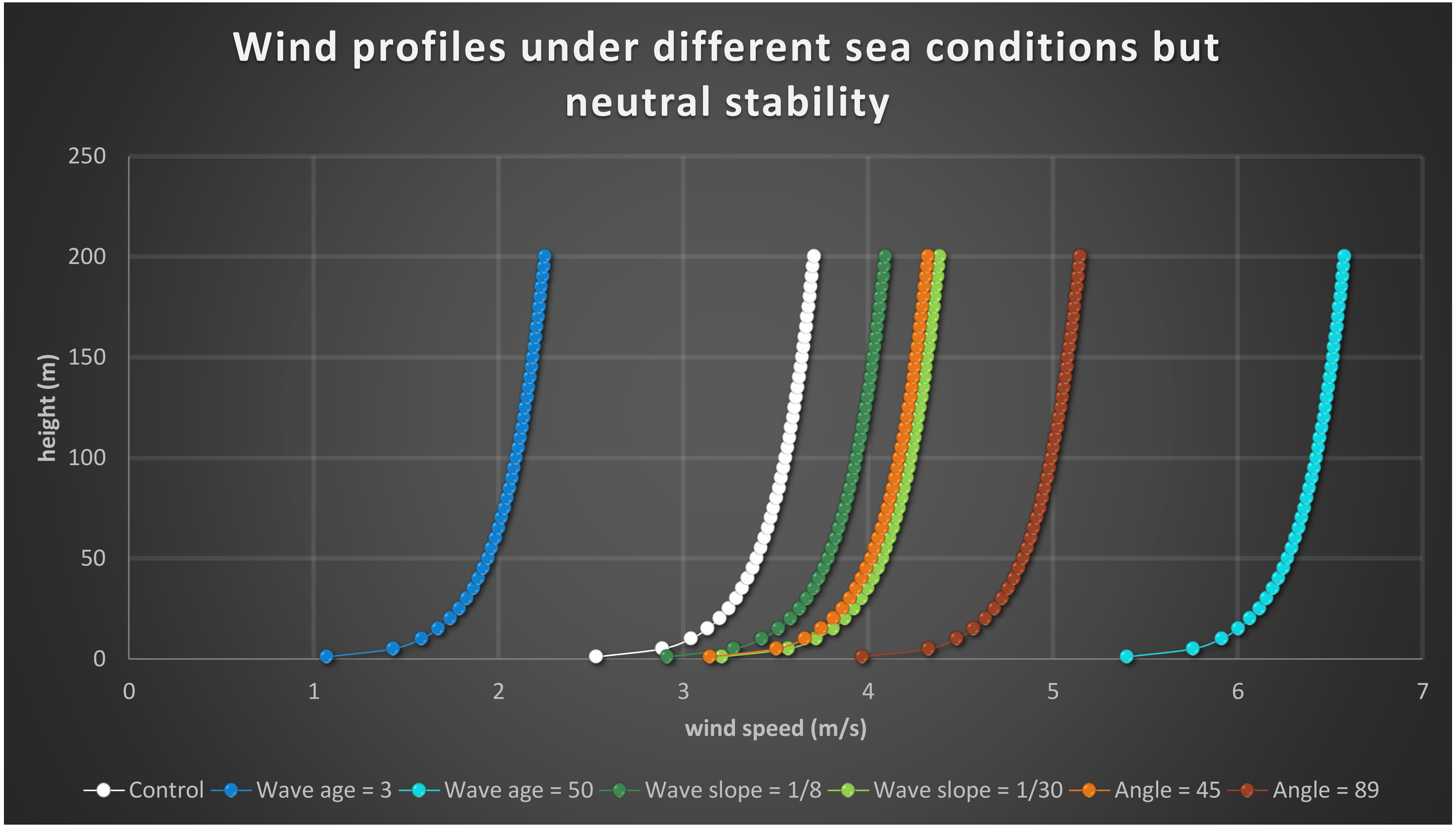
NCD *:*
Normalised cumulative difference

$$U(z) = \left(\frac{u_*}{\kappa}\right)\left[\ln\left(\frac{z}{z_0}\right) + \Psi_s\left(\frac{z}{L_s}\right) + \varepsilon_k\left(\frac{c_p}{u_*}, \frac{H_s}{L_p}, z\right)\right]$$



Sensibility analysis

Average conditions at Egmond aan Zee under neutral conditions (excepting the angle)	
u* (m/s)	0.089
H_s (m)	1.14
c_p/u^*	24.67
L_p (m)	18.24
H_s/L_p	0.0625
Angle	0
z_0 Rabaneda (m)	1.03005E-06
z_0 Charnock (m)	1.16272E-05



Conclusions

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- The younger the waves, the rougher the seas.
- The offshore logarithmic law should differentiate between wind over a static surface (onshore) and wind over a non-static, fluidic surface (offshore).
- There is a kinetic energy exchange between wind and waves.
- Wave age has a dramatic impact on the wind profile. Wave slope and the angle of difference between wind and wave directions are significant but not as relevant as wave age.
- This energy exchange does not always affect equally at all heights. The younger the waves, the higher probability of unequal energy exchange at different heights.

Further development

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- Study how the Kinetic Energy Transfer Correction varies with height.
- Repeat same study at different locations for validation.
- Analyze how much the pitch control of WT’s is affected.
- Apply Computational Fluid Dynamics to:
    - Find the wave slope point where the wind behaves from single hill turbulent regime to consecutives hills near-laminar regime.
    - Analyze if the von Karman constant is in fact the sinus of the angle between the streak ejected from the turbulent flow near a wall parallel to the fluid motion, and the wall.
    - Analyze the momentum and energy transfer along the fetch which is long enough to reach fully developed waves.

Further development

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Are you interested in a further development of the offshore logarithmic law?

Will you be interested in including a variable sea surface roughness length inside WindSim for offshore applications?

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CATAPULT Satellite Applications

CATAPULT Offshore Renewable Energy

University of Strathclyde Glasgow

Thank you