DMI
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FINNISH METEOROLOGICAL INSTITUTE

Improving storm surge forecasting by coupling ocean circulation and wave models, a case study on storm Babet October 2023.

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

Danish Meteorological Institute, Copenhagen, Denmark
Finnish Meteorological Institute, Helsinki, Finland

Atmospheric circulation of Babet Storm in Oct. 2023

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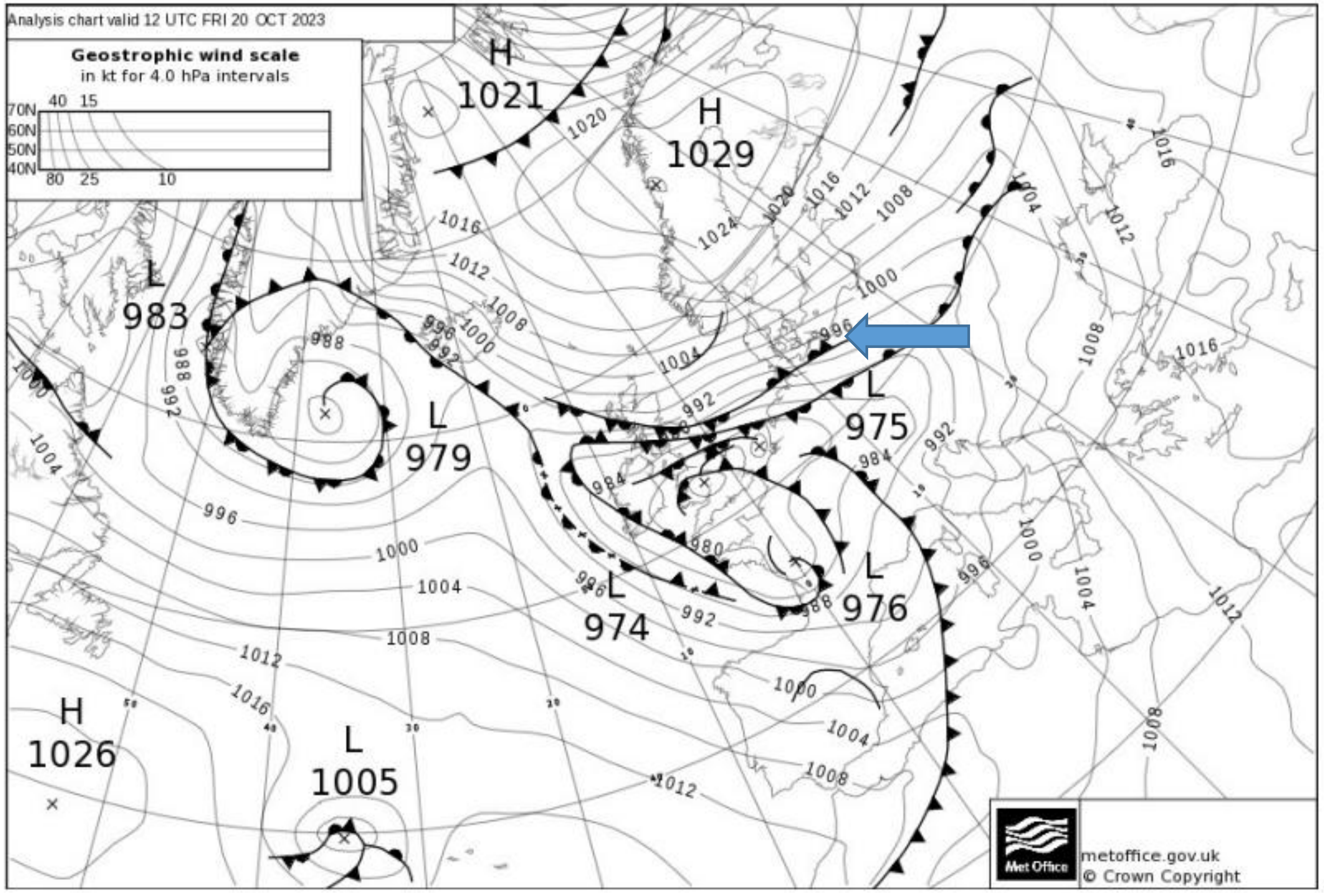


Credit: Metoffice, UK

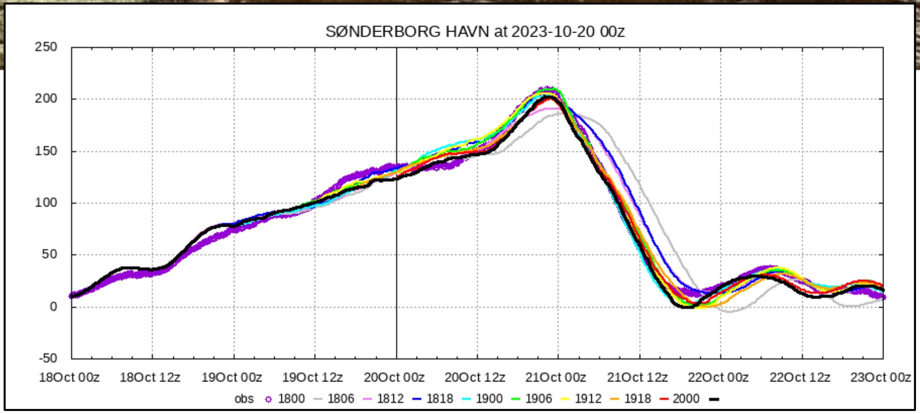
- Summary: a synopic scale (15-21Oct.), bi-pole blocking event, with blended, dynamic evolution of baroclinic and barotropical features
  - A static, deep low over Southeast of Greenland
  - A quasi-static, vertically eastward shifted geopotential high over Nordic Sea - Scandinavia
  - JetStream with large meandering in the west of the Low, reaching 41N in Atlantic shelf of Portugue
  - Baltic Sea was featured by westerlies in 10-19 Oct. And easterlies in 19-21 Oct.

Sea level and wave conditions during Babet Storm in Oct. 2023

Rødvig: Boats are left damaged in the harbour of Roedvig on Stevns as Storm Babet raged through the island of Zealand

Damage to Rødvig harbour

The water level around the harbour of Soenderborg in Southern Jutland



4th international workshop on waves, storm surges and coastal hazards. 22nd to 26th of September 2025, Santander, Spain

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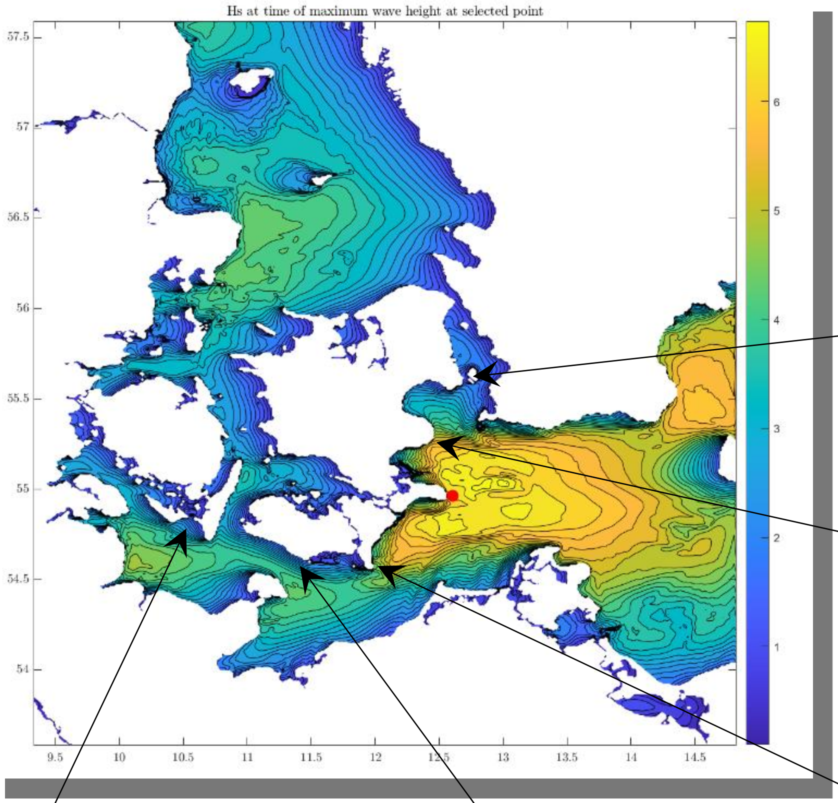
Motivation:

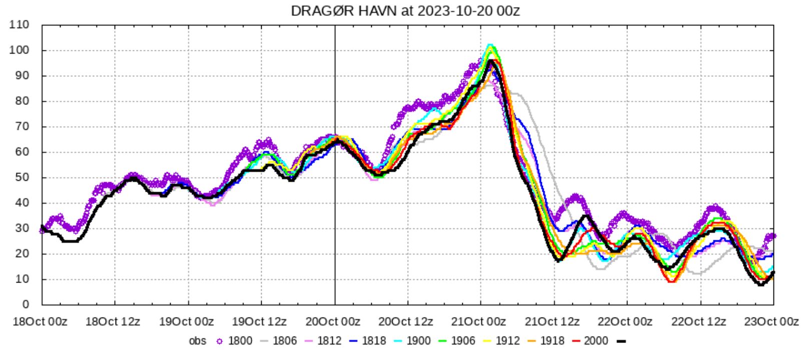
During Storm Babet, ….

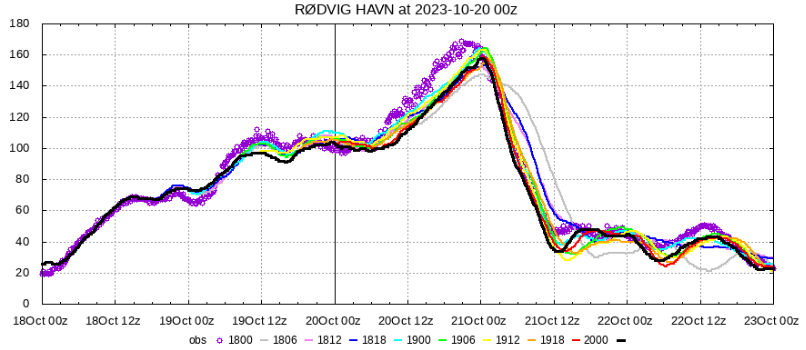
sealevel was underpredicted at exposed stations along the Danish coasts,

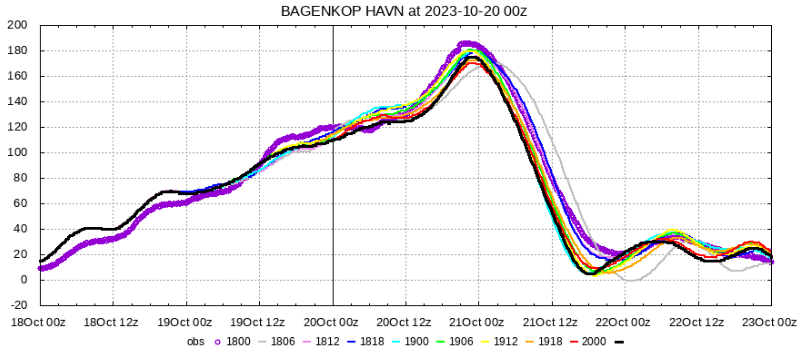
from Gedser to Drogden.

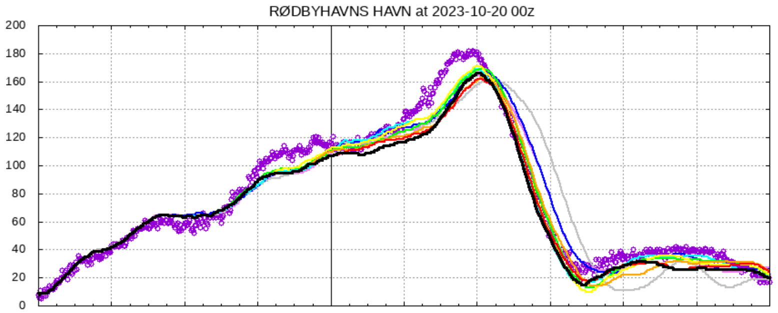
Collaboration of Baltic Sea forecasting centers: ***FMI, SMHI, BSH, DMI***, to study easterly storms: effects of prefilling, met. conditions, bathymetry and wave-ocean circulation coupling.

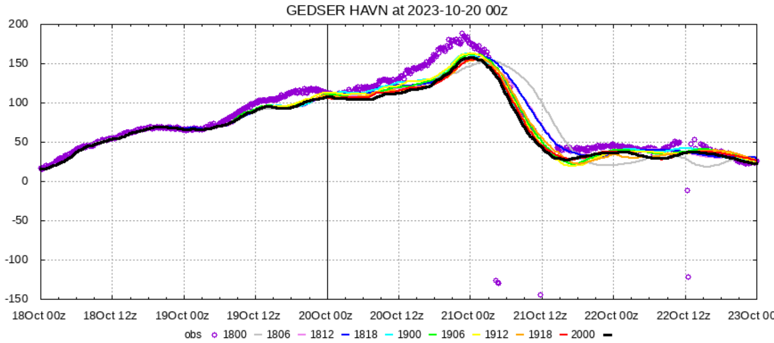




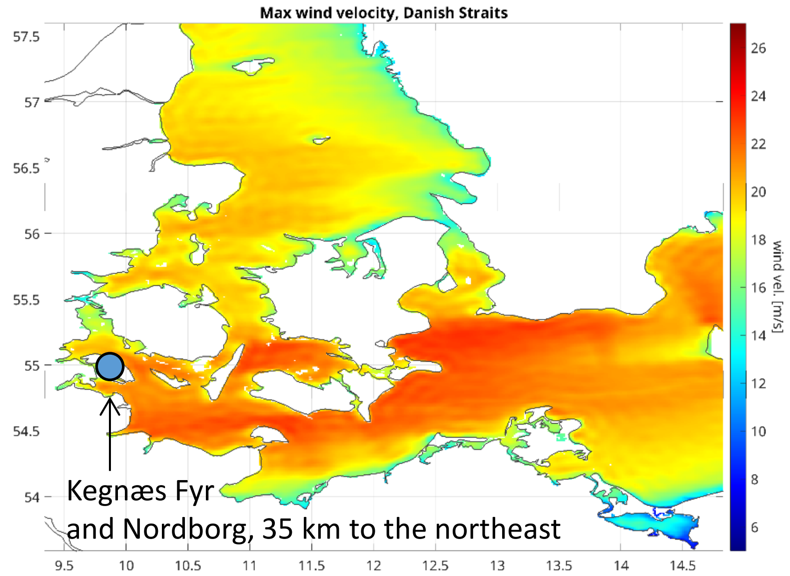


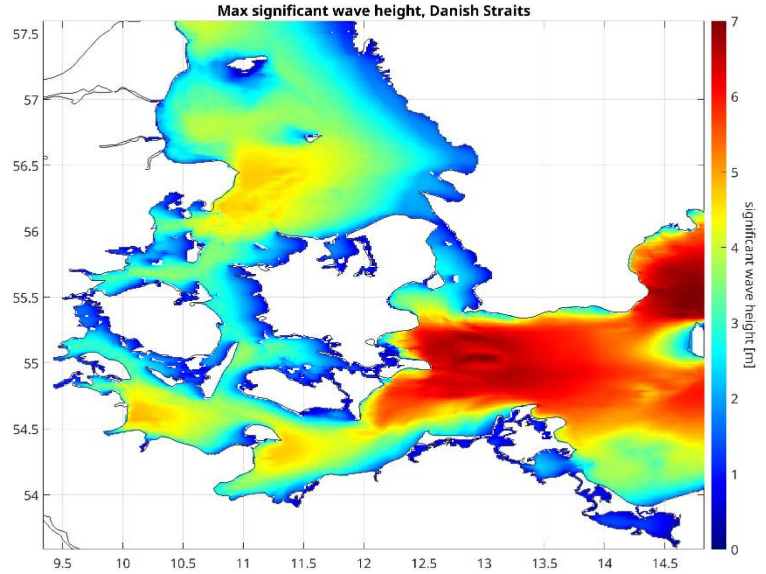






Babet Storm - The storm that was no storm in Denmark



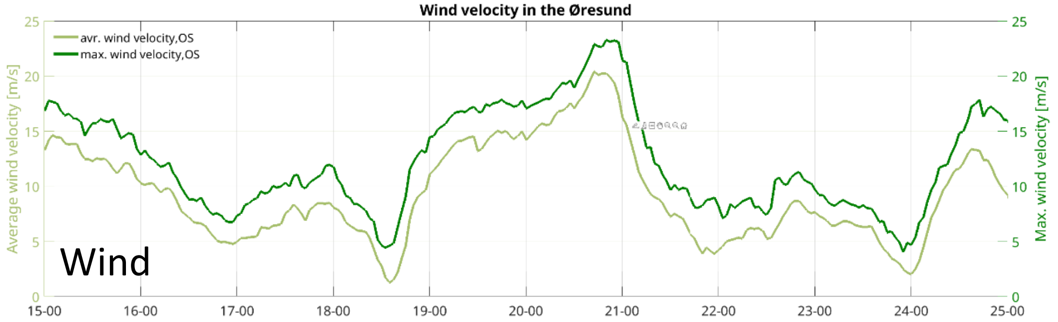


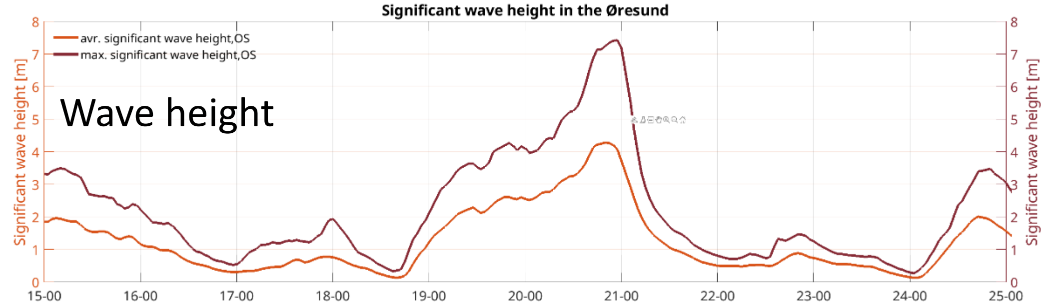
Highest measured mean wind: 28.3 m/s **at Kegnæs Fyr** (Als). This was one of the few spots reaching storm strength in the mean wind.

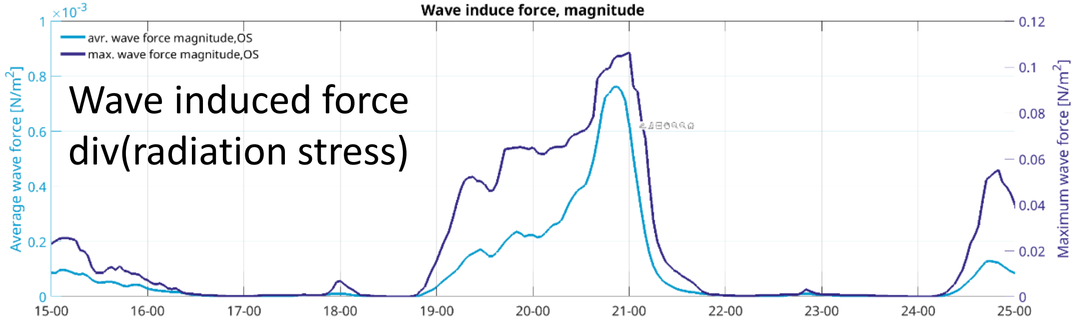
The maximum recorded gust is 34 m/s at **Nordborg.**

Babet is not classified as a storm in Denmark, as the area experiencing gale-force winds was too limited.

Nevertheless, it is considered a storm surge event.



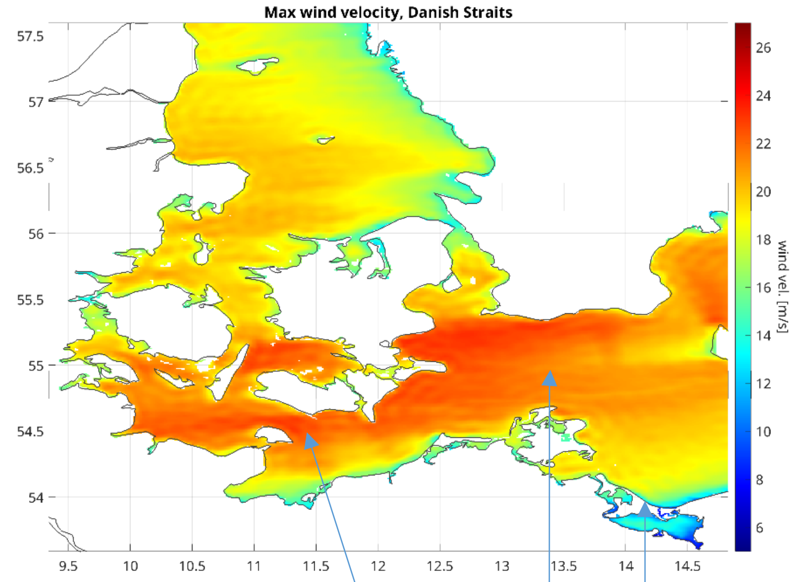


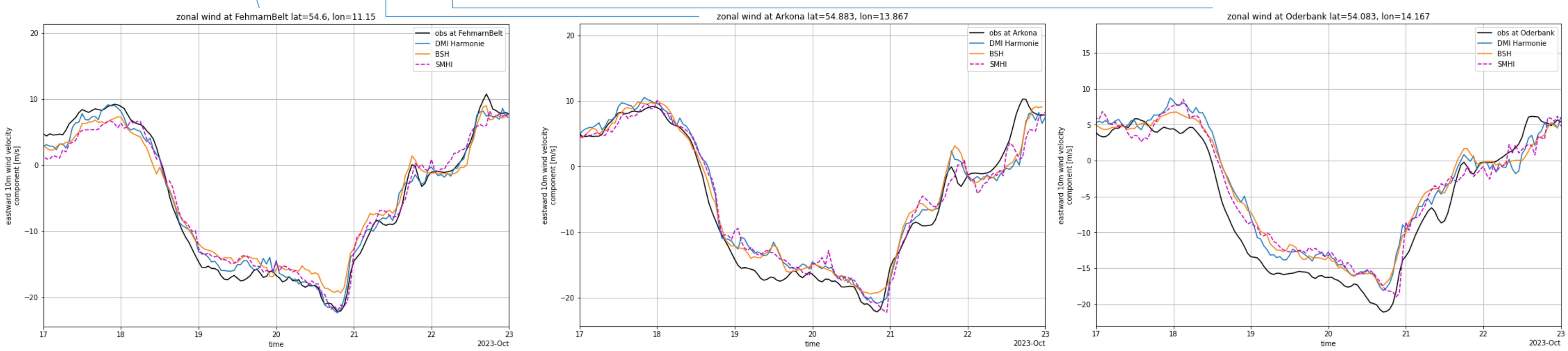


Comparisson of modelled with measured winds

Meteorological products from **Denmark (DMI), Sweden (SMHI) and Germany (DWD, BSH)** were systematical compared. Impacts on sea level forecast performance were analyzed.

The zonal winds are very similar across the datasets but **are generally too weak**. However, **SMHI winds appear to be stronger during peak wind events.**



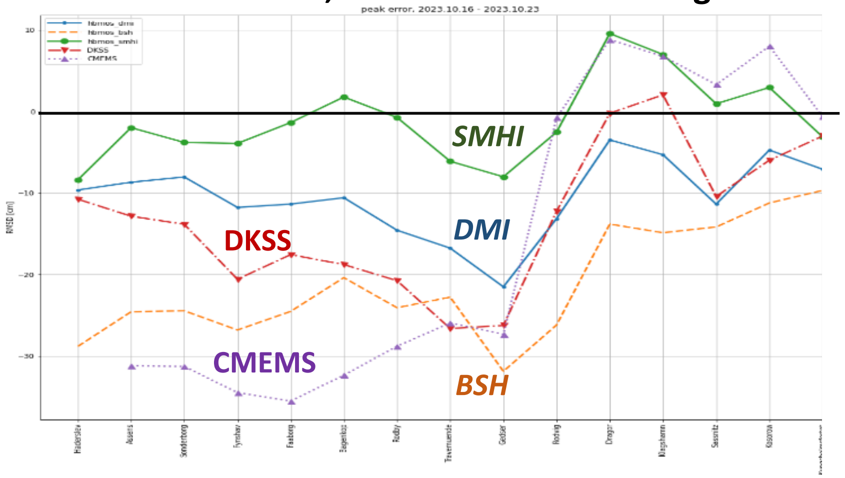


Experiment:

Test different combinations of storm surge model wind wind forcing, to identify optimum combinations and attribute differences.

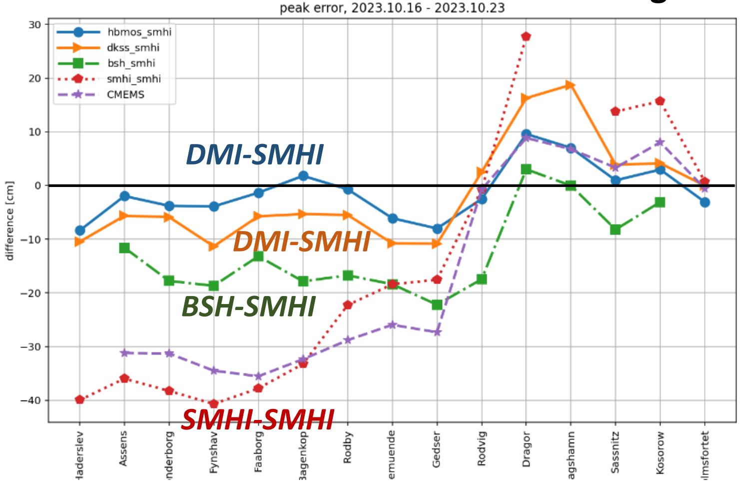
The combination **of SMHI forcing** and **DMI storm surge model** seems provide the forecast with the lowest peak error.

DMI-HBM, with of different forcing

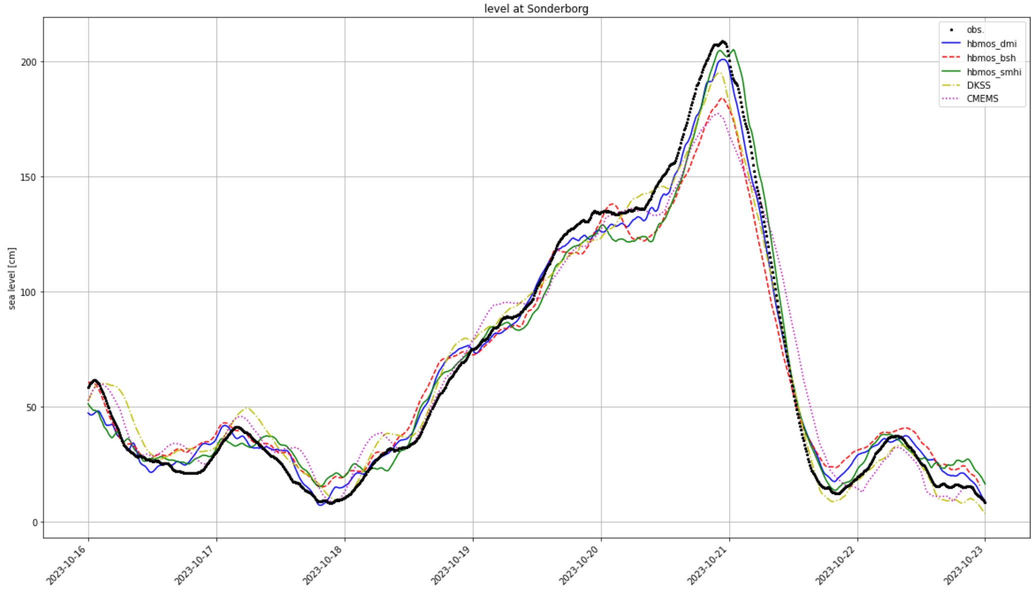


Peak error for **different met. forcing**: DMI ocean circulation model

Different model with SMHI forcing



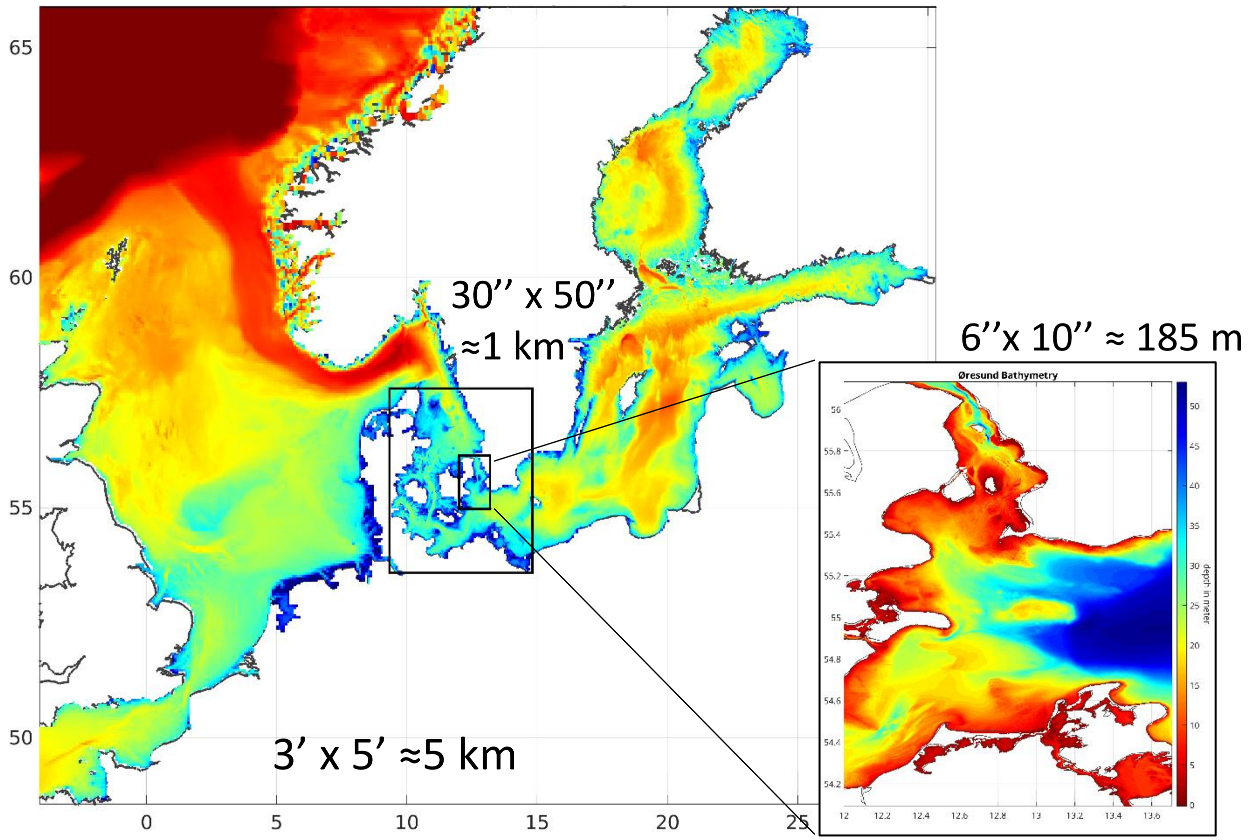
Peak error of **different ocean circulation model**, SMHI forcing



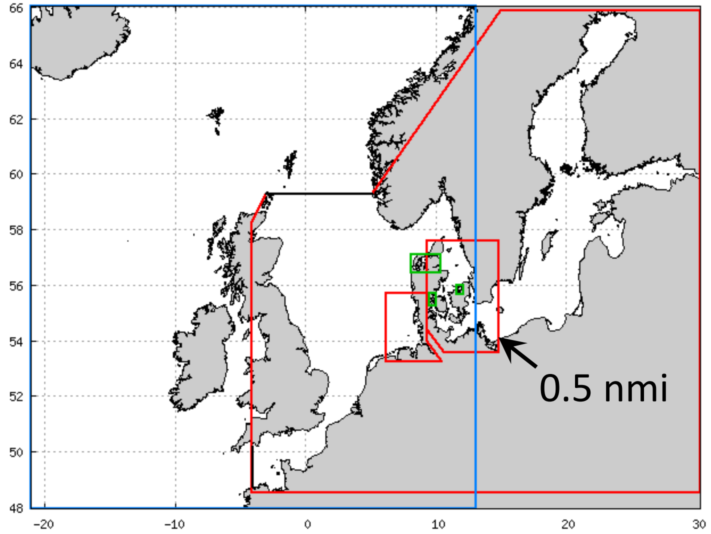
Results:

The forecast error of peak sea levels can be reduced by using an optimal combination of ocean model and wind forcing.

Wave Model configuration (WAM 4.7 model)



Storm Surge Model configuration (HBM model)



DKSS: 6 domains

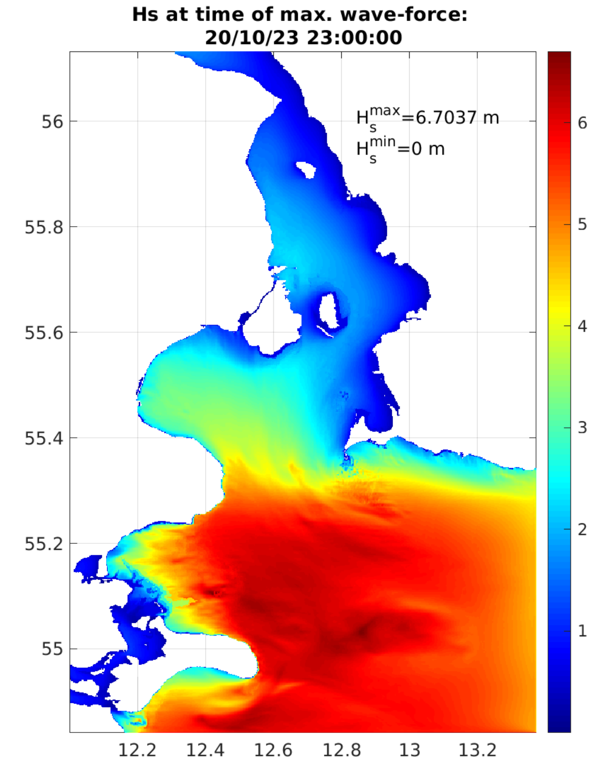
- North Sea/Baltic Sea
- Danish Straits
- Waddensea
- Roskilde Fjord
- Lillebelt
- Limfjord

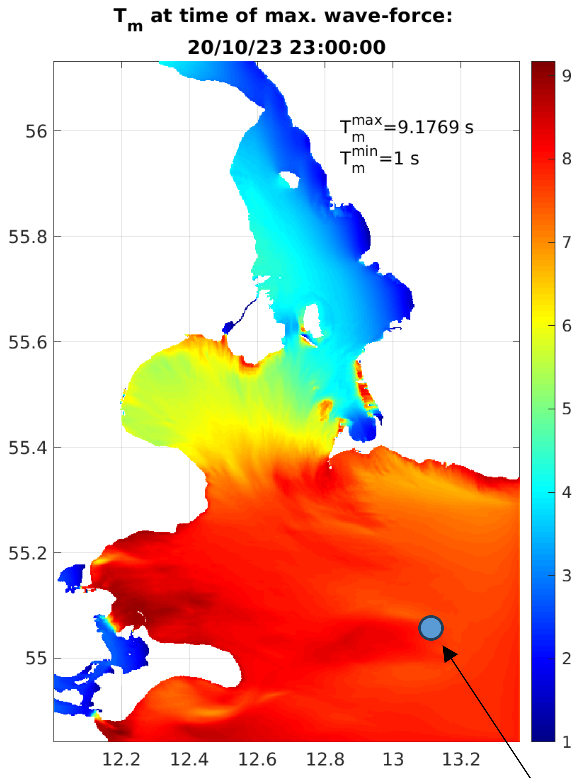
→next Øresund

- DMI's operational storm surge model HBM was offline coupled to the wave model 4.7.
- WAM and HBM share the same horizontal grid and bathymetry in the North Sea/Baltic Sea transition zone.

Model	North Sea / Baltic Sea	Danish straits	Øresund
Spatial coverage, long	4º 6' W – 30 º 19' E	9º 20' E – 14 º 49' 10'' E	12º 0' 5'' E – 13º 22' 30'' E
Spatial coverage, lat	48º 32' 30'' N – 65º 53' 30'' N	53º 35' N – 57º 35' 30'' N	54º 6' 27''N – 56º 7' 57''N
Spatial step	3' x 5'	30'' x 50''	6'' x 10''
Advection time step	45 sec	10 sec	10 sec
Source time step	6 min	1 min	1 min
Number of directions	36	36	36
Number of freq.	35	35	35
Freq1	0.04177248 Hz	0.04177248 Hz	0.04177248 Hz

WAM 4.7 uses the opertional wave model configuration.



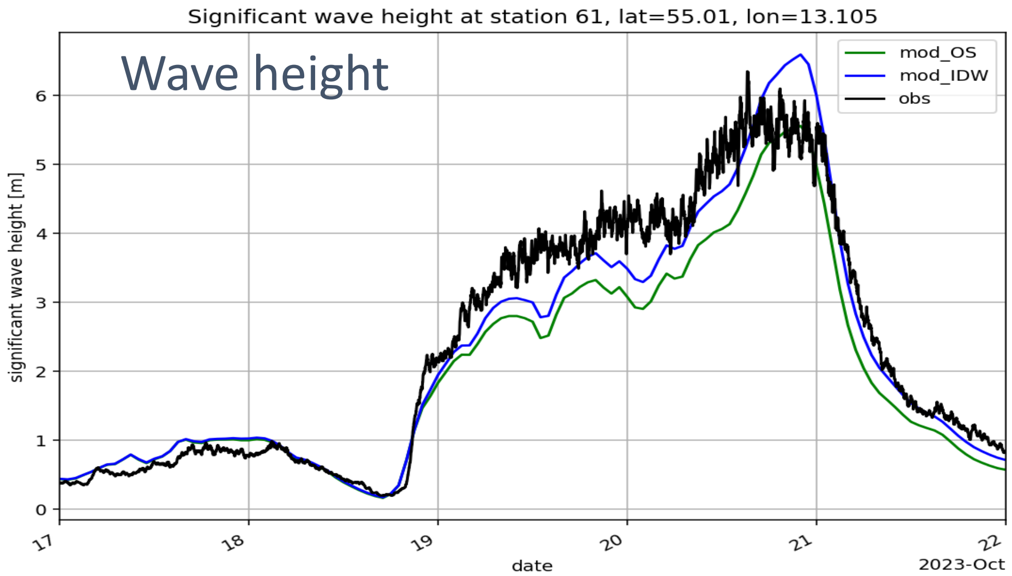


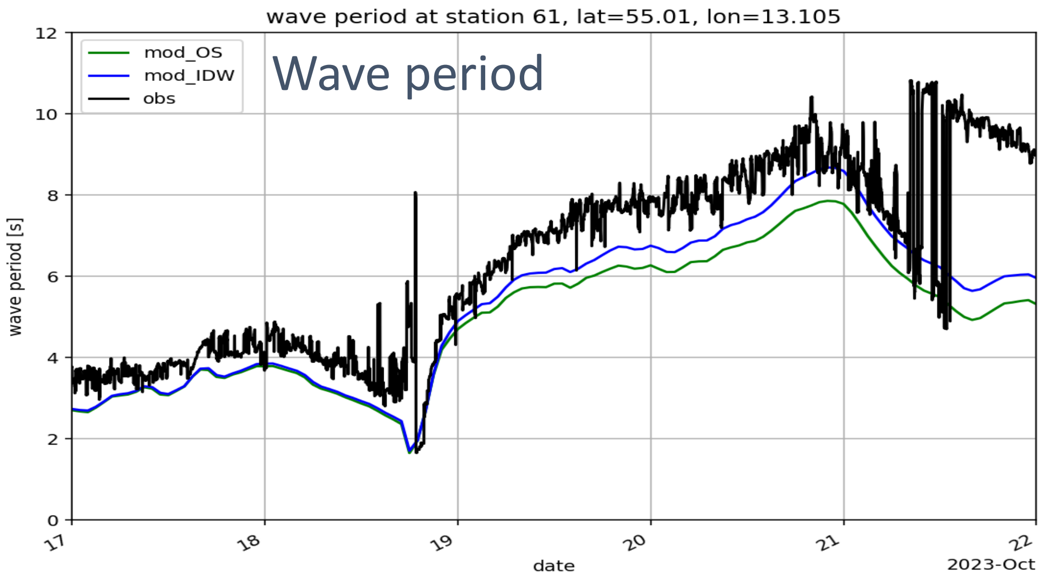
Wave conditions during storm Babet:

Comparisson with wave observations at OWF Kriegers Flak, operated by Vattenfall.

Station 61 is situated east of the OWF. Easterly waves are therefore unaffected by the turbines.

The Øresund model is able to predict the measured wave height peak. The mean period is somewhat underpredicted.





Wave data provided by Vattenfall

Coupling processes (1.): Wave induced surface force, implemented in the momentum solver of the ocean model

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Impacts of wave coupling:

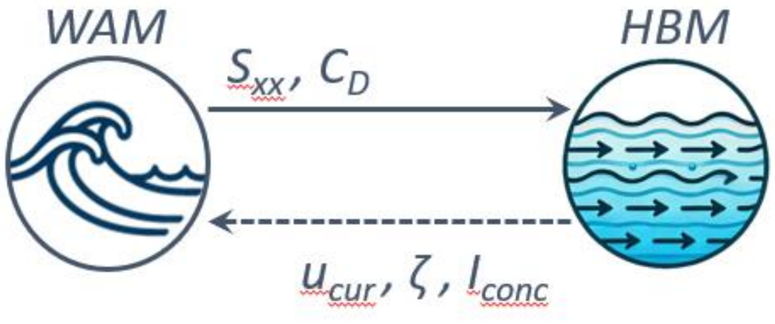
- ***Ocean currents are directly affected by waves:*** as a result, the impact on ocean currents is relatively strong.
- ***Sea level increases only in spatially confined areas***: bays, narrows where transport is geographically limited
- Wave force proportional to 1/depth. Therefore: impact is stronger in shallow waters. – ***strong impact limited to shallow and/or coastal regions***

WAM provides 2D vertically integrated wave force:

$$\frac{\partial \rho v_i}{\partial t} = \dots - \frac{\partial S_{ij}}{\partial x_j}$$

$$S_{ij} = E\frac{c_g}{c}\frac{k_i k_j}{k^2} + \delta_{ij} E\left(\frac{c_g}{c} - \frac{1}{2}\right)$$

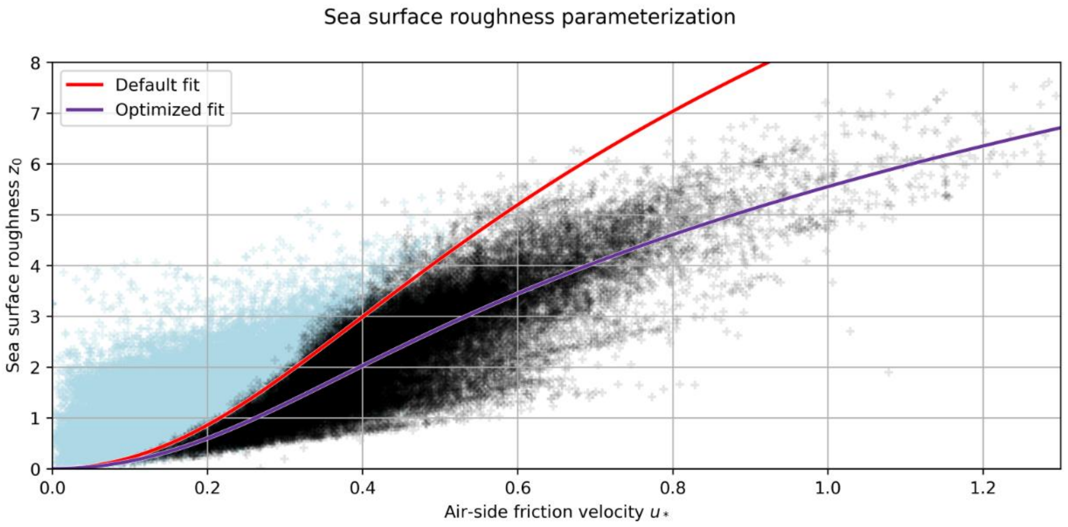
- Wave propagation, depth and current refraction
- Sea ice cover



- Wave force in the momentum Solver
- Wave induced surface and bottom drag force in the k-ω Turbulence model

Coupling processes (2.) Wave dependent turbulence production near the surface:

- Wave dependent surface roughness parameterization: $\boldsymbol{z_0 = \gamma H_S}$, with $\boldsymbol{H_S}$ from
  1. wave model
  2. wave age dependent functions: $\boldsymbol{H_S} = \frac{665\, w_*^2}{0.85\, g}\left(\text{wave\_age}_{ref} \cdot tanh\left(\frac{2\, u_{*,ref}}{u_*}\right)\right)$



Sea surface roughness parameterization, comparison with WAVEWATCH III dat used for optimizing the fit parameter, blue represents fully developed waves.

Veera Haapeniemi (FMI), Tuning of wave dependent parameterization from Rascal et al. (2008): for the Baltic Sea

Parameter	value	
γ	1.0, 1.3	
wave_age $_{ref}$	25	Wave age of fully developed sea
$u_{*,ref}$	0.3	Reference value of friction velocity

Coupling processes (3.) Wave enhanced drag force near the seabed

(1.) Contribution of *ocean currents, near the sea bed*:

The calculation of the current induced shear stress uses the bottom drag equation to calculate the drag force $\mathrm{F_D}$ per reference area A.

$$\tau_{cur} = \frac{F_D}{A} = \frac{1}{2}\rho U_{cur}^2 \cdot C_D$$

with C_D, the bottom drag coefficient.

$$C_D = \frac{\kappa^2}{\left(1 + ln\left(\frac{Z_0}{\Delta H_{kb}}\right)\right)^2}$$

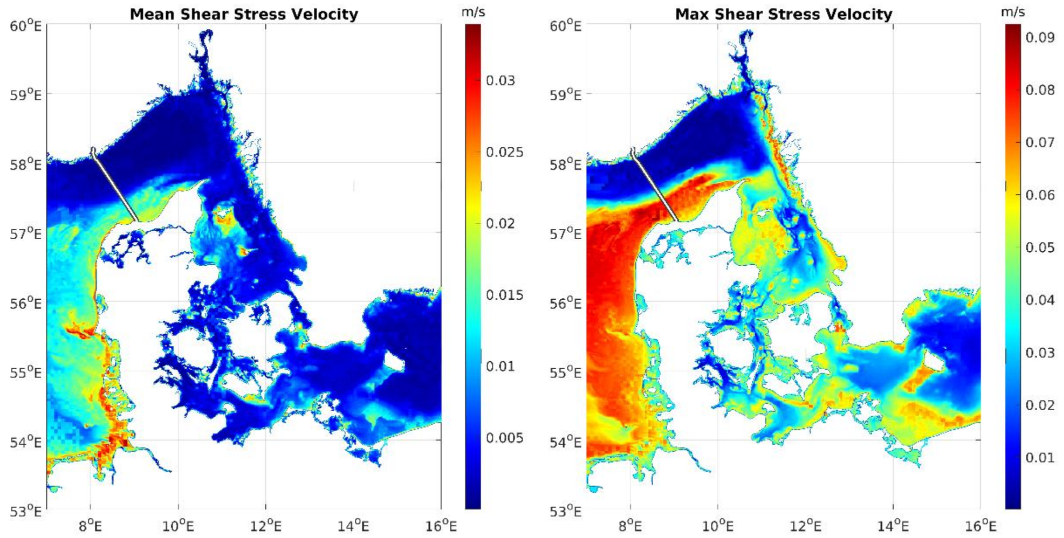


Fig: Mean and Max sea bed shear stress along the Danish coasts

(2.) Contribution of ocean waves (Airy waves):

$$\tau_{wave} = \frac{1}{4}\rho\left(\frac{\pi\, Hs}{T\, sinh(kh)}\right)^2 \cdot f_w$$

with friction parameter f_w=max($f_{ws} = c$, $f_{wr} \sim u^w T^w$)

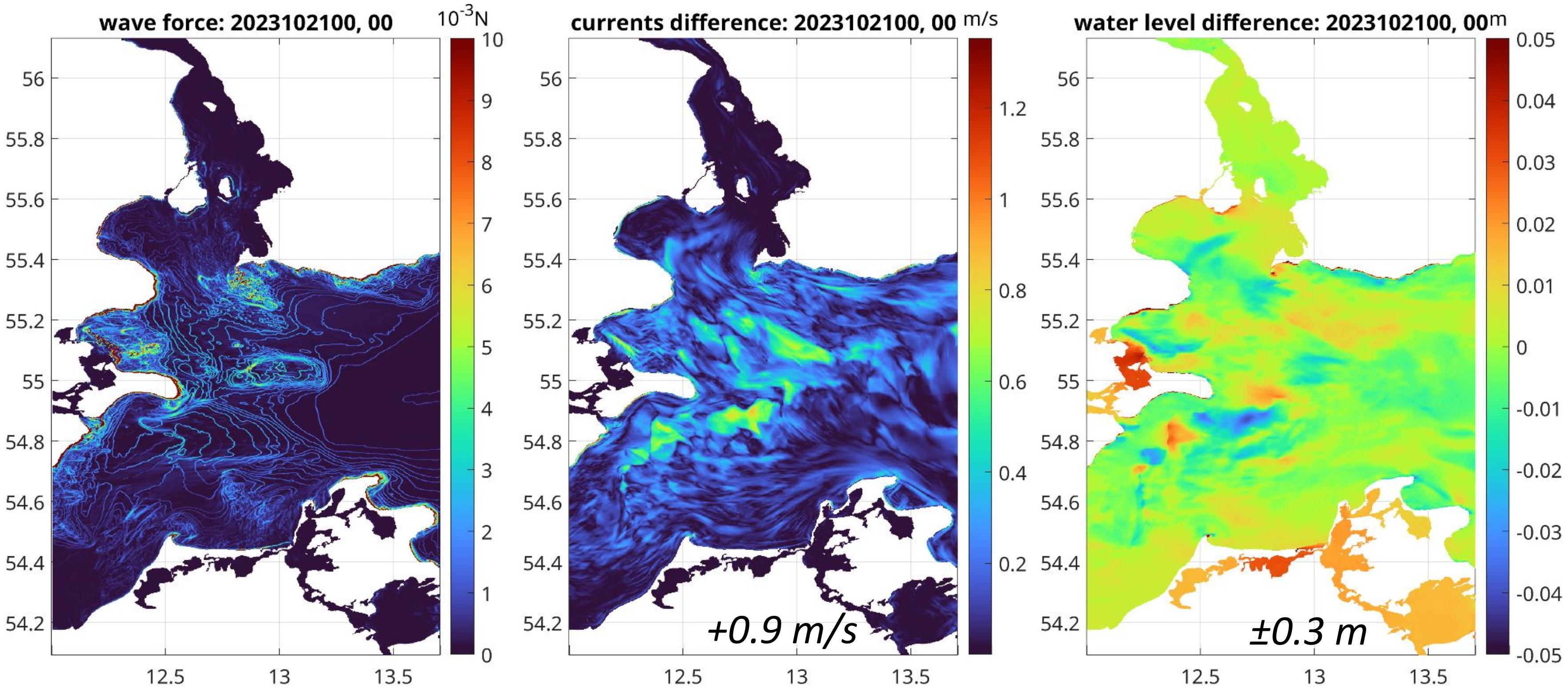
smooth Seabed friction — rough seabed friction

(3.) Combined shear stress:

$$\tau = \sqrt{(\tau_{mean} + \tau_{wave}\cos\varphi)^2 + (\tau_{wave}\sin\varphi)^2}$$

$$\tau_{mean} = \tau_{mean}(\tau_{cur}, \tau_{wave})$$

Wave induced surface force implementation in the momentum solver



Storm Babet. October 2023 with predominantly easterly winds.

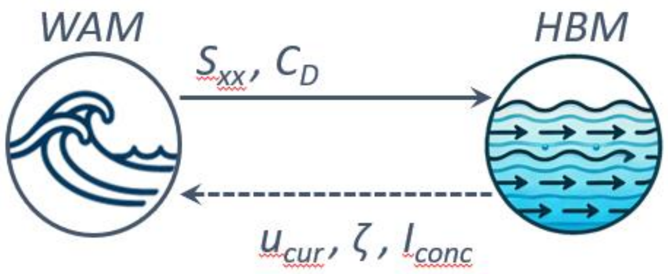
Wave induced force strongest in shallow waters, in Faxe Bay and at Kriegers Flak.

Wave induce currents reach locally magnitudes of 0.9 m/s.

Strong sea level differences occur in shallow bays, where water is moved along the shore, coastal currents.

The wave force moves water closer to the coast, increasing sea level south and west of Rødvig.

- Wave propagation, depth and current refraction
- Sea ice cover

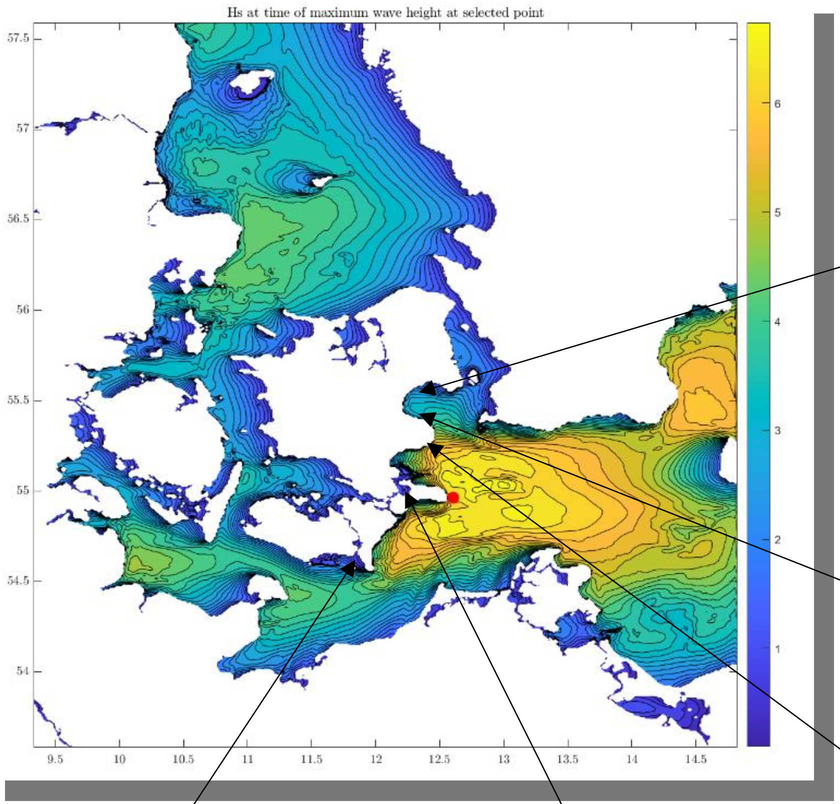


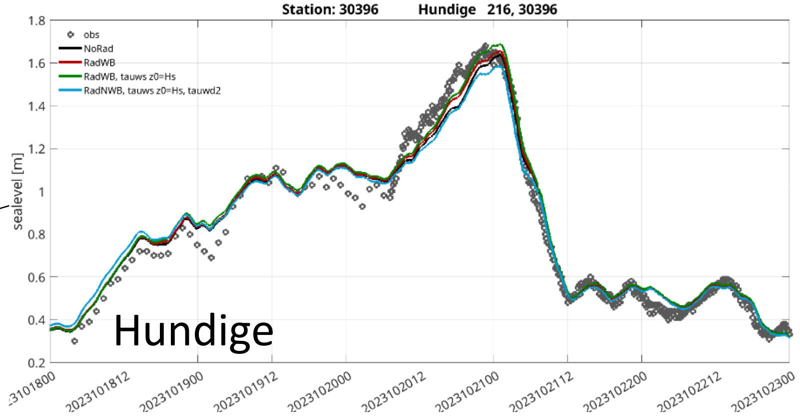
- Wave force in the momentum Solver
- Wave induced surface and bottom drag force in the k-ω Turbulence model

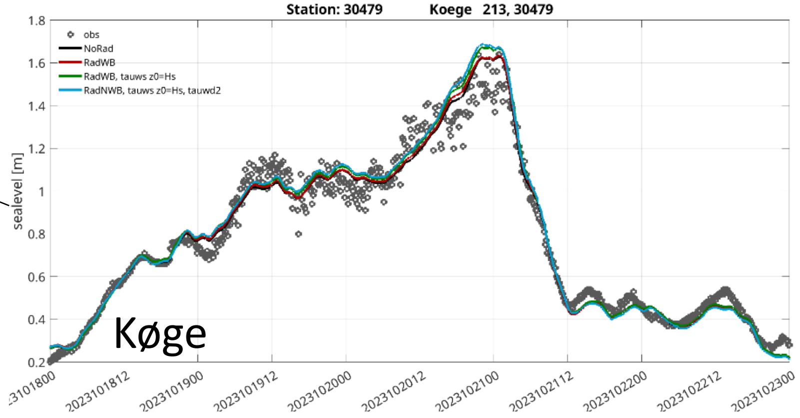
Results:

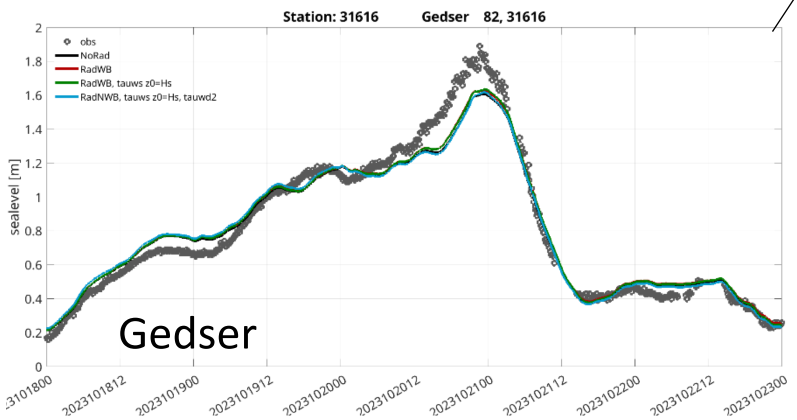
Coupling of ocean wave and circulation modelling increases the peak sea levels at most stations along the east coast.

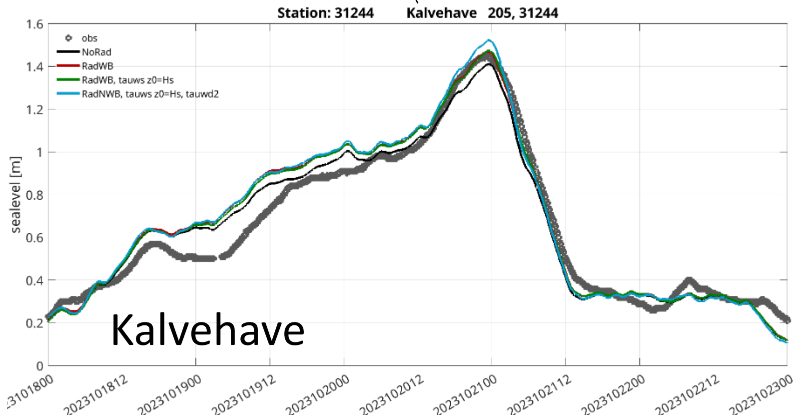
The strength of the impact depends on the angle between the waves and the coast, e.g. Rødvig and Køge.

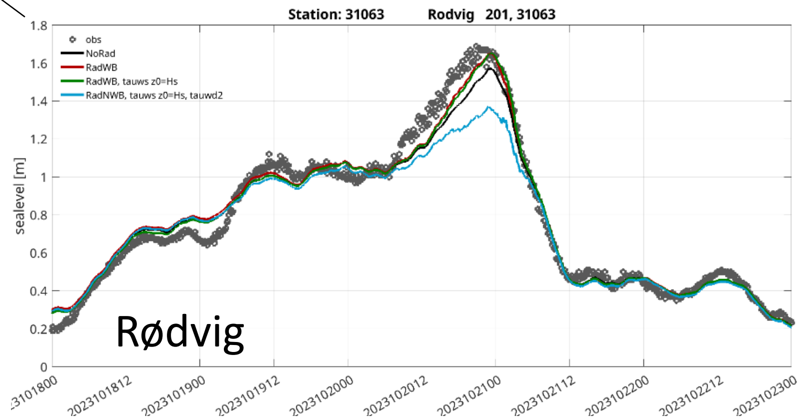




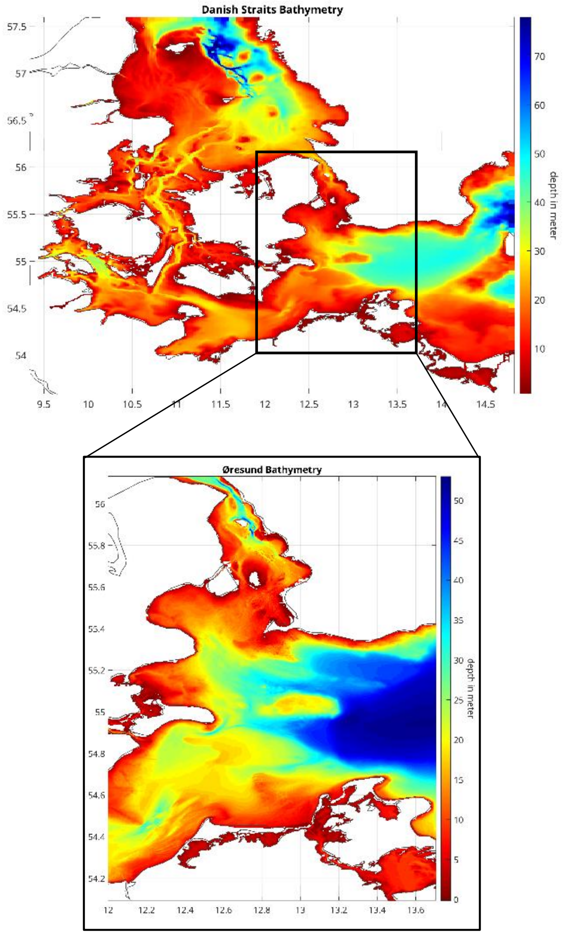


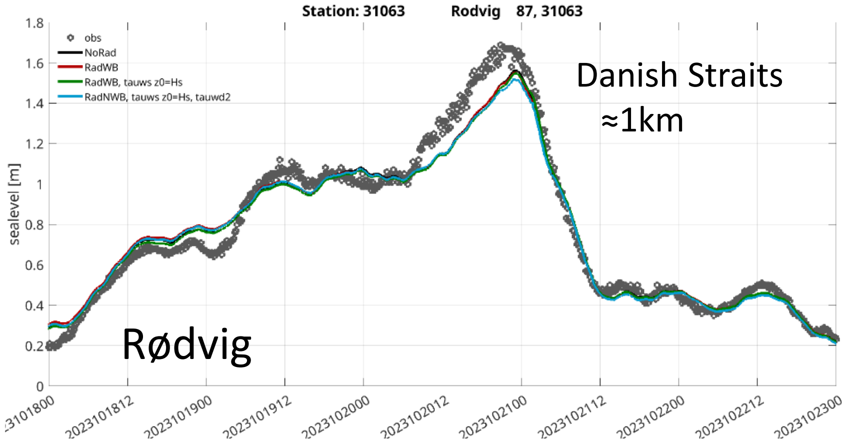


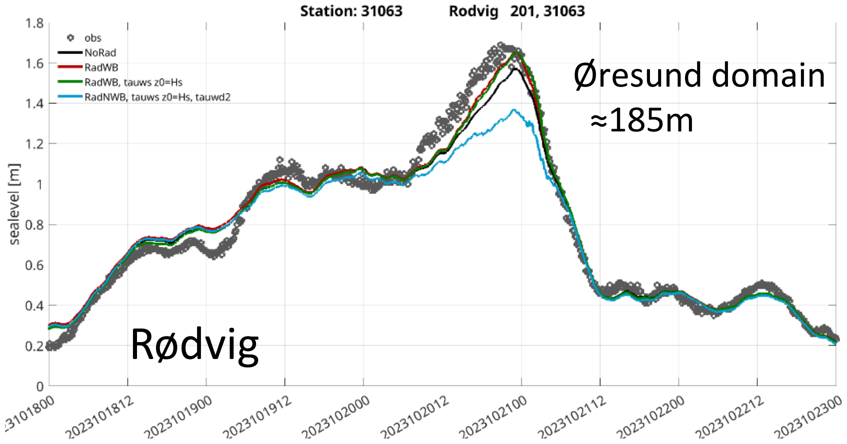


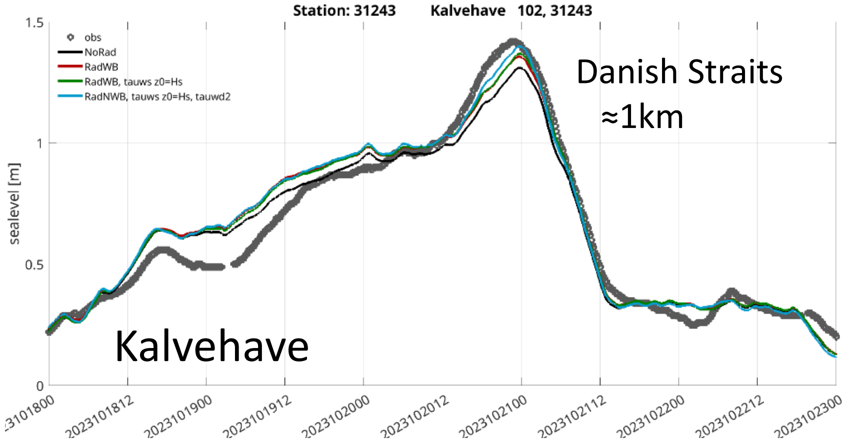


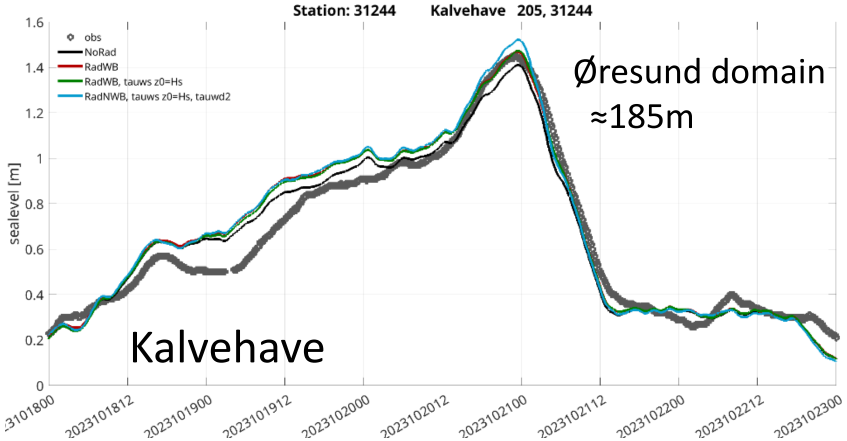
Effect of increased spatial resolution on the impact of model coupling











Wind forcing: The combination of Swedish (SMHI) meteorological forcing and Danish (DMI) storm surge model provides the best sea level forecast. SMHI winds are stronger during peak wind period.

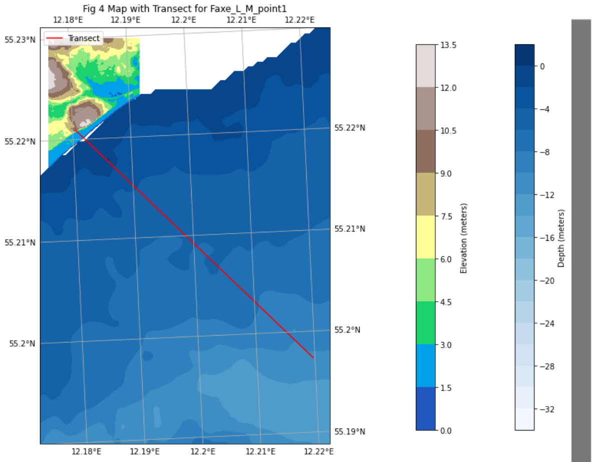
Wave induced currents and setup:

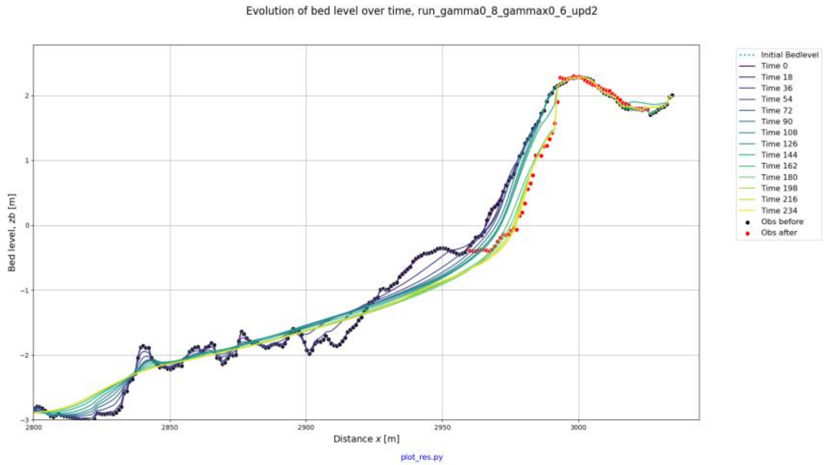
- ***Wave induced momentum***, drives the currents and generates largest wave setup during peak sea levels. **Significant in regions with strong wave height.**
- ***Wave dependent surface roughness*** and turbulence production, heterogenous wave fields (compared to winds) generate stronger surface turbulence in regions with stronger waves and weaker turbulence and eddy viscosity in regions with weaker waves. **Significant in regions with weaker waves.**
- ***Wave generated seabed friction*** and turbulence, stronger waves with larger orbital motion generate more sea bed friction and increase sea level in regions with limited transport.

Model configurations in high resolution can better represent the dynamic in the coupled model system.

Modelling coastal erosion at Faxe Ladeplads, in collaboration with the Danish coastal authorities.

A number of beach houses next to Strandvejen in Faxe Ladeplads have suffered severe damage. Some are completely destroyed after the storm. Photo: Birgitte Kraft





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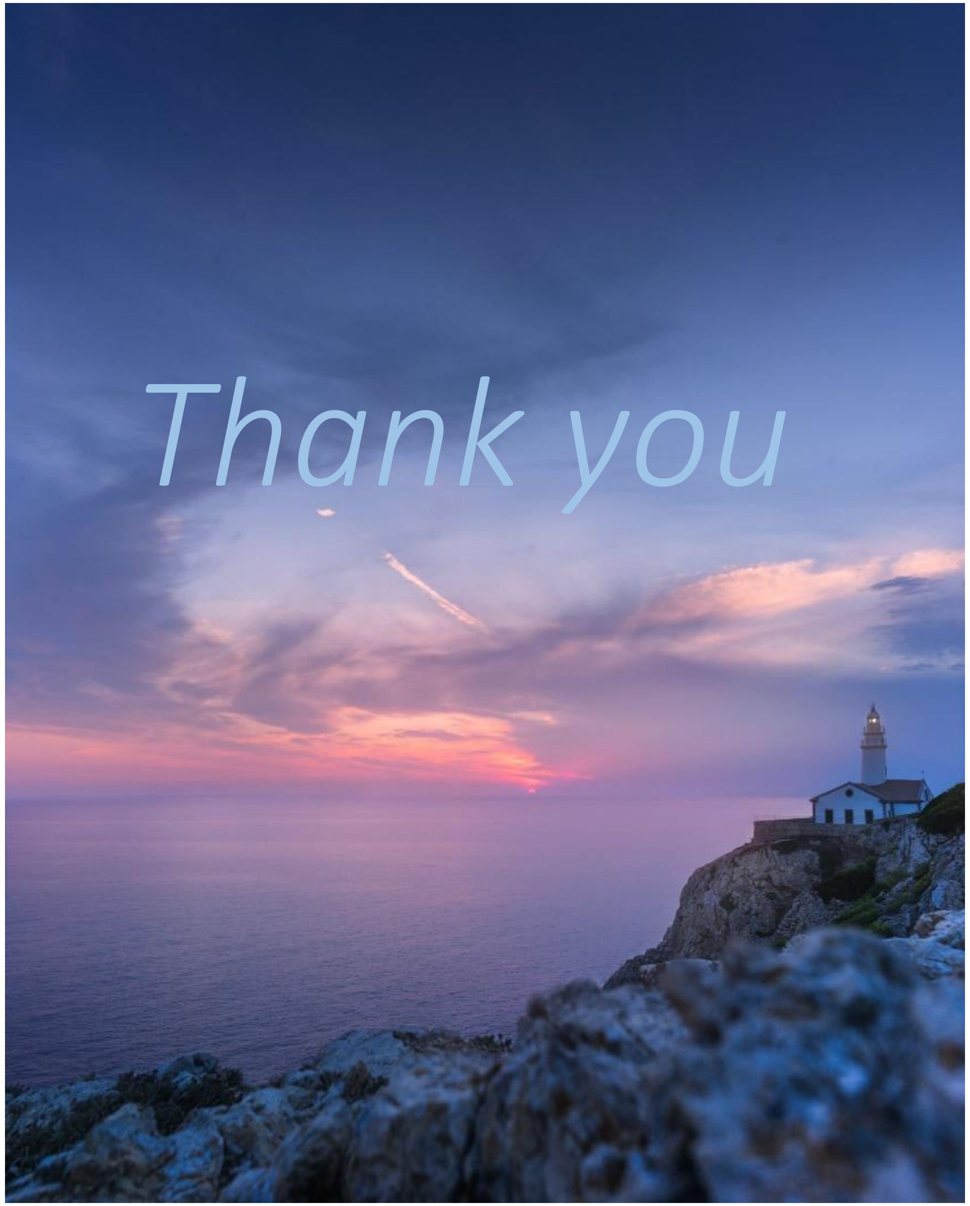
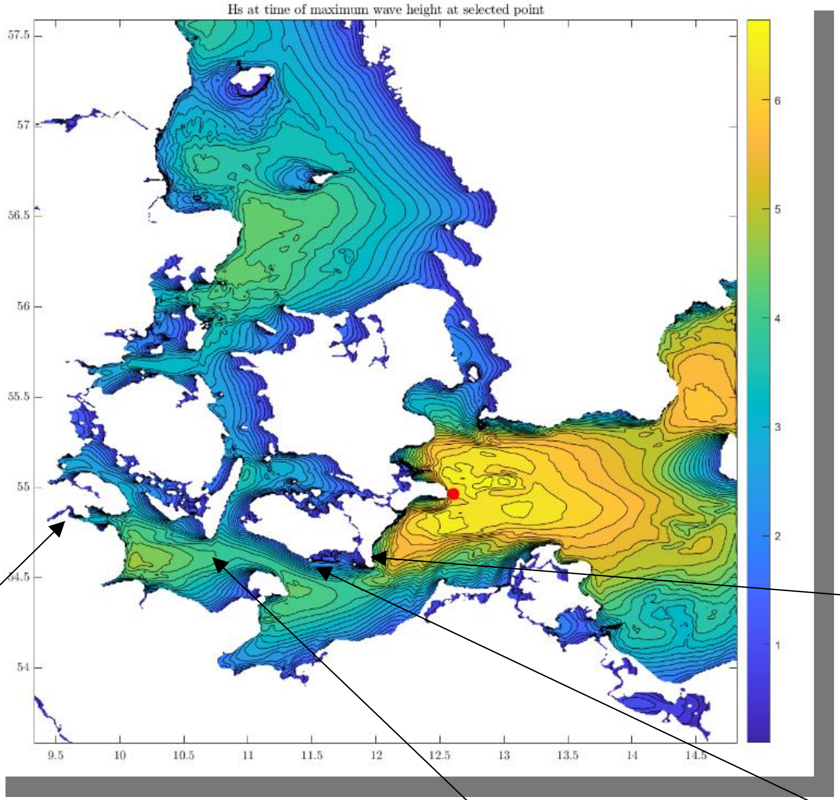


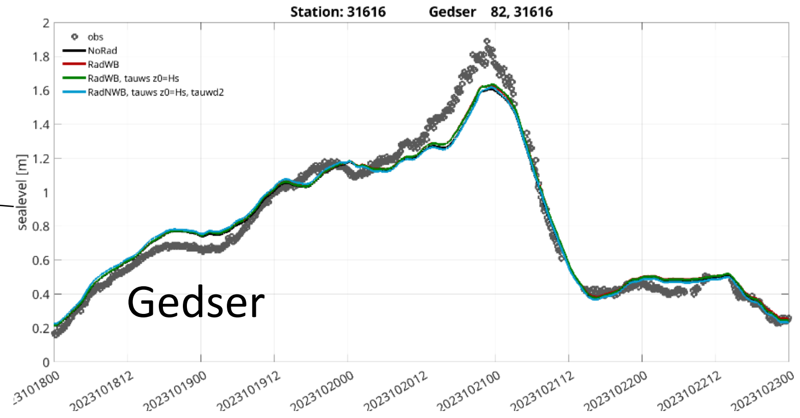
4th international workshop on waves, storm surges and coastal hazards. 22nd to 26th of September 2025, Santander, Spain

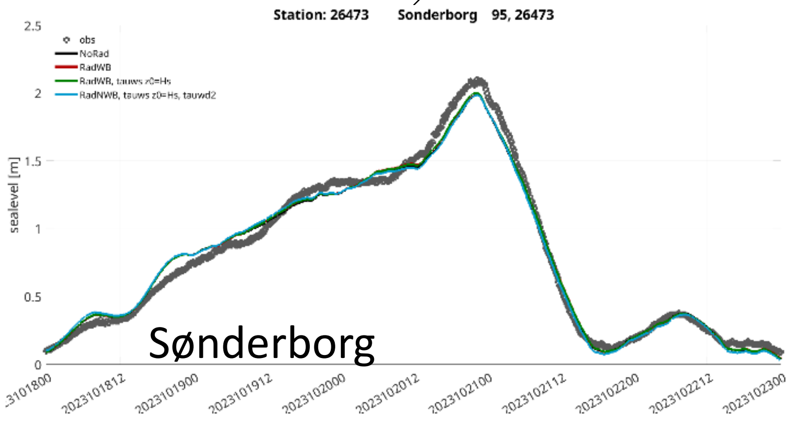
Results (2.):

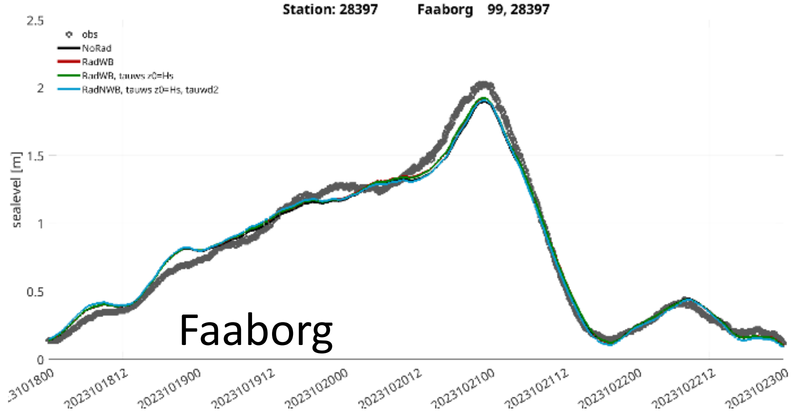
Model results along the southern coast of Denmark do not improve significantly by model coupling.

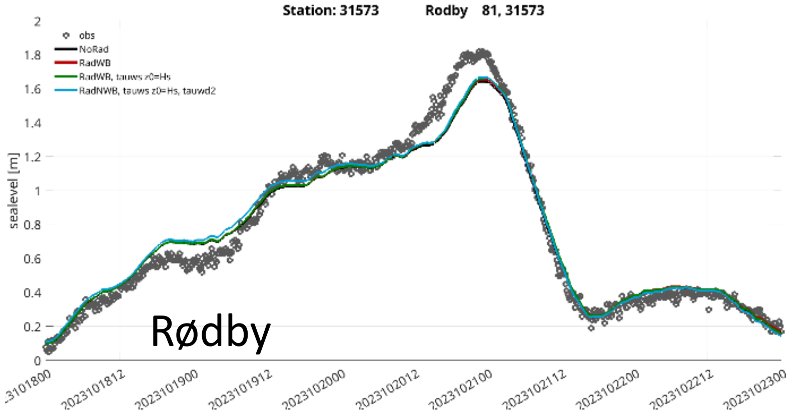
But the wave height is comparatively weak hear, due to the weak winds.

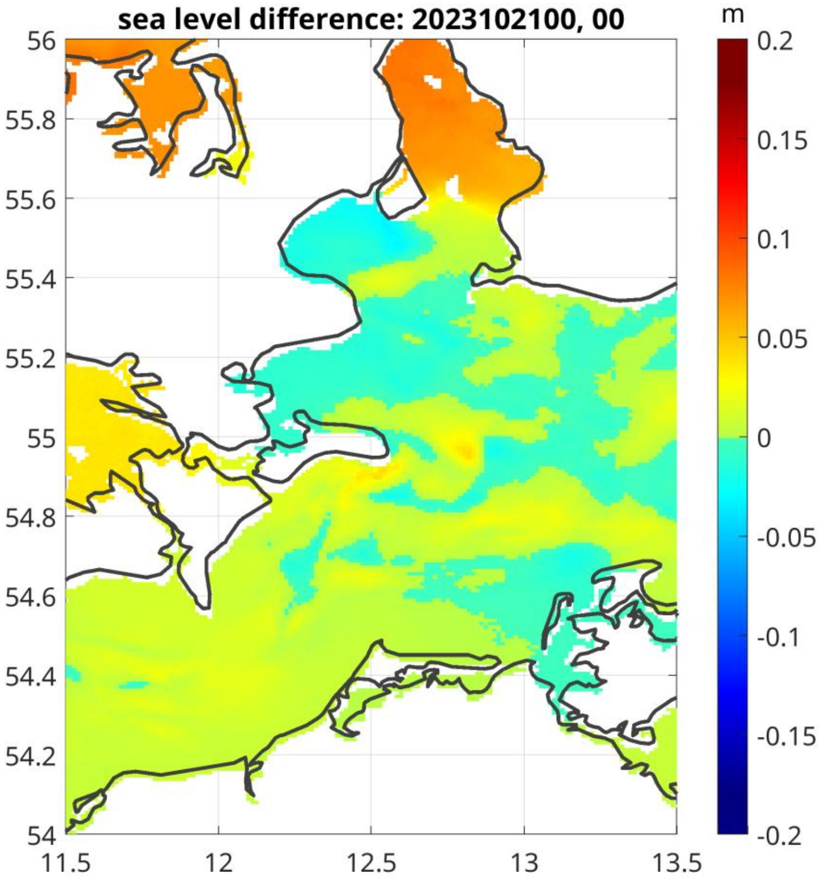


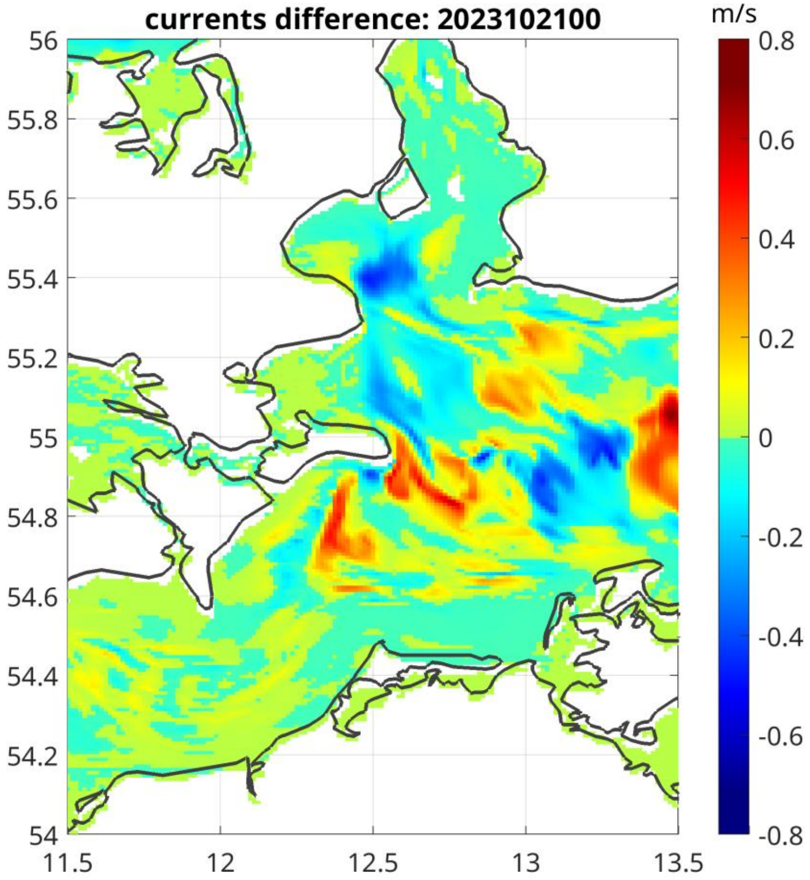


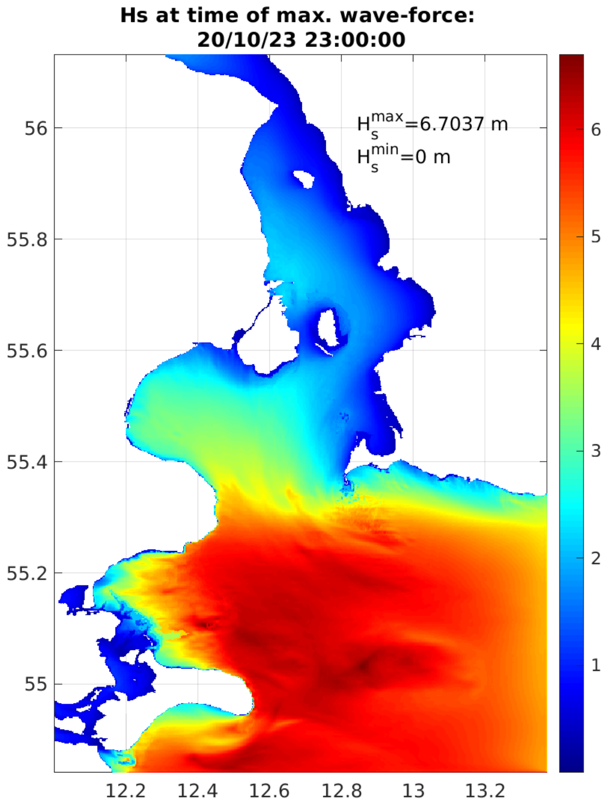












Wave breaking parameterization and TKE production:

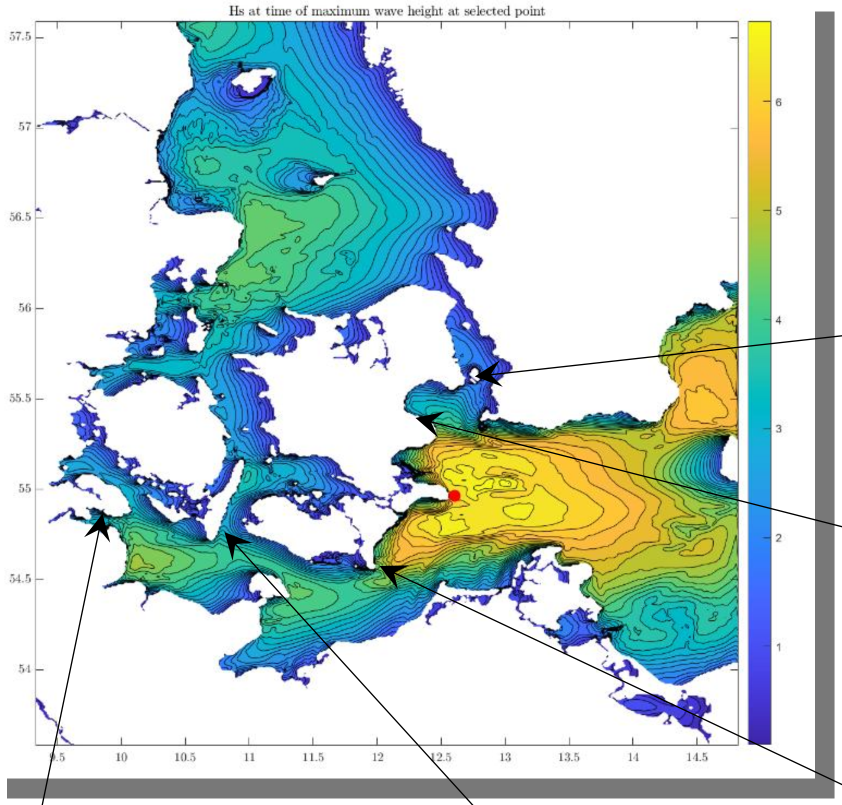
- Young waves in areas with strong significant wave height, generate a higher surface roughness, shear stress and TKE production.
- The surface TKE production due to waves is about a magnitude stronger than the previously implemented wind dependent formulation.
- Increased TKE production leads to higher eddy viscosities, locally reduced currents and increased sea level.

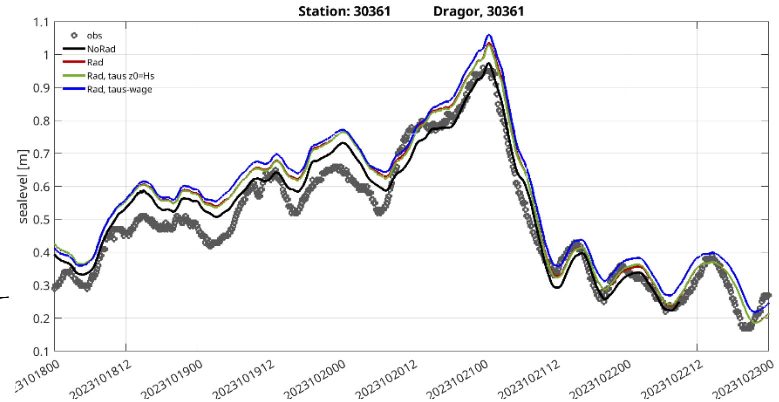
Results:

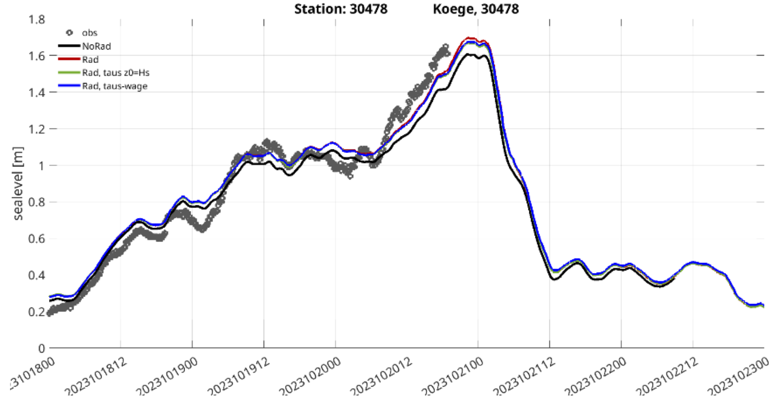
Coupling of ocean wave and circulation modelling increases the peak sea levels at most stations.

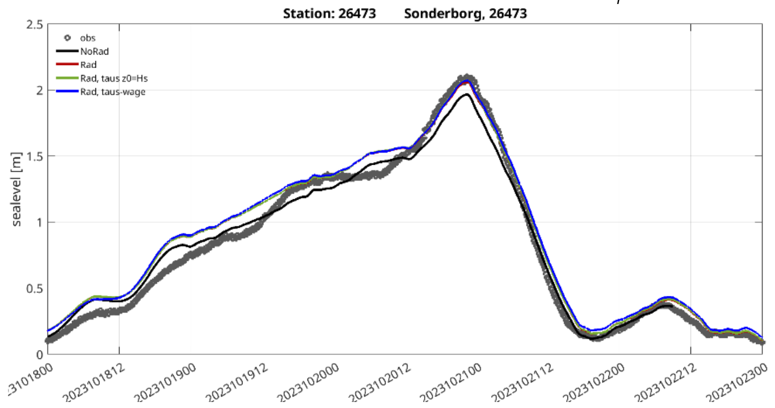
In the Øresund, coupling leads to an overprediction of sea level.

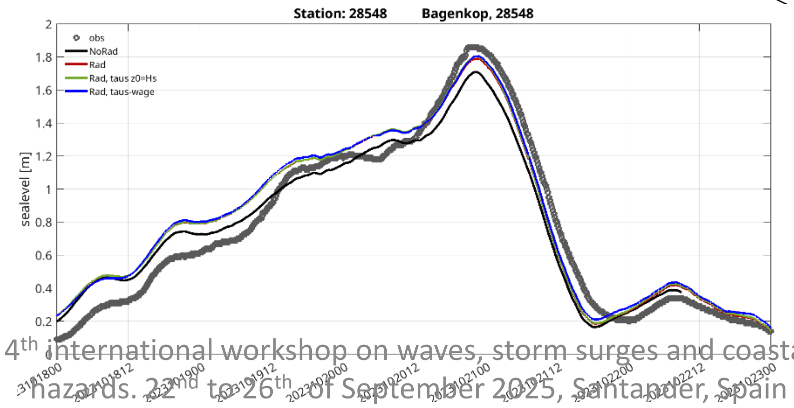
The strength of the impact depends on the angle between the waves and the coast, e.g. Rødvig and Køge.

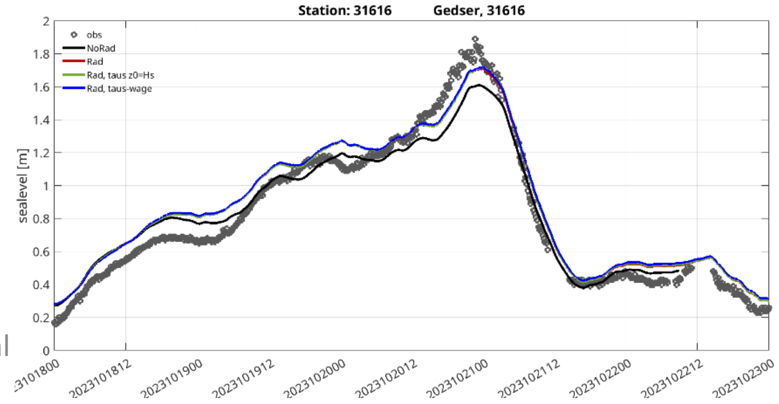










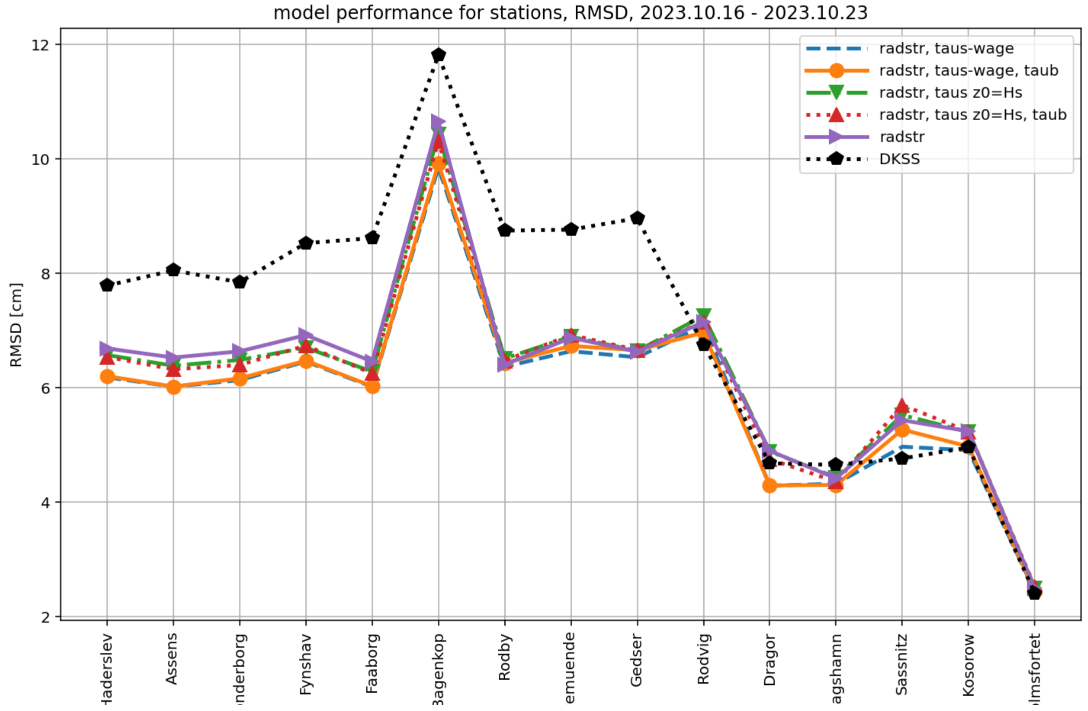


Results

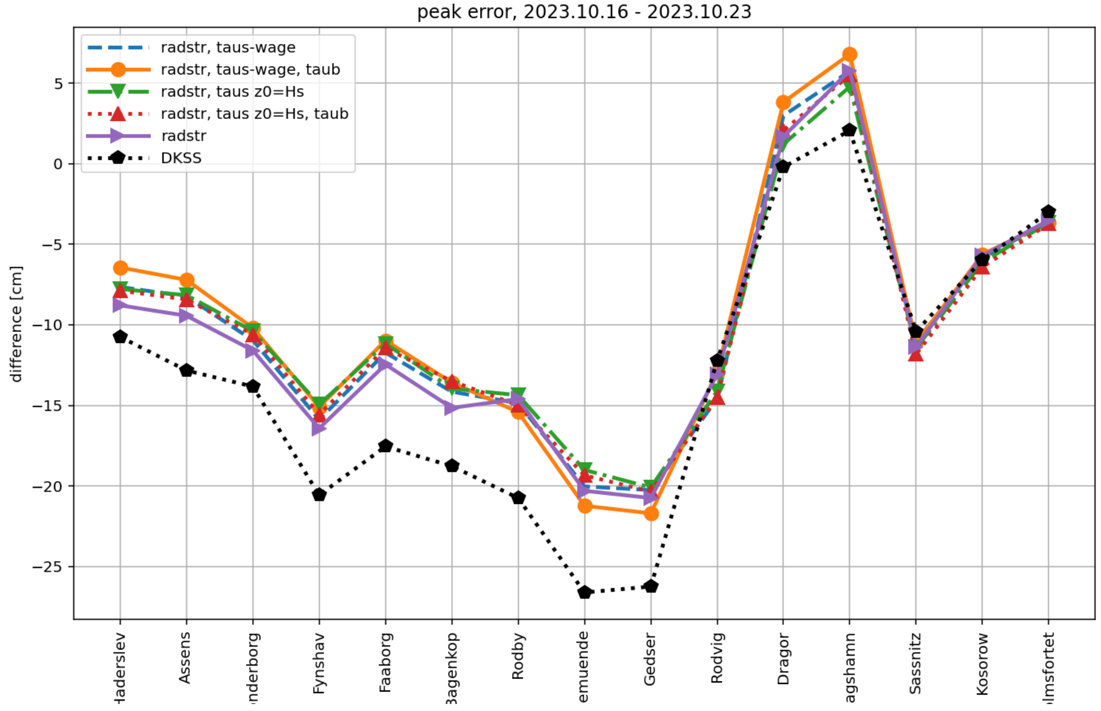
Danmarks Meteorologiske Institut

FINNISH METEOROLOGICAL INSTITUTE

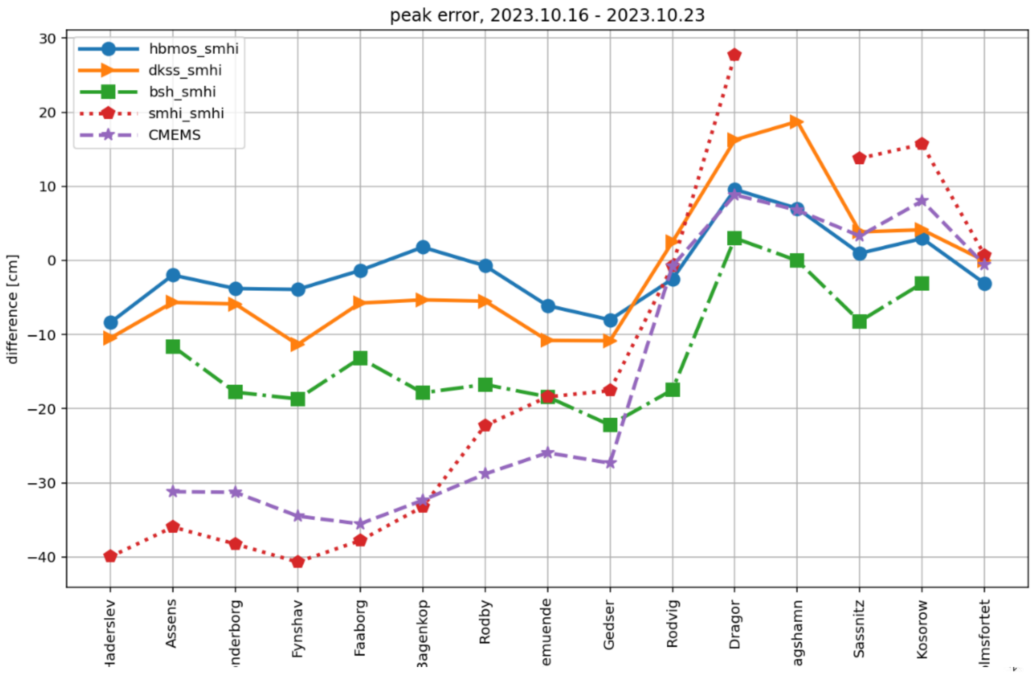
RMSD

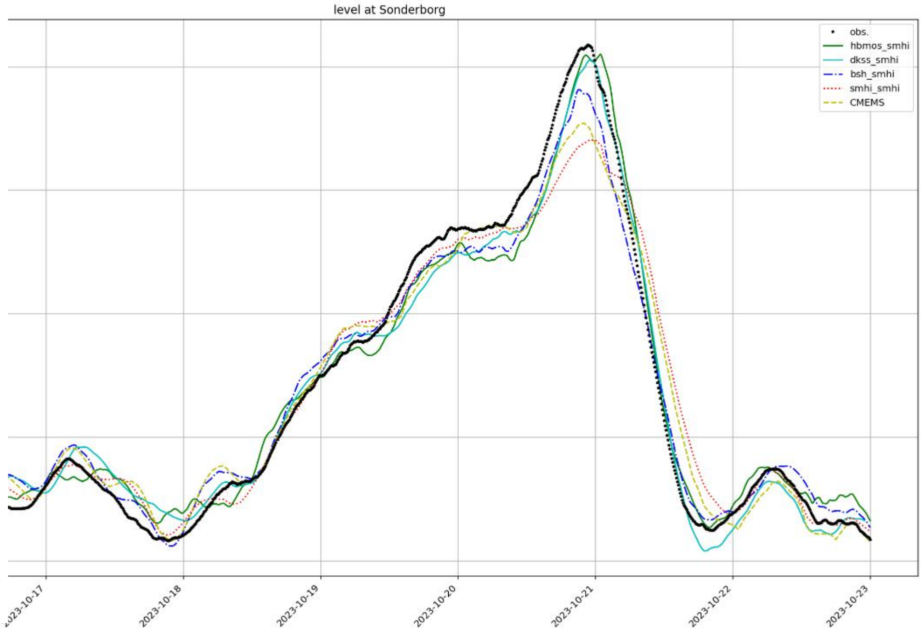


Peak Error

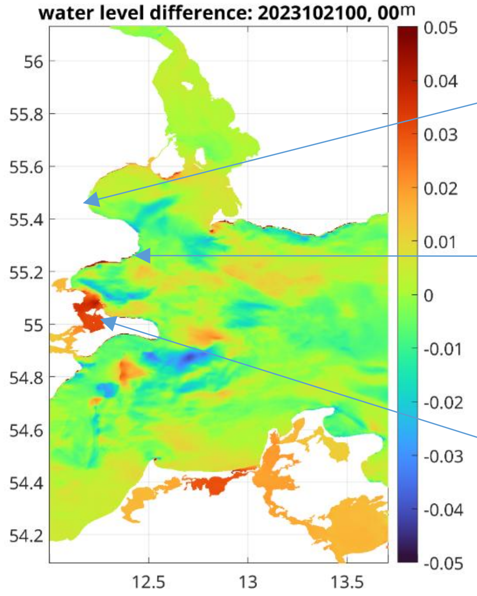


- Coupling of WAM 4.7 wave model and HBM ocean circulation model improves sealevel forecast at South-West Baltic Sea stations, from Haderslev to Gedser.
- The wave-age dependent formulation of surface roughness shows a better performance in the Little Belt area and a worse performance at Travemünde and Gedser.

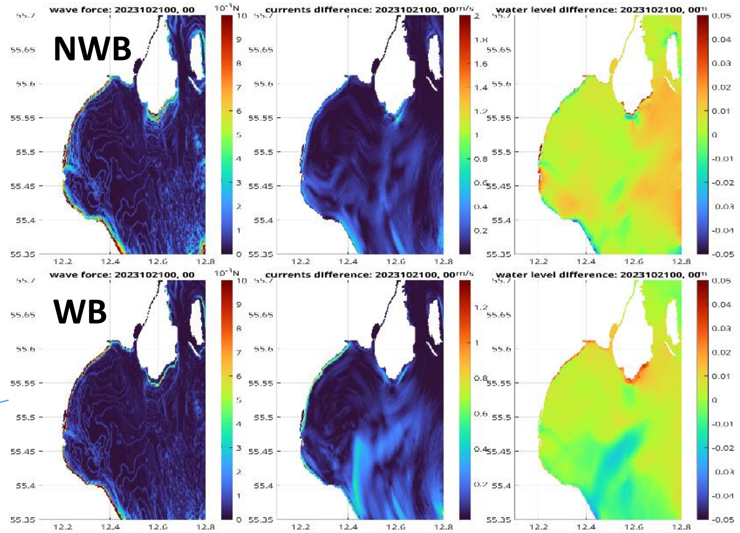

peak error, 2023.10.16 - 2023.10.23
hbmos_smhi
dkss_smhi
bsh_smhi
smhi_smhi
CMEMS
difference [cm]
30
20
10
0
−10
−20
−30
−40
Assens
Fynshav
Faaborg
Rodby
Gedser
Rodvig
Dragor
Sassnitz
Kosorow


level at Sonderborg
obs.
hbmos_smhi
dkss_smhi
bsh_smhi
smhi_smhi
CMEMS
2023-10-18
2023-10-19
2023-10-20
2023-10-21
2023-10-22
2023-10-23

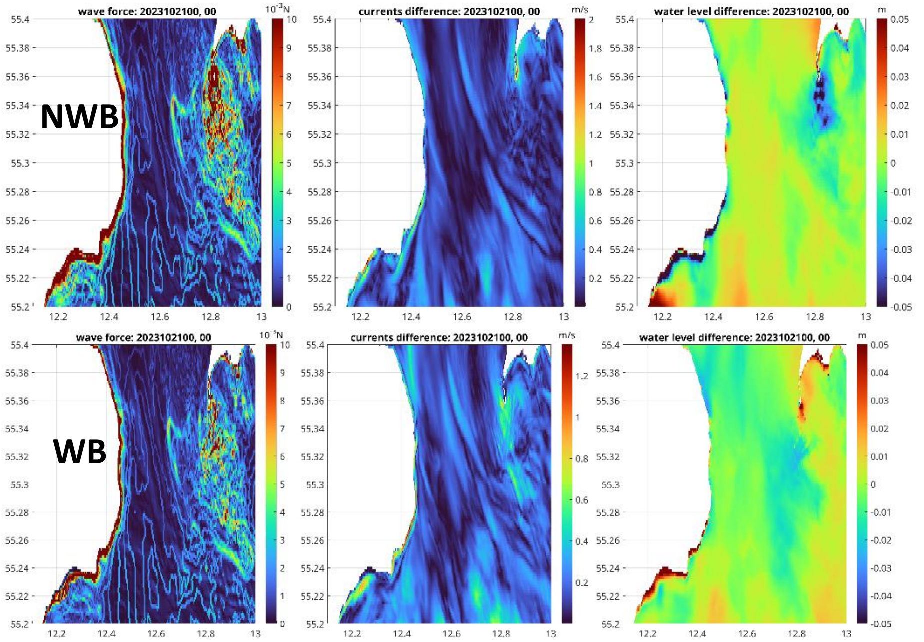
Local effects of wave breaking



Køge



Rødvig



Kalvehave