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Improving Baltic Sea forecasts during Storm Babet by enhancing wave-ocean coupling

Veera Haapaniemi[1] , Laura Tuomi[1], Jens Murawski[2], Jun She[2], Hedi Kanarik[1], Jacob Woge Nielsen[2]

1.FINNISH METEOROLOGICAL INSTITUTE (FMI), Helsinki, Finland
2.DANISH METEOROLOGICAL INSTITUTE (DMI), Copenhagen, Denmark

Coupling NEMO with WW3

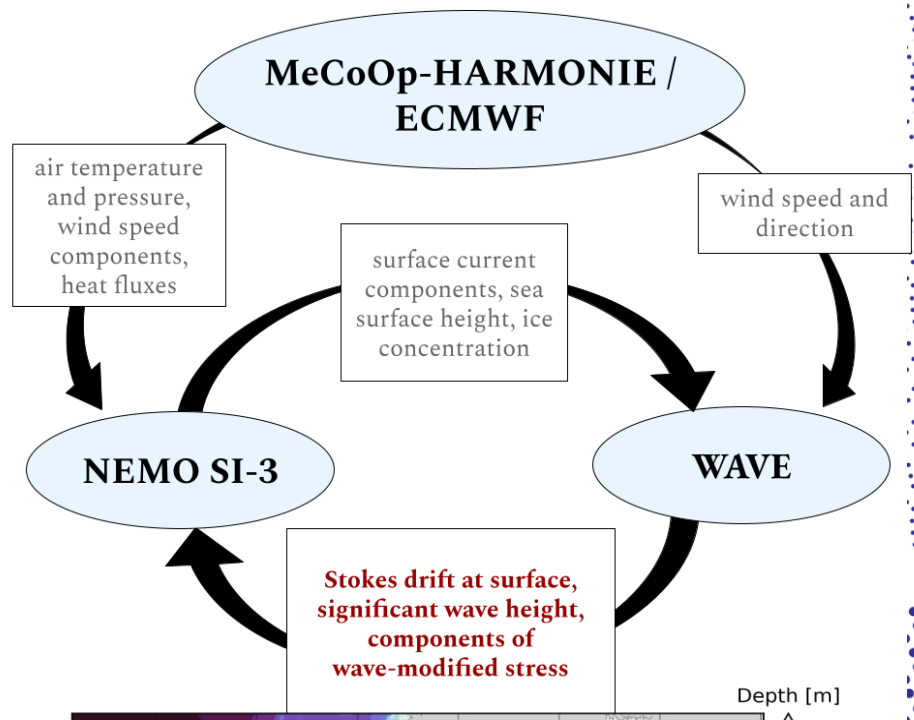
FMI coupling **Nemo Nordic** for the Baltic and North Seas with **WAVEWATCH III**

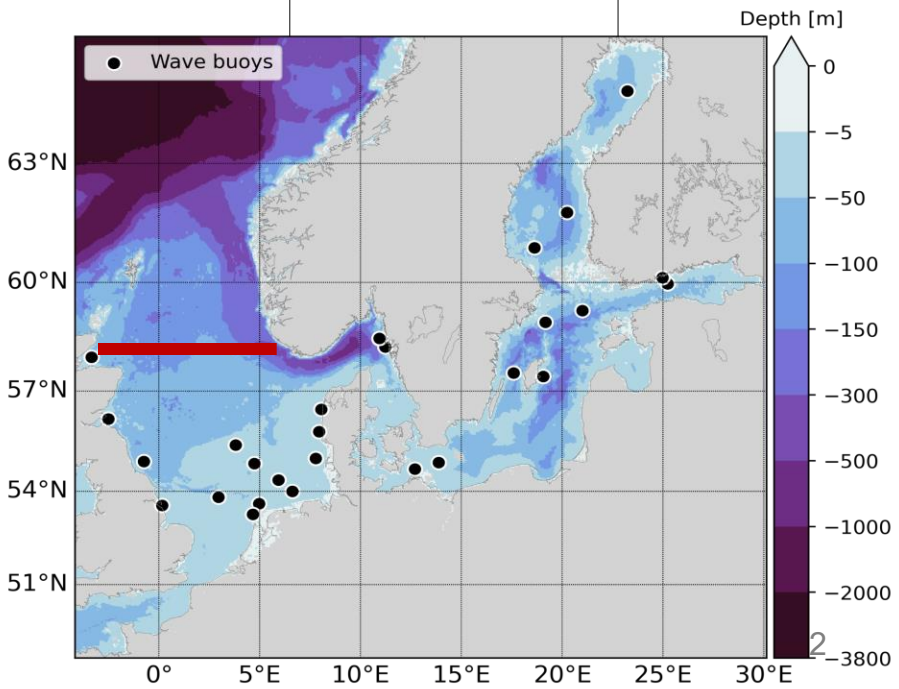
- 1 NM resolution for Baltic, 2 NM for the North Sea, ERA5 boundary conditions from dnora
- Nemo Nordic uses **GLS k-epsilon turbulence closure scheme**

Offline coupled experiments with

- Surface Stokes drift (2D), used to derive Stokes-Coriolis term
- Wave-modified momentum flux (components) as ocean-side stress

We consider the sensitivity of WW3-NEMO results to different sea surface roughness parameterizations





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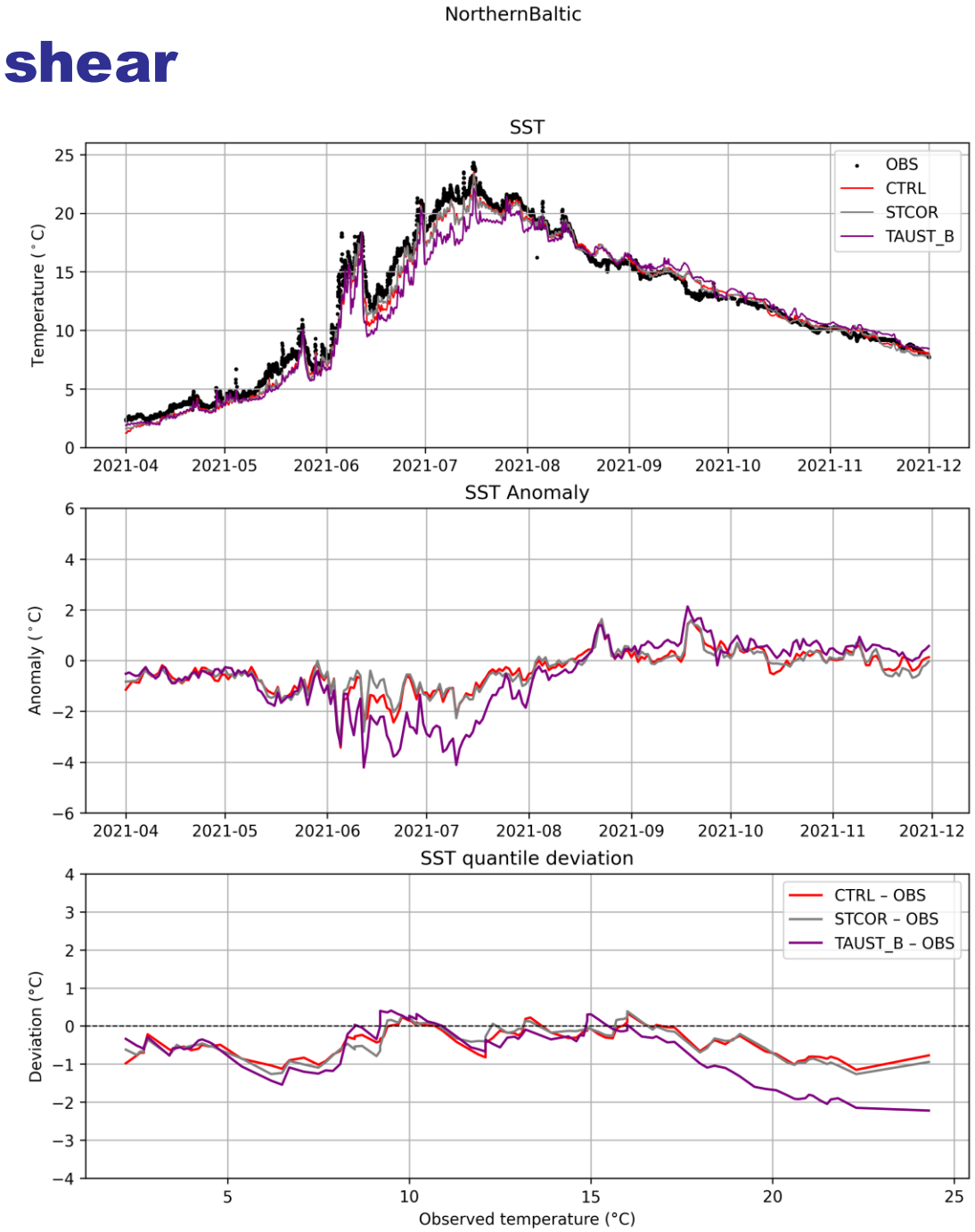
Summertime SST sensitive to shear stress definition

Experiments for year 2021 show **strong negative bias during stratified summer period** with wave-modified ocean-side stress.

The impacts of Stokes drift orders of magnitude smaller in the near-surface layer.

Whilst the impacts of TKE flux from wave model have been considered by Alari et al. (2016), the parameter is not implemented in Nemo GLS solver.

We examine the sensitivity to sea surface roughness definition used in GLS to compute vertical mixing and turbulence together with Craig and Banner (1994) parameterization.



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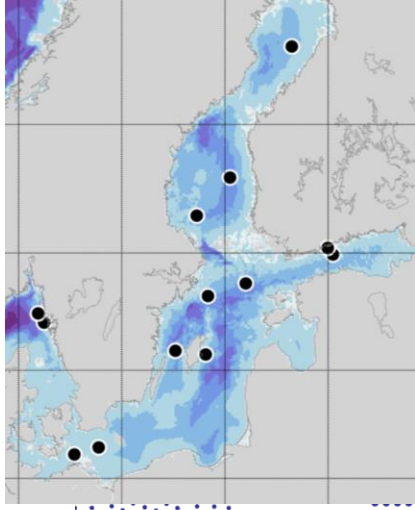
Sea surface roughness definition in GLS

$$z_0 = \gamma H_s = \gamma \frac{665\, w_*^2}{0.85\, g} \left(\left[\frac{c_p}{u_*} \right]_{\mathrm{ref}} \tanh\left(\frac{2u_{*,\mathrm{ref}}}{u_*} \right) \right)^{1.5}$$

1) Parameterized based on wind speed
2) Explicitly, provided by wave model

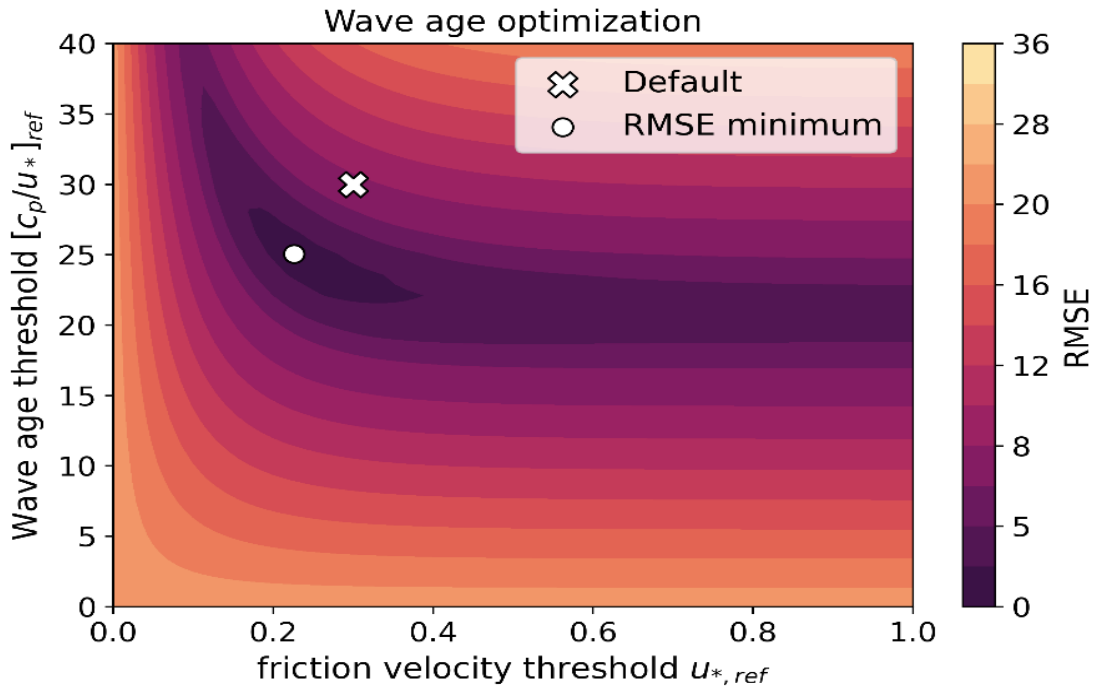


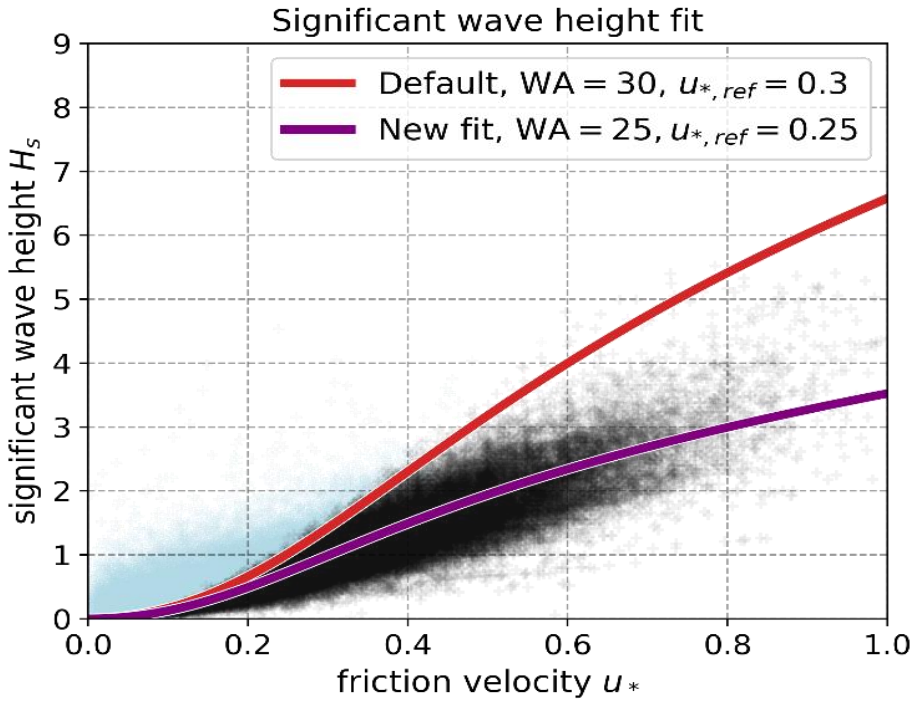
Parameterization by Rascle et al. (2008) derived based on open ocean sites, u*,ref represents friction velocity above which wave-growth gets commonly limited

$$\frac{c_p}{u_*}(u_*) = 30 \tanh\left(\frac{2 \cdot 0.3}{u_*} \right)$$

Optimization for Baltic Sea buoy locations over year 2021 suggests lower values

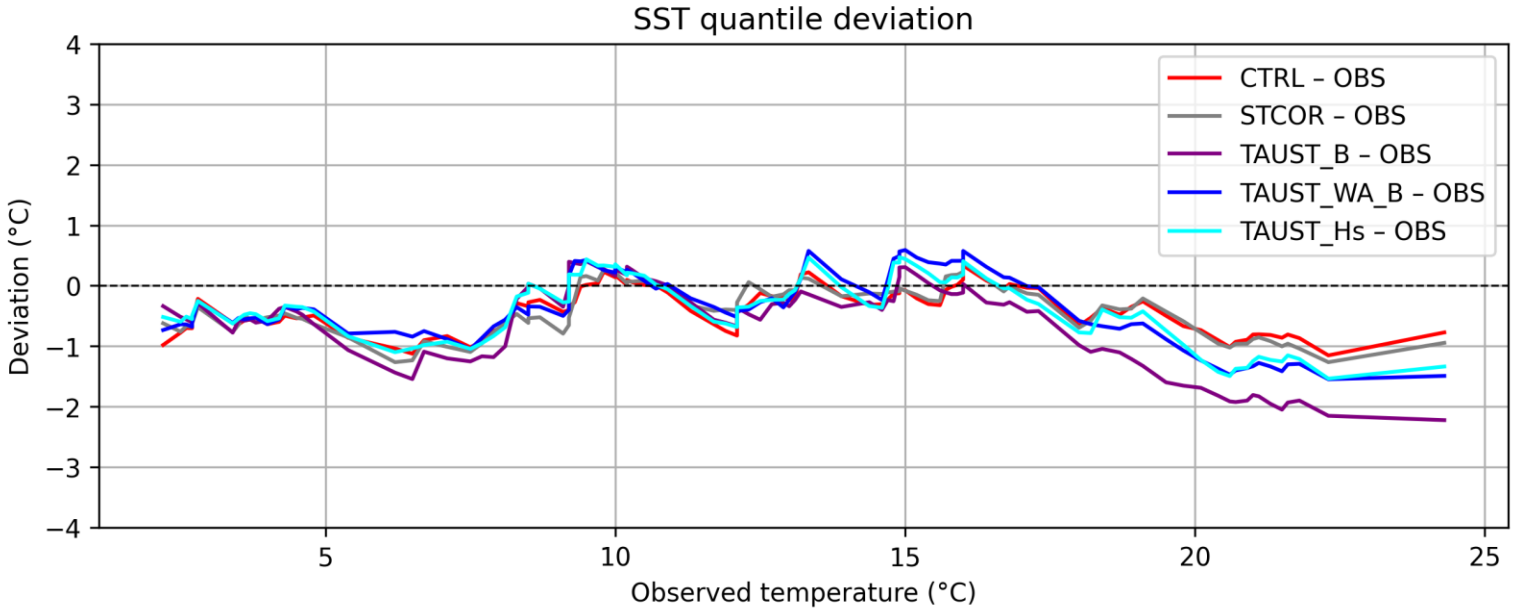
$$\frac{c_p}{u_*}(u_*) = 25 \tanh\left(\frac{2 \cdot 0.25}{u_*} \right)$$





Experiment / Parameter	Stokes	Stress	Hs	WA REF	u* REF
CTRL				30	0.3
STCOR	X			30	0.3
TAUST	X	X		30	0.3
TAUST_WA	X	X		25	0.25
TAUST_Hs	X	X	X	N/A	N/A

Optimization reduces mixing length under high winds.



Regionally computed roughness length reduces SST bias by over a degree during the summer.

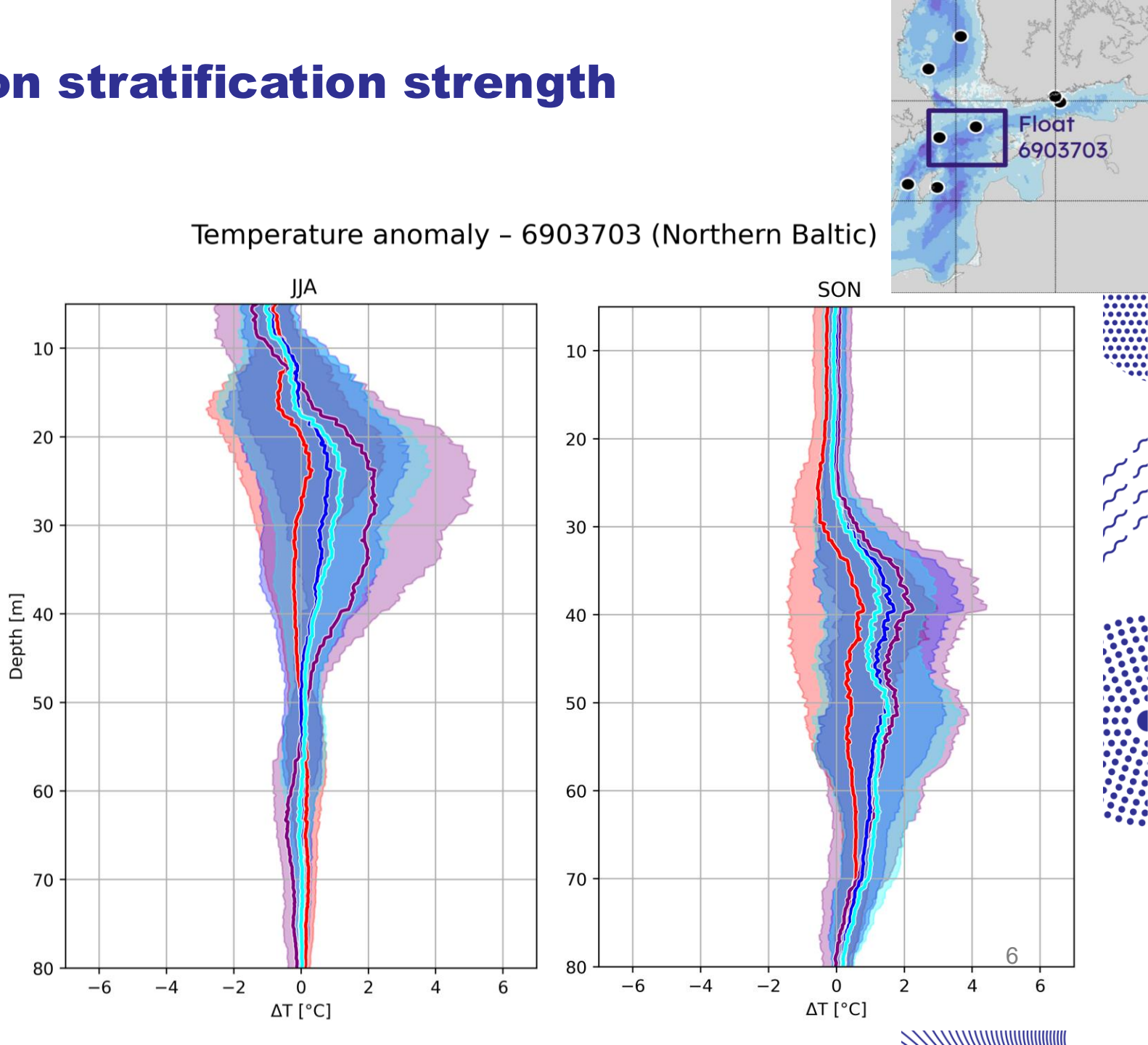
Impacts vary depending on stratification strength

In JJA, **TAUST** increases negative surface temperature bias but places thermocline too deep. Variability increases in 20-40 meters.

Both regional methods (**TAUST_WA** and **TAUST_Hs**) take results closer to **CTRL**.

In SON, temperature differences up to 30 meters small. Pattern similar as in JJA.

Reconsidering roughness definition crucial when changing to wave-modified shear stress definition with current implementation.



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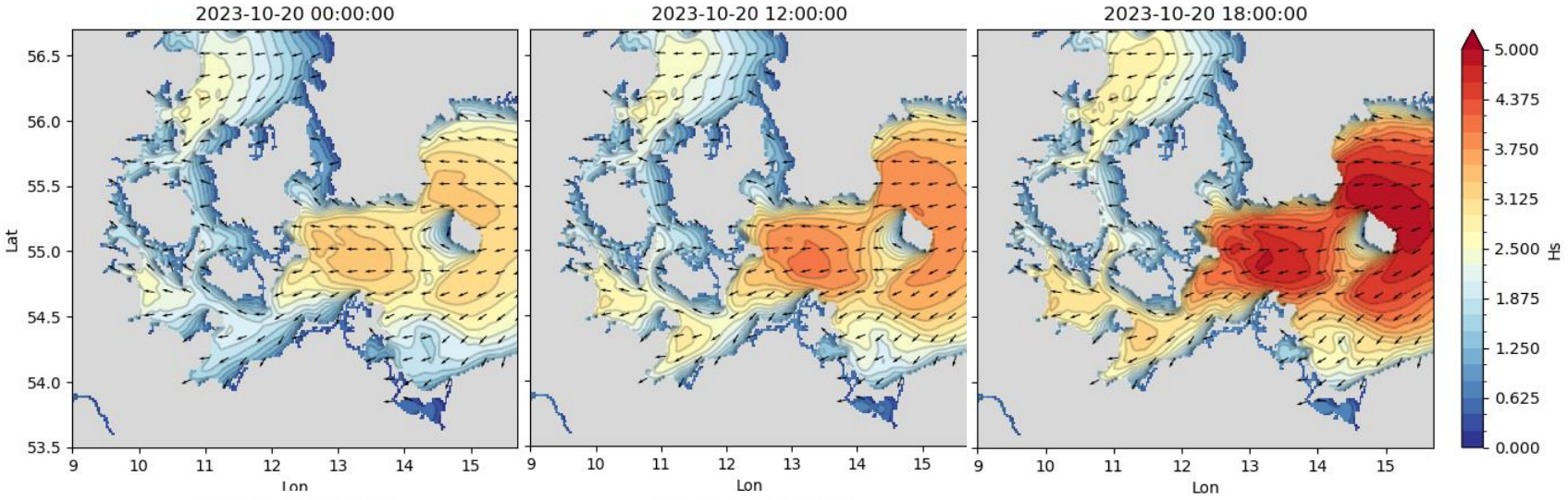
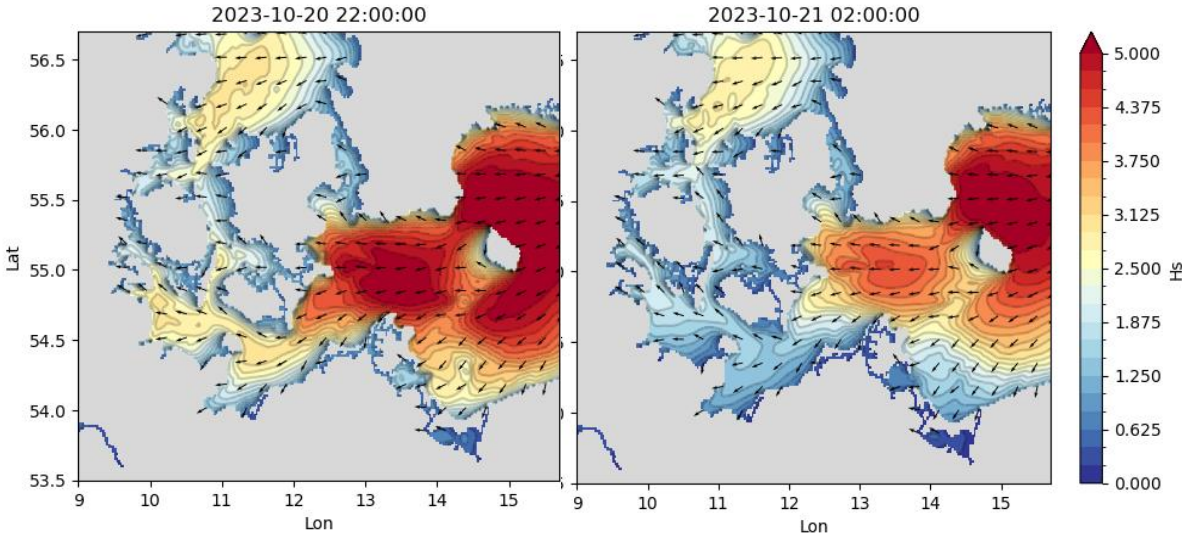
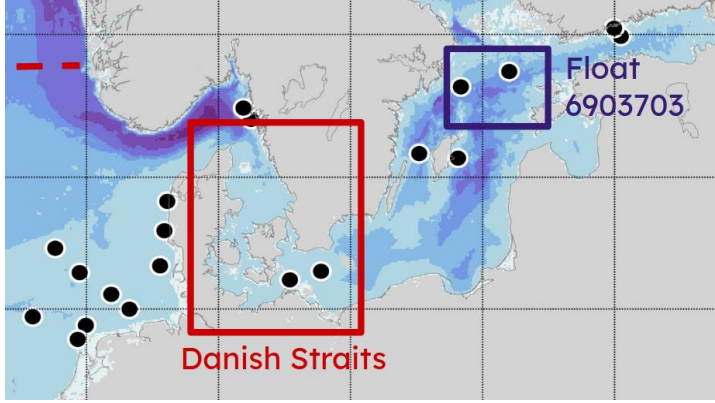
Wave forcing during Storm Babet







In October 2023, operational forecasts for the Baltic Sea significantly underpredicted the record-high sea levels in Denmark and Germany

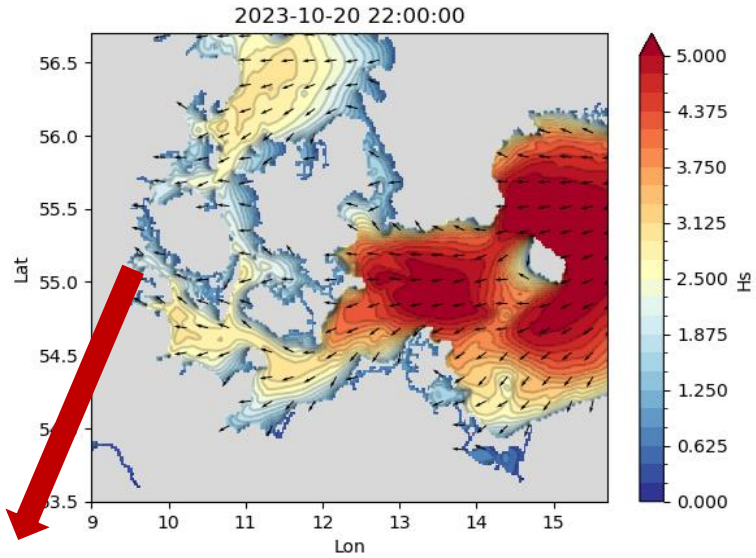
- SSH 2.1 meters above the MSL
- Wind gusts up to 34 m/s
- WW3 maximum Hs=5.6 m on 20.10.2023 before midnight

WW3 runs with nested BAL MFC – IDW – Øresund grid, resolution up to 185 meters used as forcing in Nemo (1 NM)

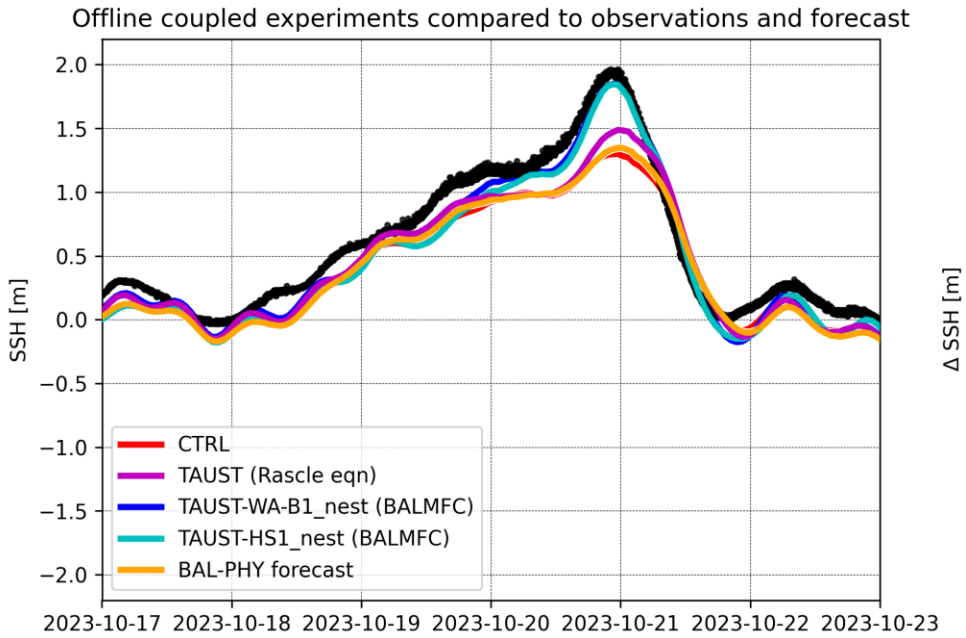
WW3-NEMO sea level impacts

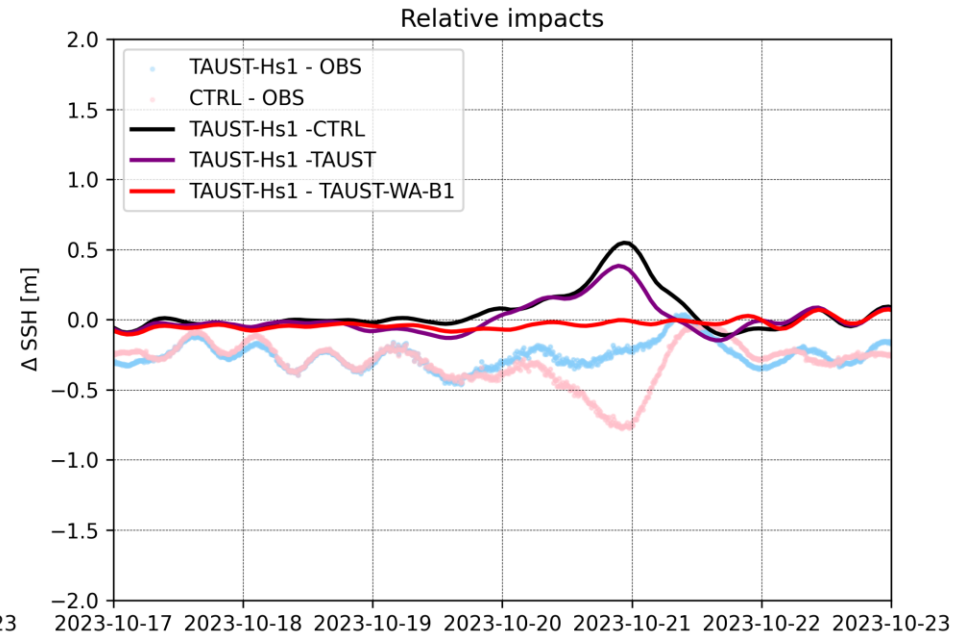
BAL MFC Nemo captured high sea level in the Øresund region, but significant prediction errors were observed in the Belts.

CTRL error up to 0.7 meters, **TAUST** increases SSH estimates reducing prediction error by 0.25 meters. Roughness definition impacts up to 0.4 meters, and **TAUST_WA** and **TAUST_Hs** estimate SSH closest to observations.

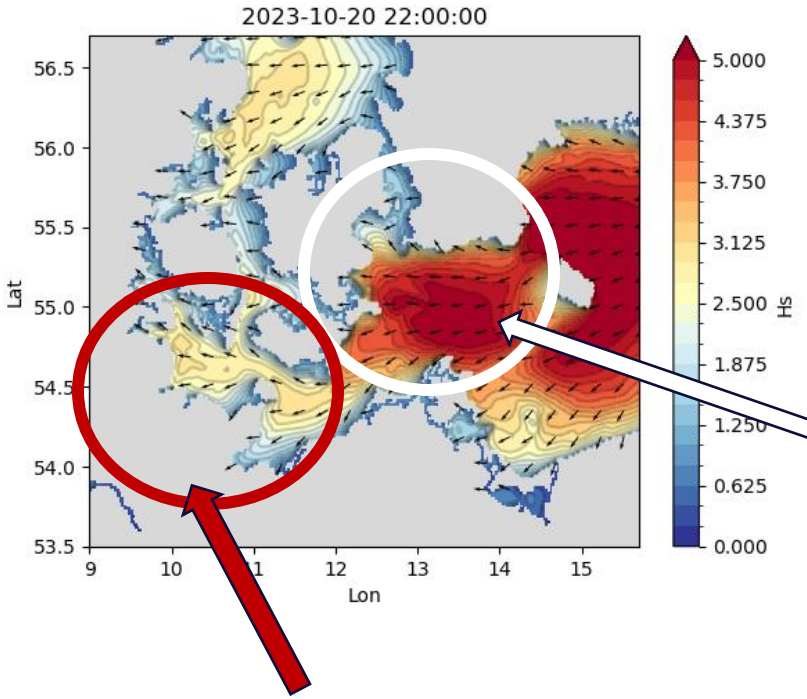


Fynshav



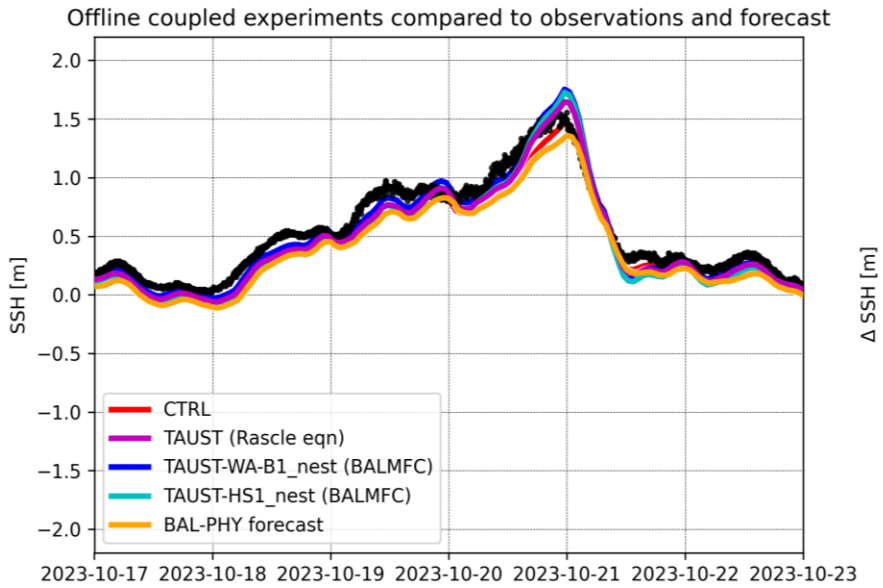


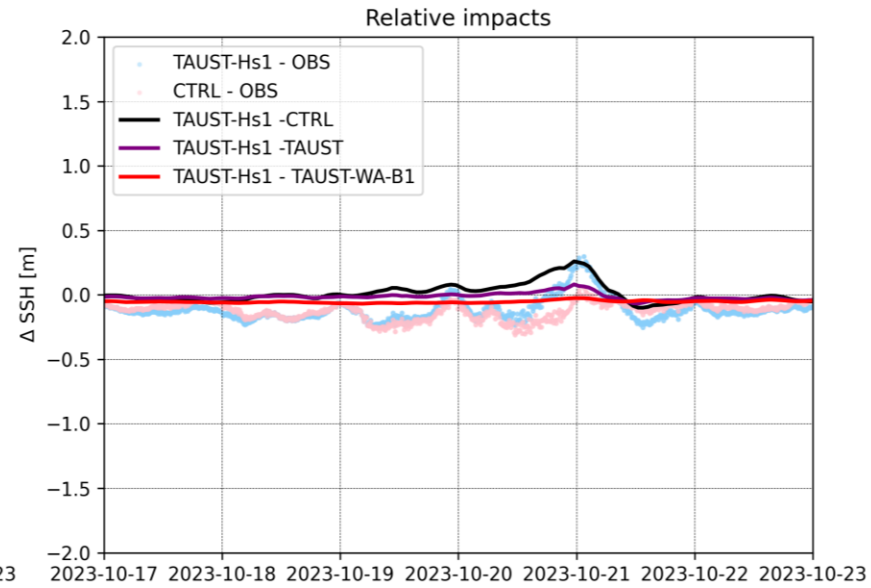
Regional differences



Wave growth and propagation more limited, BAL MFC PHY forecast showed significant underprediction.

Rodvig

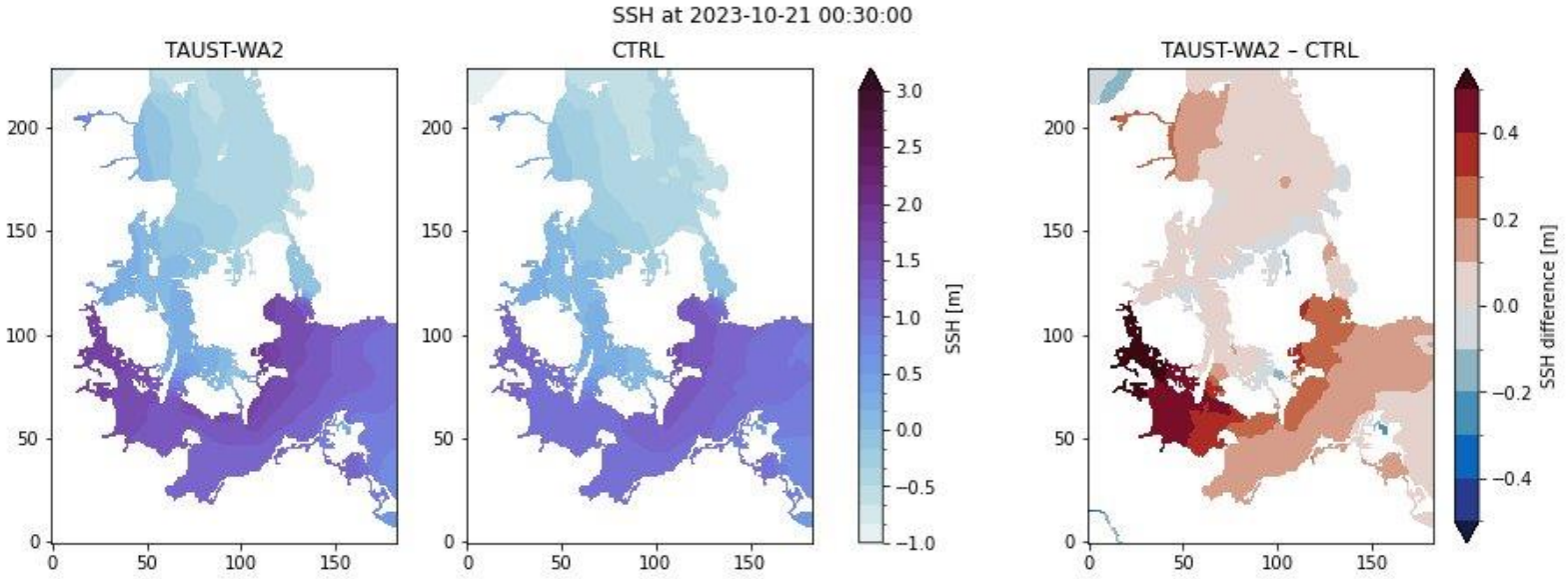


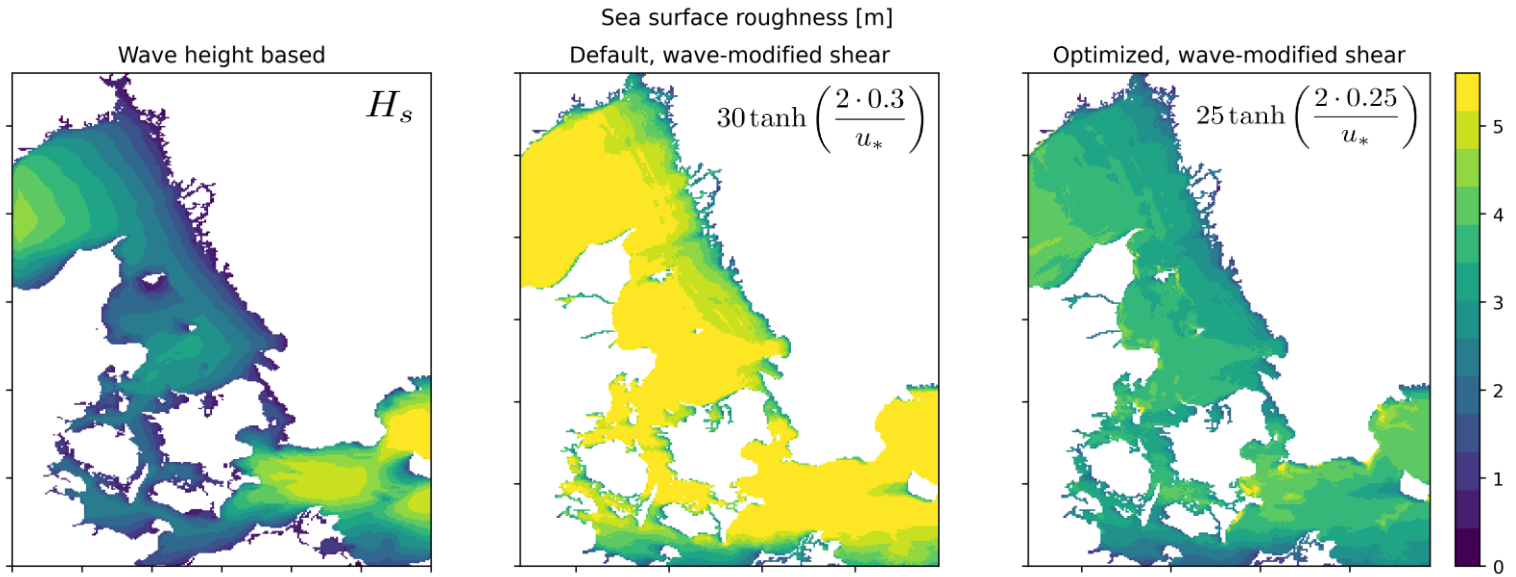


Open region, wind and waves aligned; default parameterization already close. WW3-NEMO runs overestimate SSH, with higher attribution of ocean-side stress than roughness.

Model sensitive to roughness definition, regionally optimized and wave-modified definitions result in **improved sea level response in sheltered regions** during the event. Model tuning is required to get the full benefits.

Local wind-based parameterization overestimates mixing





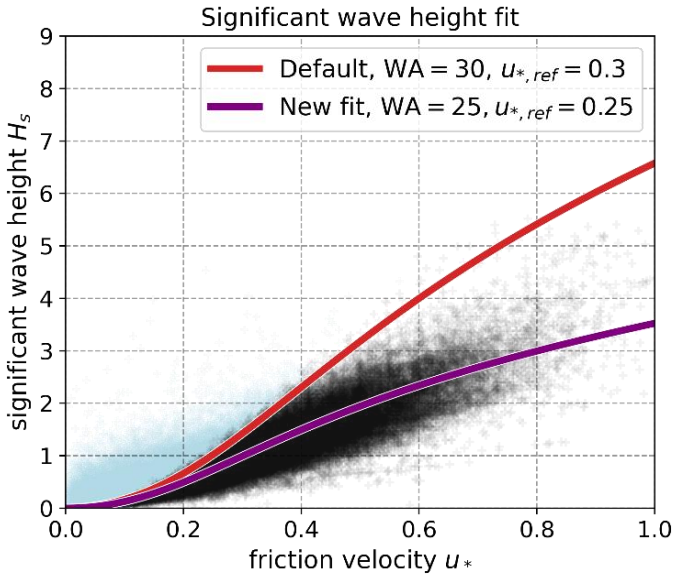
Strongest impacts in the Belts, where **parameterized sea significant wave height differs several meters** from WW3 results

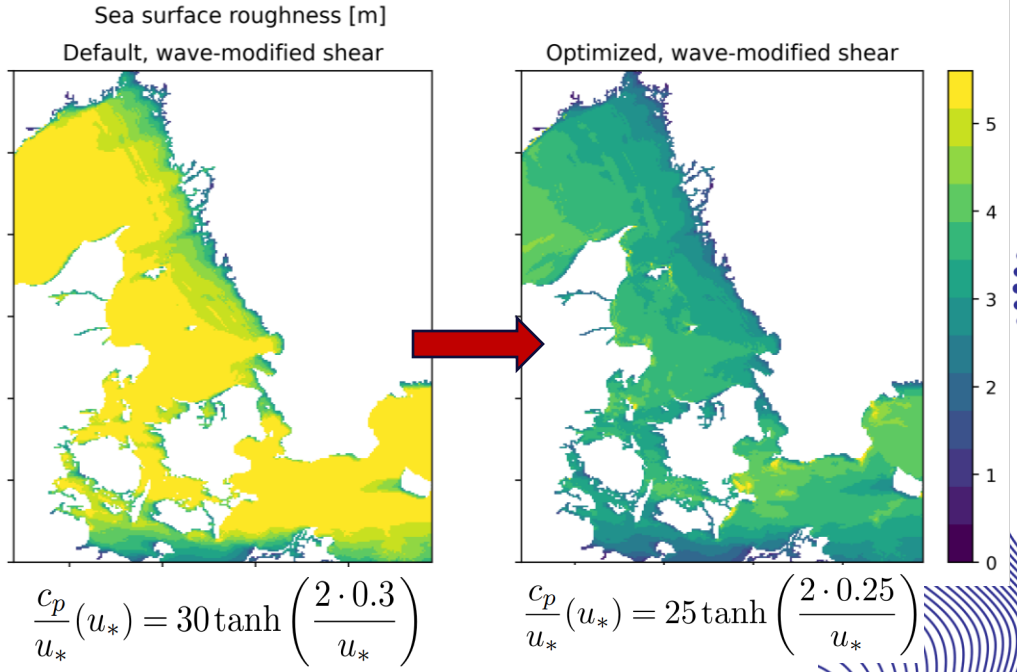
Conclusions

Local wind-based roughness parameterization **overestimates wave growth in fetch-limited conditions**, more pronounced under high winds

- Regionally optimized thresholds can improve the model performance and can be useful to consider when **tuning stand-alone hydrodynamic models**
- When wave model is available, explicit Hs should be used to capture regionally varying limitations for wave growth

In the current implementation of GLS, Craig & Banner **wave breaking parameterization sensitive to changes in roughness definition**, TKE flux definition should be reconsidered





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Thank you!

Veera Haapaniemi
veera.haapaniemi@fmi.fi

Model descriptions

Model	Nemo Nordic 2.0	WAVEWATCH III
Model version	4.0.7	7.14
Restart	02/10/2020	Cold start 1/10/2020
Horizontal grid	dlon, dlat = 0.027777, 0.01666	2 NM North Sea, 1 NM Baltic Sea
Vertical grid	56 layers, focused at surface	N/A
Spectral resolution	N/A	35 frequencies, 36 directions
$\beta_{\max}$	N/A	1.55 (Ardhuin et al., 2010)
Physics	N/A	ST4
Turbulence closure	GLS $k-\epsilon$	N/A
Time step	90s	60s
Atmospheric forcing	MetCoOp HARMONIE	MetCoOp HARMONIE
Boundary forcing	SURGE	ERA5
River forcing	EHYPE	N/A
Ice	SI-3	Exact ice concentrations from NEMO

NBP impacts on TKE and dissipation