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Foundation Ex 2025

Wind Sea and Swell Waves - Getting it right, and the impact on Fatigue Design

Bristol (UK) 2025-05-20

Date: 2025-05-12
Doc. No: 002-000-004-01
Revision: 2
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1. Objectives of this Presentation – The long version

The development of offshore wind farms requires detailed evaluations of wind, sea state, currents, and water level conditions, along with other environmental variables. Despite their interdependence, wind resource and metocean studies are often treated as separate disciplines, carried out by distinct specialists. Yield analysts focus on hub-height wind speeds, often disregarding surface wind and sea state, while metocean experts prioritize surface winds, waves, and currents, with limited attention to the atmospheric boundary layer (ABL) and its influence on turbine behaviour and design load effects.

Technically, wind across the ABL, sea state, and currents are deeply interlinked. Atmospheric stability affects wind-wave correlations and turbulence, and the relative importance of wind-sea and swell waves. Every offshore site presents a unique combination of these phenomena. Accurate characterization of these interactions through measurements and models is essential, yet there are currently no practical guidelines for aligning wind resource and metocean studies. This disconnect can lead to inefficiencies and uncertainties in yield predictions, fatigue load effect assessments, support structure design risk and project planning.

To address this, C2Wind will analyse, several methods in addressing the metocean conditions for design:

- **Total sea state** assuming no variation of stability conditions
- **Separation of wind sea and swell** through 2D spectral Hindcast data assuming no variation of stability conditions
- **Separation of wind sea and swell** through 2D spectral **combined with atmospheric stability** and account for the coherent ambient turbulence and wind shear.

The three levels of analysis complexity will be analysed and through integrated load analysis using a 15 MW generic turbine model the impact on design will be addressed. The conclusions and impact on assessing and improving alignment between wind resource and metocean studies will be outlined. C2Wind will provide a structured approach for integrating the mentioned disciplines across key phases of project development, including measurement campaigns, modelling efforts and investment cost compared to the design risk and added steel costs.

The above will be done using real-world examples from the North Sea. C2Wind will illustrate how these different approaches by evaluating the same metocean parameters will affect the Fatigue loads and support structure design.

1. Objectives of this Presentation – the short version

What will I learn from his Presentation ?	➢ Impact of metocean conditions characterisation on support structure fatigue loads and design ➢ Wind sea / Swell separation + atmospheric stability (Southern North Sea)
What to tell my colleagues?	➢ Using Total Sea State is insufficient. ➢ Separation of Wind sea and Swell is a more correct approach. ➢ Southern North Sea example shows significant load and tonnage reduction.
What is the main takeaway?	➢ **Considering Wind sea and Swell + atmospheric stability reduces support structure costs.**

2. Setting the scene on Metocean data and different analysis approaches

In the following slides, a detailed overview of each of the hindcast data and modelling assumptions to be applied in Integrated Load Analysis will be outlined.

2. Setting the scene on Metocean data and different analysis approaches

<u>Case from IJmuiden Ver (Dutch Offshore Wind Farm Zone).</u>

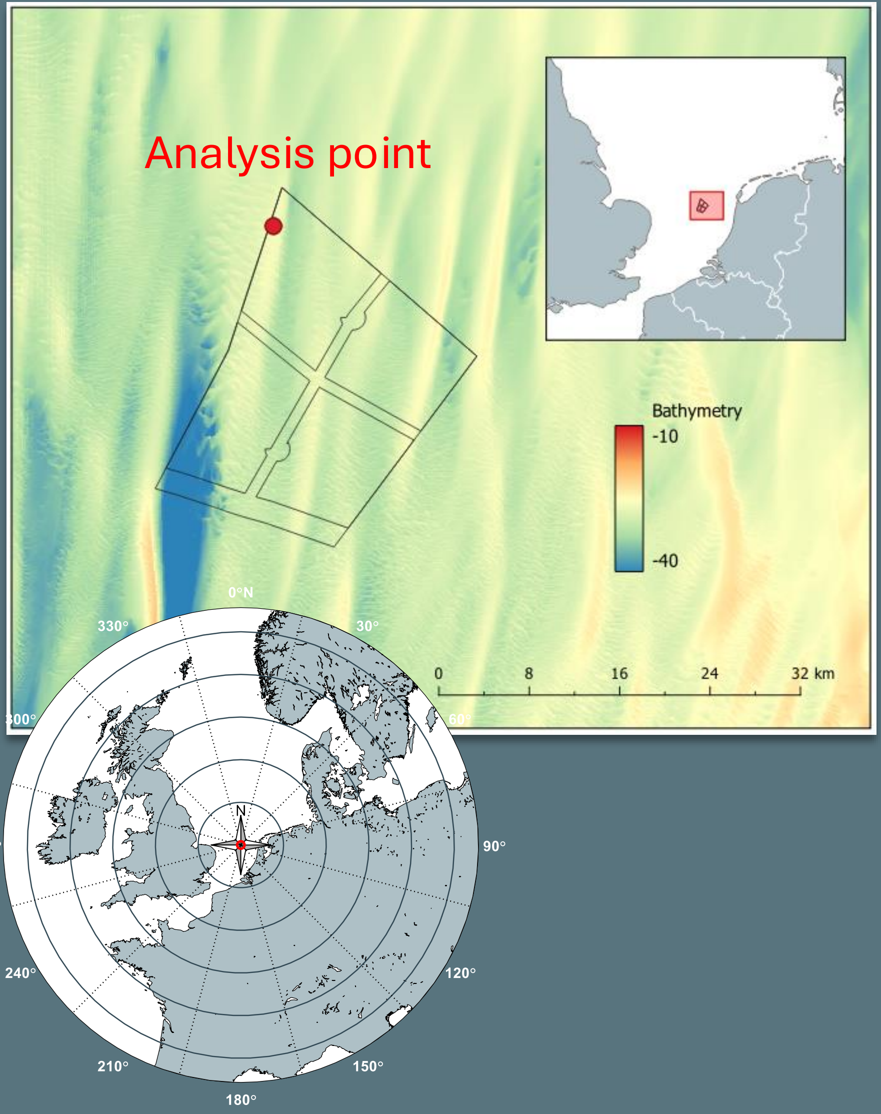
- Metocean and geotech. publicly available from RVO
- Stability assessment based on ERA5

➢ *The problem:*

- Obtaining a <u>unique</u> combination of $\{WS_{Hub}, H_{m0}, T_p, \theta\}$

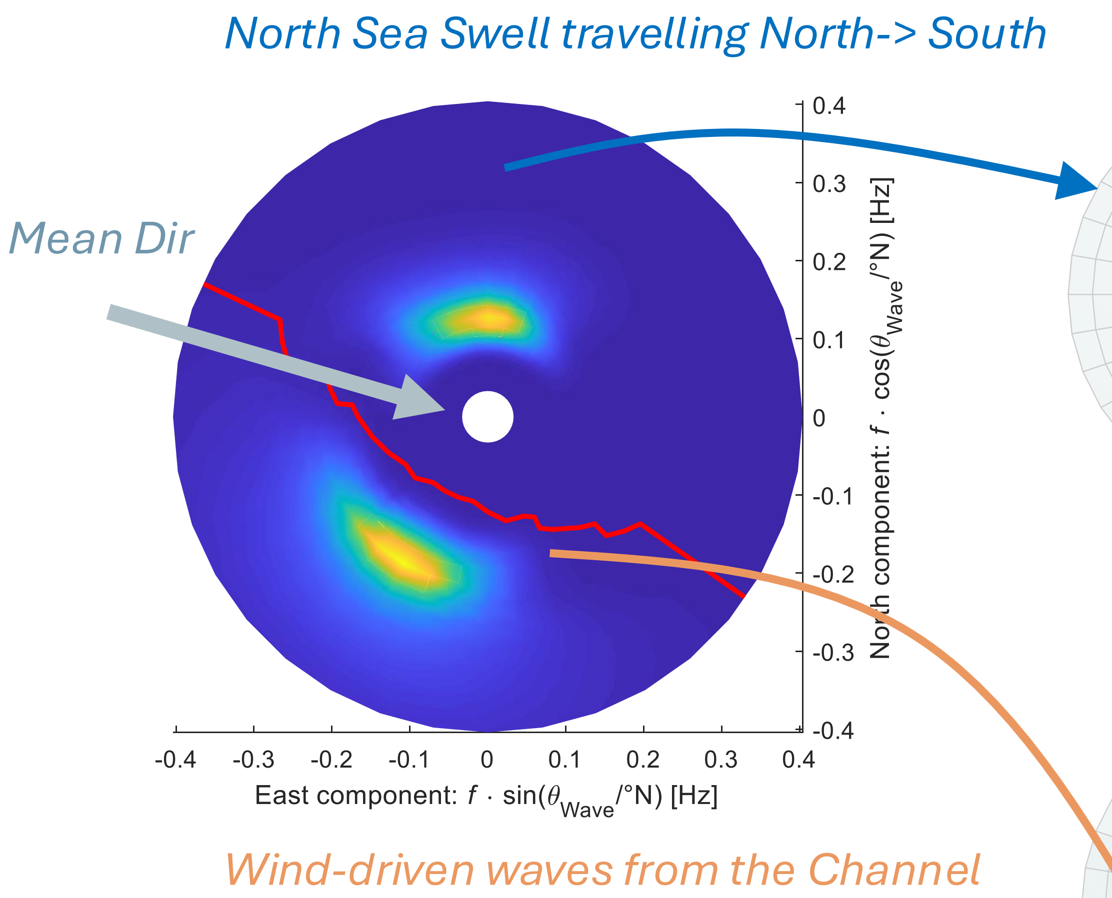
➢ *Solutions with increasing complexity:*

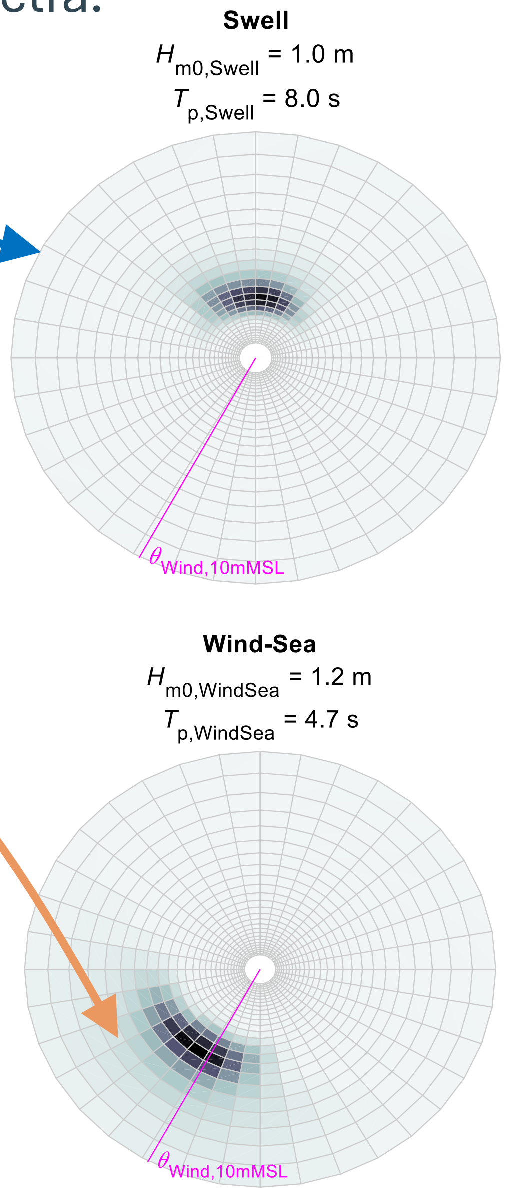
- **Total sea** state assuming no variation of stability conditions.
- **Separation of wind sea and swell** through 2D spectral Hindcast data assuming no variation of stability conditions.
- **Separation of wind sea and swell through 2D spectral combined with atmospheric stability** and account for the coherent ambient turbulence and wind shear.

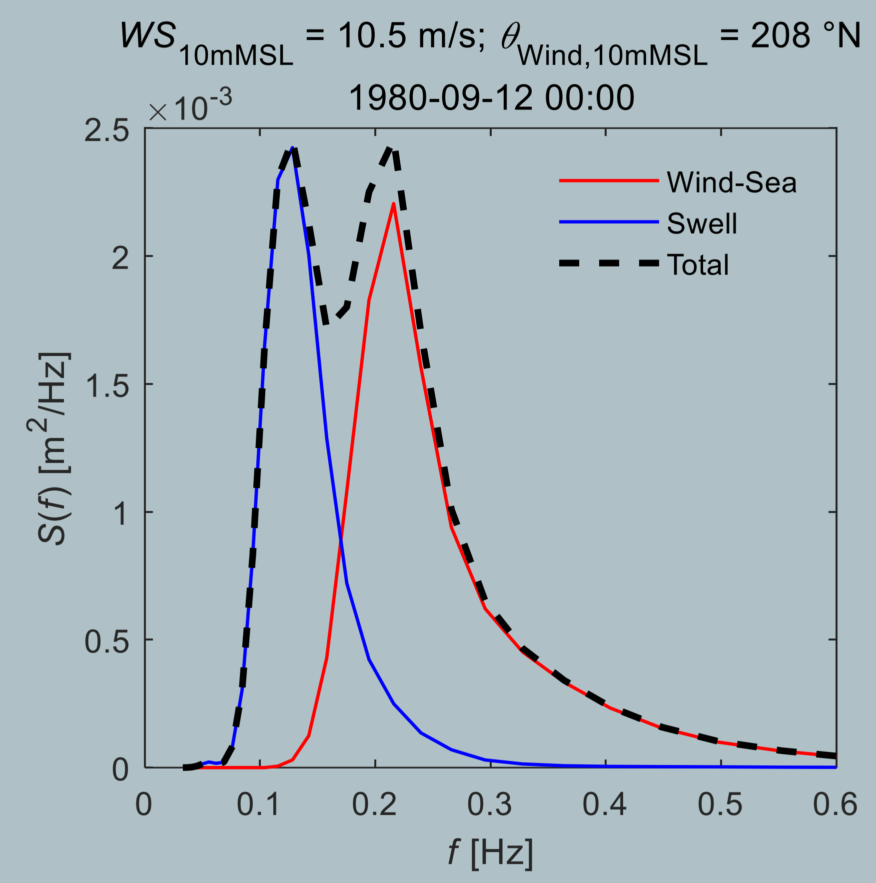


2. Setting the scene on Metocean data and different analysis approaches

For every hourly timestamp, Wind-Sea and Swell components are constructed* from the directional spectra.







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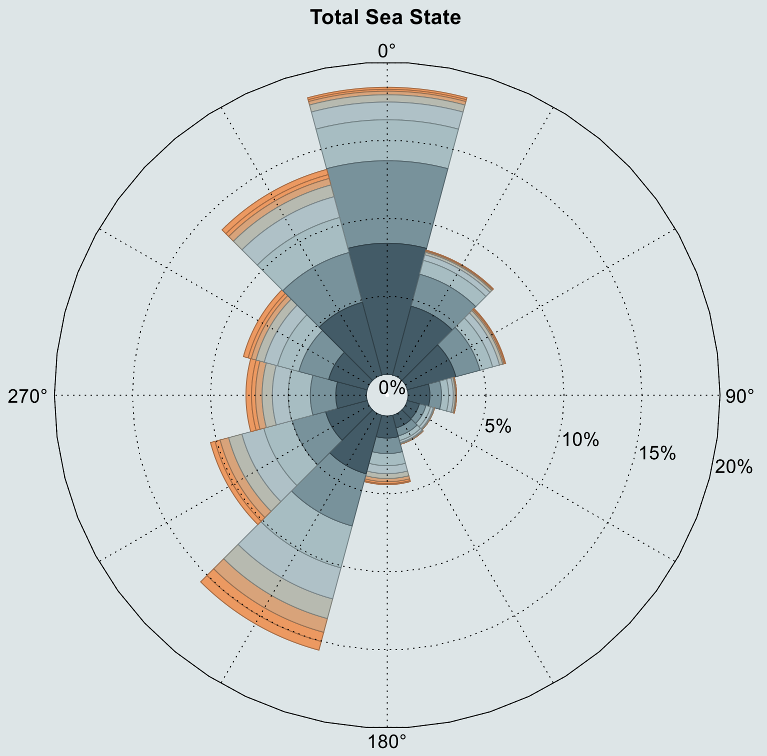
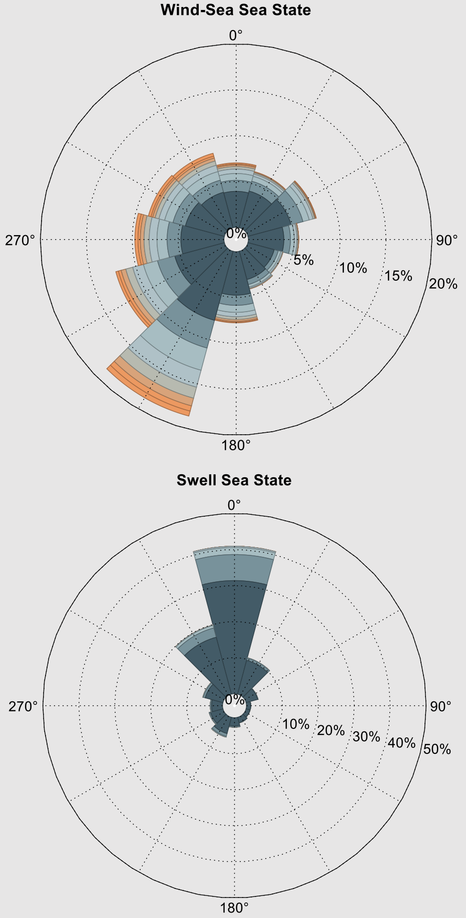
*using a modified wave-age criterion

2. Setting the scene on Metocean data and different analysis approaches

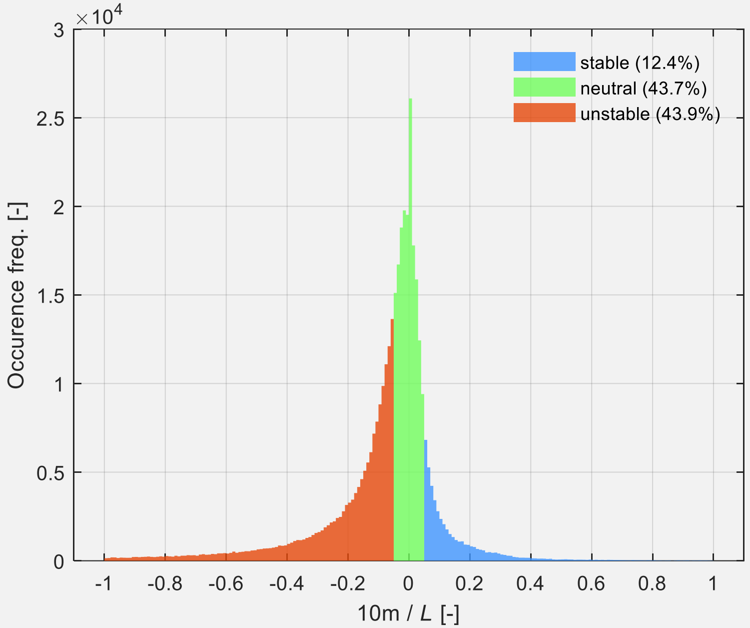
Total sea state



Wind Sea and Swell



Atmospheric stability classes



Unstable: *small wind shear*

Stable: *Large wind shear + veer*

(using Obukhov lenght L)

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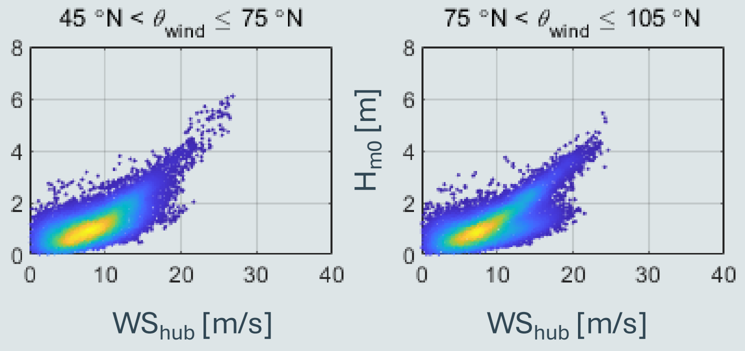
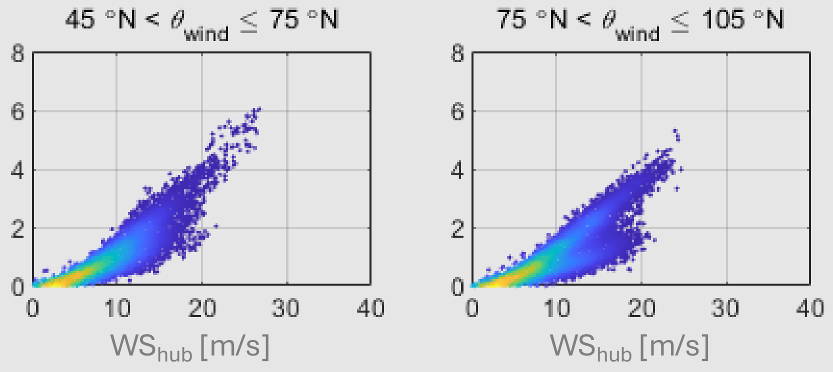
2. Setting the scene on Metocean data and different analysis approaches

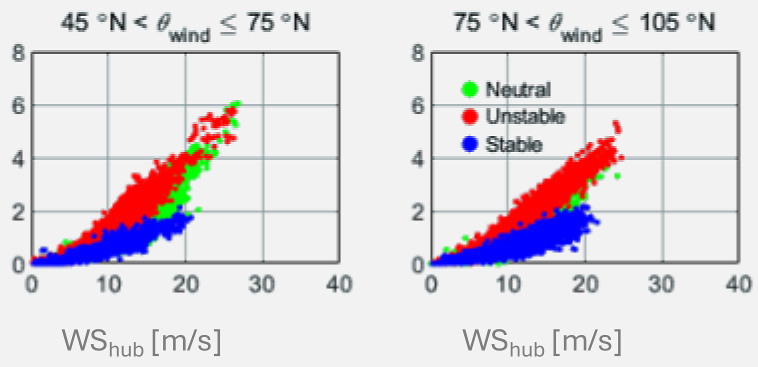
Total sea state



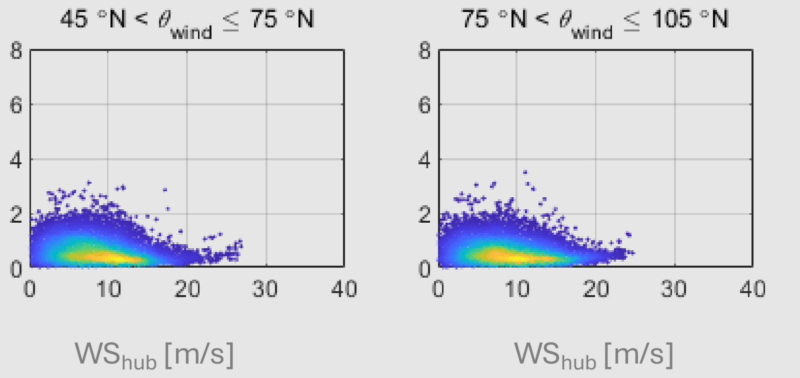
Wind Sea – all stabilities



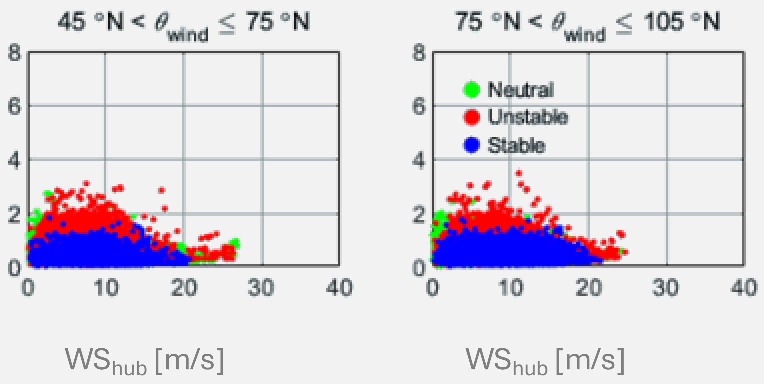
Wind Sea – 3 stability classes



Swell – all stabilities



Swell – 3 stability classes



- ✓ Increased **correlation** between Wind-Sea wave heights and hub height wind speed
- ✓ Swell remains uncorrelated with local wind conditions

Examples of NSS characterisation on 2 (out of 12) directional sectors

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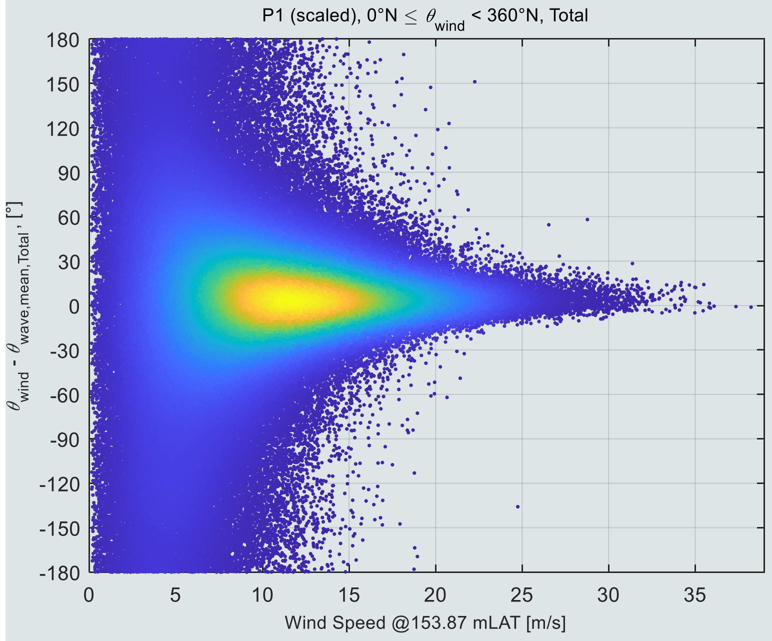
2. Setting the scene on Metocean data and different analysis approaches

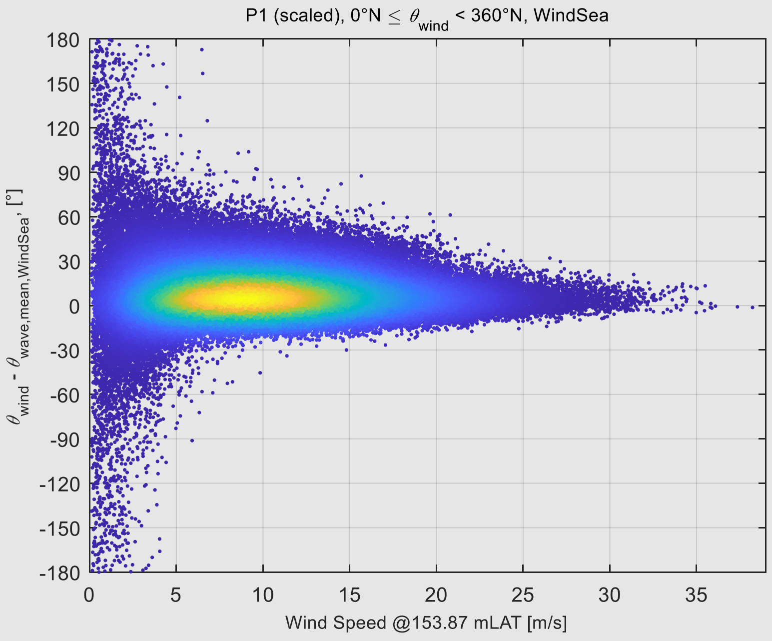
Total sea state

Unrealistic mean wave directions lead to very large scatter of misalignment



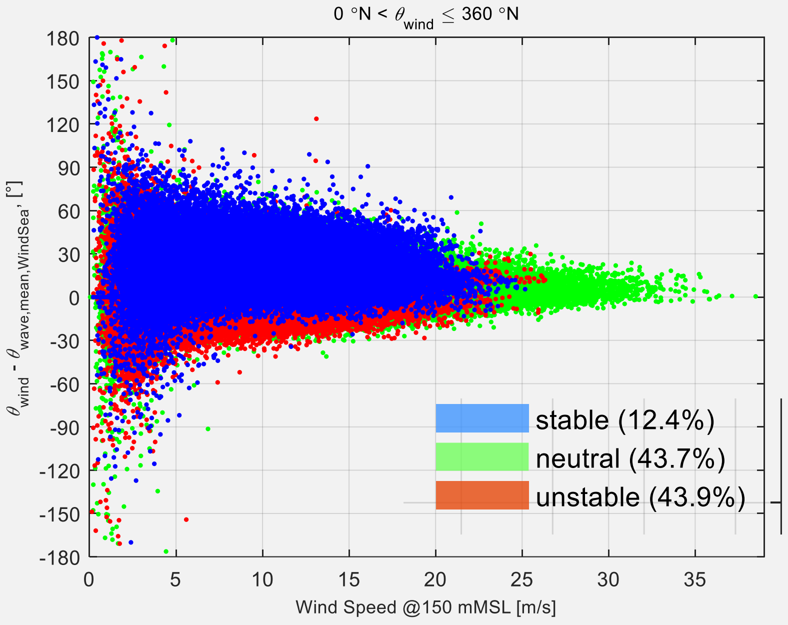
Wind-Sea

Mean Wind-Sea wave components are well correlated with local wind direction



Wind Sea + 3 stability classes

No significant effect of atmospheric stability on misalignment for this site.



3. Impact on Fatigue Design by different Metocean analysis methods

In the following slides, overview of the results form the Integrated Load Analysis, its impact on design and its assumptions will be outlined.

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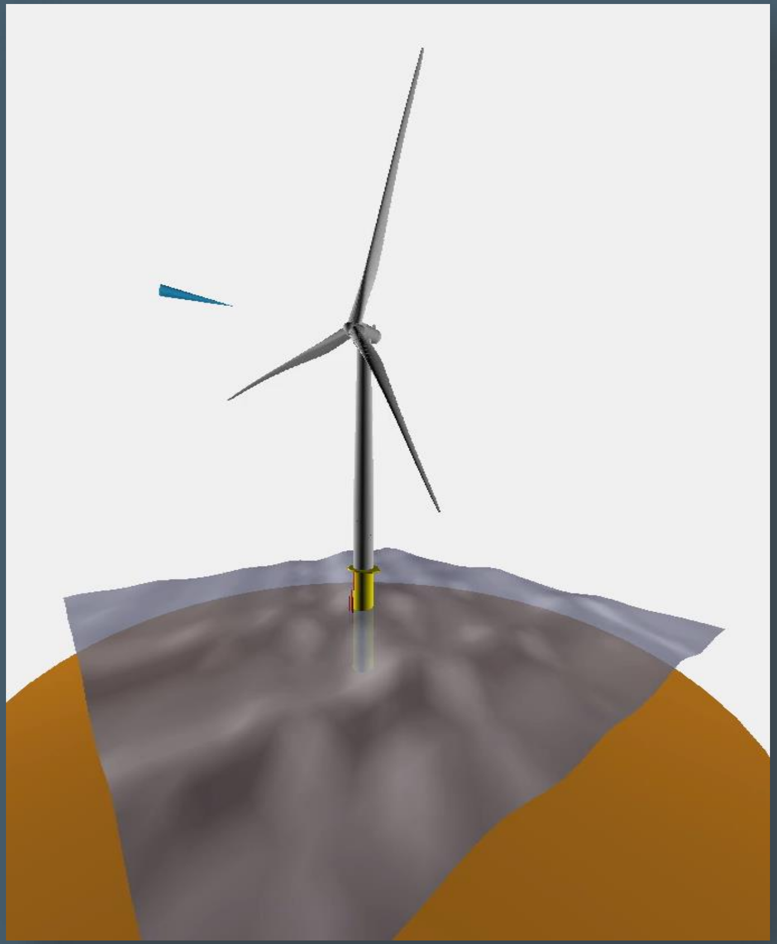
3. Impact on Fatigue Design by different Metocean analysis methods

<u>Overview of integrated load effect simulations setup.</u>

- Note that that the # Simulations does not explode

Design Load Cases	Total Sea	Wind Sea and Swell separation	Wind Sea and Swell separation incl. stability
DLC 1.2 Normal production	# 2102	# 1219	# 2737
22.5 years			
DLC 7.2 Standstill	# 2102	# 1219	# 2737
10% and 1 year of commissioning			
3.5 years			
Sum of Simulations	# 4204	# 2438	# 5474
Other items			
Seeds	1 wind and wave seed per event		
Yaw error	+6 Deg (only one YE considered)		
Directional bins	12 directional bins incl. misalignment.		
Aeroelastic code	C2FLEX (Flex5)		
Over 1st mode Damping:	7.5% Log decr. Tower damper, soil, steel and water		
Turbulence conditions	Site and layout specific ca. 15% below IEC class C		
Turbine model	**Generic 15 MW 236m rotor**		
Hub Height	154.0 mLAT		
1st mode frequency	0.15 Hz		
Other environmental conditions			
Wind shear	0.10		
Turbulence conditions	Site and layout specific		
Water depth	41.5 mLAT		
NWLR incl. sea level rise	1.1 m		



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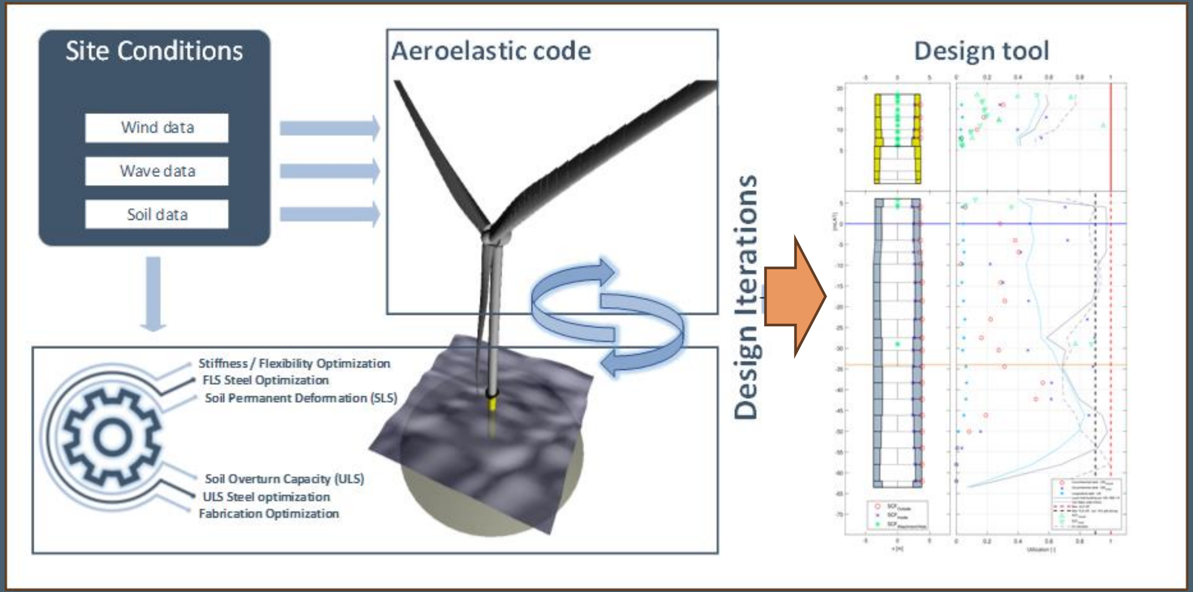
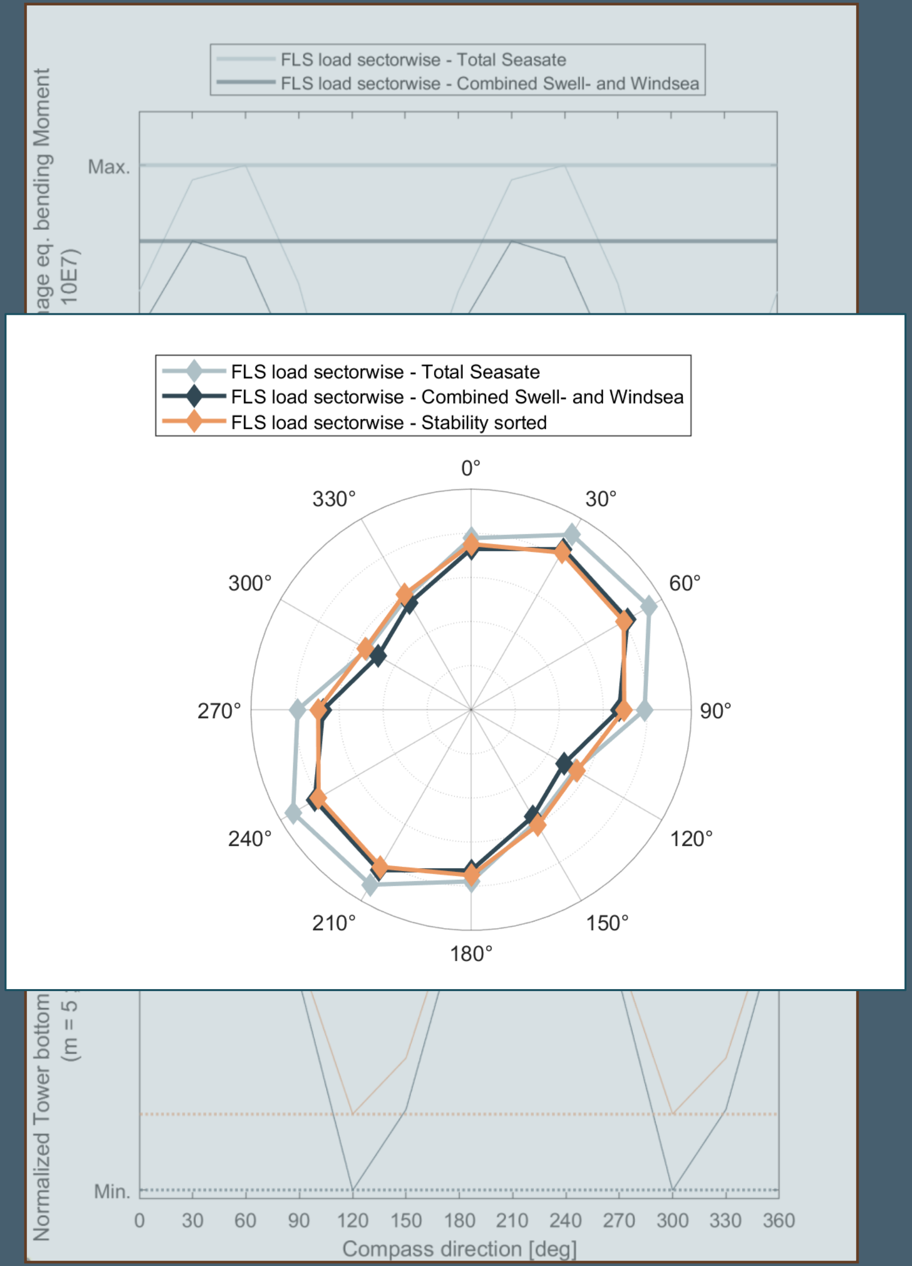
3. Impact on Fatigue Design by different Metocean analysis methods





- 5% on fatigue loads compared to Total sea state.

Directional fatigue distribution changes.

Influence of atmospheric stability is limited for this site, but not for others (ex: New England (US)).

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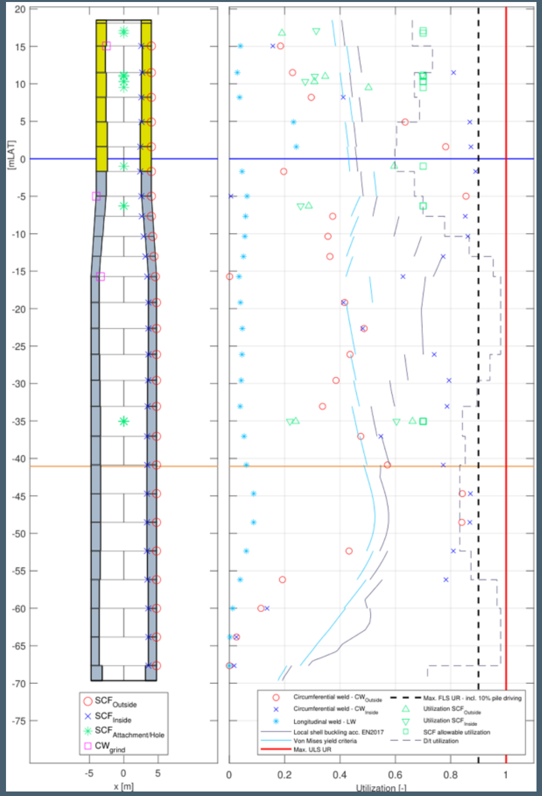
3. Impact on Fatigue Design by different Metocean analysis methods

➢ Impact on TP-less Monopile design and **potential steel cost saving.**

Total sea-state
Damage Equivalent Load =1.00

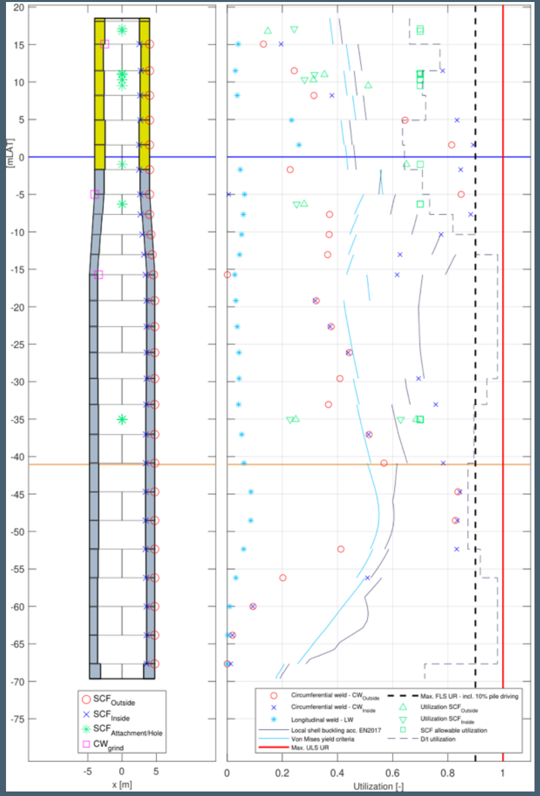


$\text{Mass} = 1623\ tonnes$

- ➢ Steel saving up to 4% can be achieved when utilising wind-sea and swell separation.
- ➢ Further avoidance of plates with large thickness → Easier sourcing of plates.
- ➢ Fatigue-critical items are de-risked.
- ➢ Any FLS load effect reduction will result in a lower utilised bolted L-flange connection.

$$\Delta_{Mass} = 56\ tonnes$$
$$\Delta_{Mass} = 4\%$$

Wind-sea and swell separated
Damage Equivalent Load =0.95



$\text{Mass} = 1558\ tonnes$

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5. Conclusions

What should I tell my colleagues?

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3.Conclusion

You should tell your colleagues:

*Considering atmospheric stability and sea state decomposition into **Wind Sea and Swell** reduces uncertainty and will provide lower support structure costs.*

Open for Questions