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# Improving Gulf of Finland wave forecasts and statistics

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*with special thanks to the whole BAL MFC team*

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[3] Natural Resources Institute Finland

16.11.2023 **Gulf of Finland Science Days 2023**

Picture by Iina Ilmola; view from Bengtskär island

# Waves in the Gulf of Finland

Narrow basin. Typically fetch limited wave growth

- frequent slanting fetch conditions

➡ the direction of the dominant waves is steered along the direction of the gulf

Highest measured significant wave height (Hs):

- **5.78 m** on 12.10.2023 measured by LainePoiss
  - operated by TalTech Institute of Marine Systems
- Previous record **5.2 m** has been measured twice (15.11.2001 and 30.11.2012)
  - by FMI GoF wave buoy

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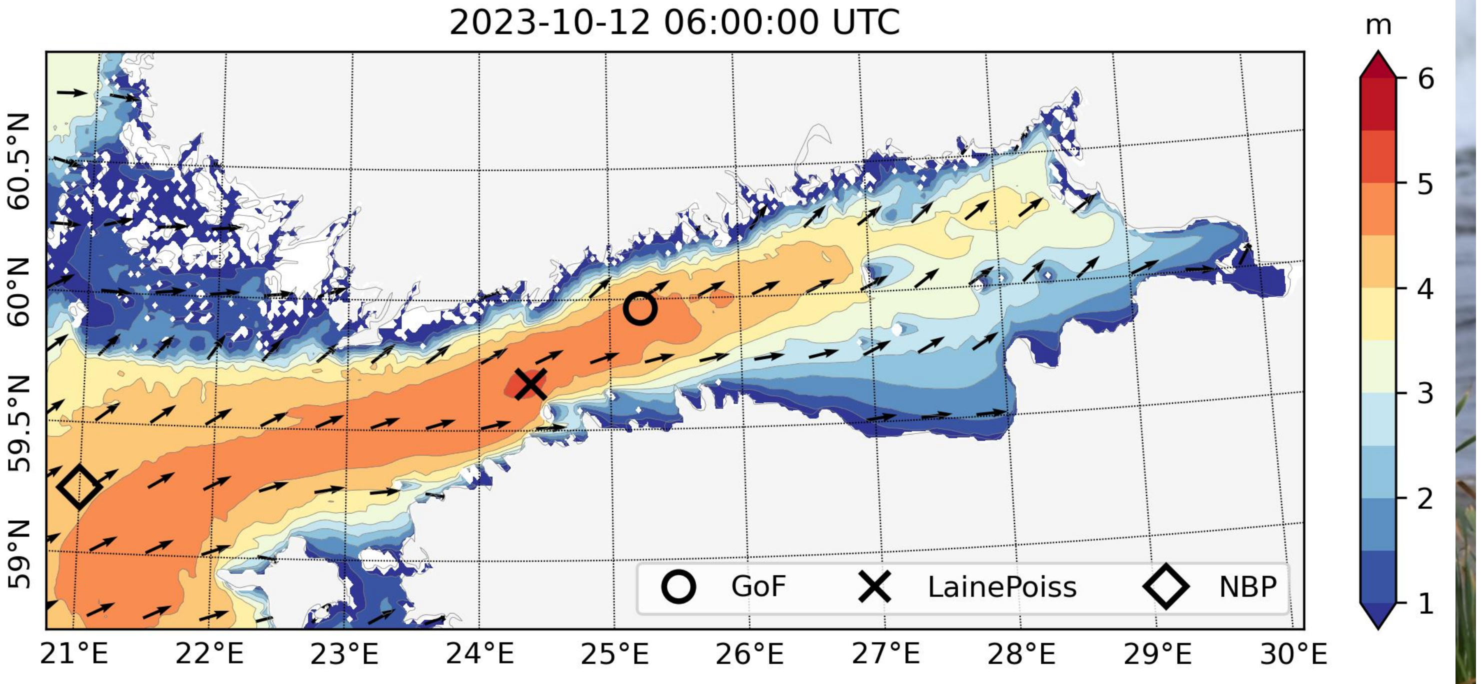
*Modelled significant wave height ($H_s$) on 12.10.2023:*




Picture by Kirsi Yliaho; view from Märket island

# Two main focuses in the wave forecast development:

**BAL MFC**: Coupling wave model with 3D ocean - ice model

| |
|---|
| 3 Forecast (NRT) products:<br>• 6 days forecast, twice/day<br>• Harmonized the atm. forcing:<br>    • MetCOOP/Harmonie (2.5 km) + ECMWF (day: 3-6)<br>• PHY-BGC: online coupled (1-way) [runs at SMHI]<br>• PHY-WAV: offline coupled (2-ways) [runs at FMI]<br>• Product grid = native grid size: 1 nautical mile |
| WAV: WAM 4.6.2 (4.7 at the end of Nov)<br>Reads: surface currents, sea surface height & ice conc. from NEMO |
| PHY-BGC: NEMOv 4.0-ERGOM<br>Reads: Stokes drift from WAM<br>DA (PDAF): SST (and sea ice at the end of Nov) |

**BAL MFC: Copernicus Marine Services Baltic Monitoring and Forecasting Centre:**

Danmarks Meteorologiske Institut

TAL TECH

SMHI

BSH
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE

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**FMI**: Improving forecasts in coastal archipelago areas


Photo: Laura Tuomi

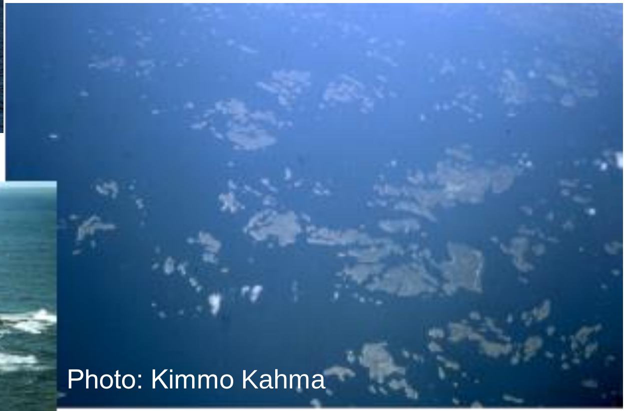
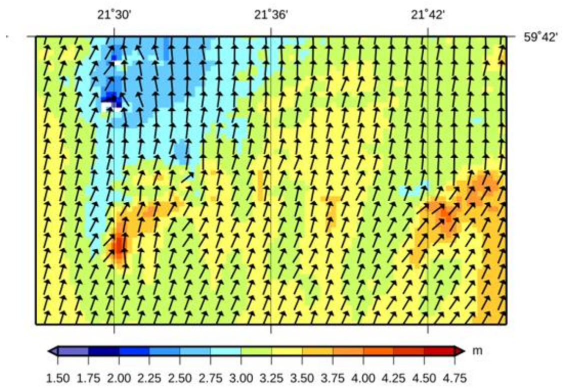
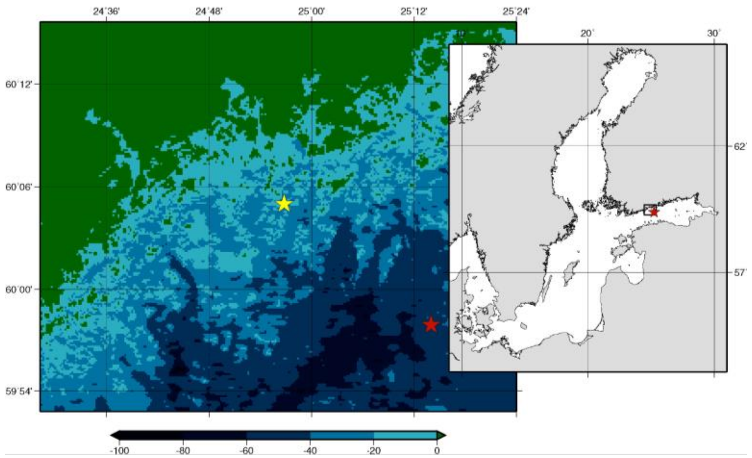


Photo: Kimmo Kahma


Photo: Kimmo Kahma

# Two main focuses in the wave forecast development: Gulf of Finland



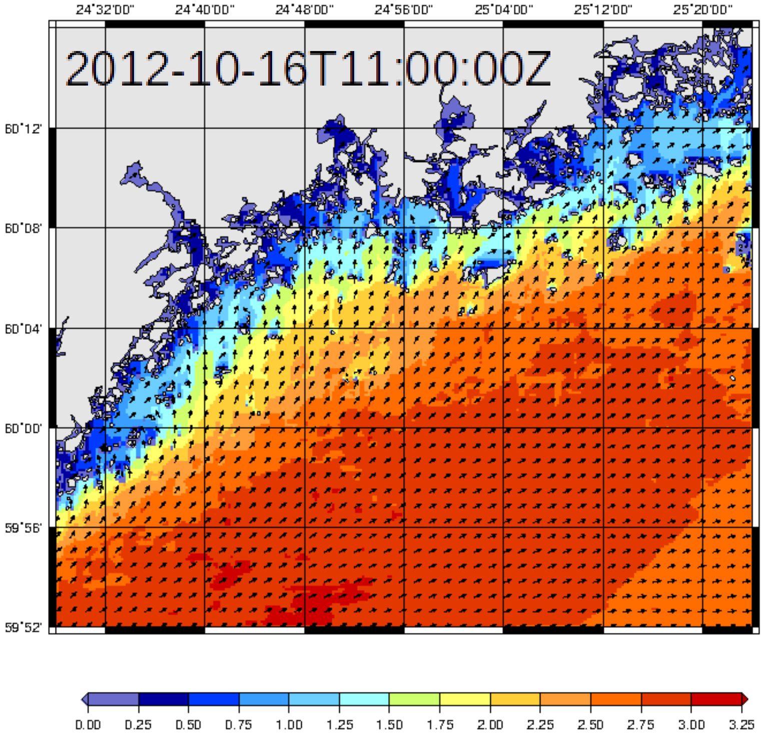




Coupling wave model with 3D ocean - ice model

- Seasonal ice cover
- Occasionally strong currents
- Large SSH variations at the end of the gulf

Improving forecasts in coastal archipelago areas

- Irregular coastline
- Archipelago
- Rugged bottom topography




*Upper left figure shows example of wave refraction due to rugged bottom topography* (from Tuomi et. al., 2014)

*Upper right figure shows the bathymetry used in high-resolution 0.1 nmi grid. Bottom figure shows modelled wave fields on 16 Oct 2012* (from Björkqvist et. al., 2017)

Tuomi, L., Pettersson, H., Fortelius, C., Tikka, K., Björkqvist, J. V., & Kahma, K. K. (2014). Wave modelling in archipelagos. *Coastal Engineering*, *83*, 205-220. https://doi.org/10.1016/j.coastaleng.2013.10.011

Björkqvist, J.-V., Tuomi, L., Fortelius, C., Pettersson, H., Tikka, K., & Kahma, K. K. (2017). Improved estimates of nearshore wave conditions in the Gulf of Finland. *Journal of Marine Systems*, *171*, 43-53. https://doi.org/10.1016/j.jmarsys.2016.07.005

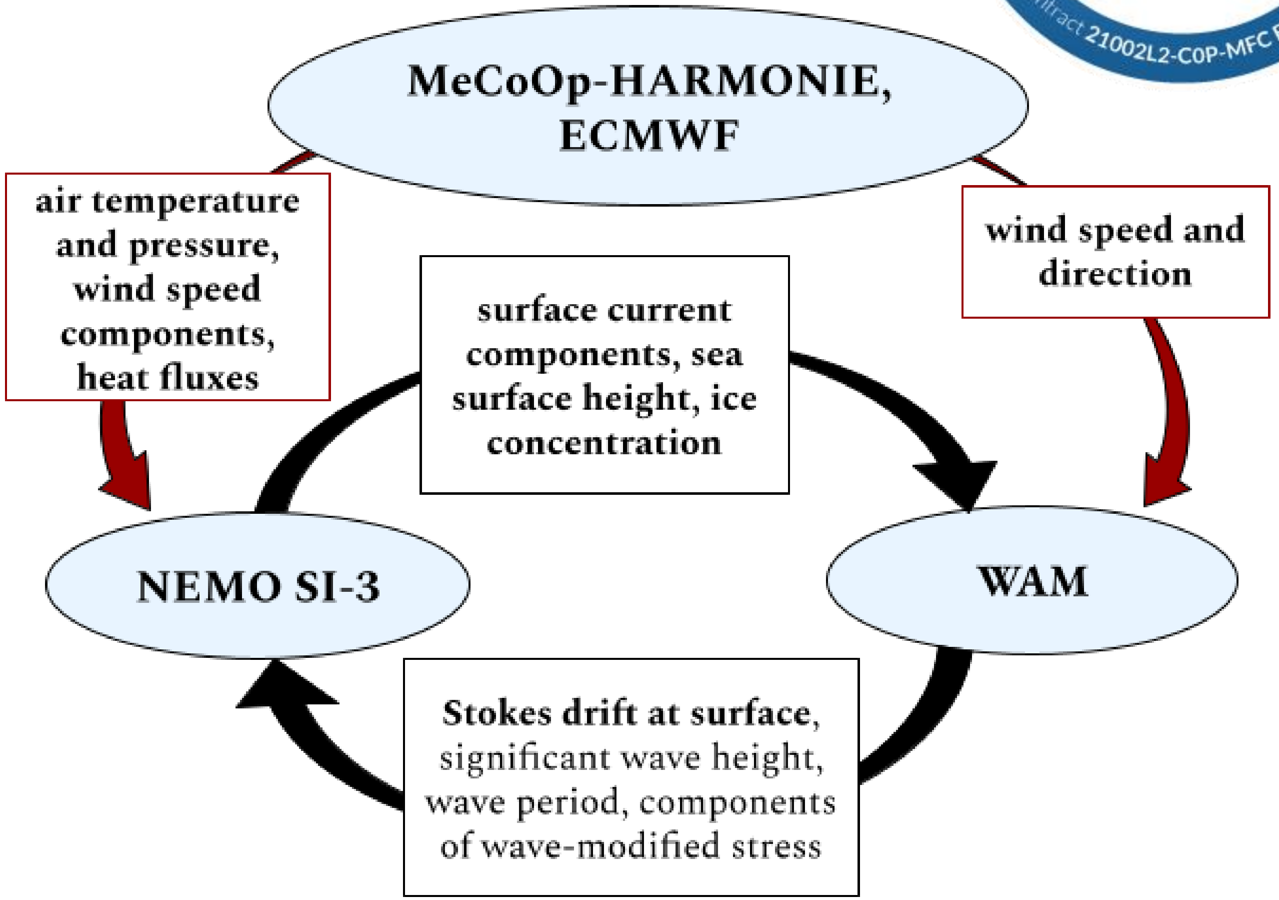
# Wave – ocean coupling

Coupling in current BALMFC system

- WAM and NEMO forced offline
  - WAM reads from NEMO:
    - Ice
    - Currents
    - SSH
  - NEMO reads from WAM:
    - Stokes-Coriolis forcing

Currently working on implementing in NEMO

- Sea-state dependent momentum flux
- **Requires online coupling**

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# WAM: Ice Concentration

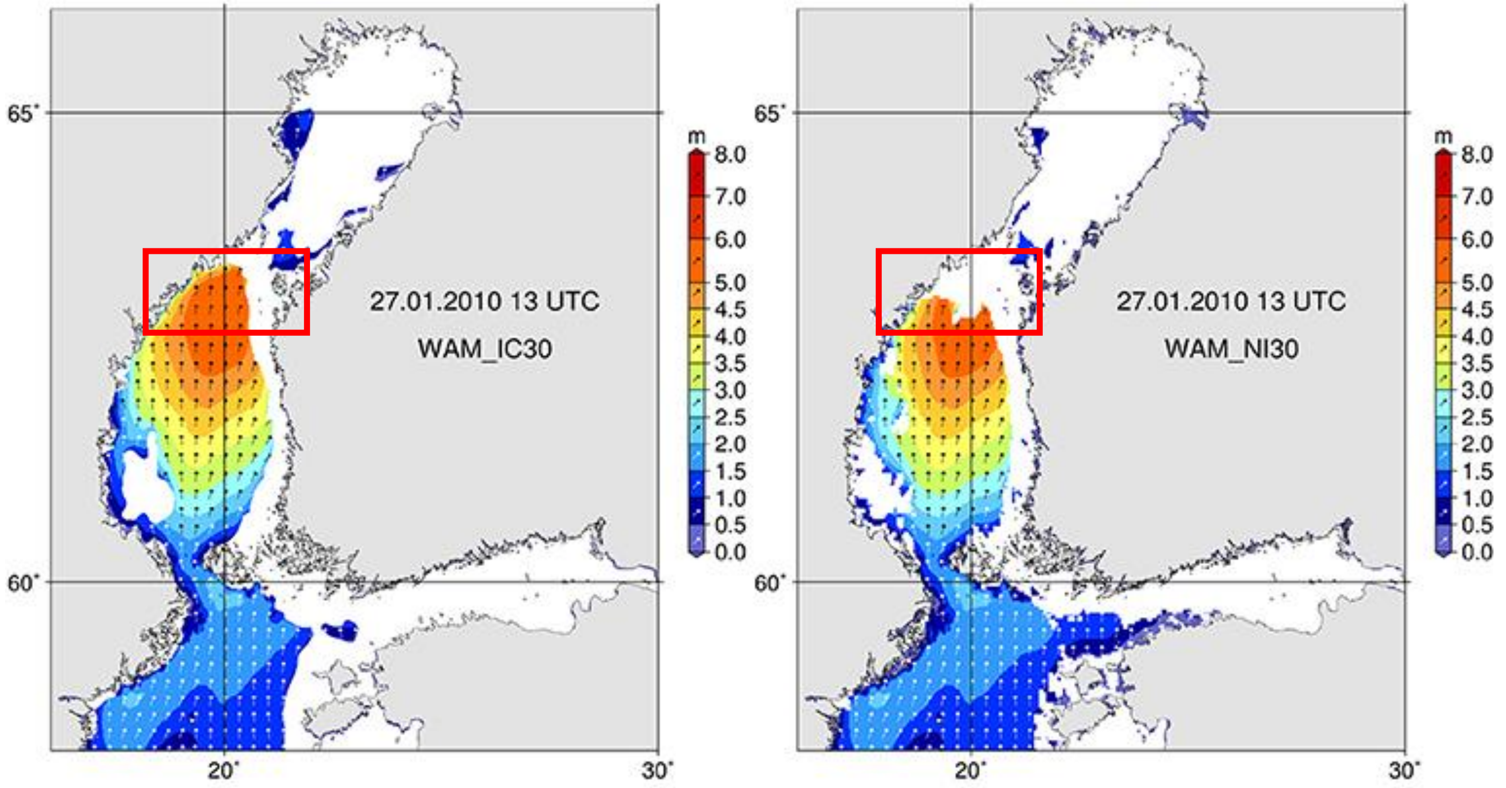
Accounting for seasonal ice conditions is important in the Baltic Sea.

The Ice Services produce information about ice conditions during wintertime (**ice charts**). This information is the **most accurate product available** and is used in the production of the Baltic Sea wave hindcast.

Although more accurate, the ice chart does not contain any **forecast for ice conditions** and therefore the BAL MFC NRT product uses NEMO ice concentration forecast.

**HINDCASTS**
ice chart

**FORECATS**
modelled ice

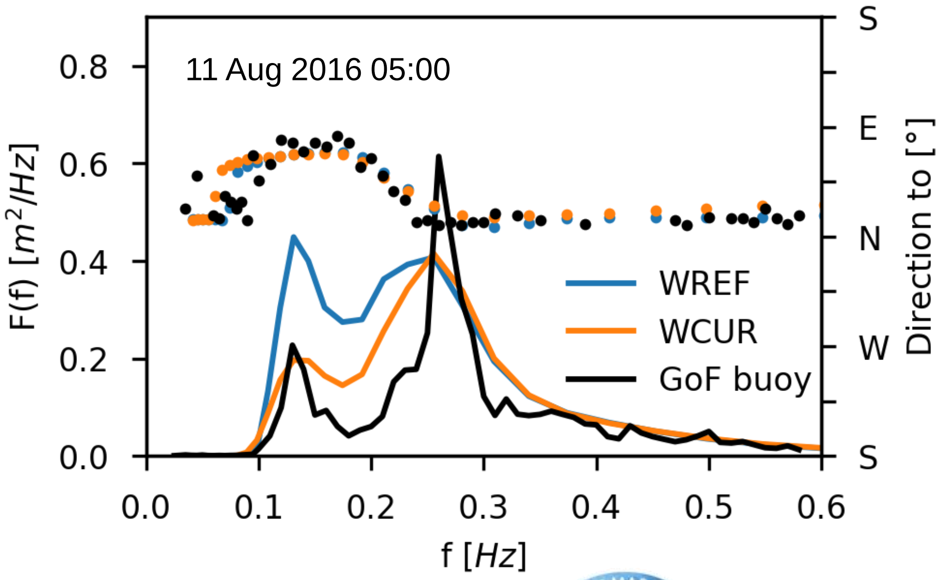


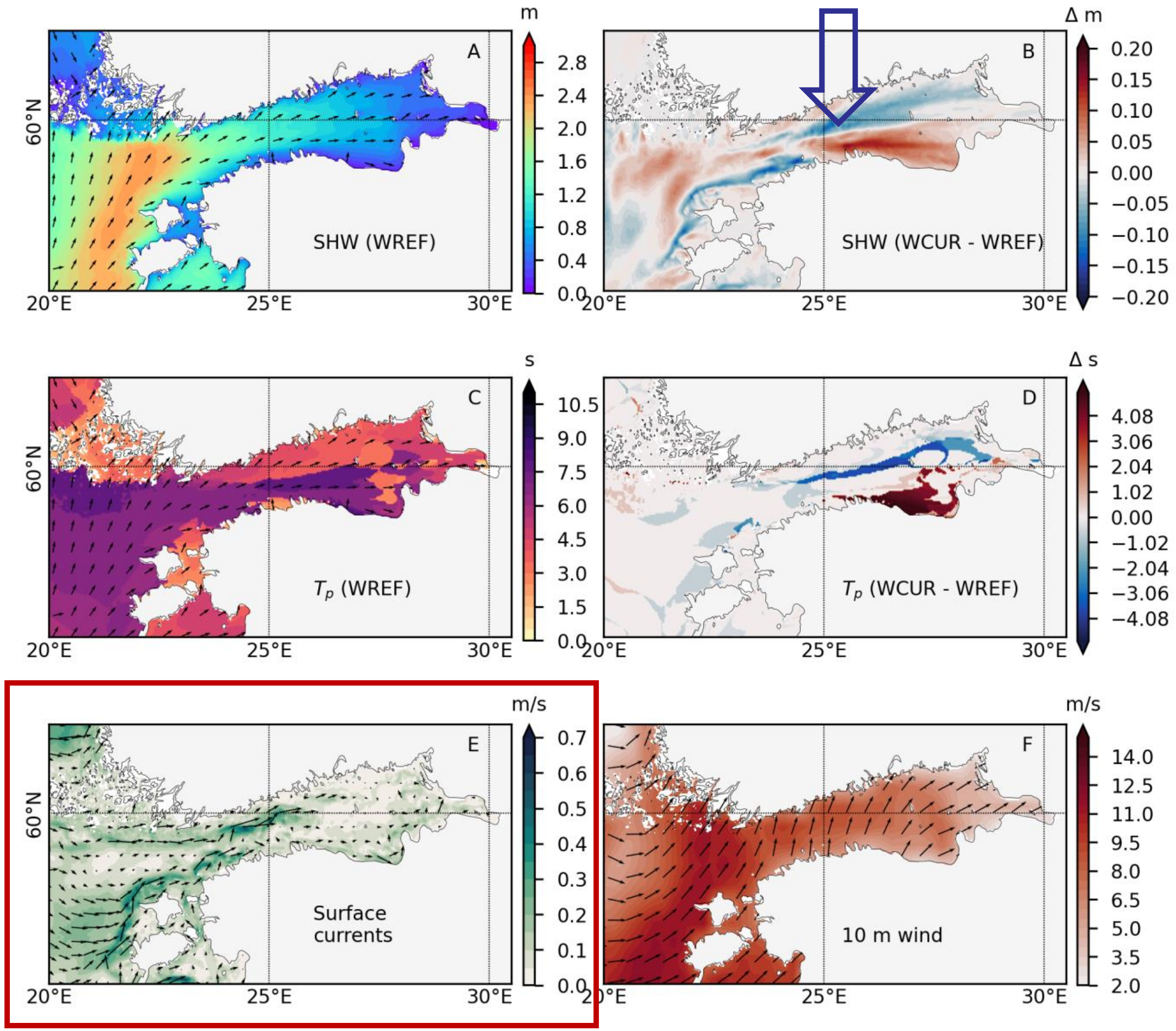



*Tuomi L, Kanarik H, Björkqvist J-V, Marjamaa R, Vainio J, Hordoir R, Höglund A and Kahma KK (2019) Impact of Ice Data Quality and Treatment on Wave Hindcast Statistics in Seasonally Ice-Covered Seas. Front. Earth Sci. 7:166. doi: [10.3389/feart.2019.00166](https://doi.org/10.3389/feart.2019.00166)*

# WAM: Wave-current interaction

Overall, **current-induced differences are small in the Baltic Sea**. However, there are some areas and situations in which the inclusion of currents improves the accuracy of the BAL MFC NRT wave product:




From NEMO forecast product

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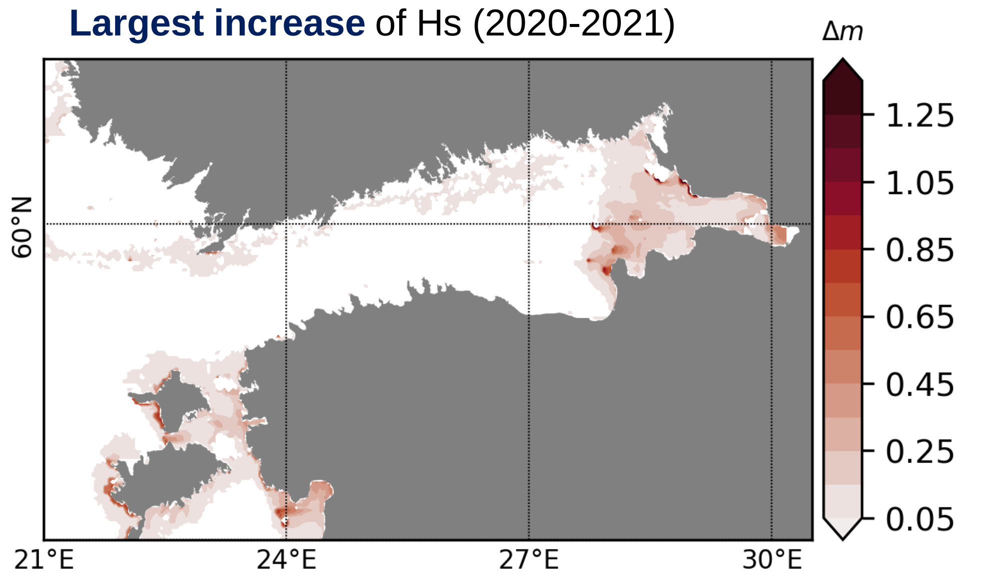
*Kanarik, H., Tuomi, L., Björkqvist, JV., Kärnä T. (2021) Improving Baltic Sea wave forecasts using modelled surface currents. Ocean Dynamics* ***71****, 635–653.* *https://doi.org/10.1007/s10236-021-01455-y*

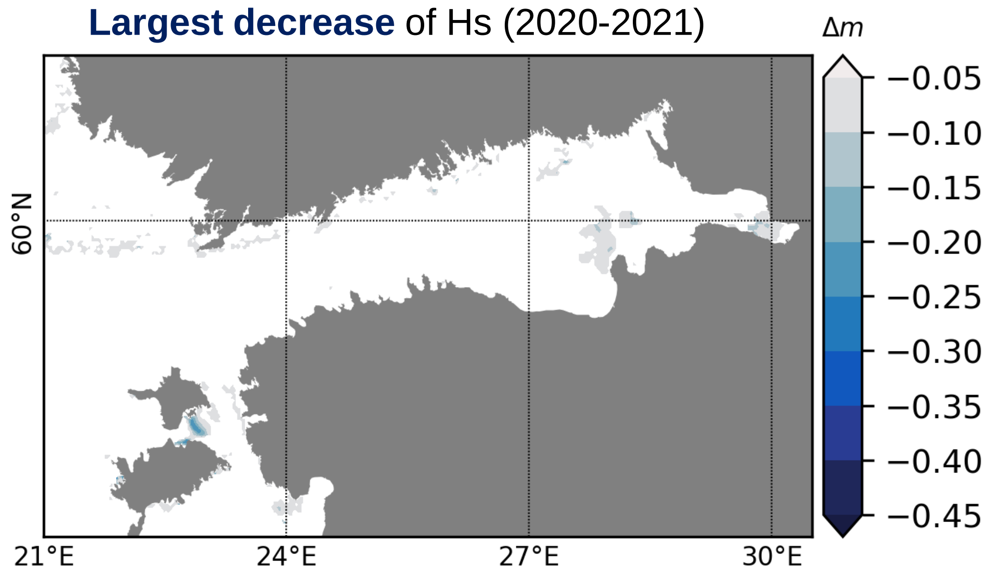
# WAM: Sea level variation

In a small semi-enclosed basin, short-term sea level variations are mainly induced by atmospheric forcing, as tidal variation is small.

The overall **effect of SSH on waves in the Baltic is small.** However, in coastal areas during high or low sea level events, changes in the SWH are visible.

*During 2-year comparison period **SSH varied between –0.8m and 1.5 m** at the end of the gulf. Increased values of Hs were more common but e.g., **10 cm increase happened only 1.4% of the study period of 2 years**.*

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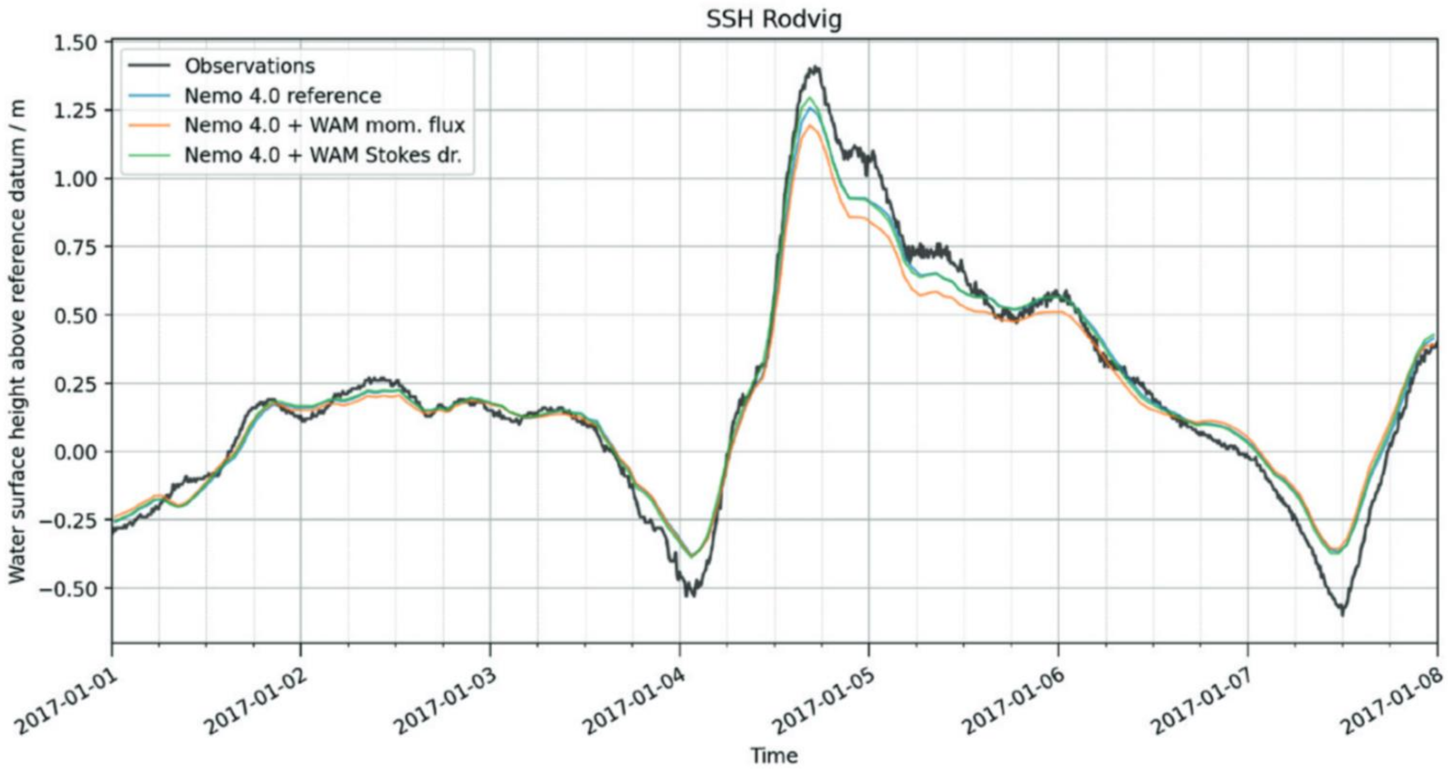
# NEMO: Stokes-Coriolis forcing

Stokes-Coriolis forcing does not have a large impact on the physical model results in general.

However, in storm situations the Stokes drift plays a more important role and can, in some situations, effect the results quite significantly.

*Figure shows sea level at the Danish tide gauge station Rödvig during a winter storm. The Stokes drift increased the peak value by several centimeters.*

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*Nord, A., Kärnä, T., Lindenthal, A., Ljungemyr, P., Maljutenko, I., Falahat S., Ringgaard I., Korabel V., Kanarik H., Verjovkina S., Jandt S. (2021). New Coupled Forecasting System for the Baltic Sea Area. 9th EuroGOOS International conference, Shom; Ifremer; EuroGOOS AISBL, May 2021, Brest, France. pp.238-244.* https://hal.science/hal-03328374v1

# WAM-NEMO coupling: sea-state dependent momentum flux

Uncoupled Nemo calculates shear stress using only atmospheric forcing and does not take account of the sea state.

Stress modification due to waves ( $\tau_w$ ) can either increase of decrease the shear stress felt by the ocean, depending on the ratio of $S_{in}$ and $S_{ds}$

- $S_{in}$ = *wave growth induced by the wind,* ***always positive***
- $S_{ds}$ = *(dissipation due to white capping),* ***always negative***

$$\tau_{oc} = \tau_{atm} - \tau_w$$

$$\tau_w = \rho g \int \frac{dk}{c_p}(S_{in} + S_{nl} + S_{ds})$$

***In coupled WAM-NEMO****: In areas where waves grow, ocean model experiences less stress than it would if stress were calculated using only atmospheric forcing. Conversely, in areas where the dissipation exceeds the wave growth, the ocean experiences stronger stress.*

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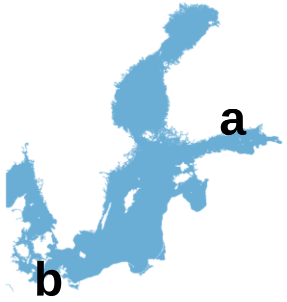
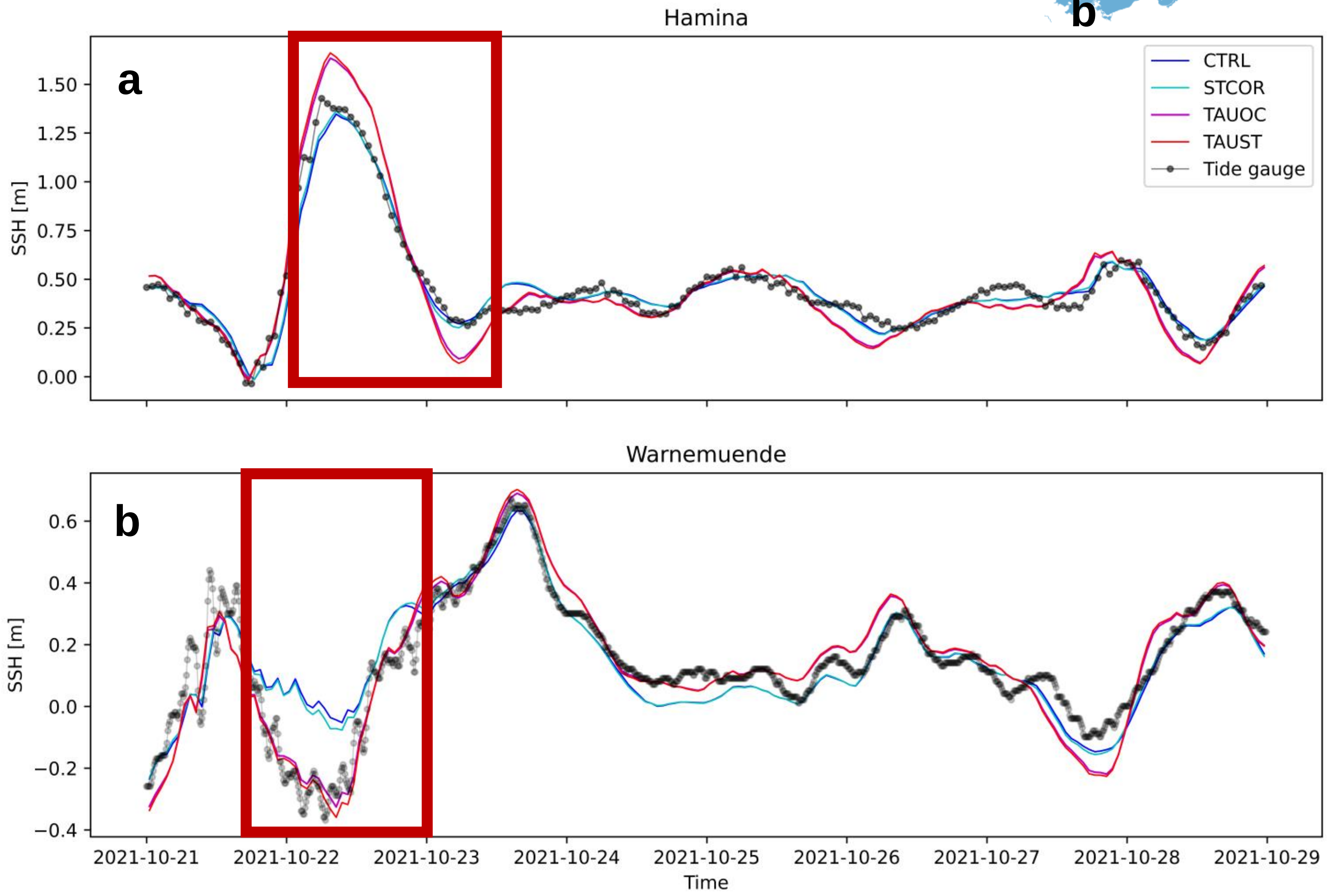
# WAM-NEMO coupling: testing wave-modified stress in Nemo




Sea-state-dependent momentum flux tested together with Stokes drift via 4 simulations for 1.4.-31.12.2021:

CTRL (neither) STCOR (Stokes)
TAUOC (stress) TAUST (both)




*a) Wave-modified stress produces clear differences in SSH, currents and mixed layer depth. However* ***tuning is needed*** *to get the benefits in model performance.*

*b)* There are also some events, during which **accounting for waves leads to significantly better estimates of sea level.**

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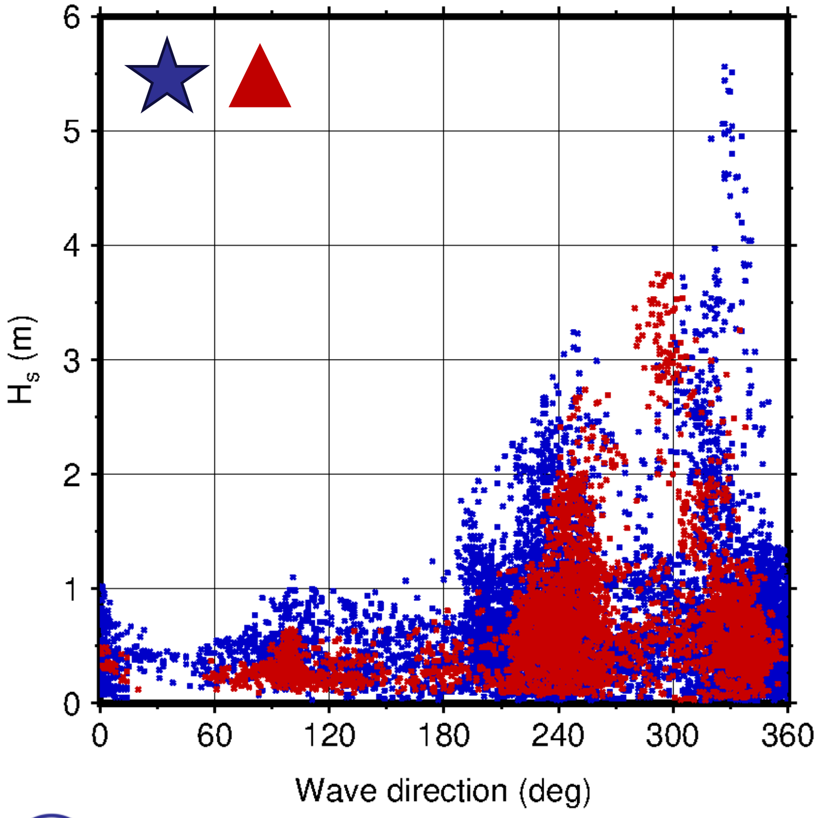
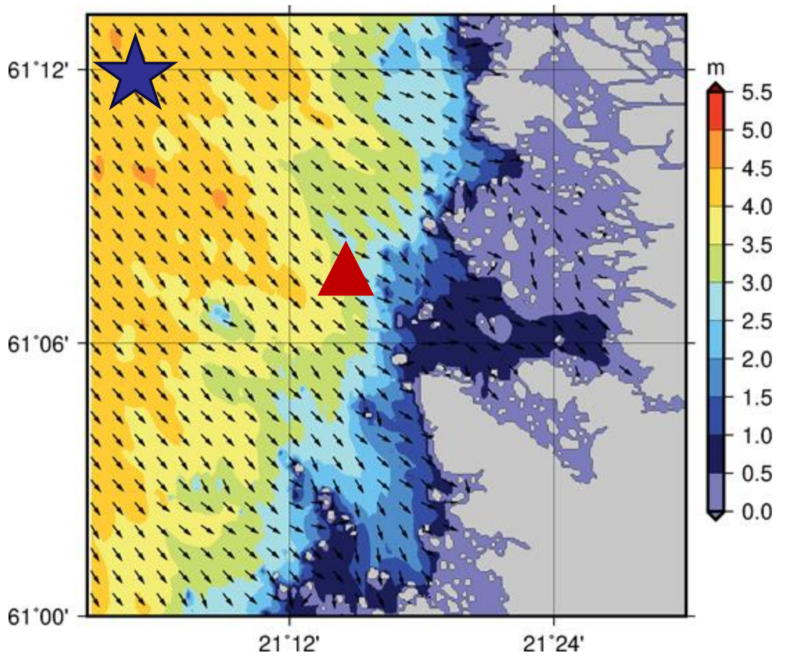
# Modelling coastal archipelago areas

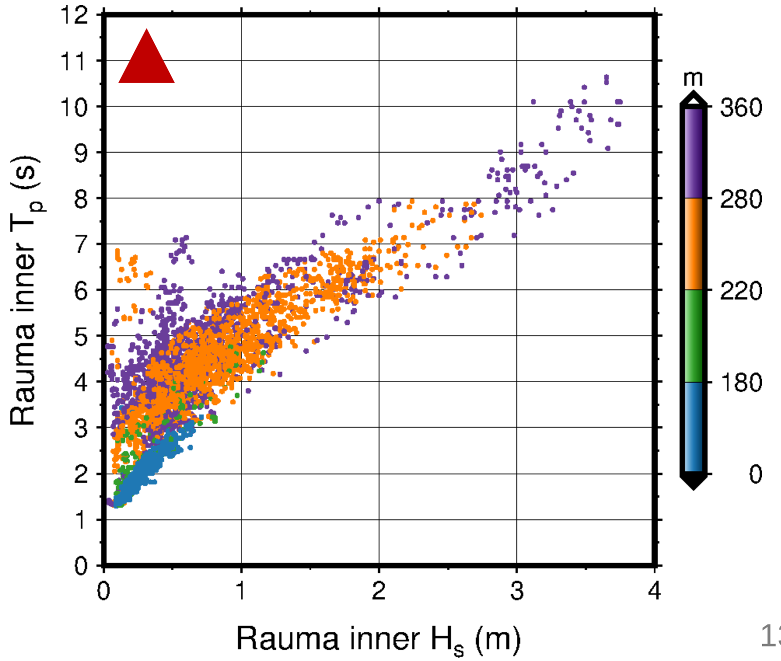
## – Example from Rauma harbor




High waves from north-westerly and westerly sectors. Waves attenuate and refract when propagating to shallower coastal areas

Even though waves from southerly and southwesterly sectors are considerably smaller, they have shorter periods compared to the other sectors and are steeper



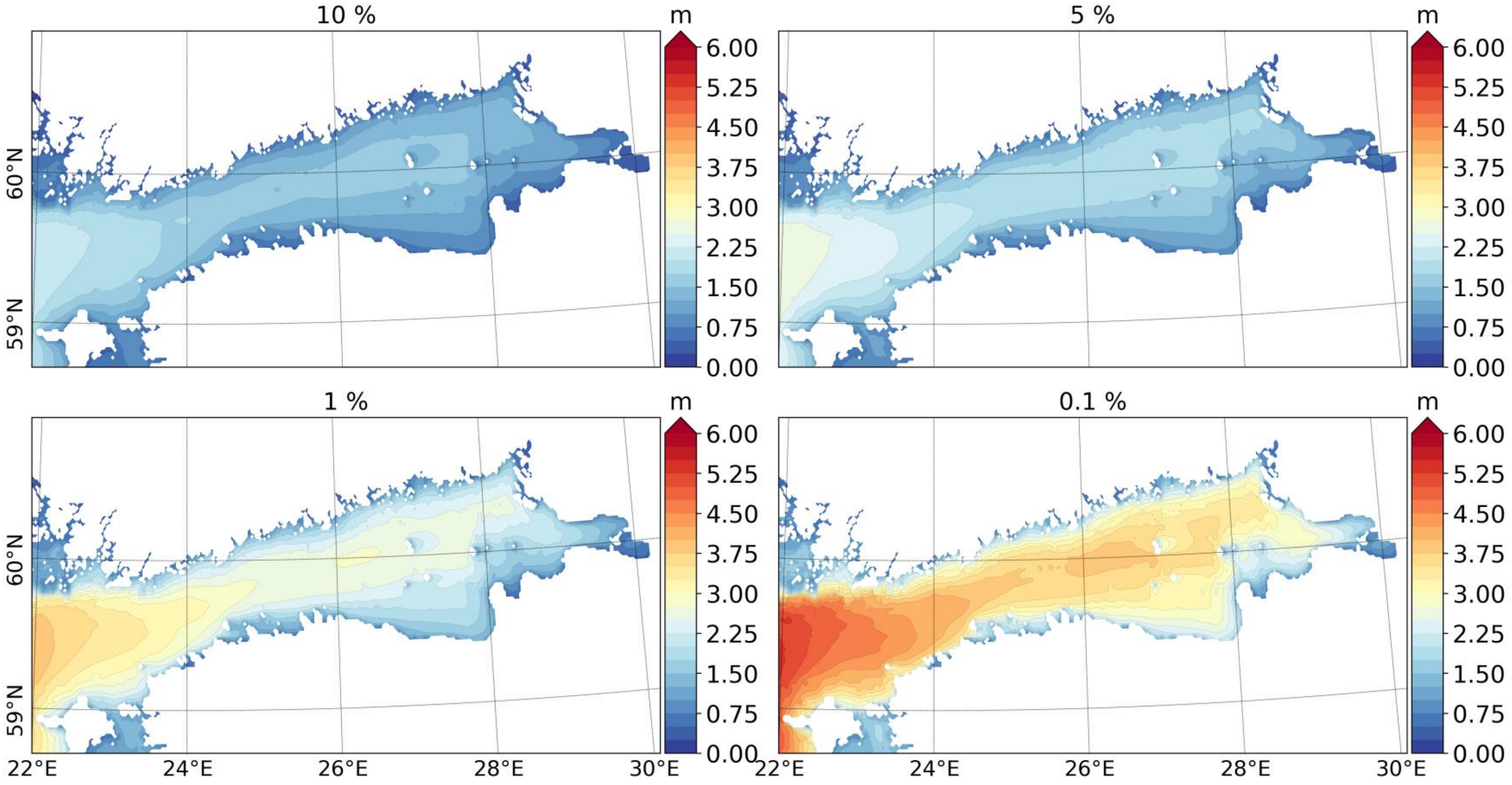



# Traditional wave statistics
## in Gulf of Finland

- Mean, percentiles etc. of wave parameters in Baltic Sea are well known
  - Calculated in multiple hindcasts using different atmospherics models

- Large seasonal variation
  - Highest waves in winter and autumn, lowest in spring

*Figure shows percentiles highest significant wave heights (ice free statistics) from 29 year hindcast (1993-2021) available in Copernicus Marine Services*

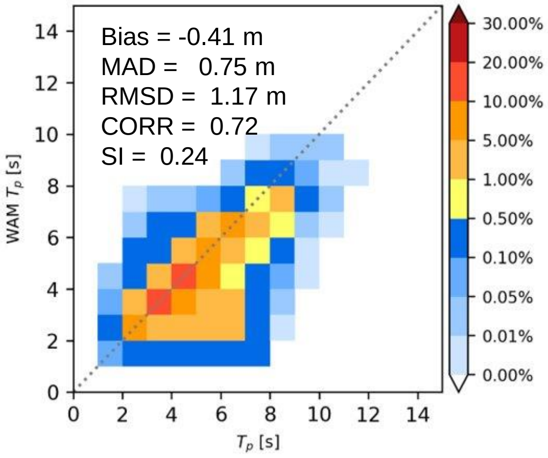


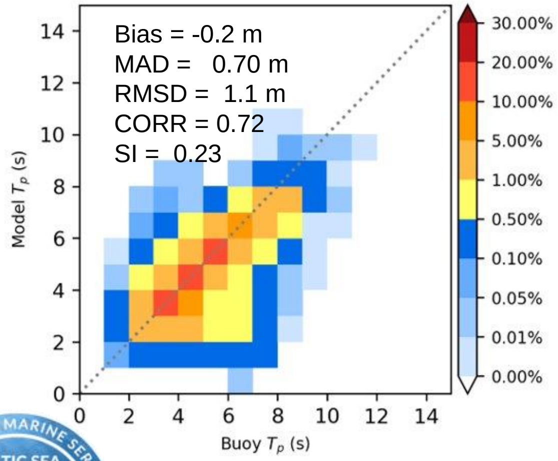
# Wave hindcast

Product available in https://marine.copernicus.eu/

- Extended every 6 months (next update in Jan 2024)
- Following figures cover 1993-2021

*Figures below compare modelled peak period against GoF wave buoy measurements using traditional WAM physics (left) and ST4 physics (right) from 2-year test period. New hindcast will be produced using ST4 physics, which has been shown to produce better quality results in coastal regions.*

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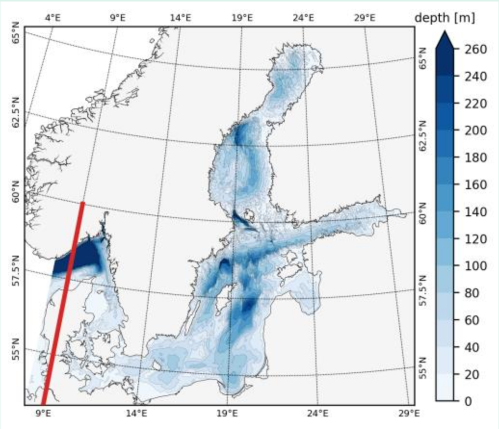
**Baltic Sea Wave Hindcast:**
https://doi.org/10.48670/moi-00014

**Currently available for years 1993-2022**




**System Description:**
WAM cycle 4.6.2
- Horizontal resolution = 1 nmi
- 35 logarithmically spaced frequencies (0.0418–1.067 Hz) and 24 directions with 15° intervals
- Hourly instantaneous values
- Modifications for specific features of the Baltic Sea (ice and archipelago)
- Atmospheric forcing: ERA5

Boundary conditions: wave spectra from ERA5 wave hindcast
Ice concentration input: SMHI/FMI ice charts (ice concentration > 30 %)

Presently available for years 1993-2022. Extended twice per year.

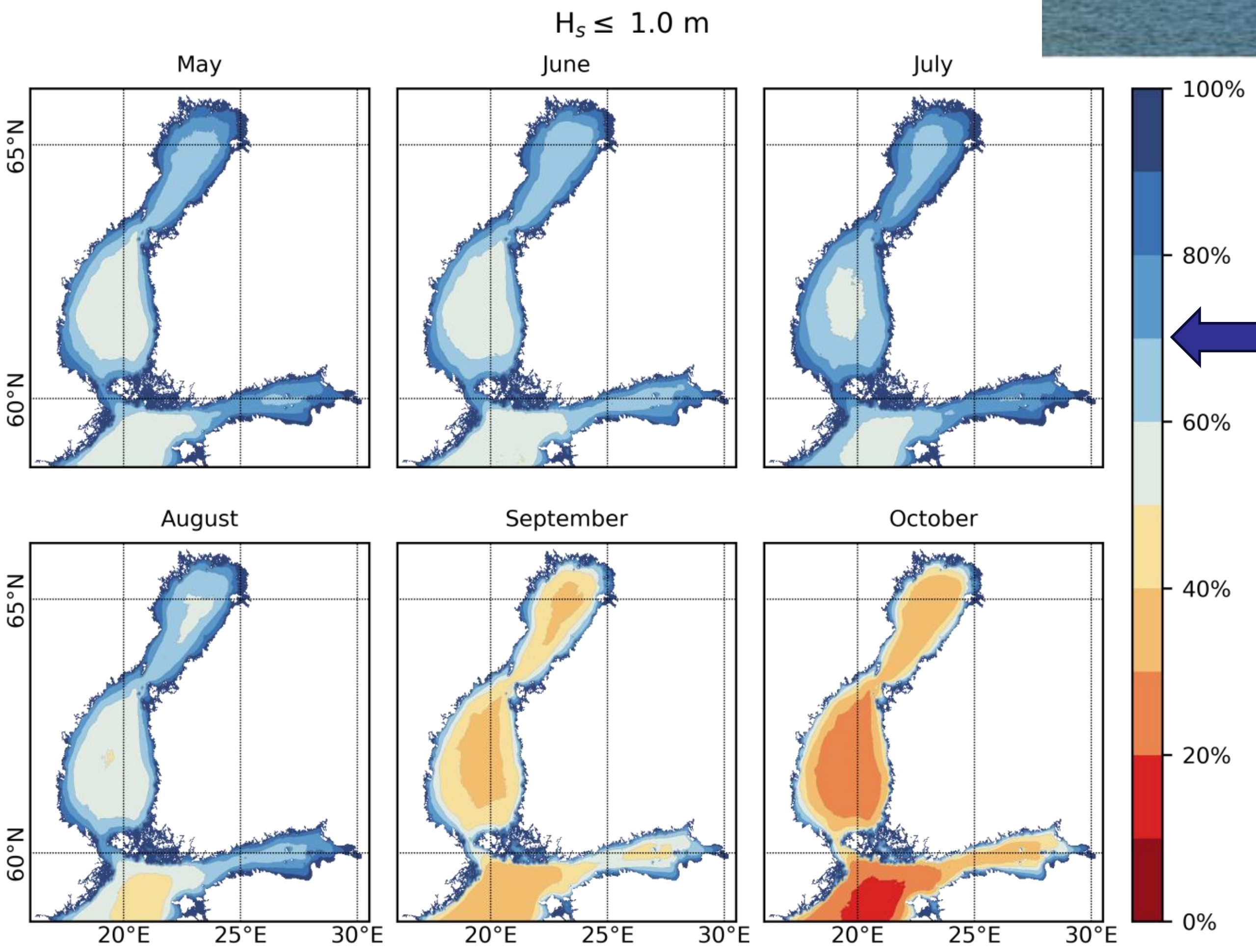
**New version will be released in Nov 2024:**
- WAM cycle 4.7
- ST4 physics (source term package for parametrization for dissipation of wind-generated waves)
- Updated EMODnet bathymetry and obstruction fields
- Time period 1980-2022+

# Research to support aquaculture


Critical values of significant wave height required for different operations in fish farms:

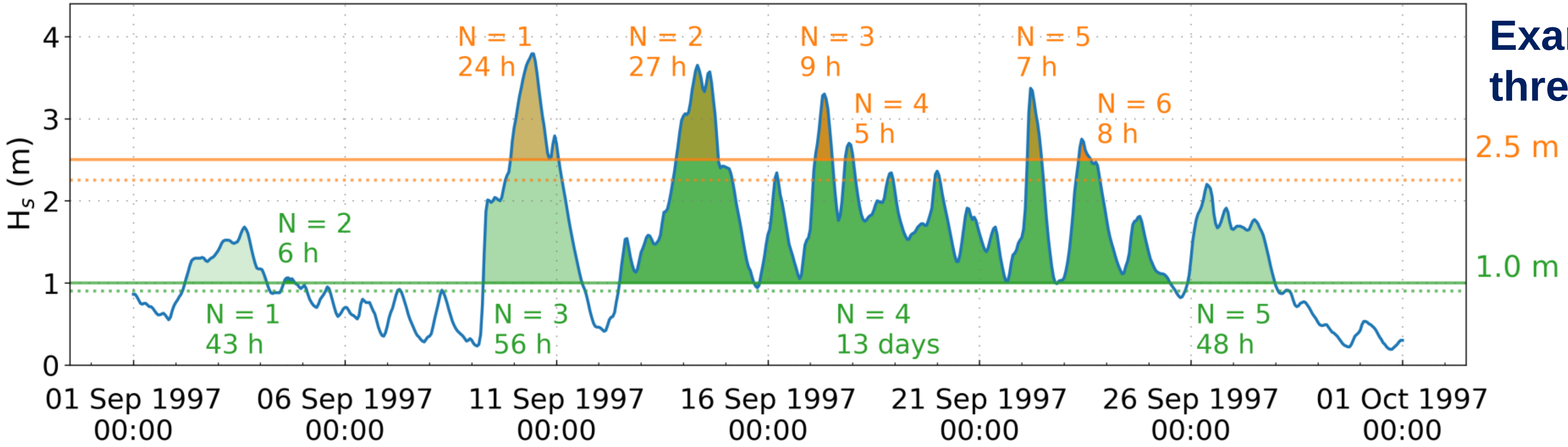
- $H_s < 1.0m$ for feeding
- $H_s < 0.6m$ for maintenance
- $H_s < 0.3m$ for placement/harvesting

*Figure shows percentage of days when the daily maximum Hs was below the threshold for feeding activities (< 1 m), during the operating months at the fish farm*




Feeding should be possible 70 % of the time

# Event-based wave statistics




**Example thresholds**

= **When**, **how many times**, and **for how long** significant wave height (Hs) exceeded the critical threshold for operations at sea

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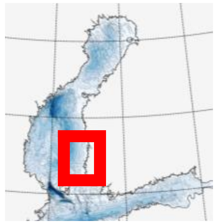
Björkqvist, J.-V., Kanarik, H., Tuomi L., Niskanen L., and Kankainen M., "Event-based wave statistics for the Baltic Sea." *State of the Planet* 8th edition of the Copernicus Ocean State Report (in review). https://doi.org/10.5194/sp-2023-16

# Event-based wave statistics for spatial planning



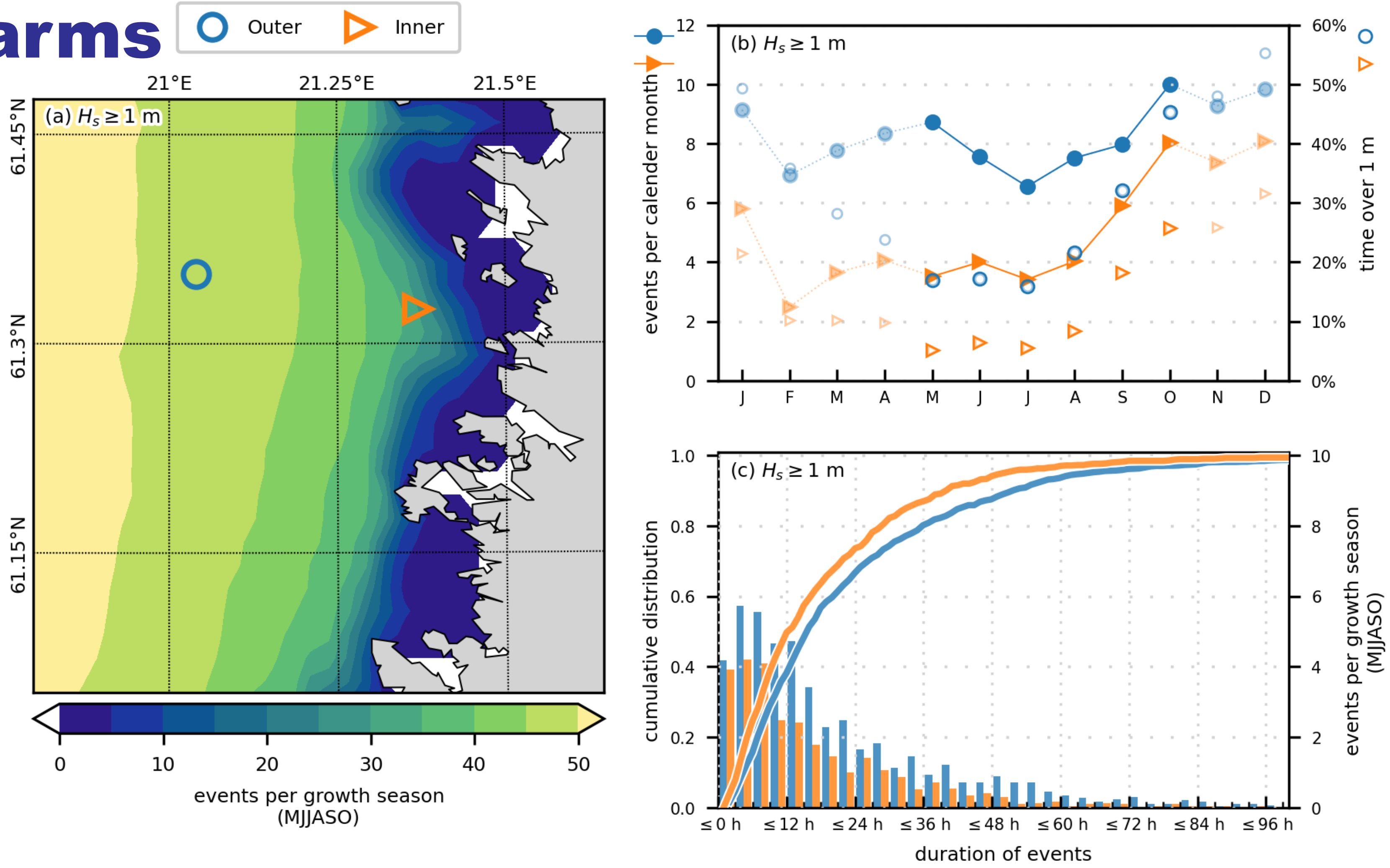
## Case study: fish farms

Fish farms have identified 1 m SWH as an upper limit for many operations at sea.

**Figure shows number or events exceeding 1 m in two locations of possible fish farms during the growth season of Rainbow trout in Finland (May to October)**

a) Number of events between May-Oct
b) Monthly number of events (left) and the duration of events (right)
c) Cumulative distribution of the event duration (left) and the number of event of given length (right)

**The number of 1 m wave events can double within 20 km in nearshore areas**

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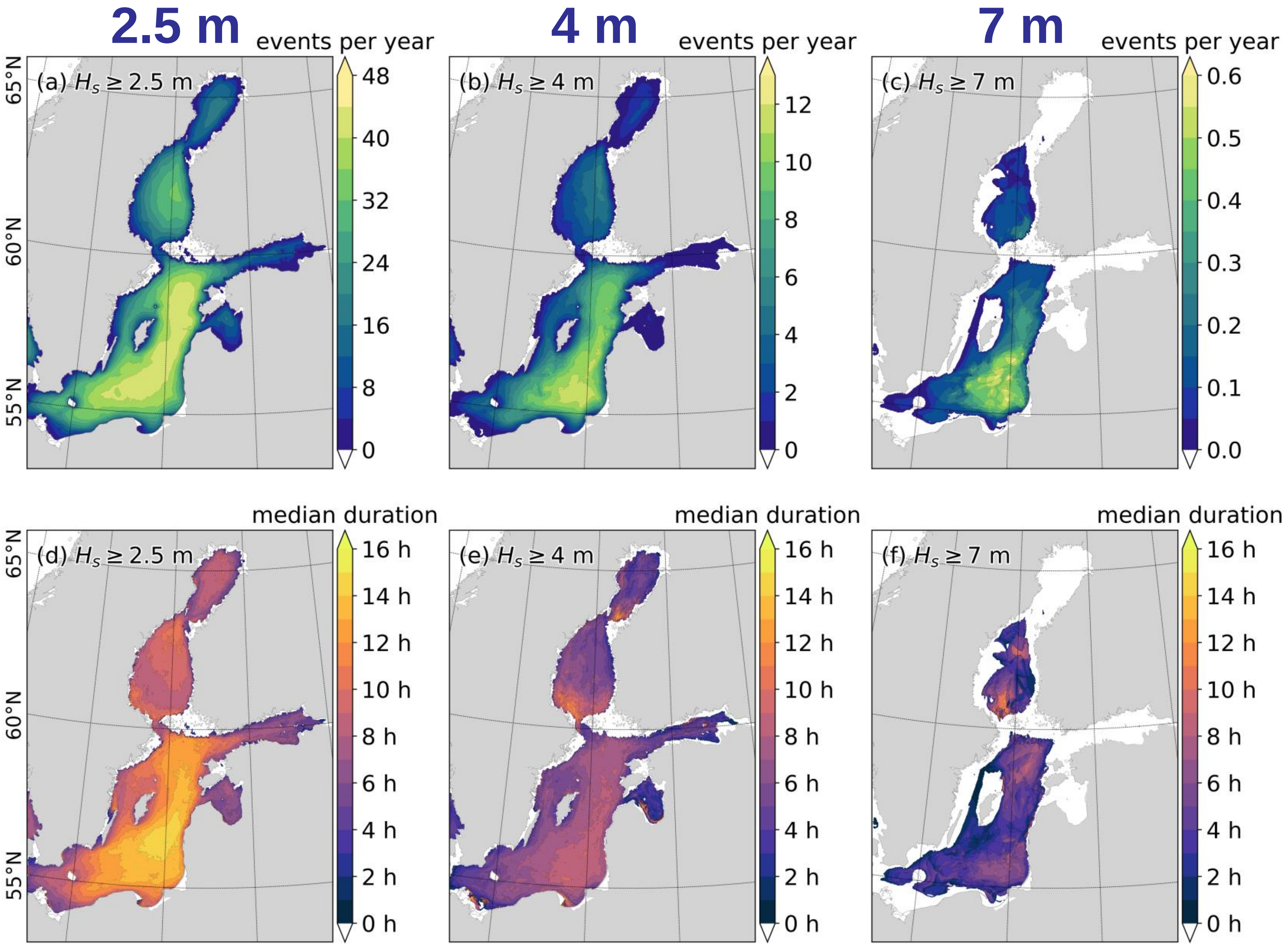
# Event-based wave statistics for ship traffic

FMI gives warnings to sea areas if Hs is predicted to exceed:

- **2.5 m** as possibly dangerous for small vessels
  ➡ Used only during spring-autumn
- **4 m** as dangerous
- **7 m** as very dangerous

Waves exceeding 7 m occur even in the most frequent areas only once every other year on average.







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# Summary

1. Development of coupled wave-ocean-ice model

2. Coastal modelling
   ➡ Improving the usability of nearshore forecasts

3. Tailored statistics for maritime traffic and different offshore activities
   ➡ Event-based statistics

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Picture by Laura Tuomi; Aranda's tail wave bumping into Baltic Sea waves

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# Thank you for your attention!

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