A New Source Term for MIKE 21 SW: Improving Wave Predictions and Wind Stress Estimates Under Extreme Conditions

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Agenda

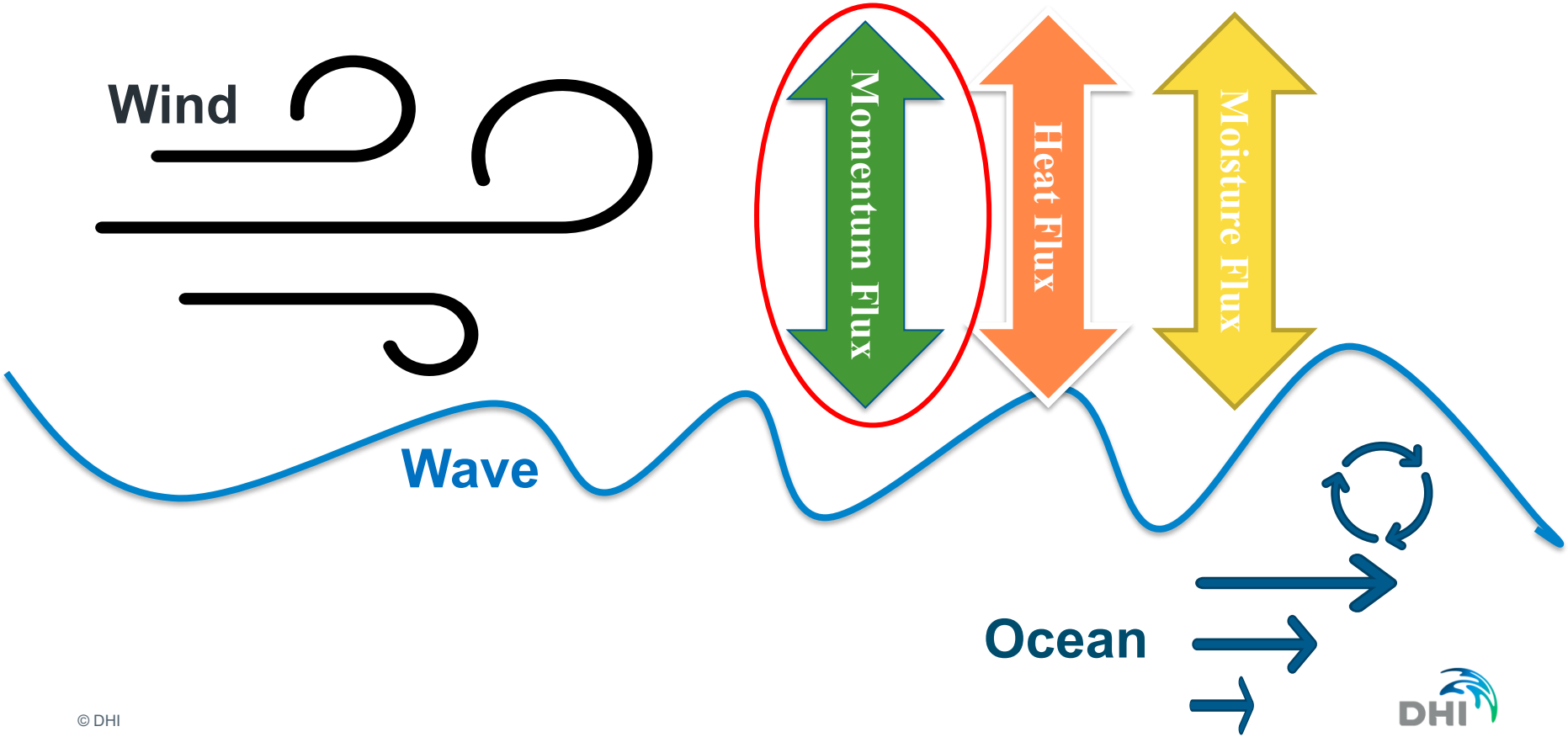
ENGINEERING MOTIVATION: This implementation mainly concerns the extreme sea states, that is, when wind is stronger than say 25-30m/s. That is often less than 1 % of the time - but that 1 % is fundamental for design - and that is what practicing engineers are working with for safe and economic design of offshore and marine structures, and what is being challenged by clients and certifiers.

- The role of waves in air-sea interactions
- Wind-input source terms in MIKE 21 SW
- Wave simulation & validation
- Summary & Outlooks

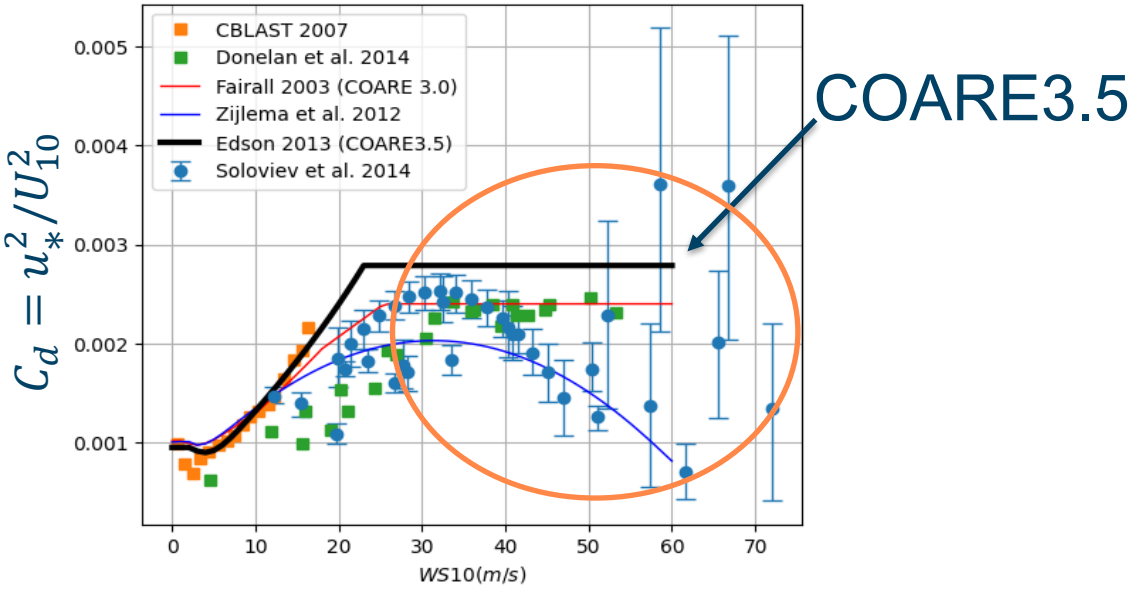
01.

The role of waves in air-sea interactions

Air-Sea Interactions

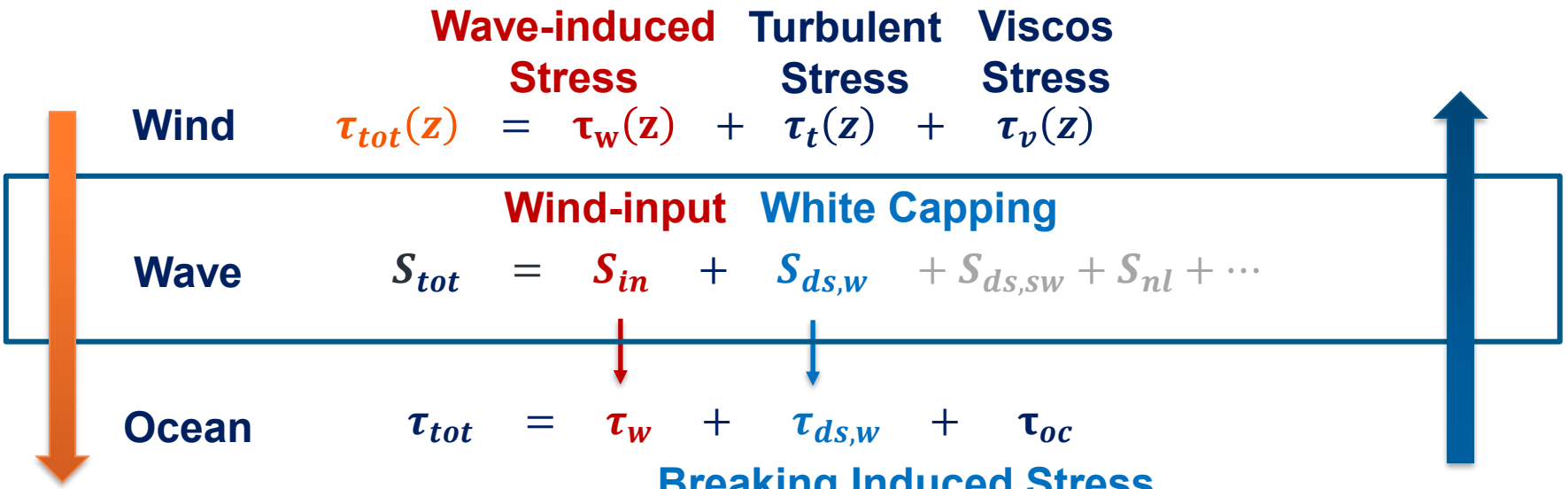


z_0, C_d, U_{10}, and U_* in Wind and Wave Models



COARE3.5: Combined MBL, RASEX, CBLAST, and CLIMODE dataset

The role of waves in air-sea interactions



Ocean side stress:

$$\tau_{oc} = \tau_{tot} - \tau_w - \tau_{ds,w} = \tau_{tot} - \rho_w g \int_0^{\infty} \int_{-\pi}^{\pi} \frac{k}{\sigma} [S_{in} + S_{ds,w}] d\theta d\sigma$$

Viscos Stress τ_v

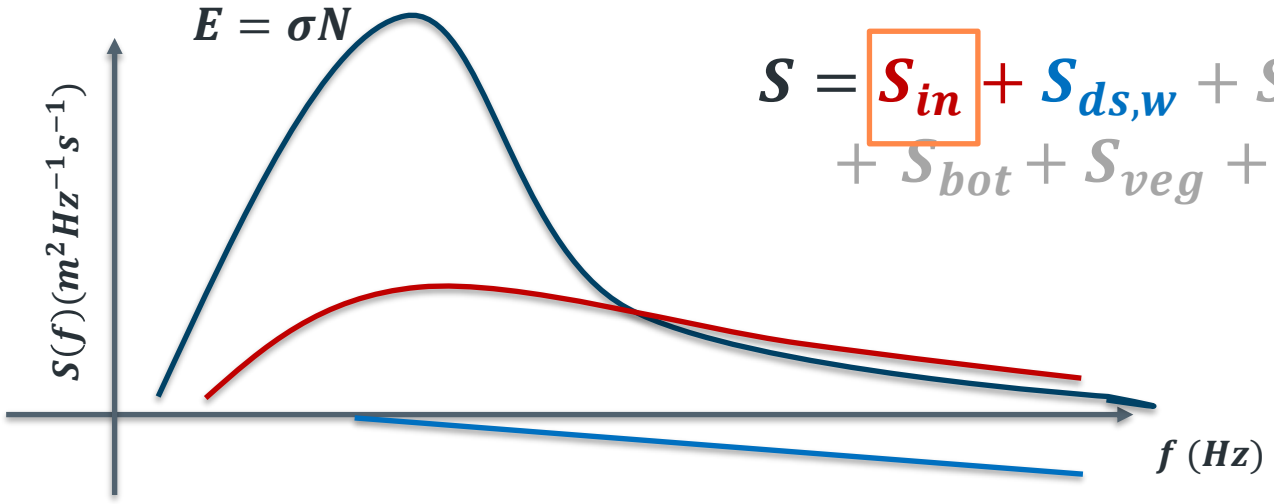
02.

Wind-input source terms in MIKE 21 SW

MIKE 21 SW ocean surface wave model

MIKE 21 SW is a 3rd generation Spectral wave model developed and maintained by DHI.

$$\frac{\partial N}{\partial t} + \nabla \cdot (\vec{v} N) = \frac{S}{\sigma}$$



$$S = S_{in} + S_{ds,w} + S_{ds,sw} + S_{nl} + S_{bot} + S_{veg} + S_{mud} + S_{surf}$$

Source terms in MIKE 21 SW

MIKE 21 SW 2025 originally has two different parameterizations for the source terms for wind-input, swell dissipation and white-capping.

- ❑ Modified **WAM Cycle 4** term, which uses the wind-wave coupling method of **Janssen (1989, 1991)**.

- ❑ **Ardhuin et al. (2010)** terms, which introduced new **swell dissipation**, **saturation-based dissipation, accumulative dissipation** and **stress correction** due to spectral sheltering effect.

- ➢ **In this study**, we implemented a new term for the air-sea interaction with focus on high wind, by introducing the **nonlinear wave growth** theory and **gravity-capillary wave** spectrum contribution according to **Janssen & Bidlot (2023).**

WAM Cycle 4 Source Term (Janssen 1989, 1991)

Wind-input source function:

$$S_{in} = \gamma \cdot \mathrm{E}(f,\theta)$$

$$\gamma = \frac{\rho_a}{\rho_w}\beta\sigma\frac{\boldsymbol{u_*^2}}{c^2}cos^2(\theta-\theta_w)$$

$$\beta = \frac{\beta_{max}}{\kappa^2}\tanh(kd)\mu ln^4(\mu)$$

Wave-induced stress:

$$\boldsymbol{\tau_w} = \int_0^\infty \frac{dP}{dt}df = \rho_w \cdot g \iint \frac{S_{in}}{c}dfd\theta$$

Momentum conservation:

$$\tau_{tot} = \tau_w + \tau_v, where \tau_{tot} = \rho_a u_*^2$$

Stress calculation:

$$\begin{cases} \mathbf{u}(\boldsymbol{z}) = \dfrac{\boldsymbol{u_*}}{\kappa} ln\left(\dfrac{z+z_0}{z_0}\right) \\ z_0 = \alpha \cdot \boldsymbol{u_*^2}/g \\ \alpha = \dfrac{\alpha_0}{\sqrt{1-\boldsymbol{\tau_w}/\boldsymbol{\tau_{tot}}}} \end{cases}$$

Ardhuin et al. (2010) Source Term

Friction velocity correction:

$$u'^{2}_{*} = \left| u^{2}_{*}(\cos\theta, \sin\theta) - \boldsymbol{s_u} g \frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{a}}} \iint \frac{S_{in}}{c}(\cos\theta, \sin\theta) df d\theta \right|$$

Saturation dissipation:

$$S_{ds}(f,\theta) = \sigma C_{ds}^{sat} \left(\delta_d max\left(\frac{B(f)}{B_r} - 1{,}0\right)^2 + (1-\delta_d) max\left(\frac{B'(f,\theta)}{B_r} - 1{,}0\right)^2 \right) E(f,\theta)$$

Swell dissipation:

$$S_{swell,vis}(f,\theta) = -s_5 \frac{\rho_{\mathrm{a}}}{\rho_w}\left(2k\sqrt{2\nu_a\sigma}\right)E(f,\theta)$$

$$S_{swell,tur}(f,\theta) = \frac{\rho_{\mathrm{a}}}{\rho_w}(16 f_e \sigma^2 u_{orb}/g)E(f,\theta)$$

Janssen & Bidlot (2023) Source Term

- The partial **sheltering effect** of Ardhuin et al. (2010) has been replaced by the **nonlinear wind-input source function**.

  -- Logarithmic wind profile → nonlogarithmic

$$\gamma_0 = \frac{\rho_a}{\rho_w}\beta\sigma\frac{u_*^2}{c^2}cos^2(\theta-\theta_w) \rightarrow \gamma = \gamma_0\frac{1+N_1}{1+N_2}$$

$$N_2 = \frac{k^3}{\epsilon\kappa u_*}\int d\theta\gamma_0 F(k,\theta)$$

$$N_1 = \frac{k^3}{\epsilon\kappa u_*}\int d\theta\gamma_0 F(k,\theta)\sin^2\theta$$

- A model for **gravity-capillary waves (High Frequency tail)**
  -- Dominated by three-wave interactions

$$B_{3w} = \left(\frac{\Phi_0}{2\alpha_3}\right)^{1/2} c_0^{-3/2}\frac{y(1+3y^2)^{1/2}}{(1+y^2)(y+y^3)^{1/4}}$$

Note: In this study, it looks like the gravity-capillary waves stress is replacing the viscous stress.

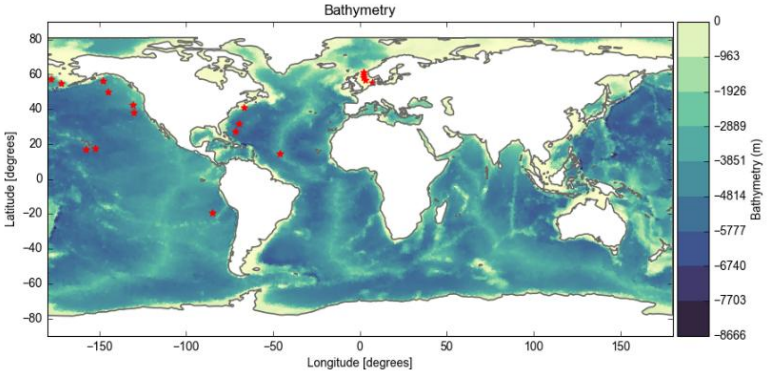
03.

Wave simulation & Validation

Global wave simulation & validation

- 36 directions
- 36 frequencies (0.035 ~ 0.98 Hz)
- Spatial resolution: 15 ~ 50 km
- Wind forcing: ERA5 10m wind

Storm events at Ekofisk & Fino3			Station (Hm0)	
#	Date	Name	Ekofisk	Fino3
1	01/11/2006	Britta	8.4*	
2	09/12/2011	Friedhelm	9.5	
3	04/01/2012	Ulli& Andrea	9.4*	
4	06/12/2013	Bodil	9.6	
5	10/01/2015	Nina		7.5
6	04/01/2017	--	8.5	6.9



Key Parameters	Ardhuin et al. (2010)	Janssen & Bidlot (2023)
β_{max}	1.42	1.39
$C_{ds,sat}$	-2.2e-5	-2.2e-5
$C_{d,cap}$	0.0036	**off**
$\tau_{w,max}$	5	**off**

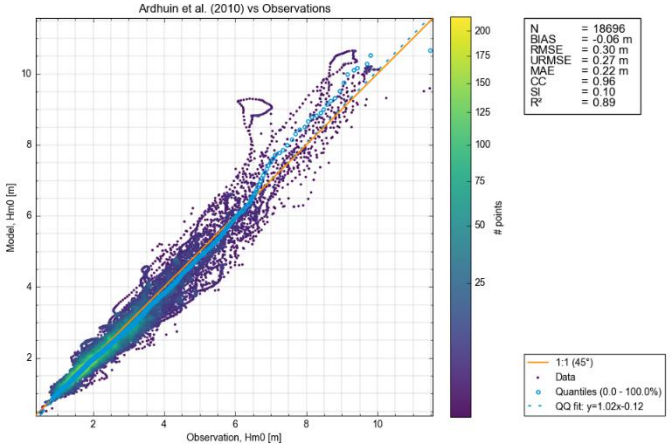
Global wave validation

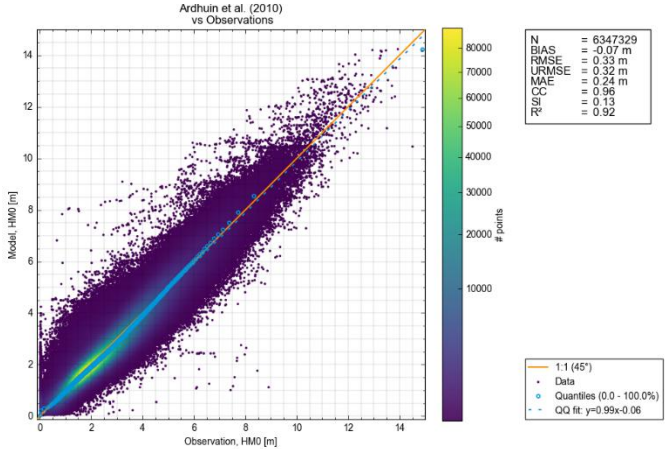
In-situ Measurements Hm0

Satellites:

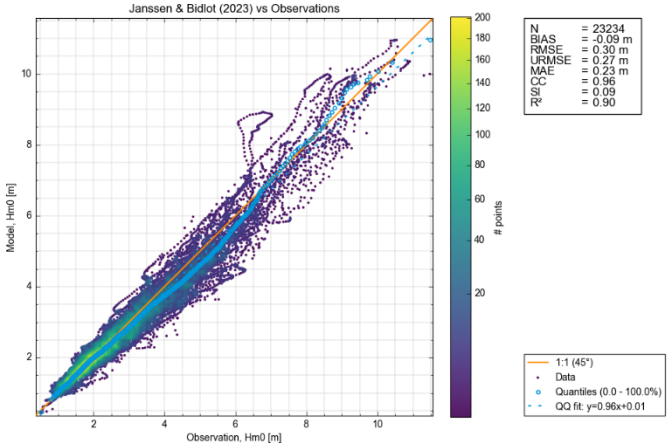
CryoSat-2
ERS-2
Envisat
GFO
Jason-2
SARAL
Sentinel-6A
Sentinel-3B
Jason-1
Sentinel-3A
Jason-3

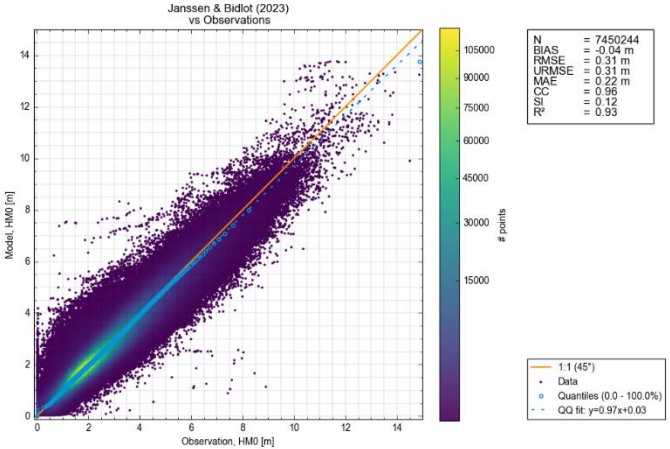
Ardhuin et al.





Janssen & Bidlot





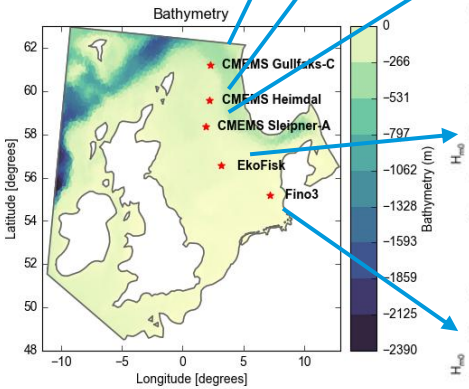
North Sea wave validation

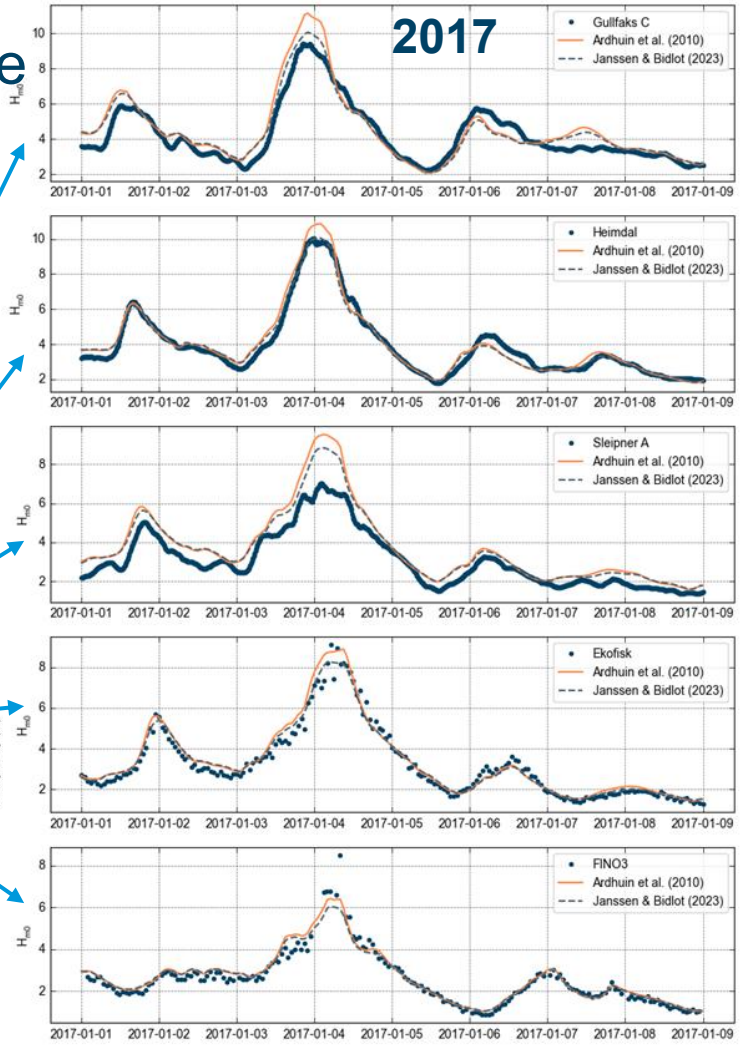
Higher resolutions

Wind forcing:

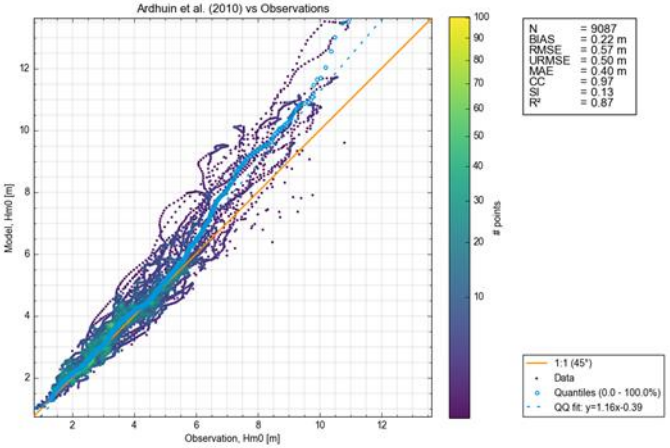
NORA3

In-situ Measurements (Hm0)

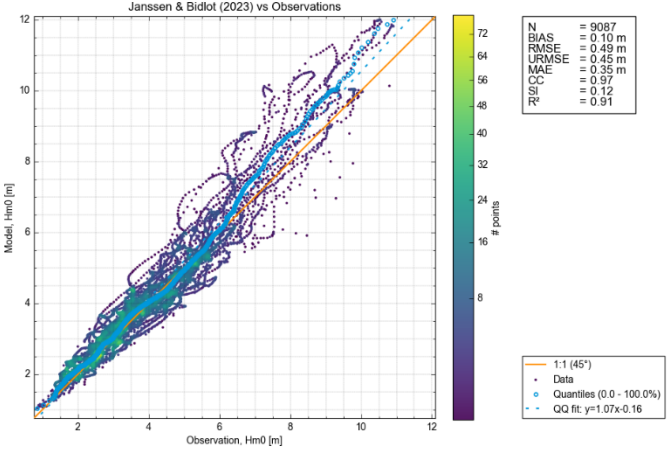




Ardhuin et al.



Janssen & Bidlot



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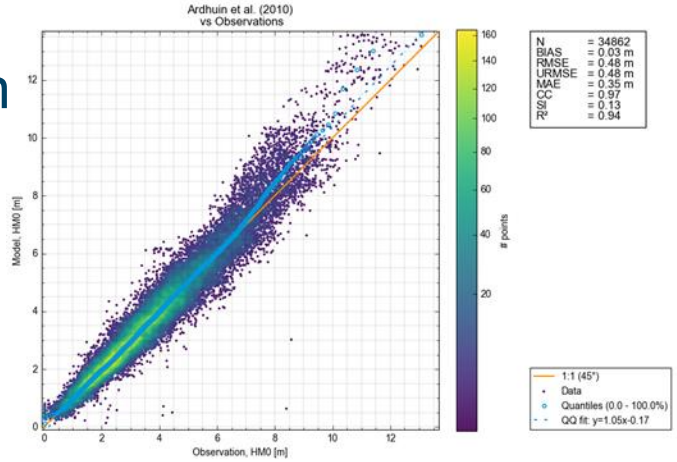
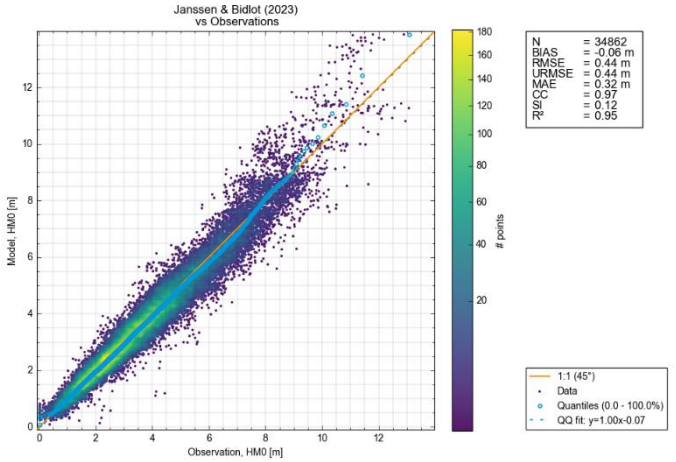
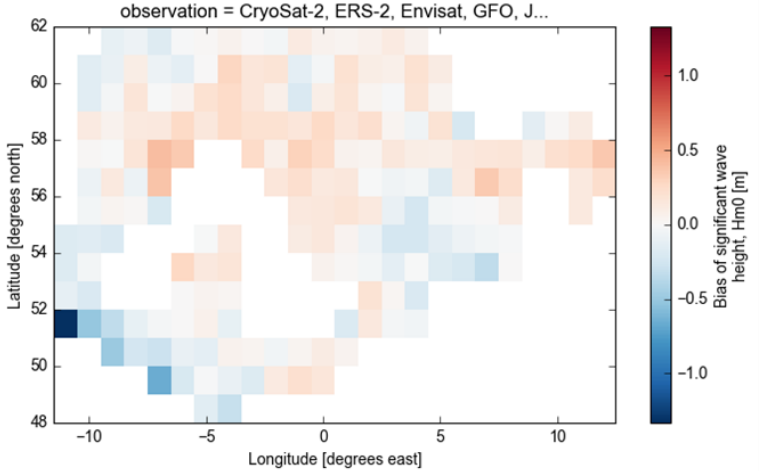
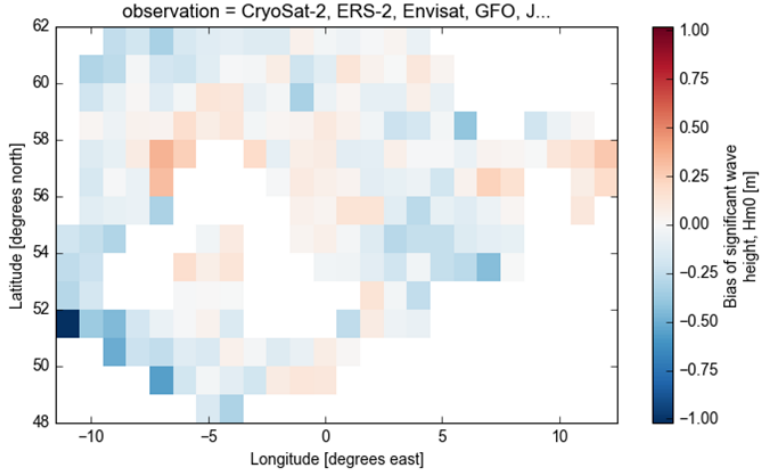


Janssen & Bidlot

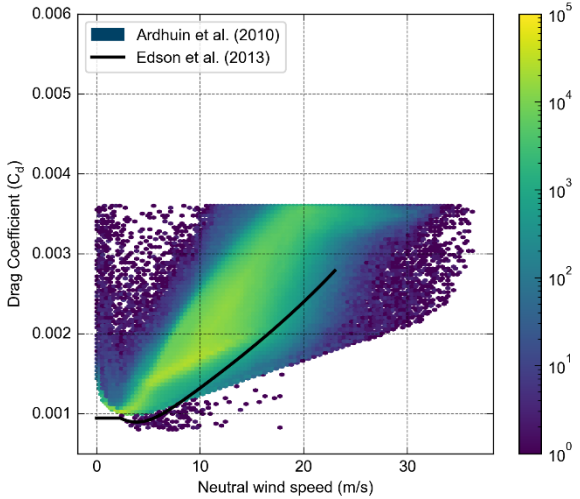




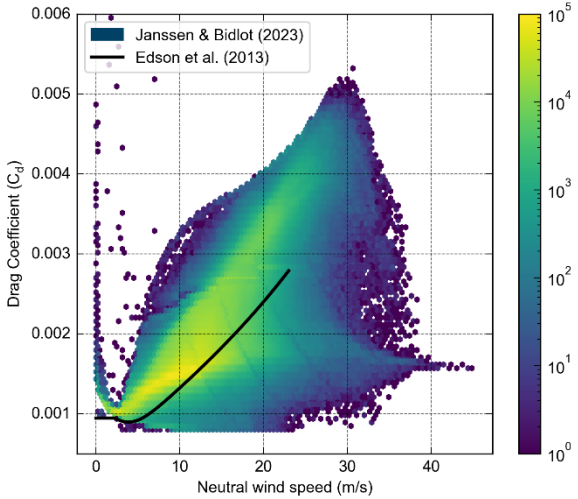


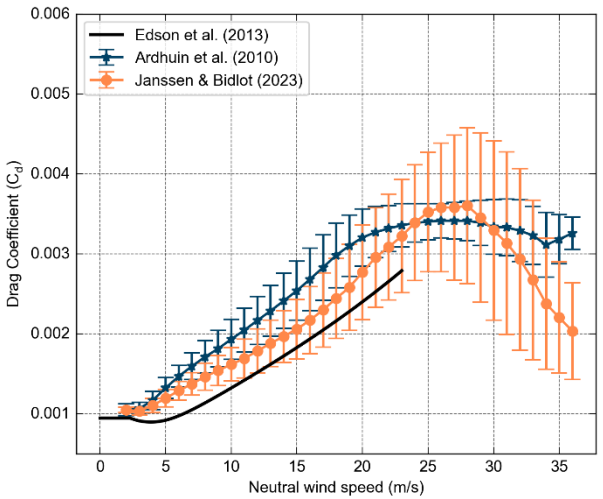
Drag coefficient vs. Wind Speed

Ardhuin et al.



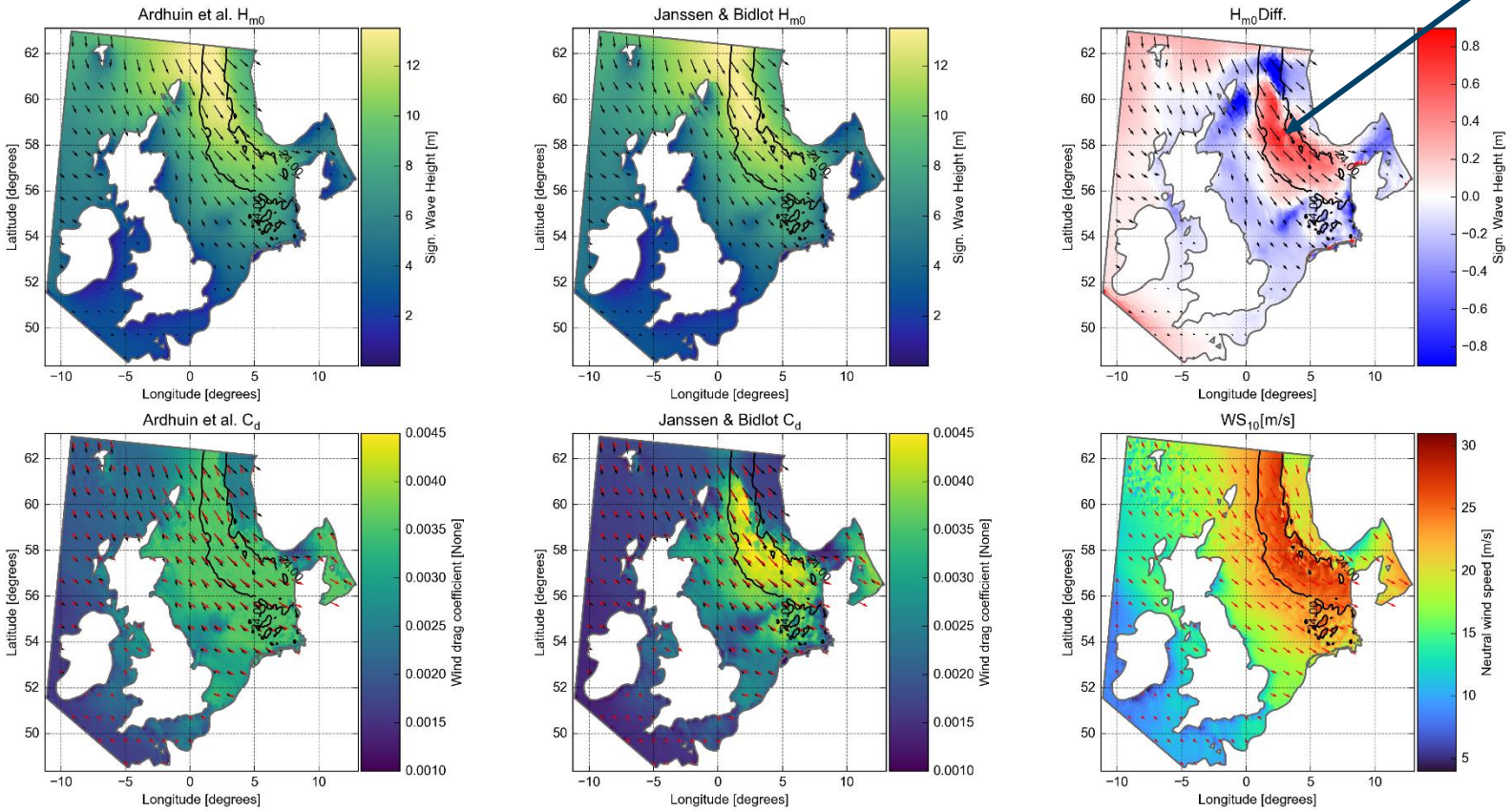
Janssen & Bidlot





Spatial distribution of Hm0, Cd & WS10 (2013-12-06)

WS10=24 [m/s]



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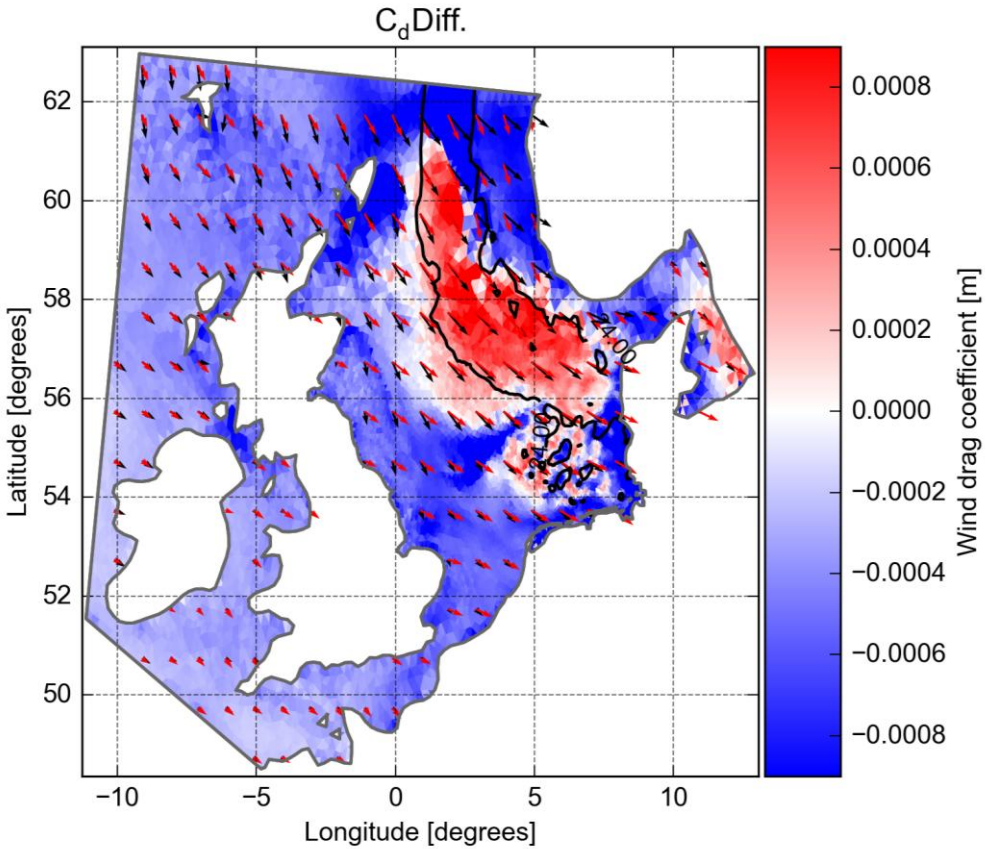
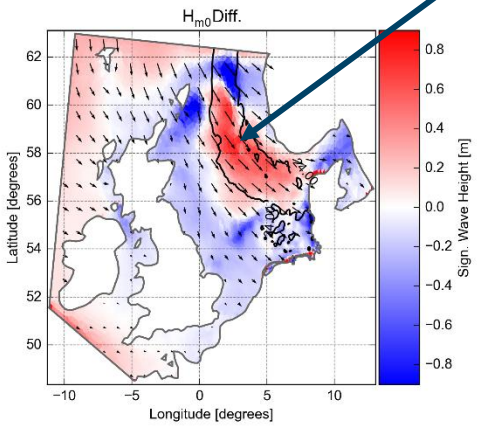
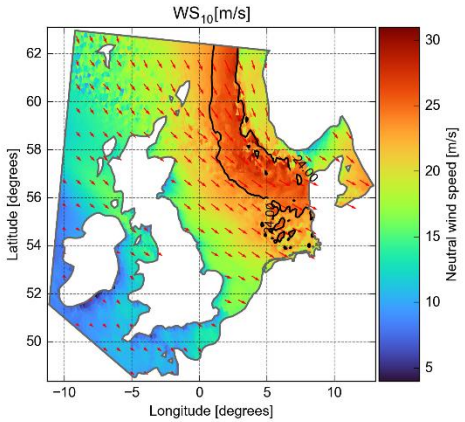






04.

Summary & Outlooks

Summary:

- The **new source term** Janssen & Bidlot (2023) is implemented in **MIKE 21 SW 2026** in addition to the original WAM Cycle 4 and Ardhuin et al. (2010).
- The Ardhuin et al. (2010) and the new source terms are analyzed and compared against **in-situ and satellite data** in **global** and regional wave simulations during 6 North Sea storms.
- Results indicate that the new source term performs well in global and regional wave simulation when all the **caps and limits** on the drag are removed.

Outlooks:

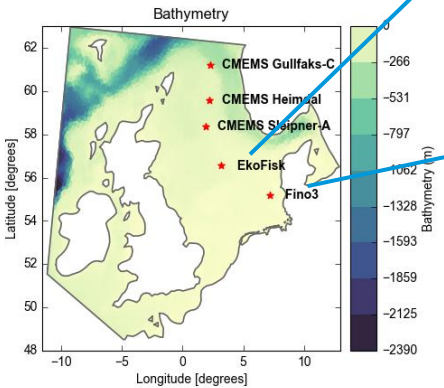
- Further **calibration of dissipation parameters** is needed to better capture extreme waves.
- Mote validation under more extreme conditions, such as **tropical cyclones**, is required.
- Additional investigation is needed for the **coupling with atmospheric and ocean models**.

Thank you! Questions?

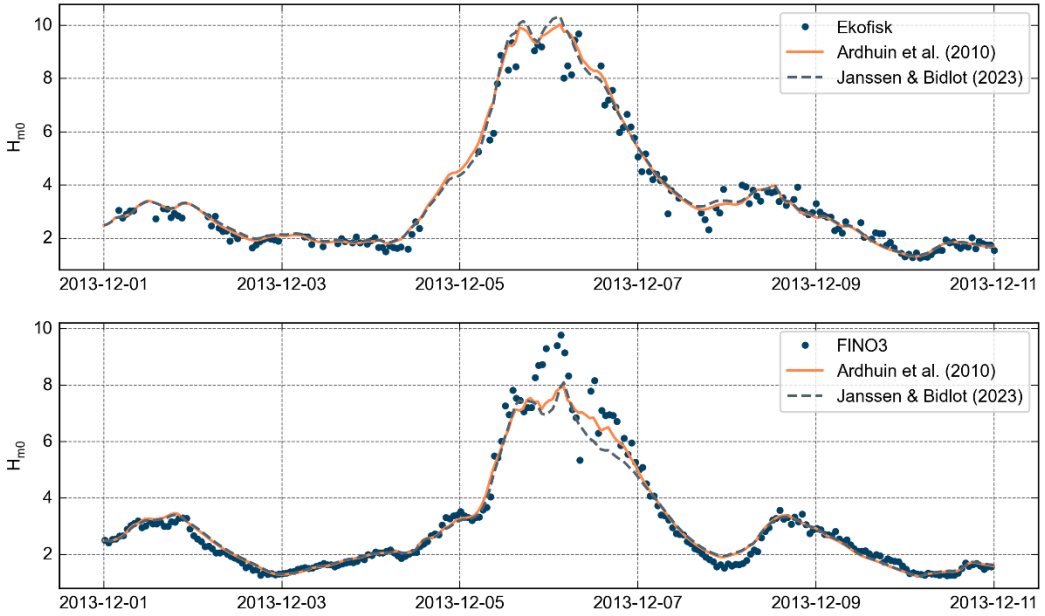
North Sea wave validation

Higher resolutions
Wind forcing:
NORA3

In-situ Measurements (Hm0)



2013



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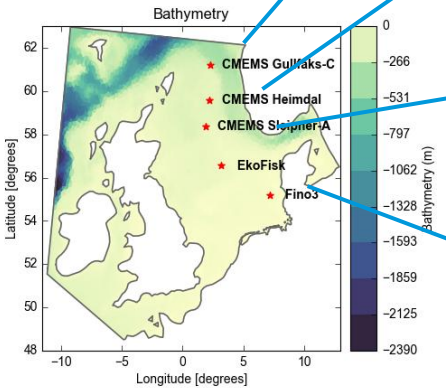
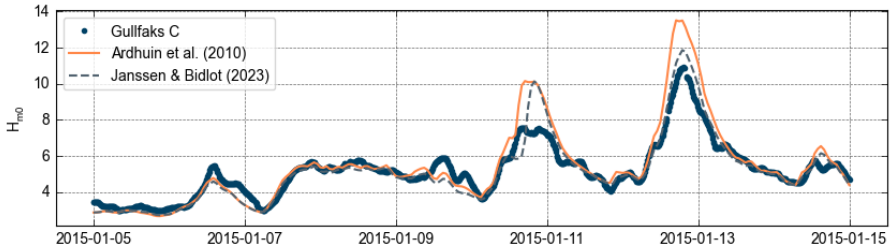
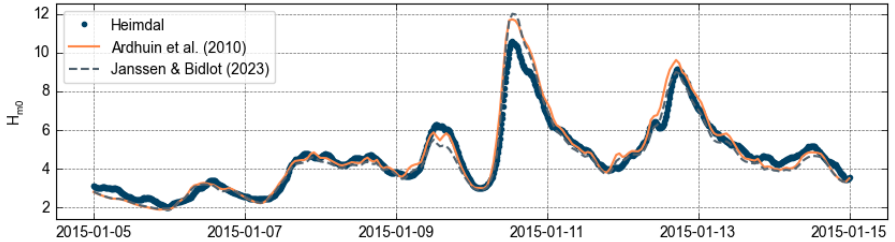
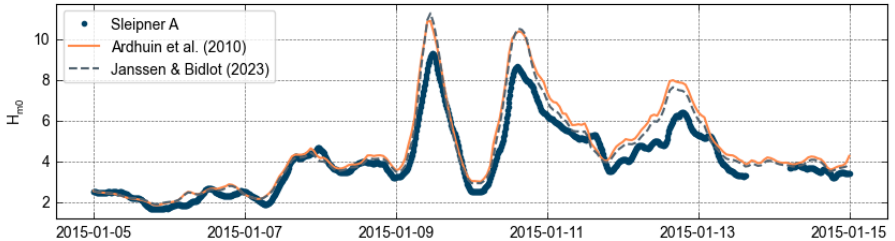
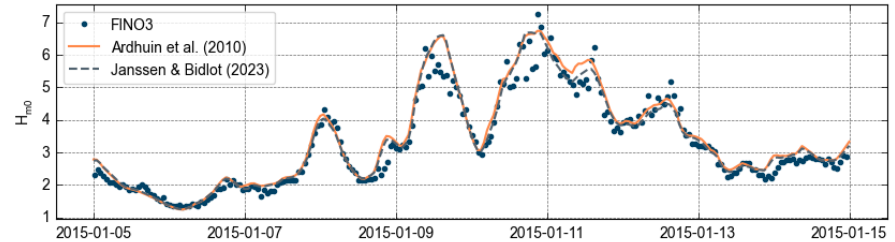


2015









North Sea wave validation

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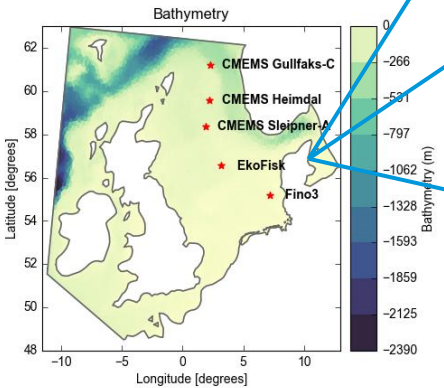
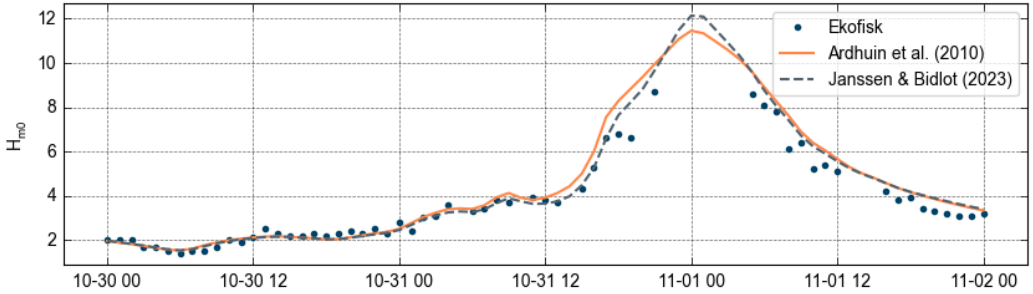
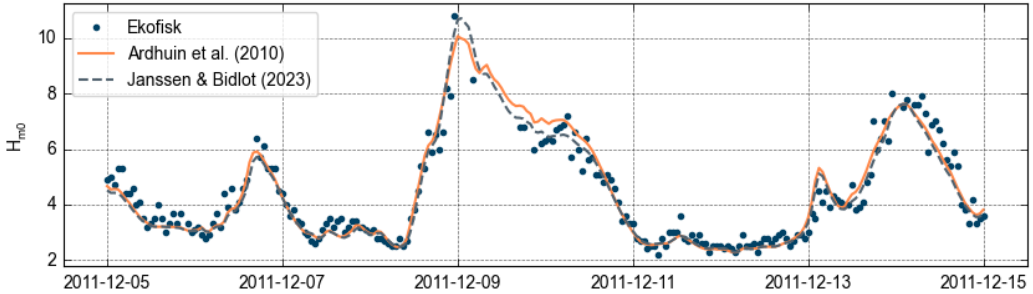


2006



2011



2012