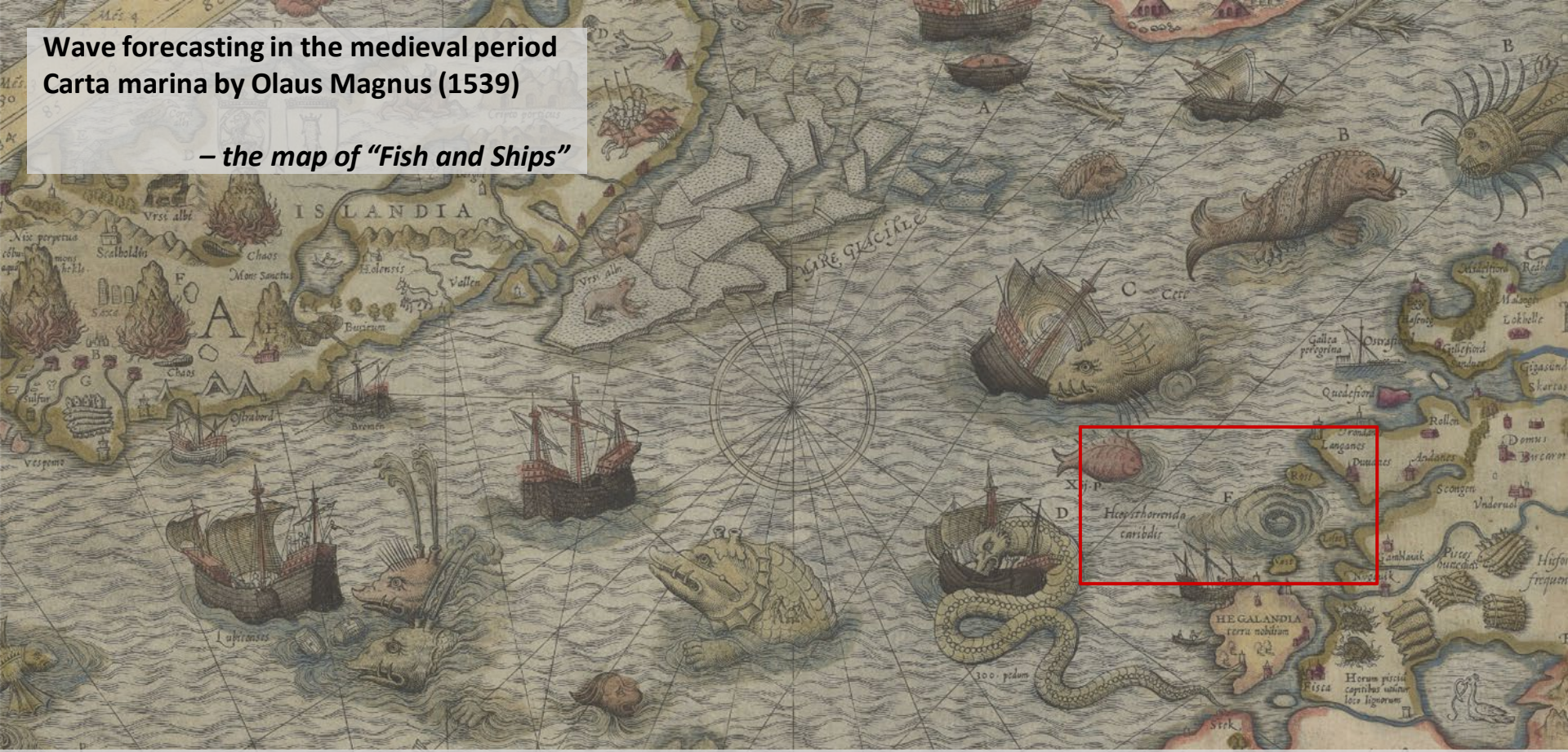


Wave–current interaction in operational wave forecasting

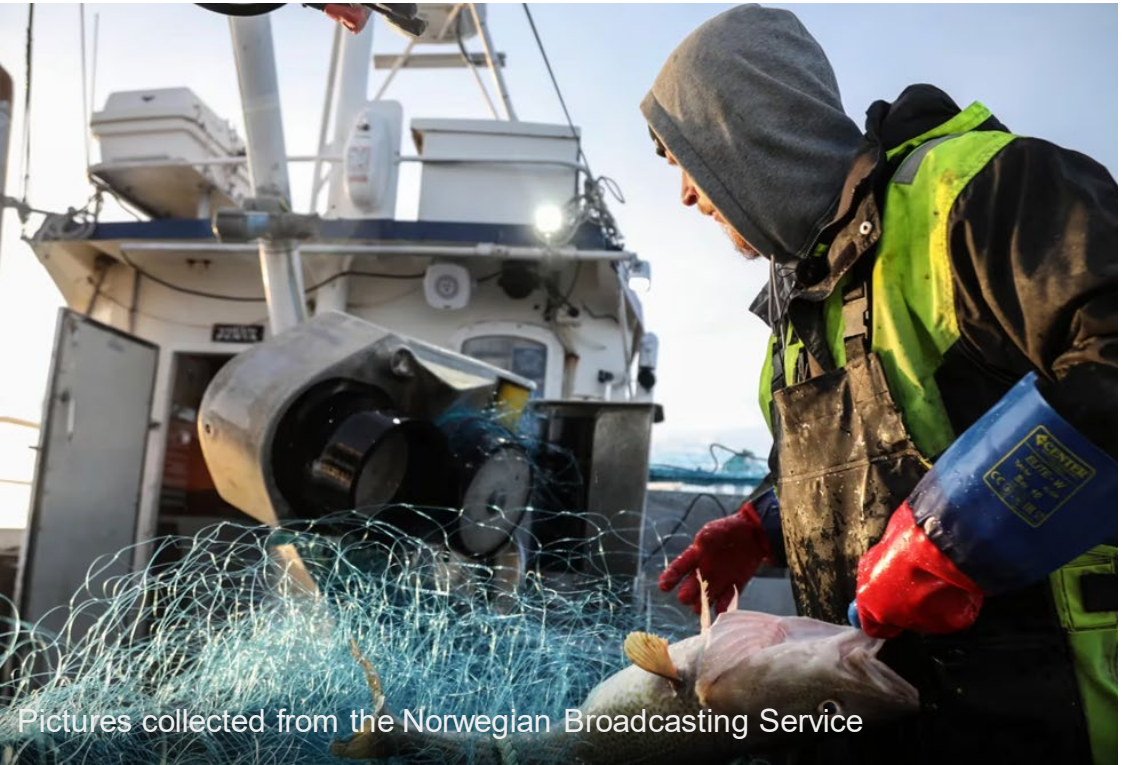
Trygve Halsne and co-authors

Reading April 2024

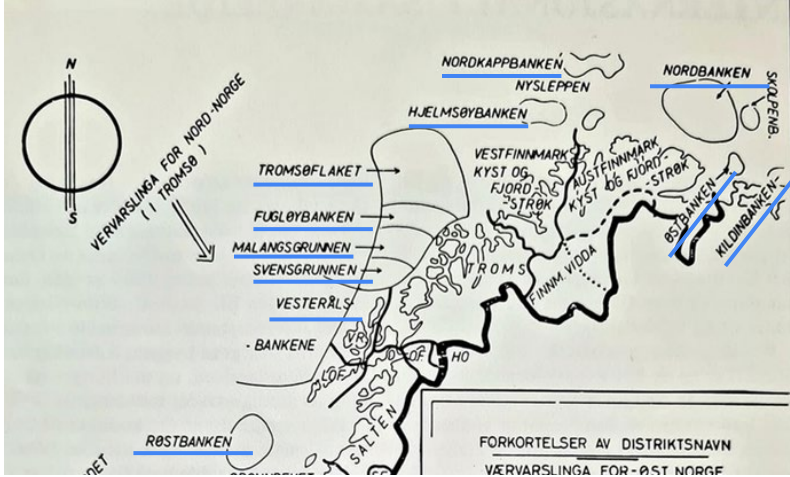
Norwegian Meteorological Institute

UNIVERSITAS BERGENSIS

This story is about Peter



Pictures collected from the Norwegian Broadcasting Service



Fishing Banks in northern Norway

Peter is exposed to a depressing statistical distribution

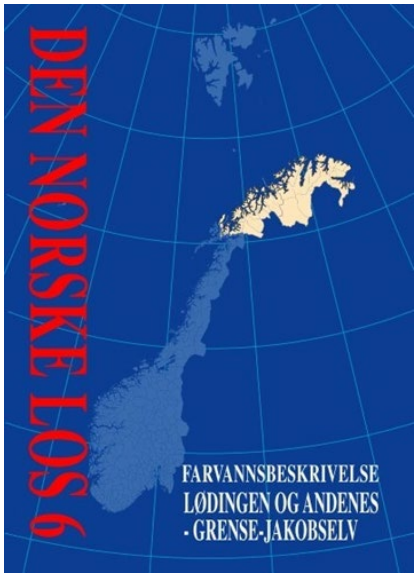
Between 2000–2022

- **156** fishermen lost their lives
  - One every second month
- More than 50 % on coastal fishing vessels
  - 6–11 m length
    - They work alone
    - Geopolitical strategy to ensure coastal settlements

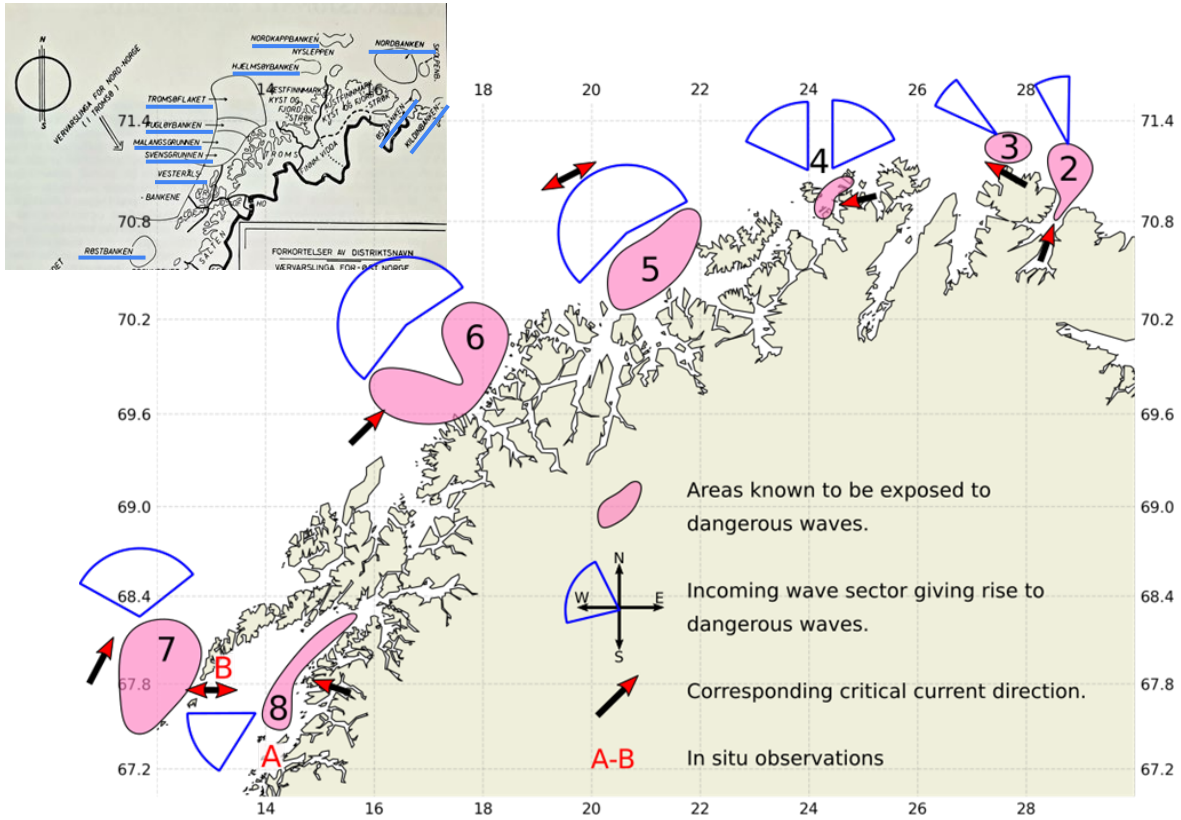
Out of 40 detailed reports (2013–2023)

- Shipwrecks AND deaths (13)
  - **“Strong currents, wind and complicated sea states” (12)**

Fishing banks and areas know for dangerous waves



Norwegian Pilot Guide for Maritime Navigation



In an operational perspective:

- Smaller ships 
- Significant wave height, Hs
- Coastal areas
  - Further offshore → larger ships
- Smooth to moderate(+) sea states*
  - Hs: 0.5 m – 3 m
  - Wind–sea and swell conditions
- Short-term (< 2 days)

**Douglas sea scale*

The overarching questions

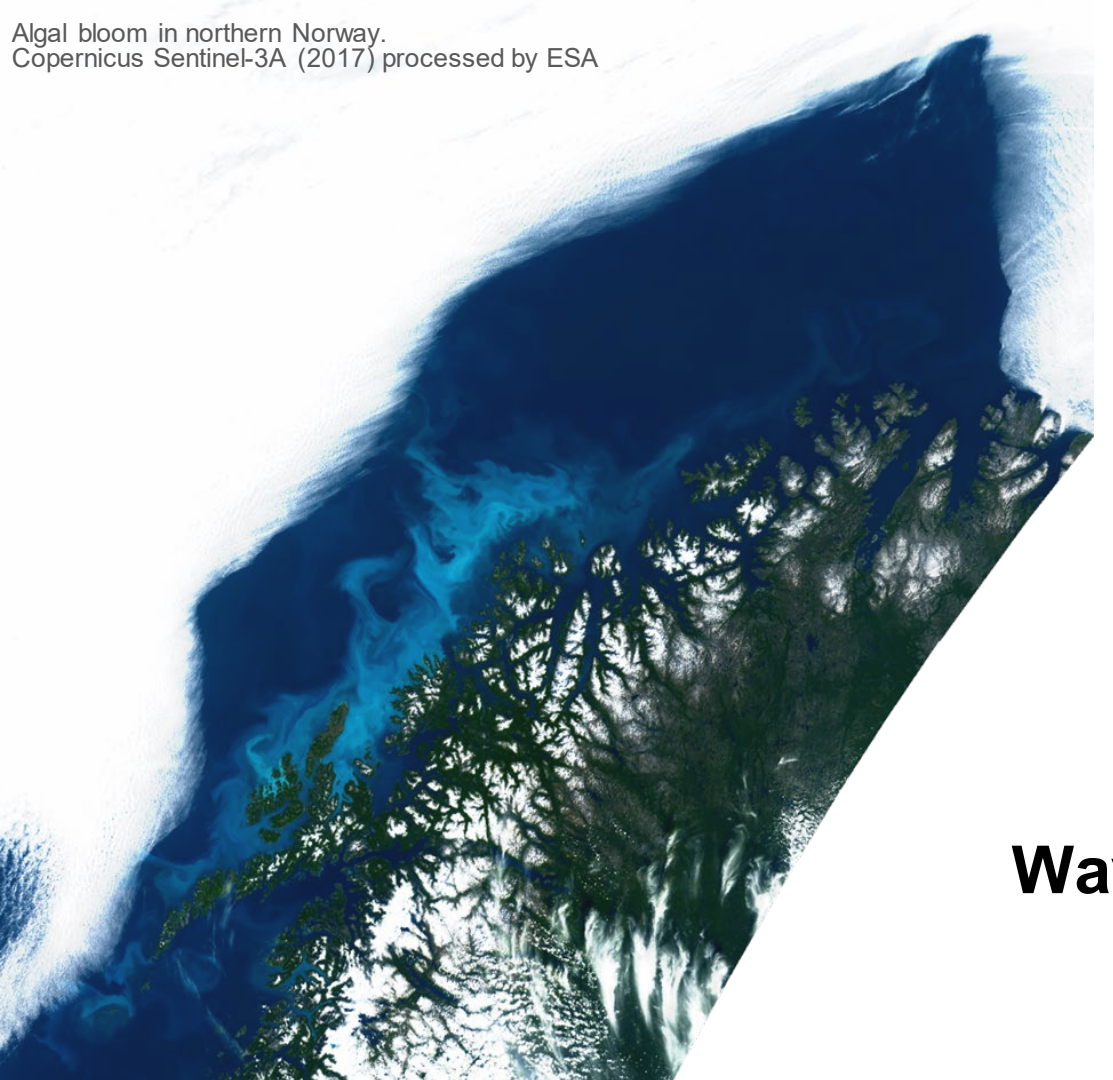
Q: Why is current forcing usually left out in operational wave models?

Q: How to assess their influence with limited observations?

Q: Can we provide better forecast than what we do today?

Study domains

*Surface currents from MET Norway's ROMS implementation



Algal bloom in northern Norway.
Copernicus Sentinel-3A (2017) processed by ESA

Wave–current interaction at operational scales

The wave action balance equation

– The current speed |**U**| is not essential, but the magnitude of the horizontal gradients –

Wave action N →

$$\frac{\partial N}{\partial t} + \nabla_{\mathrm{h}} \cdot \left(\dot{\mathbf{x}} N\right) + \nabla_{\mathrm{k}} \cdot \left(\dot{\mathbf{k}} N\right) = \frac{S}{\sigma}$$

Wave kinematics

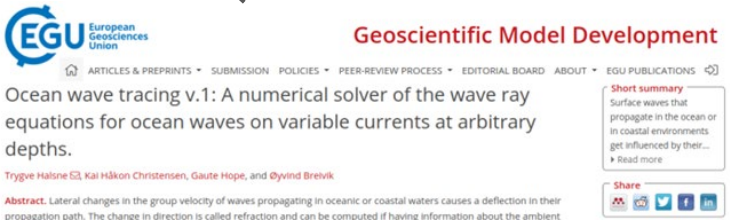
Wave physics
S – source terms
σ – angular freq.

Advection →
$$\dot{\mathbf{x}} = \mathbf{c}_{\mathrm{g}} + \mathbf{U}(\mathbf{x}),$$

Change in wave number and direction →
$$\dot{\mathbf{k}} = -\nabla_{\mathrm{h}}\sigma - \mathbf{k} \cdot \nabla_{\mathrm{h}}\mathbf{U}(\mathbf{x}),$$

Change in absolute frequency →
$$\dot{\omega} = 0.$$

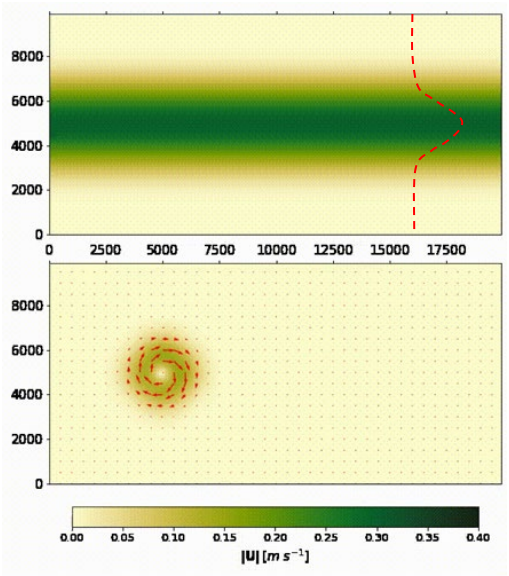
} *"The wave ray equations"*



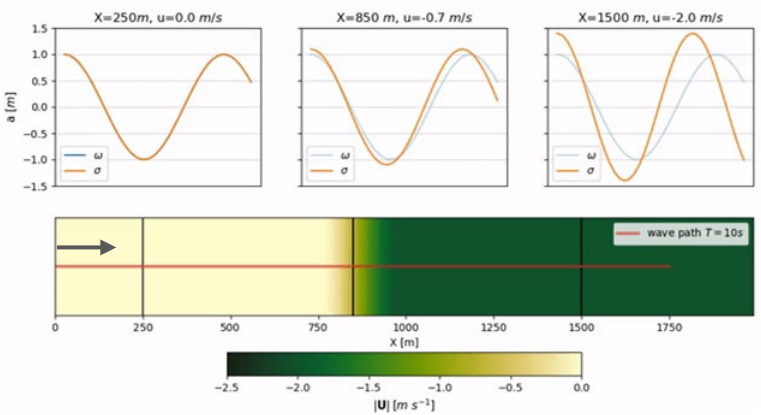
Wave kinematics (example mechanisms)

Variable currents may change the **direction**, **amplitude** and **frequency** of ocean waves

(non-local) (local)



Current-induced refraction



Doppler shift and amplitude modulation: Wave straining

Currents and wave height modulations (1/2)

What do currents do?

- Govern the horizontal wave height variability (1–200 km)

What kind of currents?

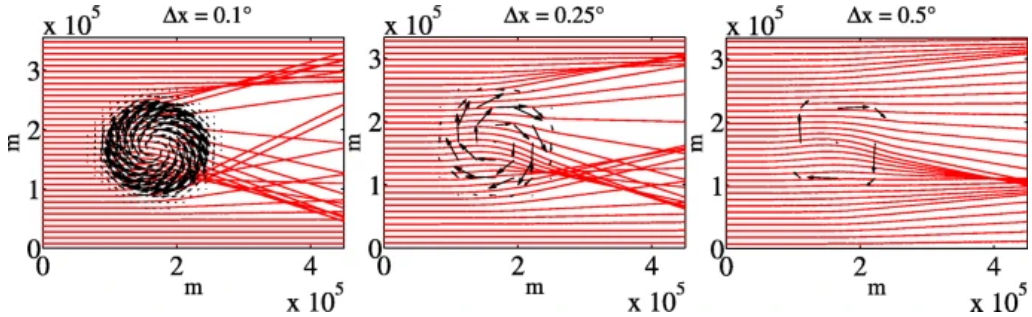
- Rotational component (long–crested)
- Depth-averaged effective currents

What scales?

- Up to 200 km, and beyond
- Sufficient horizontal resolution

How much? (**Hs** 0.5–3 m)

- 20–40 % offshore
- Up to 50 % in major currents
  - Agulhas, Kuroshio, …
- > 50 % coastal and nearshore



Rapizo et al. (2018)

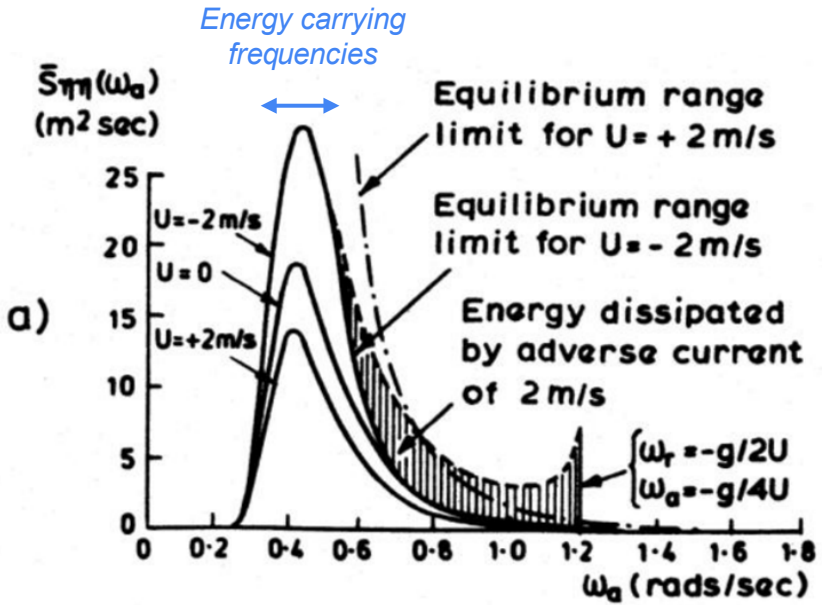
Currents and wave height modulations (2/2)

What mechanisms govern Hs variability?

- Sea state dependant!

$$U/c_g \ll 1 \text{ and } \varepsilon \ll 1$$

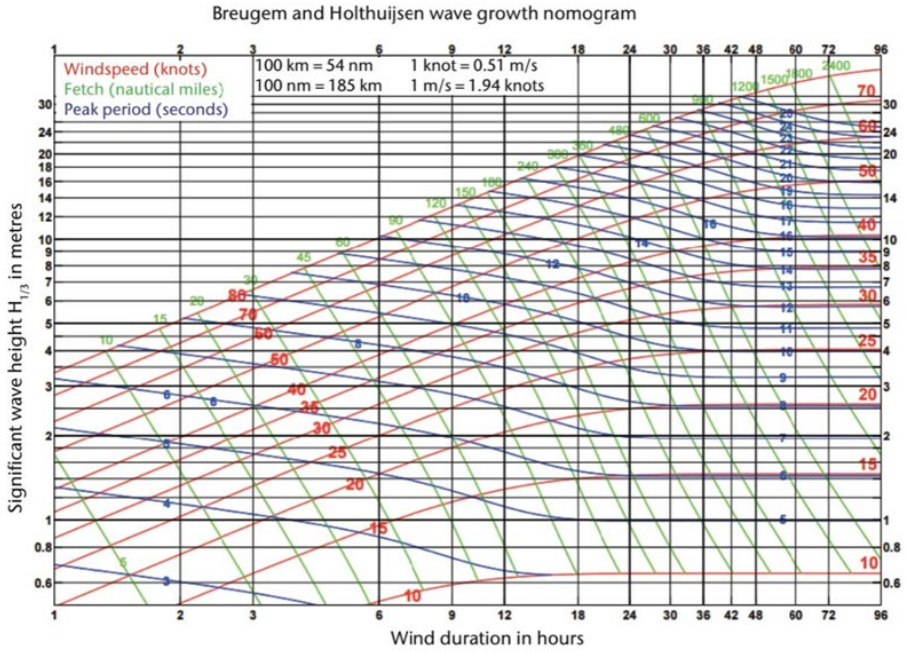
- Current-induced refraction



Hedges (1981)

So, why are currents left out as forcing?

1. Lack of verification data!
    a. Which—if available—are difficult to interpret
2. “Distrust” in the ocean currents
    a. E.g. submesoscales
3. Third generation models are tuned for wind forcing conditions, only
    a. Wind variability > currents
4. Computational cost



Guide to wave analysis and wave forecasting (WMO-No.702)

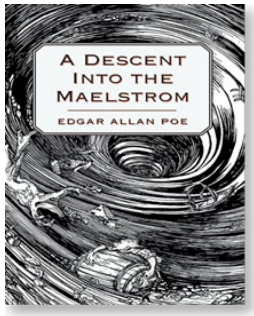
*“And if it so happens **that counterwinds blow**,*

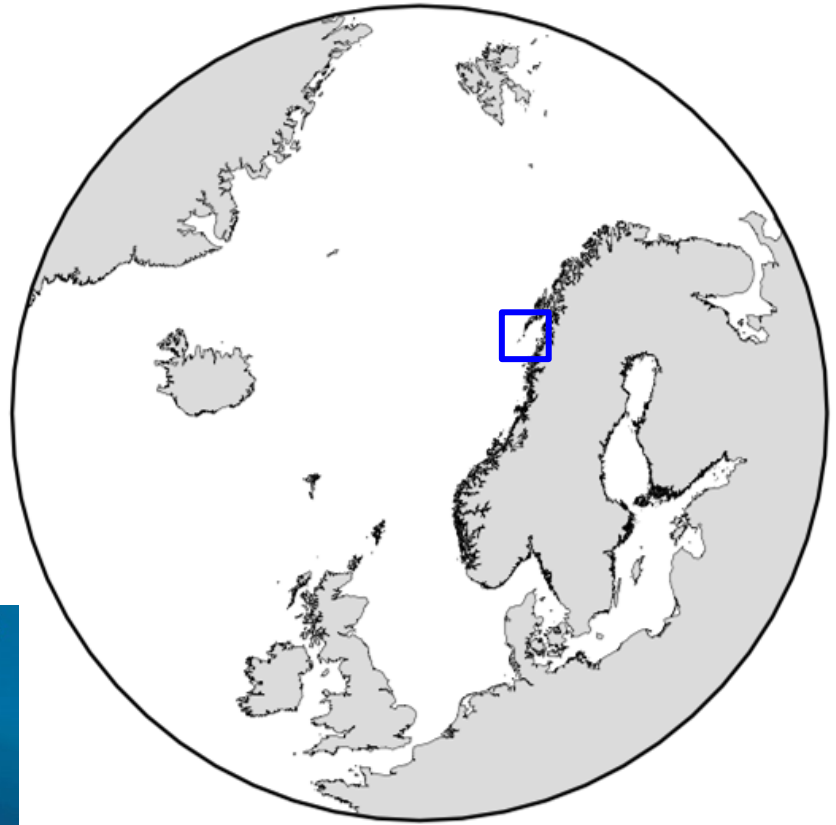
The waves will as high as the mountaintops flow

And have nothing comparable elsewhere.”

–Petter Dass (1685)

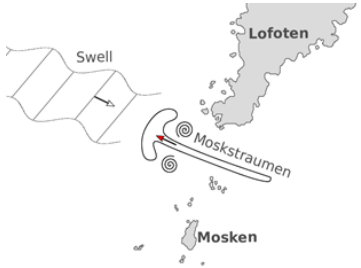
- Wave and tidal current interactions in the Lofoten Maelstrom

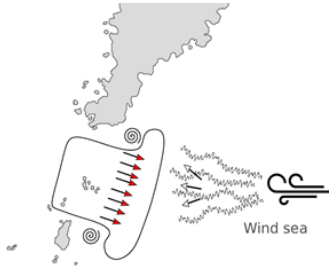


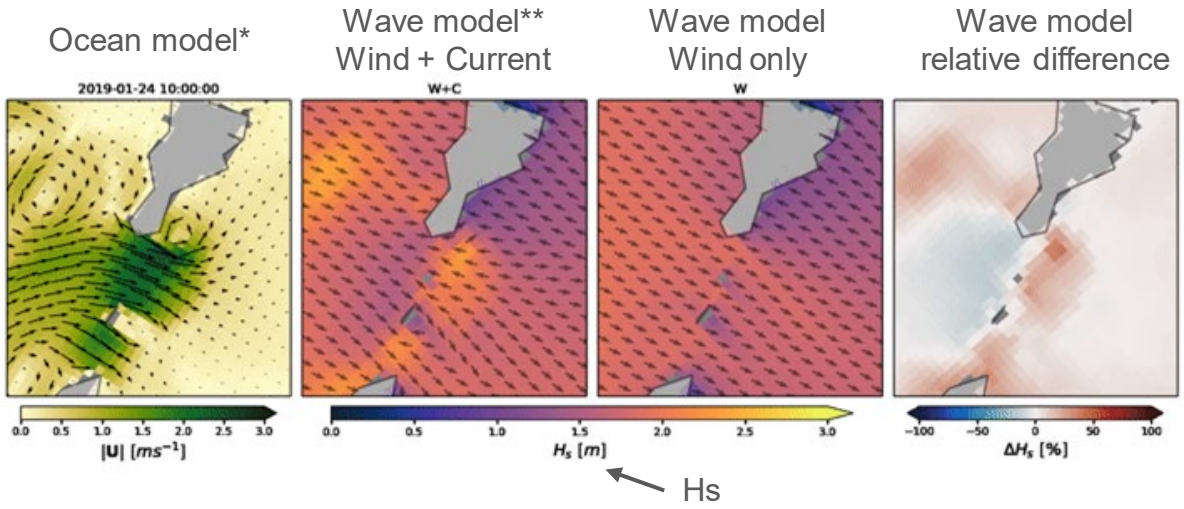


The Maelstrom (*Mosktraumen* locally)

- One of the world's strongest open ocean tidal currents
  - At least 3 m/s
  - Higher volume flux than the Amazon river
  - Barotropic
- Characteristic flow field and wave conditions







* ROMS 800 m surface(!) current

** WAM v. 4.7 800 m

See Saetra et al. (2021)

North

△ ADCP deployment in 2018

600 masl

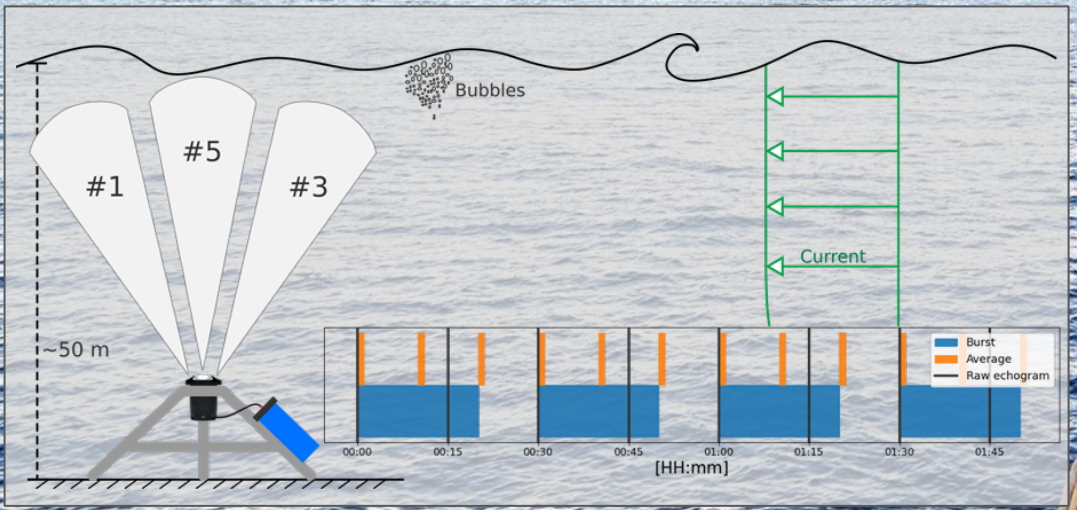
400 masl

Værøy

Røst

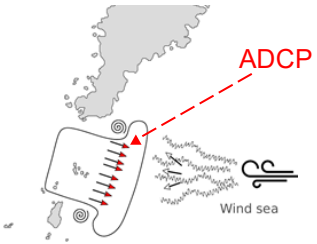
Mosken

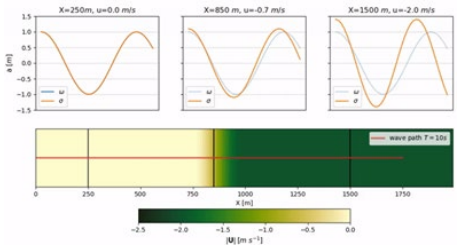
Lofotodden

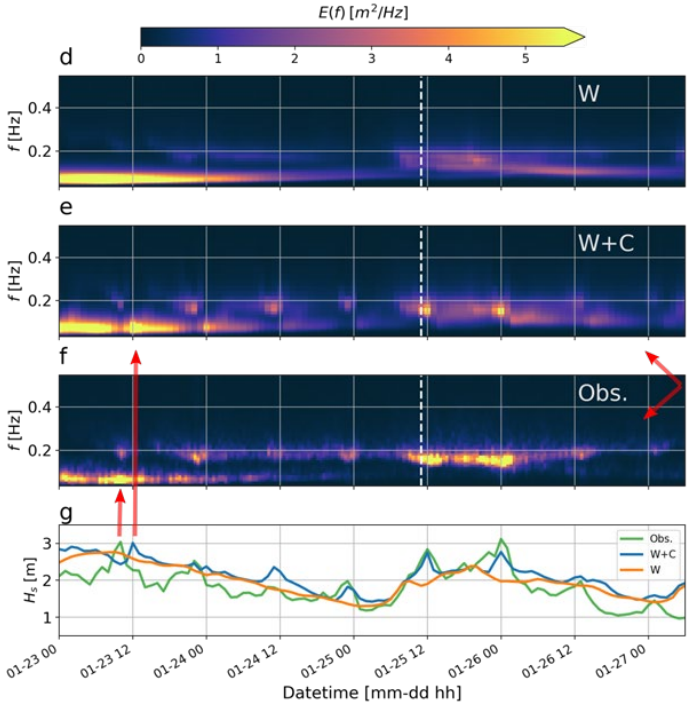


The Maelstrom: East side

- Temporal variability resolved when including currents
- Locally modulated waves due to opposing currents
- Bi-modal sea state + small scale dynamics



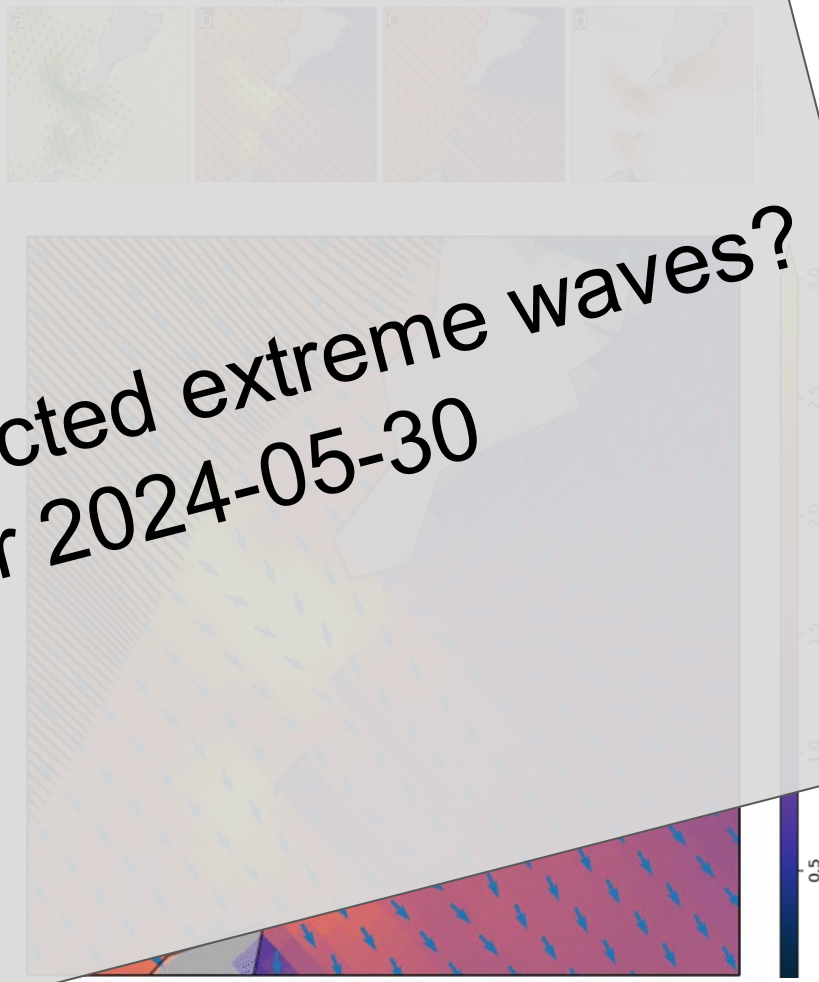




Halsne et al. (2023)b

The Maelstrom: West side

- Current-induced refraction cause focal points
  - Crossing seas
  - Non-local effect on wave a
- Up to 90% (2 out of 4 m) increase

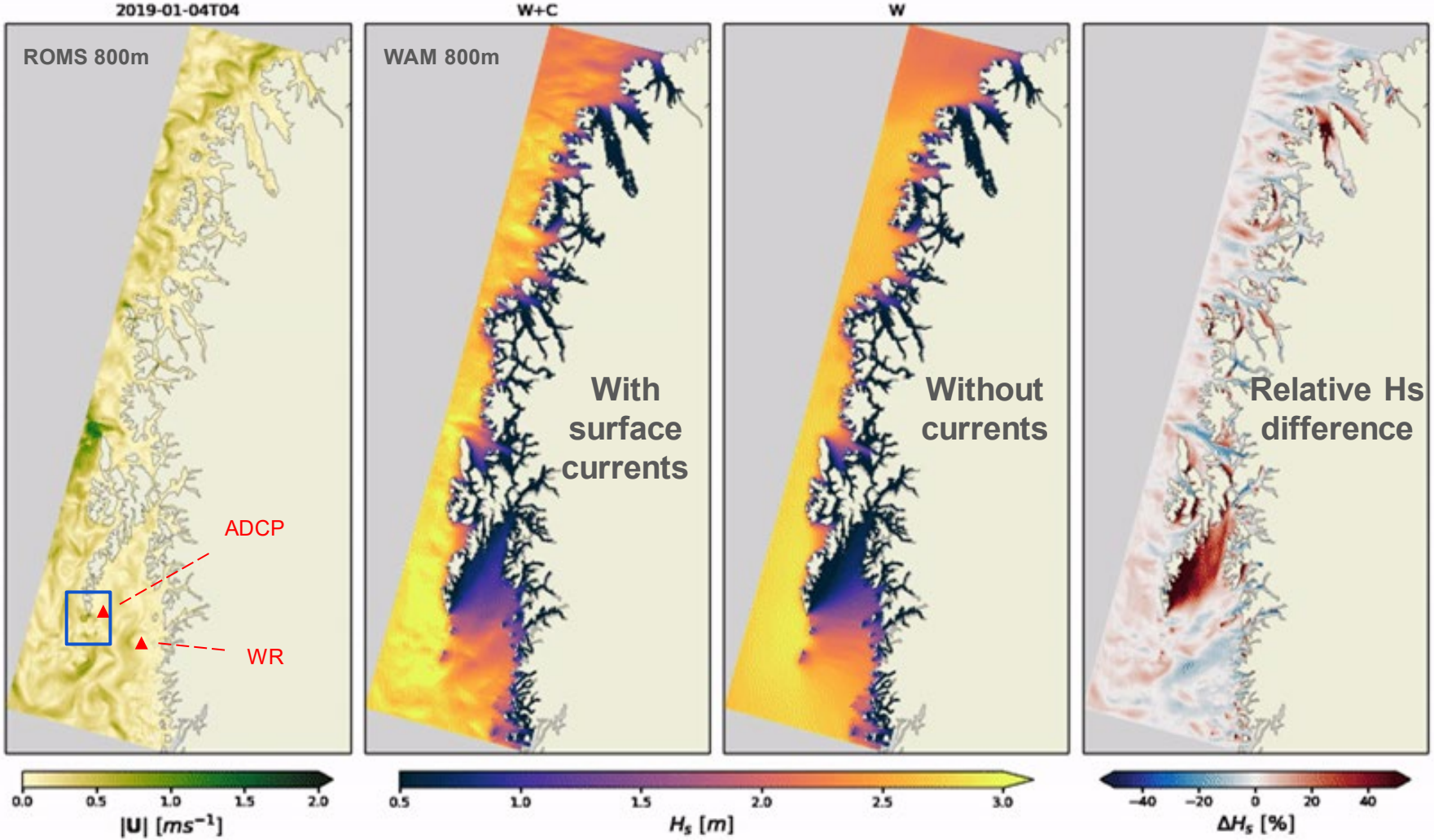


*wave rays from Halsne et al. (2023)a

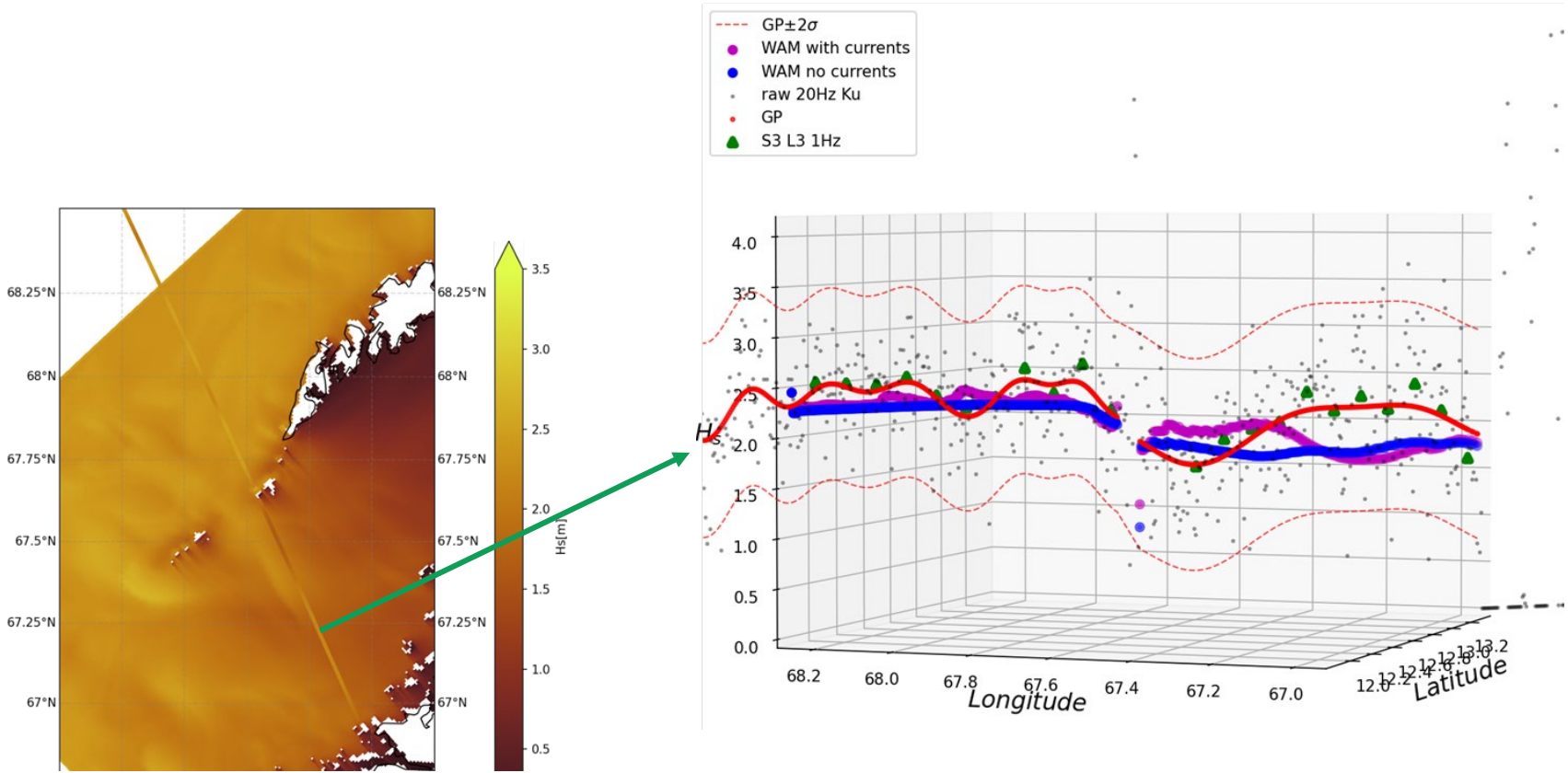
The Maelstrom and expected extreme waves?
WISE zoominar 2024-05-30

Resolving regions know for dangerous waves in northern Norway

Halsne et al. (2022)

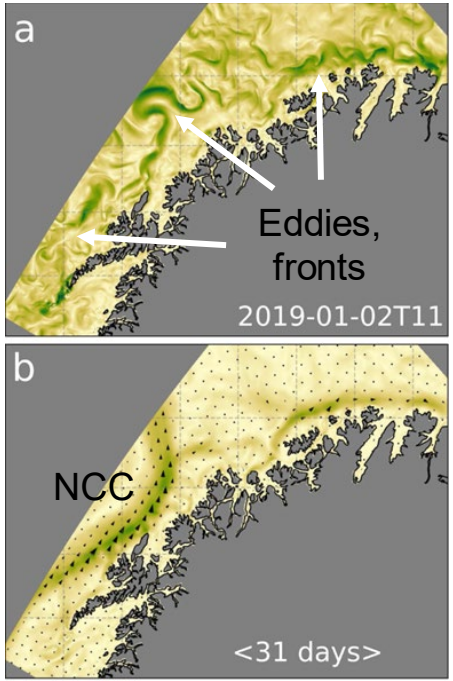

2019-01-04T04
ROMS 800m
W+C
WAM 800m
With surface currents
W
Without currents
Relative Hs difference
ADCP
WR
0.0
0.5
1.0
1.5
2.0
|U| [ms⁻¹]
0.5
1.0
1.5
2.0
2.5
3.0
Hs [m]
−40
−20
0
20
40
ΔHs [%]

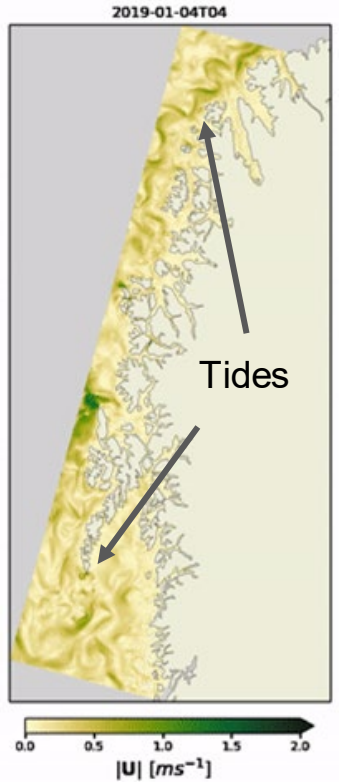
Challenging to compare with satellite altimeter observations



On the variability in the domain: A multiscale problem

Flow field	Temporal variability	Horizontal length scale	Predicta-bility	Impact on the wave field
Norwegian coastal current	~ month	~ 10^2 km	Good	Marginal
Sub-mesoscales	~ day	~ 10^1 km	Statistics are OK, but not their location*	Substantial
Tides	~ hours	~ 10^0 km	Good	Substantial



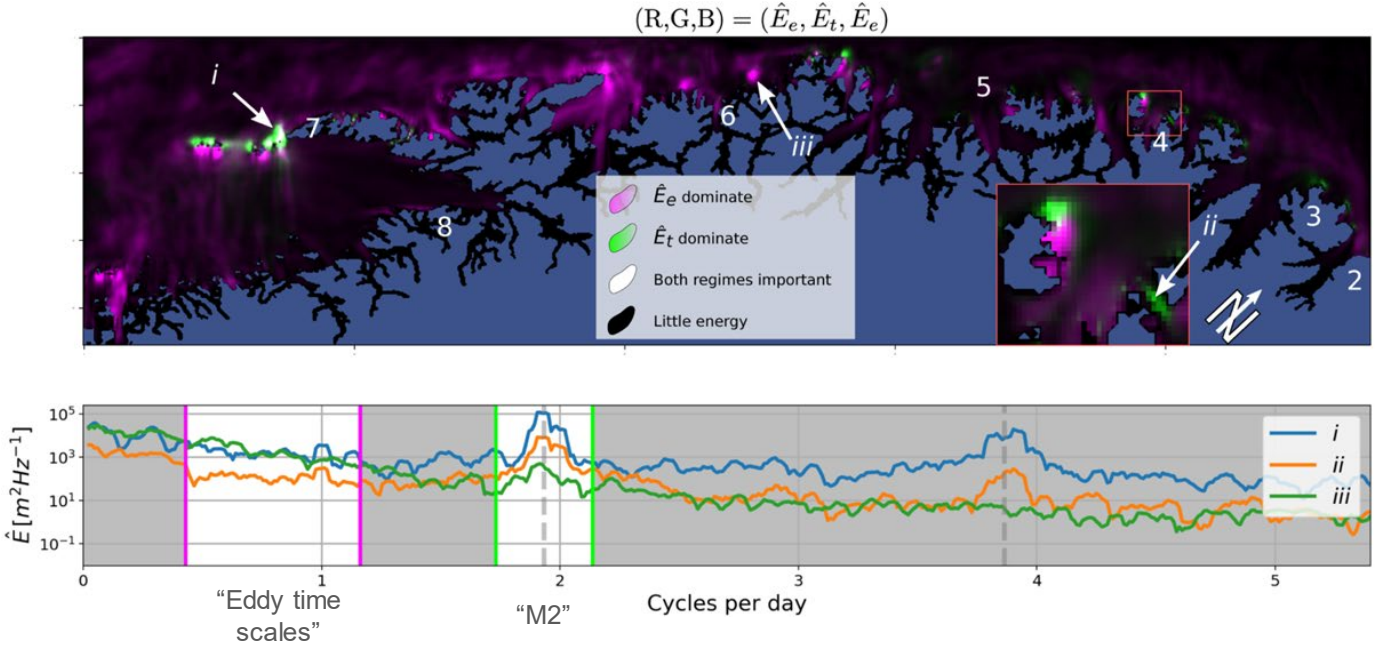


*NOTE: Wind-driven inertial currents are very close to M2. *vertically sheared currents*

Mapping the spatio–temporal variability

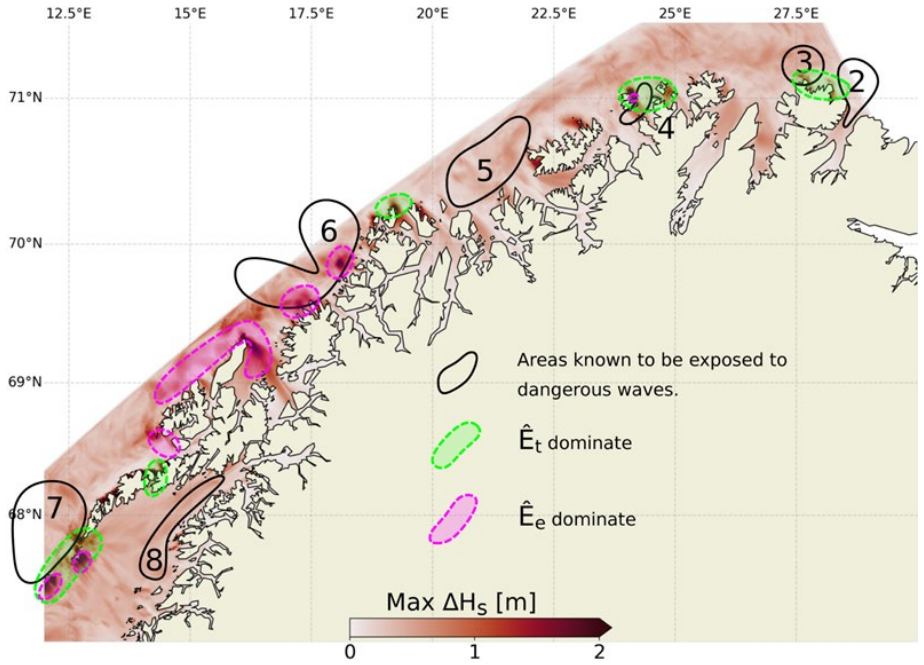
- FFT analysis of model difference
  - Magenta areas are also affected by tides
  - Depend on the (wind) wave conditions

$$\widehat{E}_{e,(i,j)} = \int_{\delta f_0}^{M_1+\delta f} \mathrm{PSD}\,(\Delta H_s)_{(i,j)}\, df,$$
$$\widehat{E}_{t,(i,j)} = \int_{M_2-\delta f}^{M_2+\delta f} \mathrm{PSD}\,(\Delta H_s)_{(i,j)}\, df.$$



Can we reproduce the areas of dangerous waves?

- Most areas (2–8) are qualitatively resolved
  - Including the physical mechanisms
- New areas are identified
  - Need be verified
- Uncertainty associated with the ocean dynamics

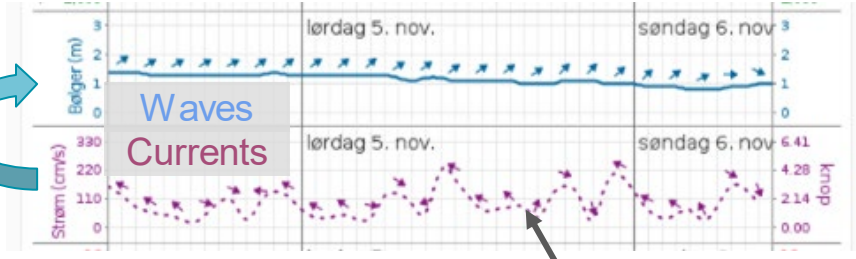


Halsne et al. (2022)

Is there any value in adding currents as forcing?

My answer is: Yes, in some areas.

Marinogram from the coastal wave forecasts



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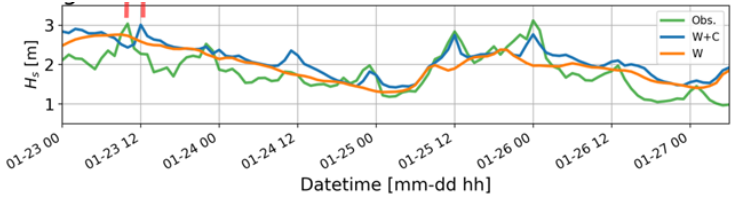
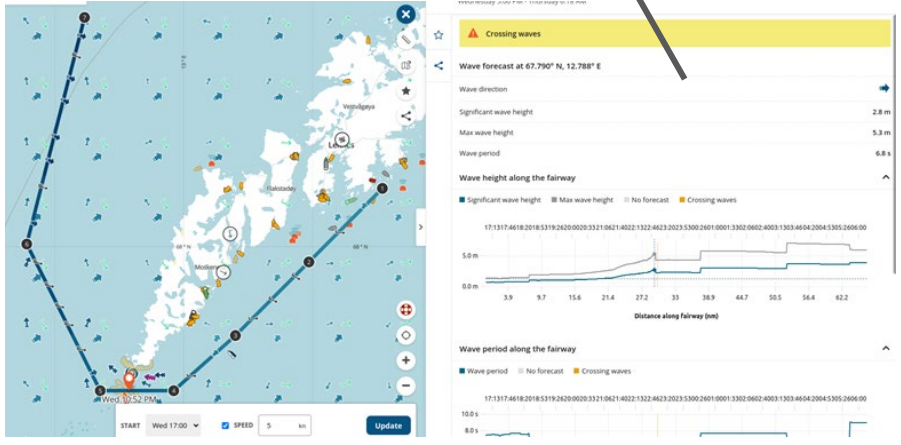




Fishing trawler Iselin capsized at Moskstraumen near Norway

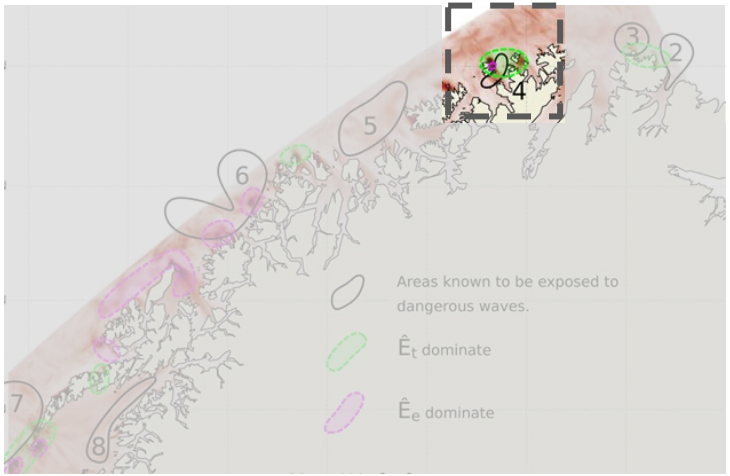
Shipping Accidents March 30, 2017 PRINT EMAIL A- A+

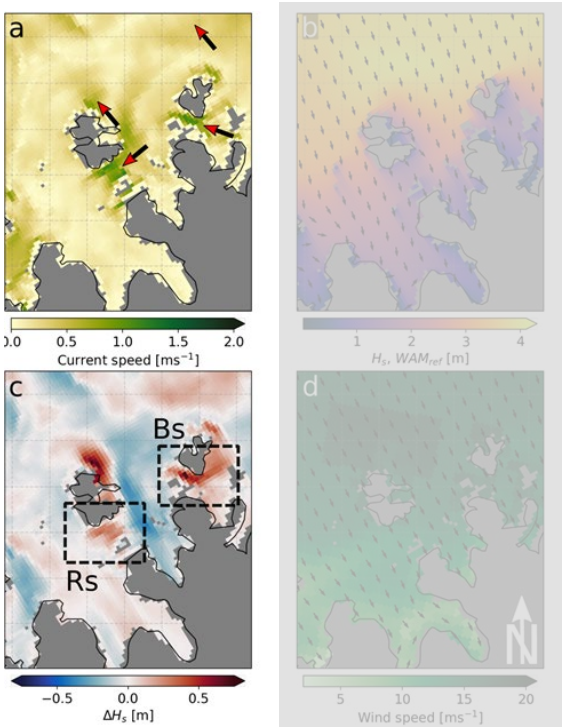
The fishing trawler Iselin capsized and started sinking at Moskstraumen near the Lofoten archipelago, Norway. The vessel's nets and ropes embrangled into the propeller, which caused increasing list to starboard. The fishing trawler with three crew on board remained gearless and adrift under the strong winds and heavy waves at southwest end of Moskenesoya in Nordland. The fishing vessel Iselin was getting water ingress and

...uested immediate assistance.

Maritime Herald (2017)

My answer is: Yes, if tidal currents are predictive.





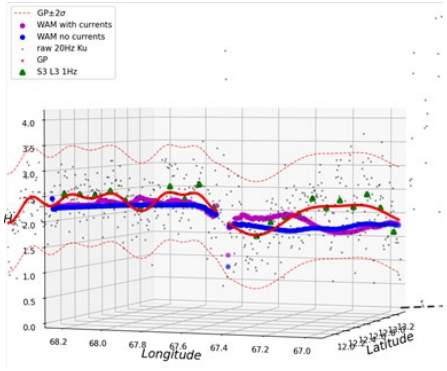
Why should we not add current forcing?

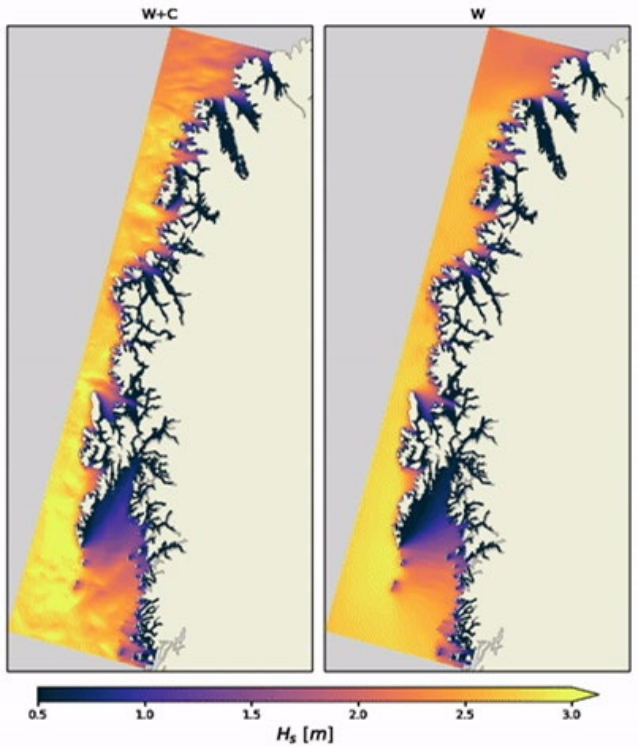
Because

- Uncertainty associated with the dynamics
  - Realistic but inaccurate

However

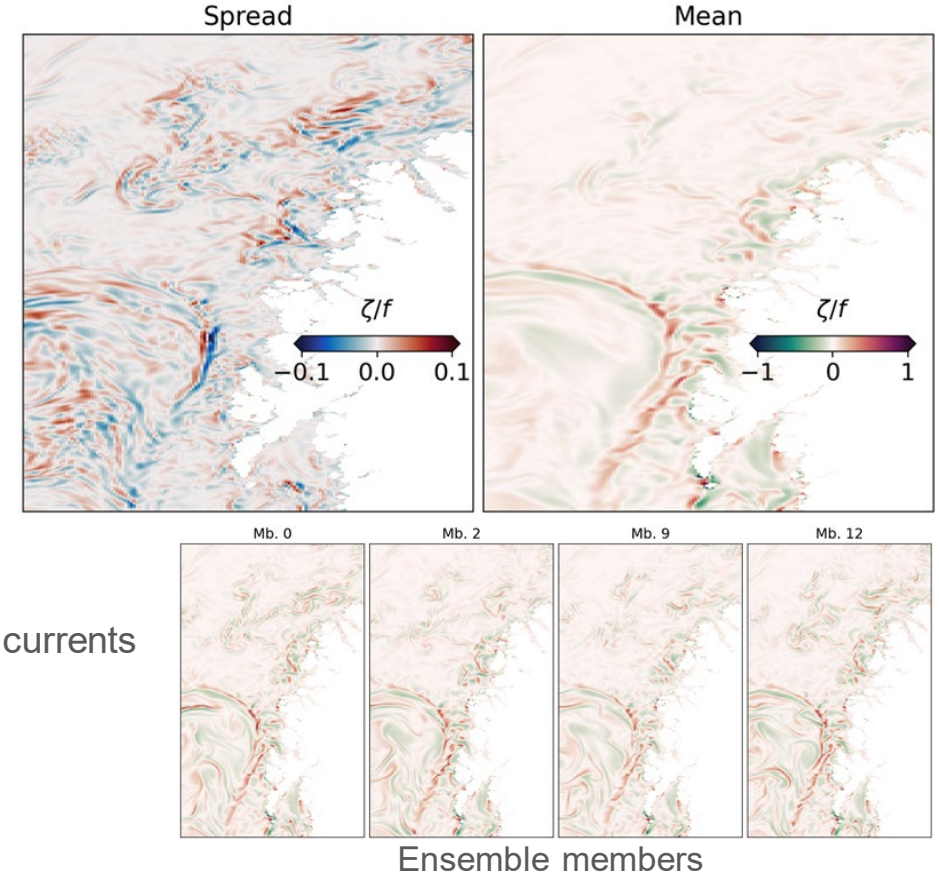
- Highlight the horizontal variability
- Good supplement to wind-only forecasts





Barents 2.5 km ROMS ensemble [see Röhrs et al. (2023)]

How can we improve?



Observations

- Small, expendable, drifting wave buoys
- Remote sensing: SWOT, CFOSAT

Ensembles?

- Unrealistic to run ensembles for both wind and currents
  - Interpret uncertainty ocean dynamics
- Ensemble mean current as forcing?
  - Filters out small-scale scatterers
- Ensemble spread as uncertainty?

Revisiting the research questions—conclusions

Q: Why is current forcing usually left out in operational wave models?

- We lack validation data!
- We don't trust the ocean models

Q: How to assess their influence with limited observations?

- Characterizing the type of flow field is helpful
- Local knowledge is a valuable source of information
- Using ensembles?

Q: Can we provide better forecast than what we do today?

- Yes, we can!
- The predictability depends on the ocean dynamics

Thank you for your attention

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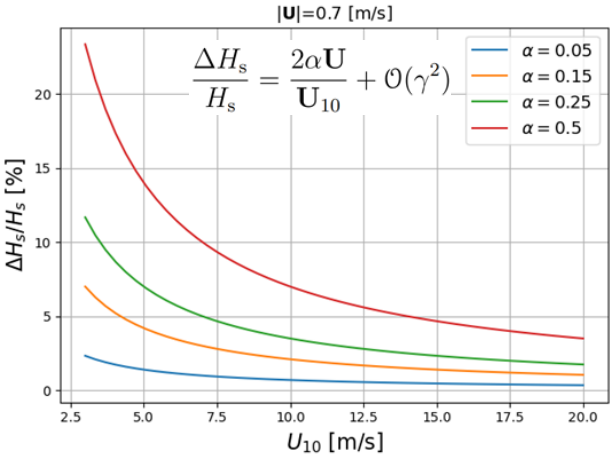
Mail: trygve.halsne@met.no

Kai Håkon Christensen, Ana Carrasco, Øyvind Saetra, Patrik Bohlinger, Alvise Benetazzo, Francesco Barbariol, Patrik Bohlinger, and Øyvind Breivik

$$S = S_{\mathrm{in}} + S_{\mathrm{nl}} + S_{\mathrm{ds}}$$

Relative wind

$$\mathbf{U}_{10,\mathrm{r}} = \mathbf{U}_{10} + \alpha\mathbf{U},$$



Gemmrich and Garrett (2012)
Rapizo et al. (2018)
Guimarães et al. (2022)
Ardhuin et al. (2012)
Romero et al. (2020)
Hersbach and Bidlot (2008)

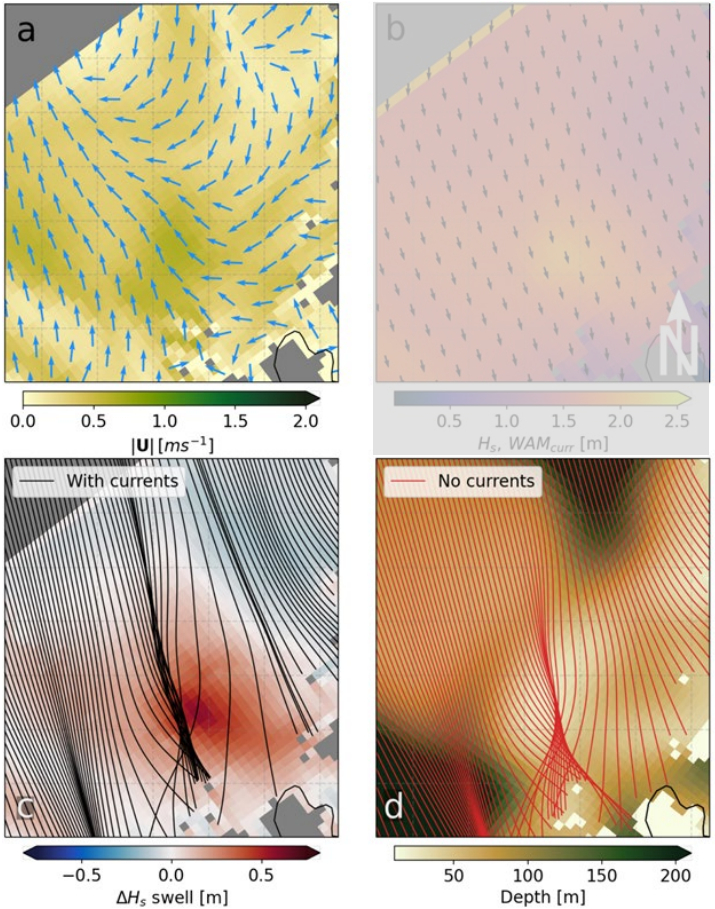
Wave–wave interaction

Rapizo et al. (2016)
Tamura et al. (2008)

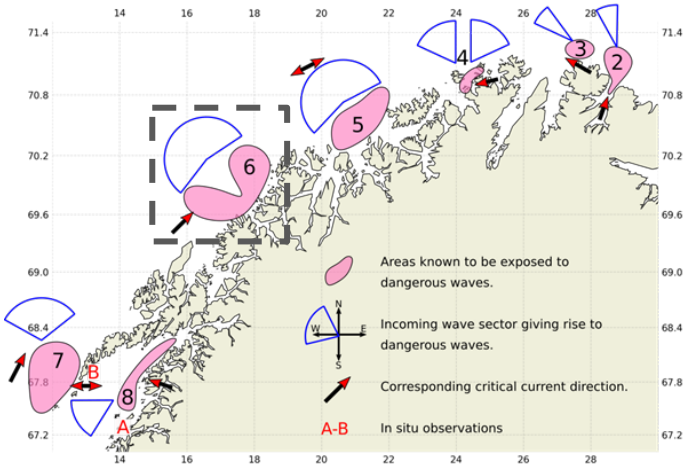
Dissipation

Rapizo et al. (2017)
Chawla and Kirby (2002)
Ris and Holthuijsen (1996)
van der Westhuysen (2008)

Source terms (deep–water)



Wave–current and wave–bathymetry interaction



Example description from the Pilot Guide

This area N and NW of Senja and Kvaløya consists of large, shallow banks. Between the banks the depths are greater than 400 m and outside the banks the slope is very steep.

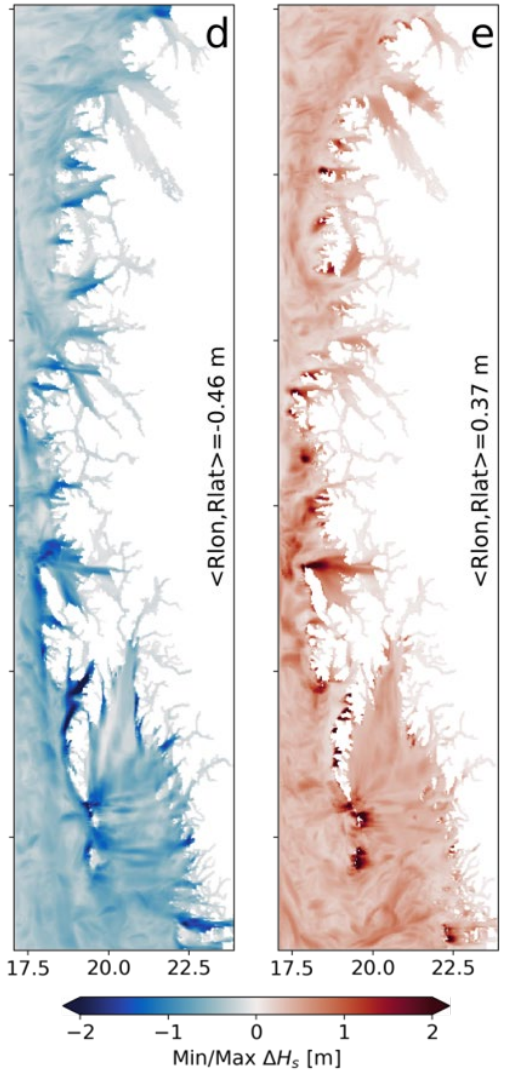
The **current is dominated** *by the NE coastal current as well as the normal tidal current, which moves NE with rising water.*

With **waves from NE to SW**, *several* **refraction centers** *occur in the area.*

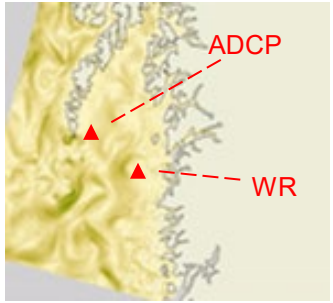
The interaction between waves from NE to NW and NE current can lead to breaking waves.

The extreme inter-model events

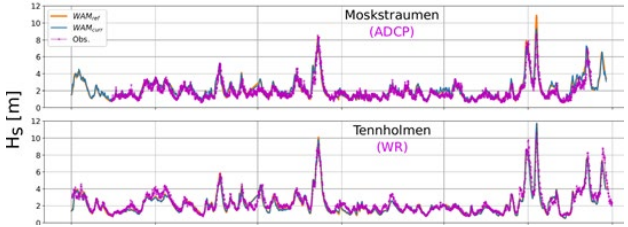
- Increased variability when adding currents
- Small inter-model differences in bulk statistics like the mean and the standard deviation



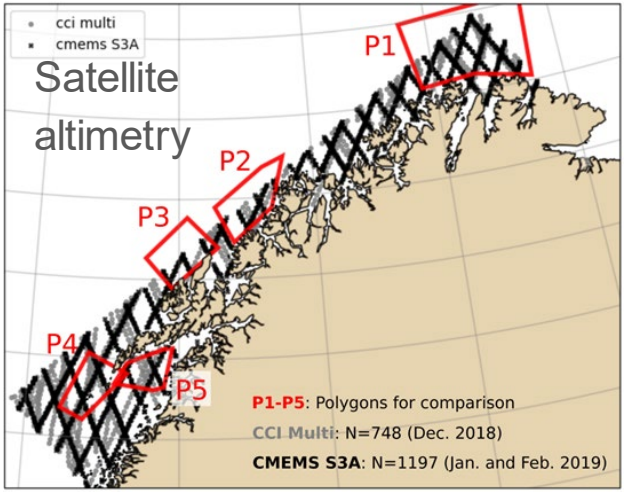
Statistics from 180 days



In situ



Time (three months)



	NBIAS		NRMSE		r	
	WAM_{curr}	WAM_{ref}	WAM_{curr}	WAM_{ref}	WAM_{curr}	WAM_{ref}
December 2018 CCI multimission						
P1 (N = 62)	0.18	0.17	0.21	0.21	0.91	0.91
P2 (N = 21)	0.00	−0.02	0.17	0.15	0.64	0.70
P3 (N = 37)	0.12	0.12	0.18	0.18	0.92	0.92
P4 (N = 165)	−0.01	−0.01	0.12	0.13	0.93	0.92
P5 (N = 29)	0.47	0.63	0.53	0.71	0.40	0.25
January–February 2019 CMEMS						
P1 (N = 88)	0.05	0.04	0.20	0.18	0.87	0.89
P2 (N = 93)	−0.04	−0.04	0.19	0.19	0.94	0.94
P3 (N = 106)	−0.01	−0.01	0.27	0.26	0.71	0.73
P4 (N = 344)	0.10	0.10	0.24	0.24	0.89	0.90
P5 (N = 76)	0.26	0.32	0.33	0.37	0.91	0.90

Validation against observations

Minor improvements in terms of bulk statistics

- Hs with currents are slightly out of phase with the observations
- Satellite altimeter wave height retrievals are too coarse in space

- Wave and tidal current interactions in the Lofoten Maelstrom

North

600 masl

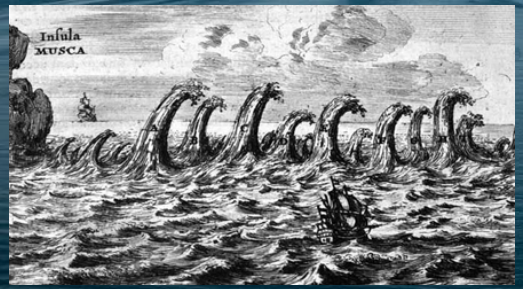
Lofotodden

400 masl

Værøy

Røst

Mosken



Fishing trawler Iselin capsized at Moskstraumen near Norway

Shipping Accidents March 30, 2017 PRINT EMAIL A- A+

The fishing trawler Iselin capsized and started sinking at Moskstraumen near the Lofoten archipelago, Norway. The vessel's nets and ropes embrangled into the propeller, which caused increasing list to starboard. The fishing trawler with three crew on board remained gearless and adrift under the strong winds and heavy waves at southwest end of Moskenesoya in Nordland. The fishing vessel Iselin was getting water ingress and

quested immediate assistance.

Maritime Herald (2017)

dit: Jørn Røssvoll (2009)