Wave refraction in weak currents over slowly varying bathymetry

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1 Norwegian Meteorological Institute

2 Universitas Bergensis

Wave refraction 170 km East of here

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[2] UNIVERSITAS BERGENSIS

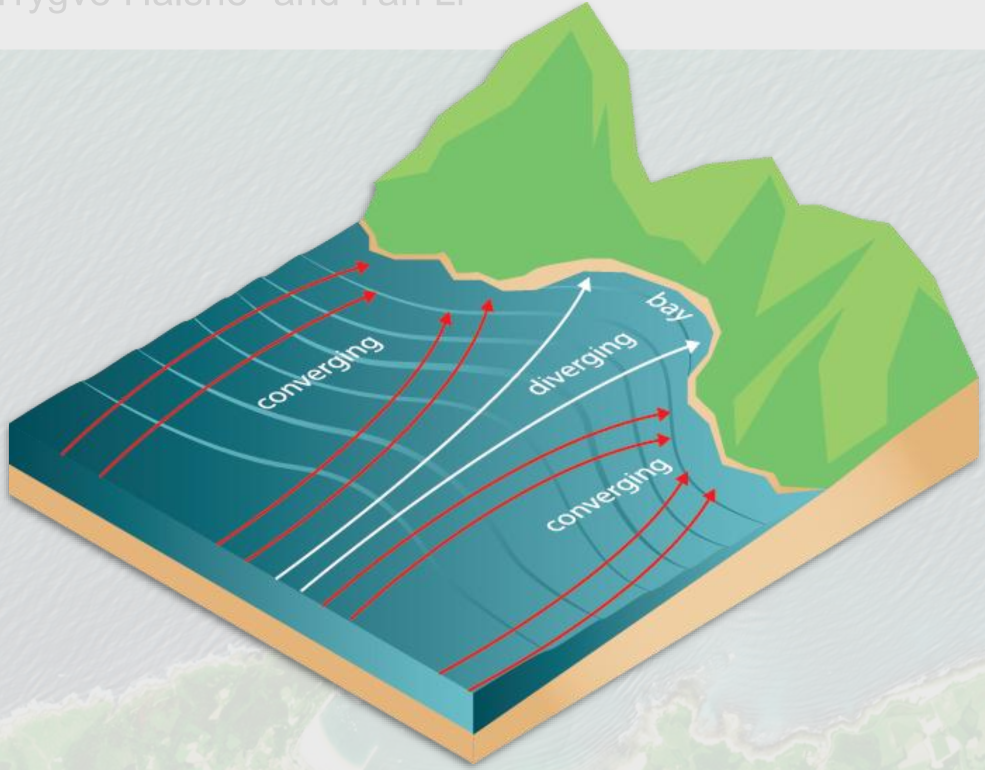
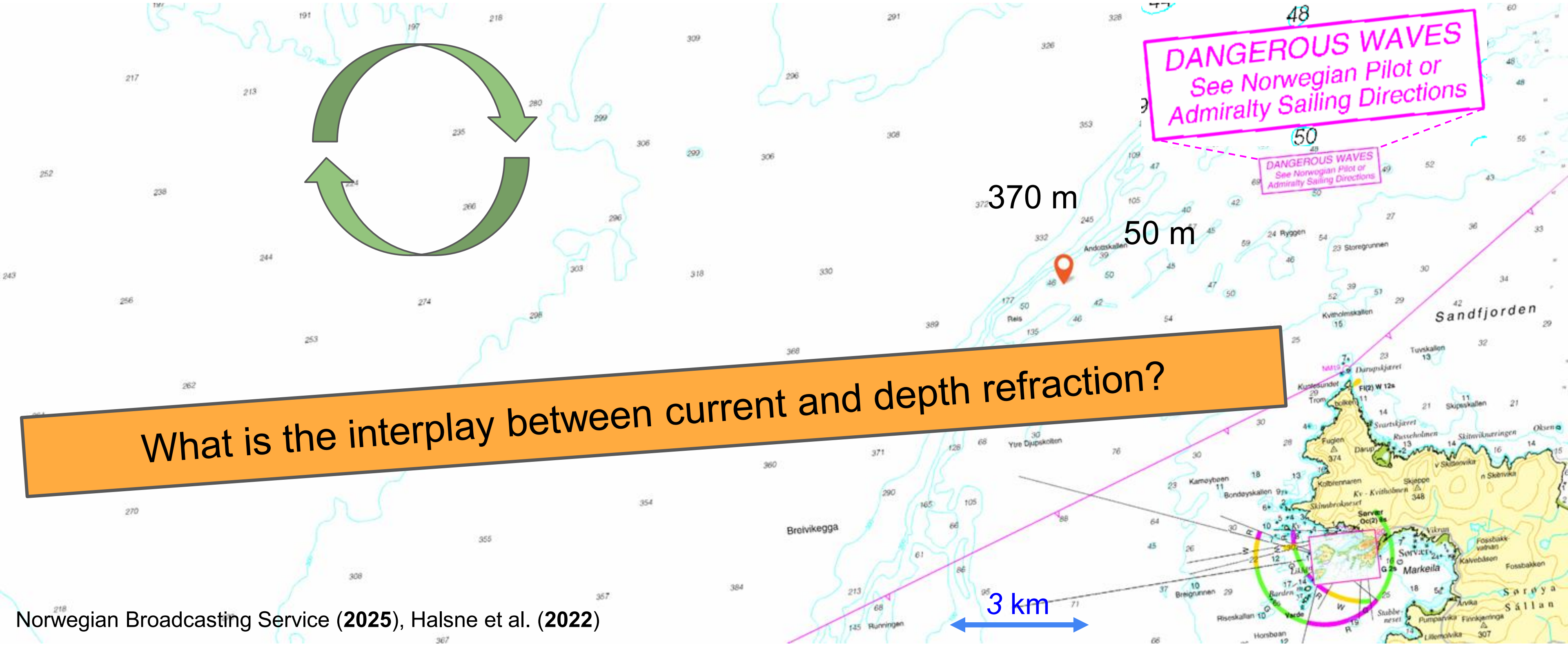


Image from manoa.hawaii.edu

Strong current- and depth-gradients in Northern Norway

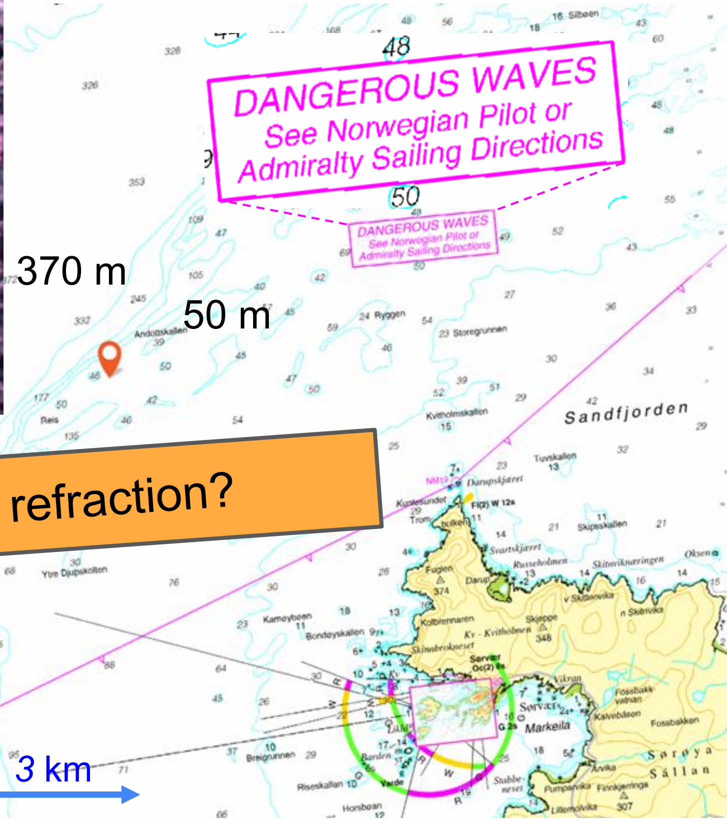


What is the interplay between current and depth refraction?

Norwegian Broadcasting Service (**2025**), Halsne et al. (**2022**)

“Loenget [captain] also says that the estimated waves were 4–5 meters high.

– So it was rough seas, he says.”



What is the interplay between current and depth refraction?

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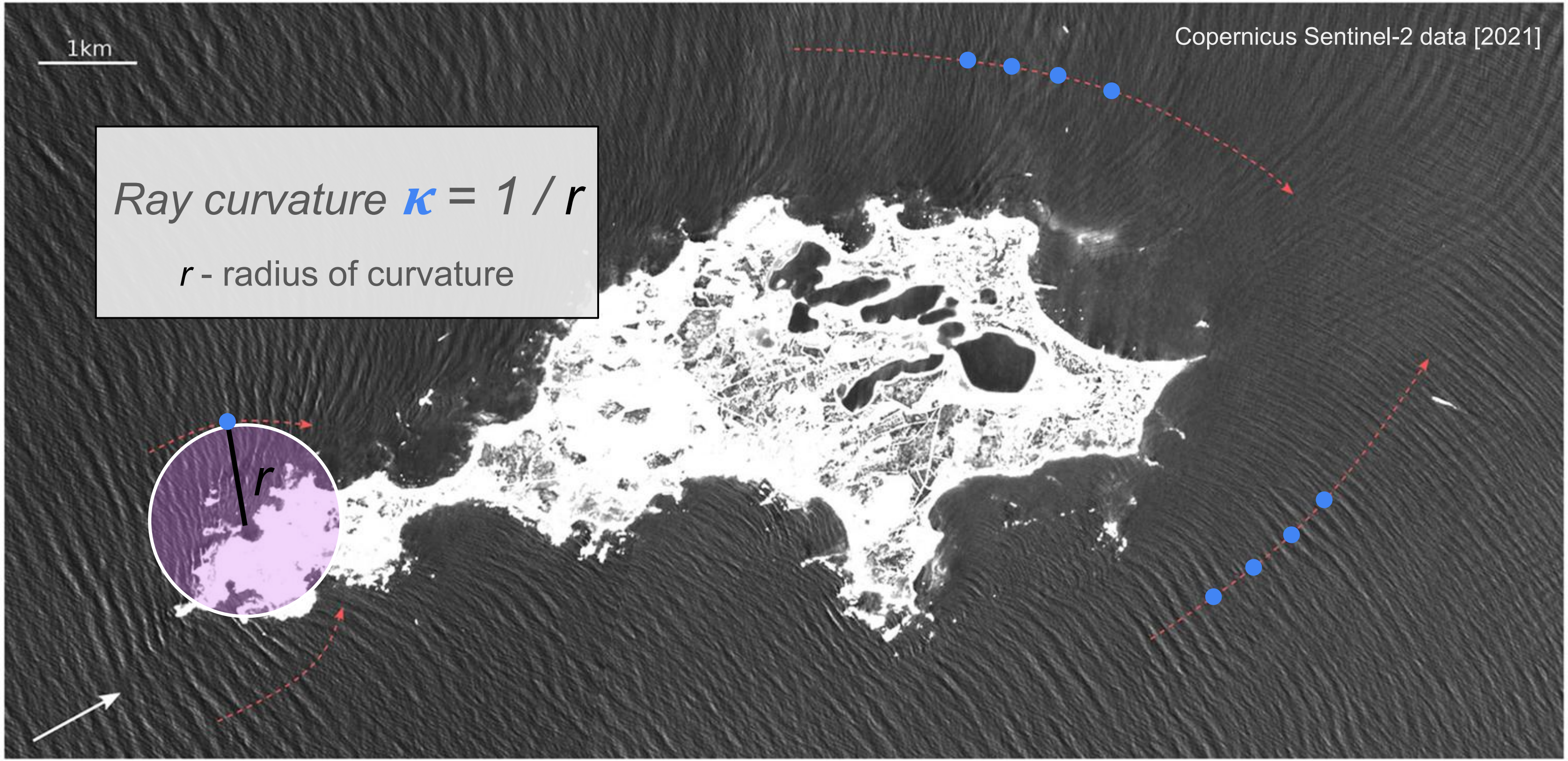


Curvature: a measure of the deviation from straightness

Long story short*: The approximate ray curvature solution

From the stationary wave ray equations, collecting terms to *O(ε = |**U**|/cg)*, we obtain

$$\kappa_{\approx} = \underbrace{\boxed{\frac{\partial_x U_2 - \partial_y U_1}{c_{g,i}}}}_{\kappa_c} + \underbrace{\frac{\boxed{\mathbf{e}_{k,\perp}} \cdot \nabla c}{c_{g,i}}}_{\kappa_d}$$

Vertical vorticity component

Directional dependence

Recovers

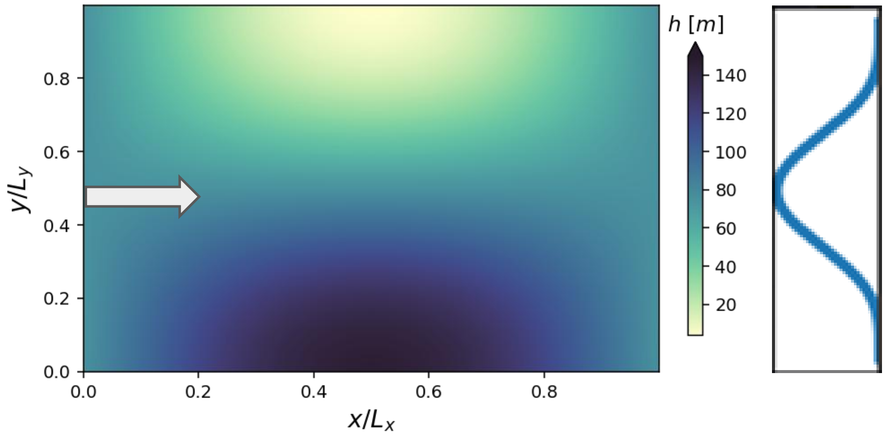
- Deep-water limit: Kenyon (**1971**) and Dysthe (**2001**).
- Zero currents: Arthur et al. (**1952**).

*See Halsne and Li (**2025**) for more details

c–phase speed, (U_1 , U_2)–current

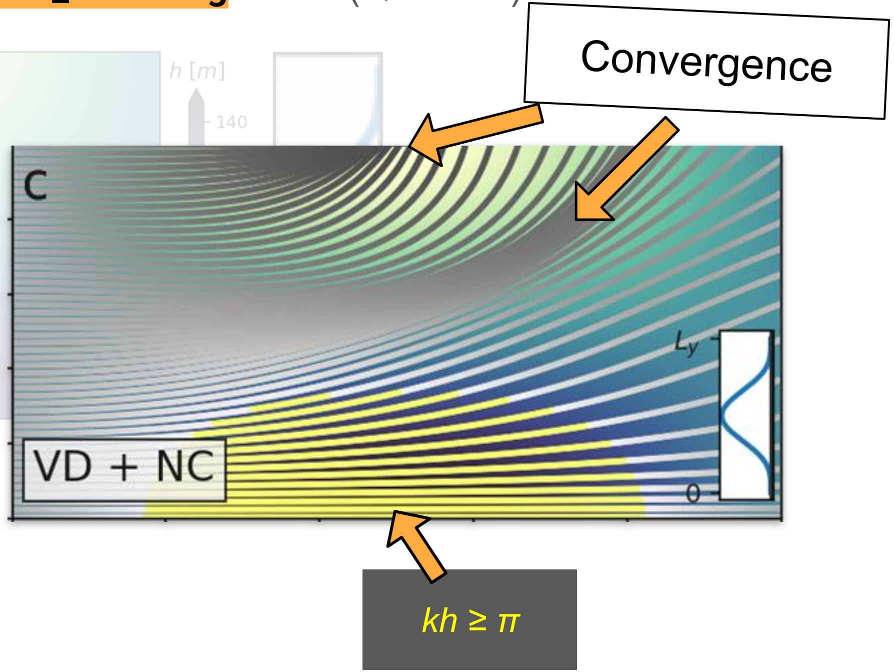
Ray tracing: highlighting the physics

- Variable depth bathymetry (VD)
- Negative current jet (NC)



Ray tracing: highlighting the physics

- Variable depth bathymetry (VD)
- Negative current jet (NC)
- Framework: `ocean_wave_tracing` solver (QR-code)



Ray tracing: highlighting the physics

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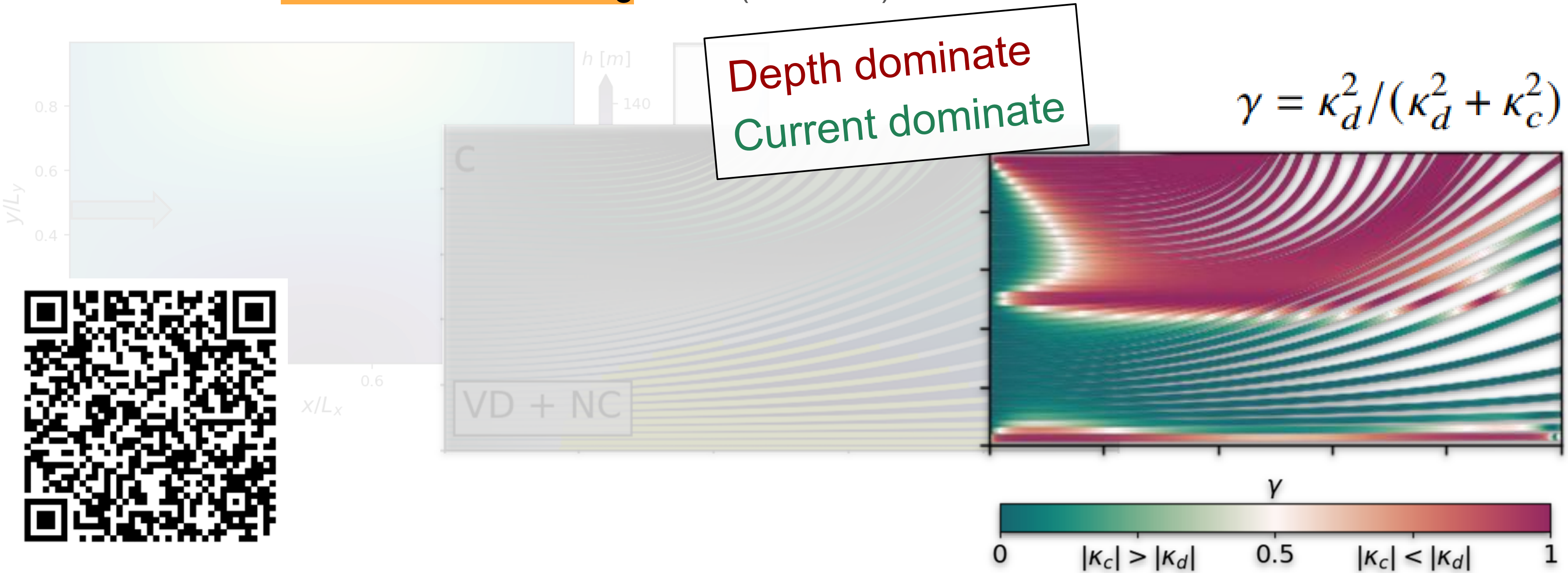
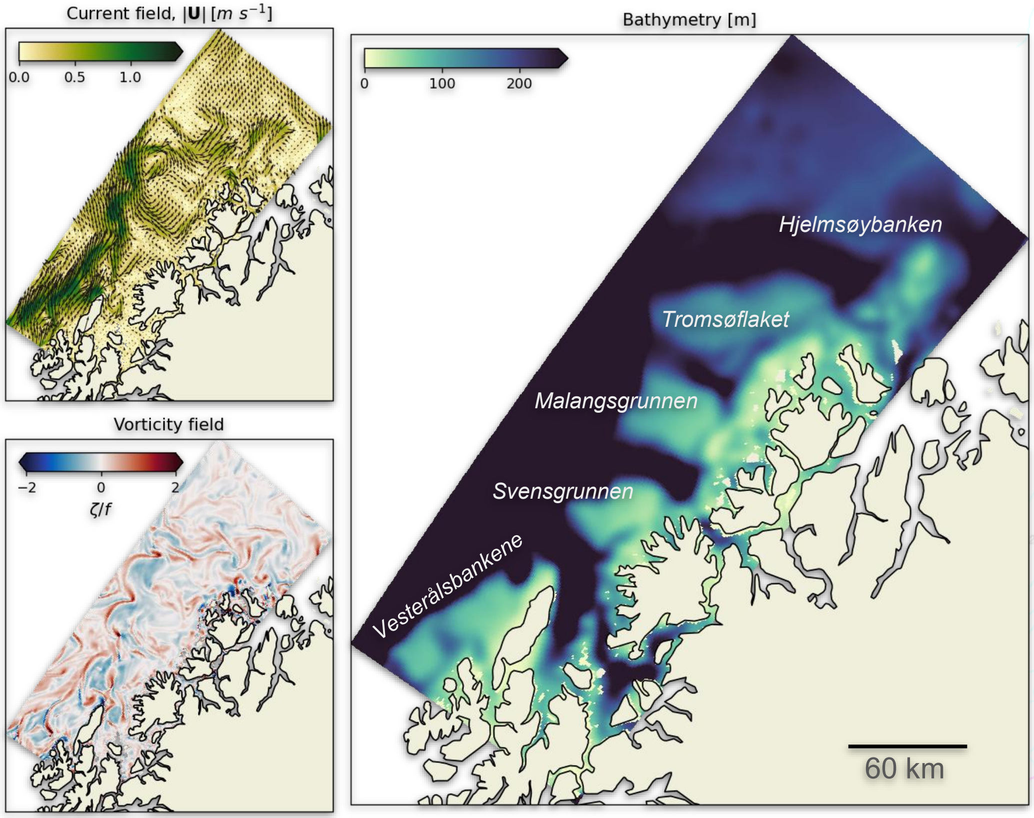
- Mapping the dominating wave scatterer

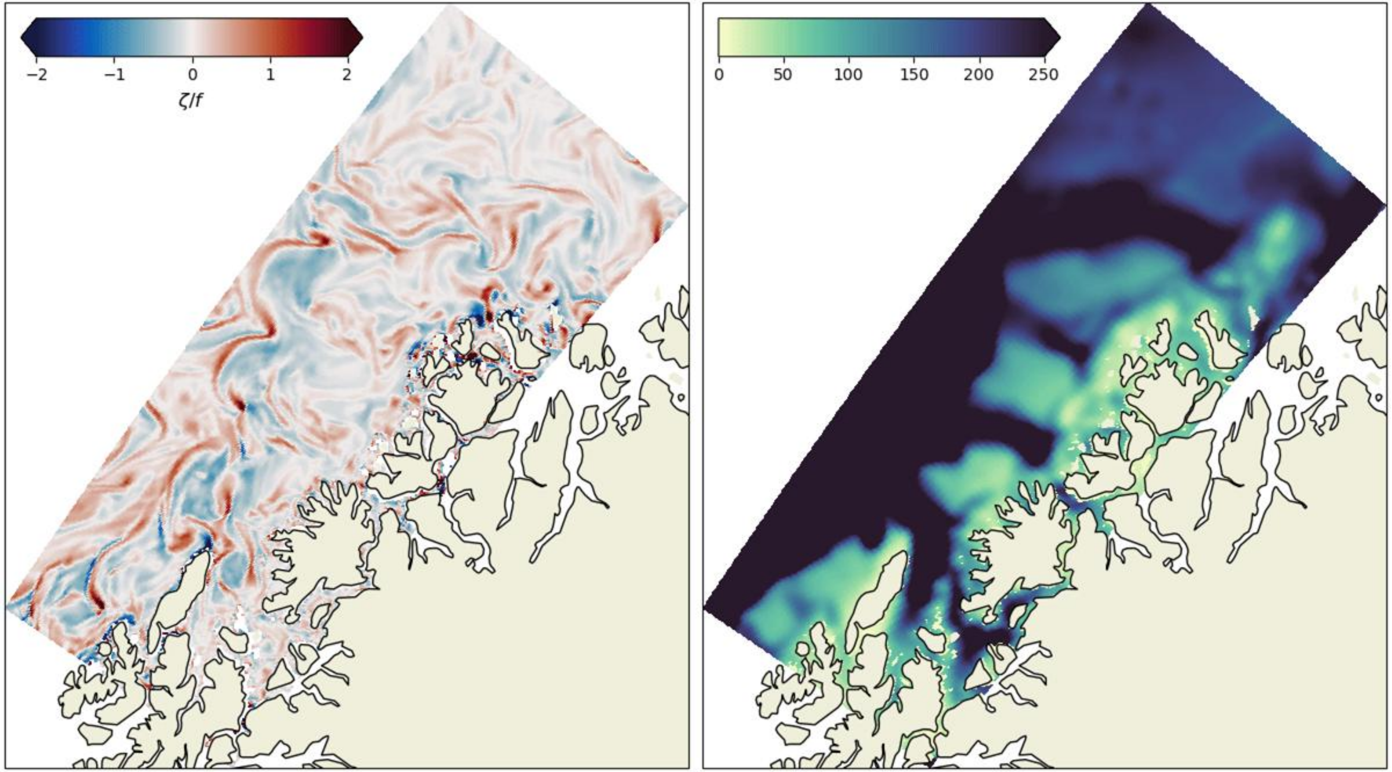


Applying the framework in realistic conditions



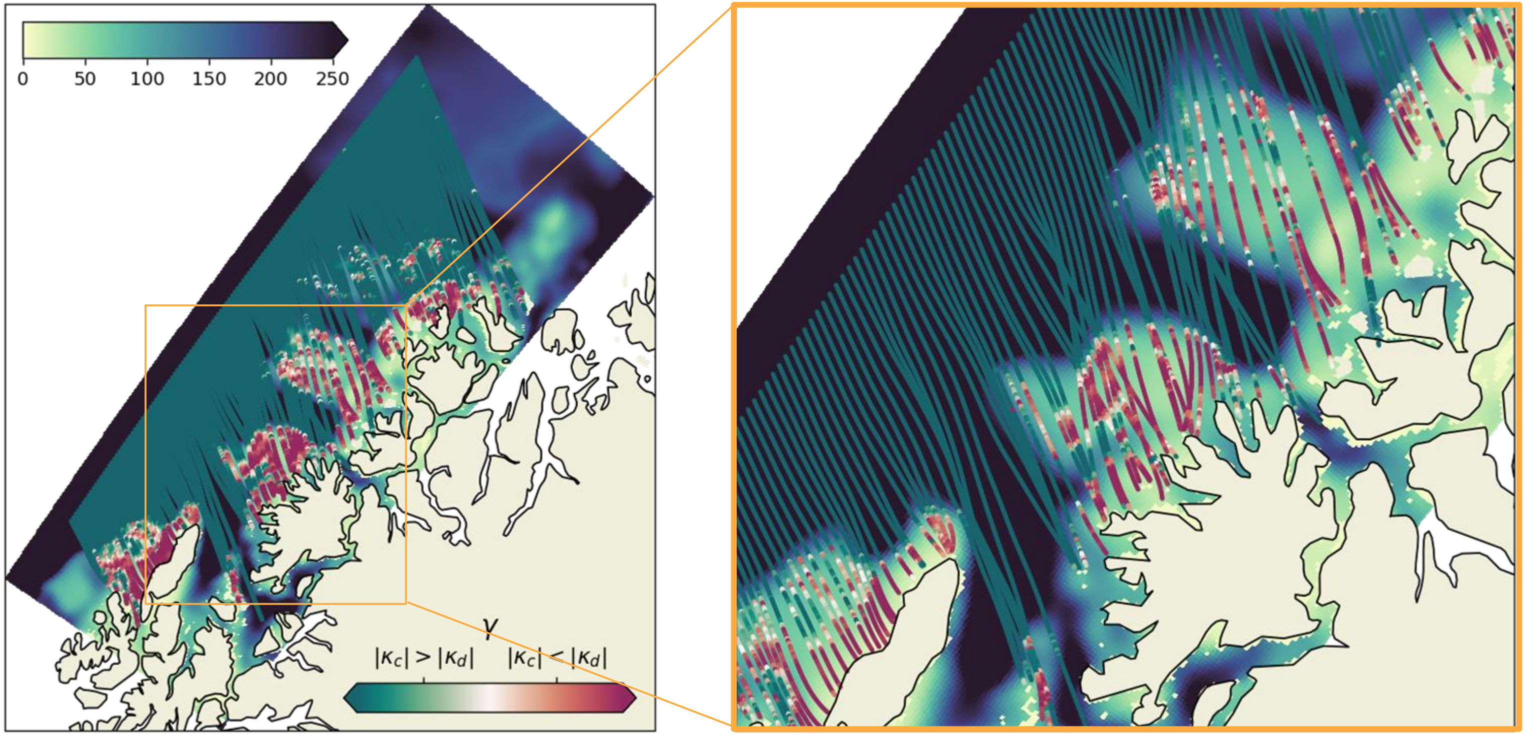
Surface currents and bathymetry from MET Norway’s operational coastal ROMS model: Norkyst

Wave rays reflecting peak period (12 s) and direction for a given sea state

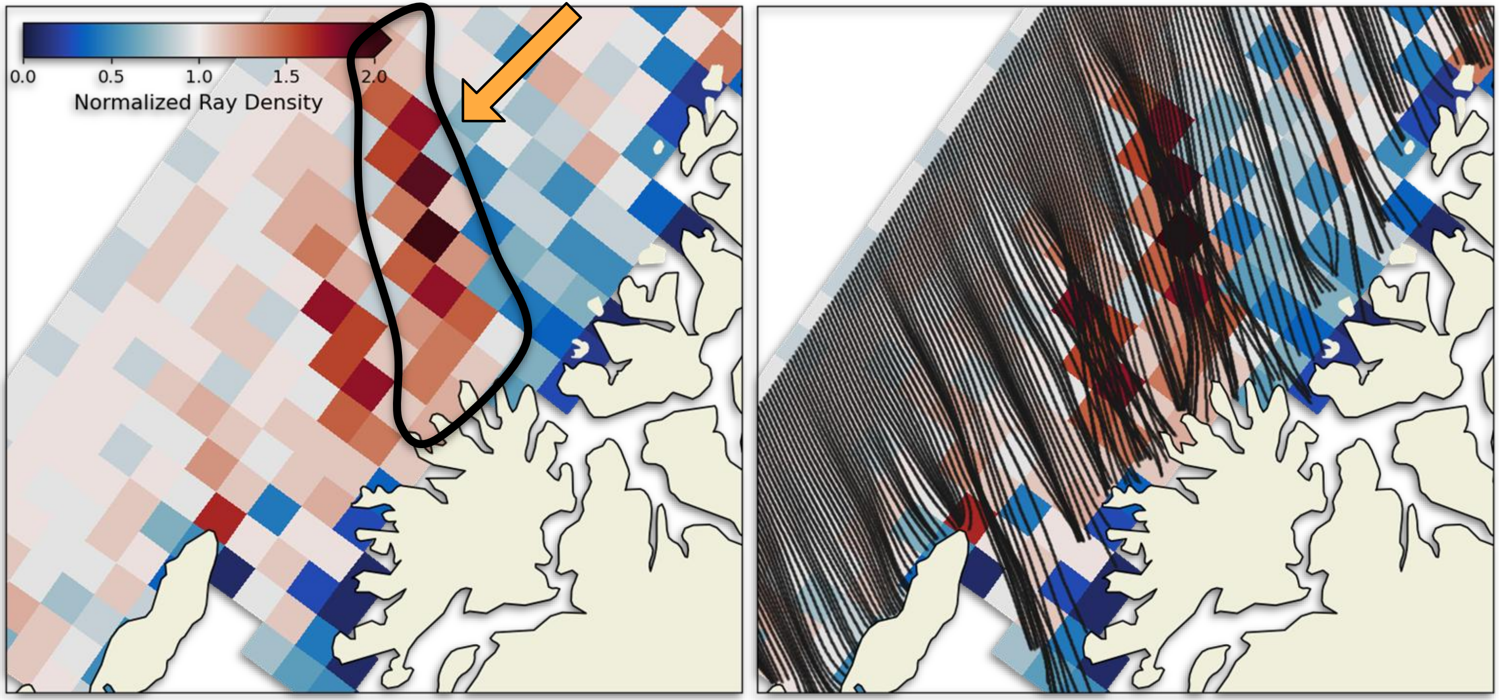


Mapping the dominant wave scatterer

● Depth dominate
● Current dominate



This may allow for order-of-magnitude wave height analysis

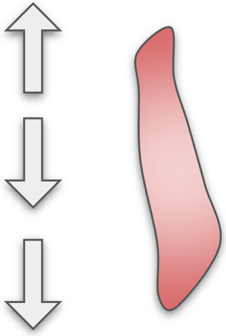


Wave–current–depth interactions: disentangling mechanisms

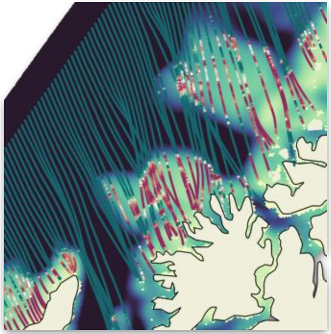
Refraction

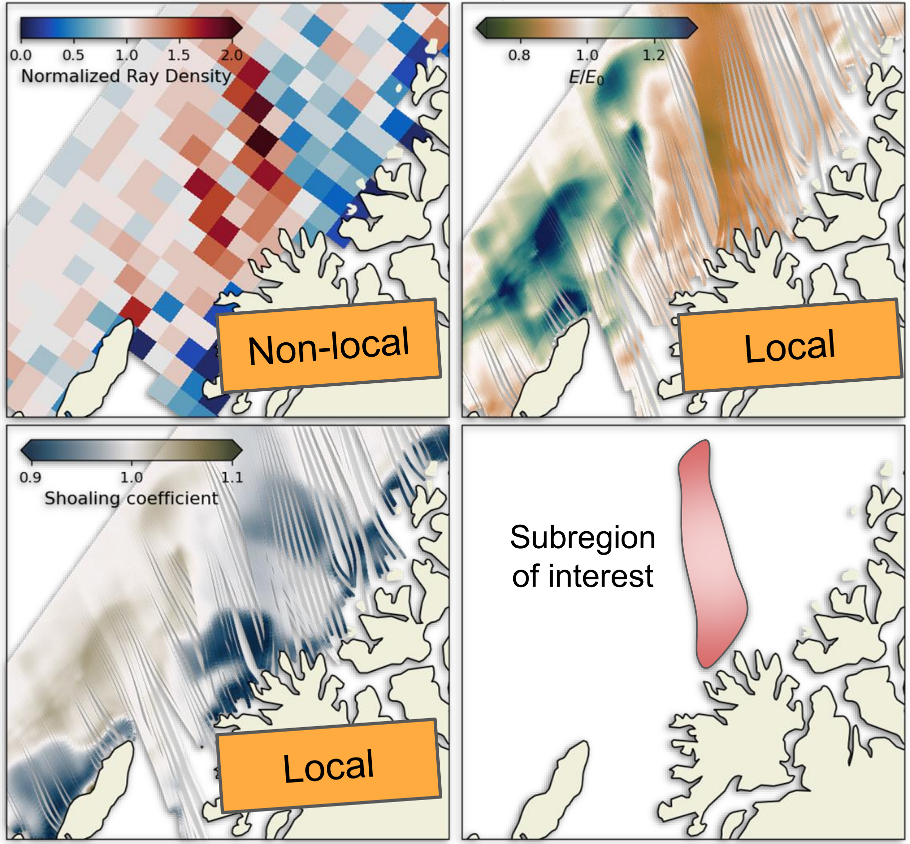
Shoaling

E/E_0

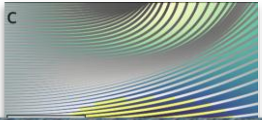


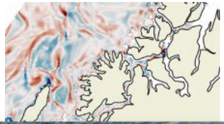
“Opposing waves and currents”

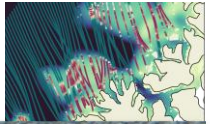




Summary and conclusions







- We have developed an approximate ray cu
  propagating in weak currents over slowly v
- We have highlighted their complex interact

- Future / ongoing work:
  - Assess the importance of different eff
  - Compare simulations with ray paths d

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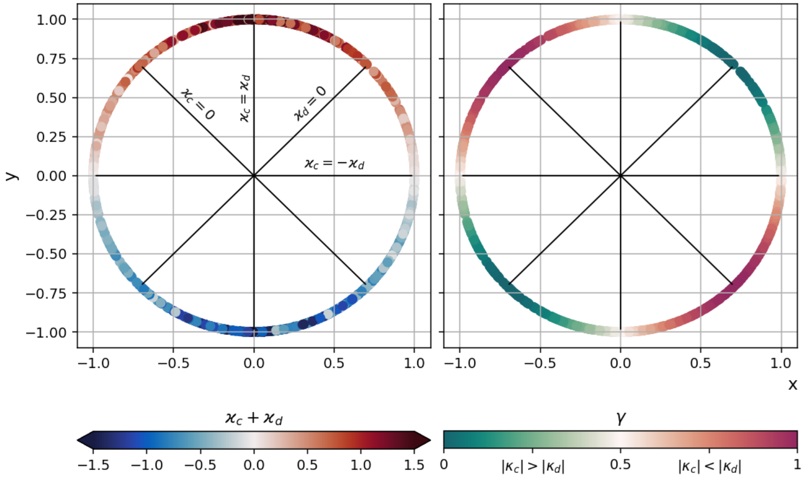
Extra slides

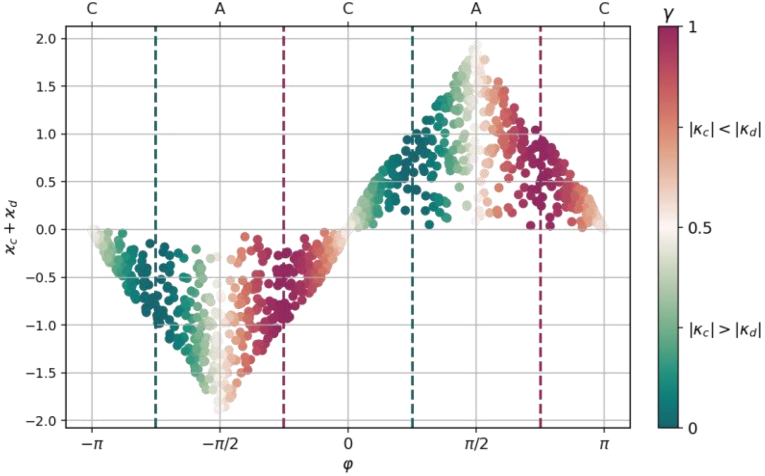
Properly mapping dominating condition: Turner Angle analogy

$$\hat{\mathbf{d}} = \frac{\mathbf{d}}{|\mathbf{d}|} = \frac{(\kappa_c - \kappa_d, \kappa_c + \kappa_d)}{\sqrt{2(\kappa_c^2 + \kappa_d^2)}},$$

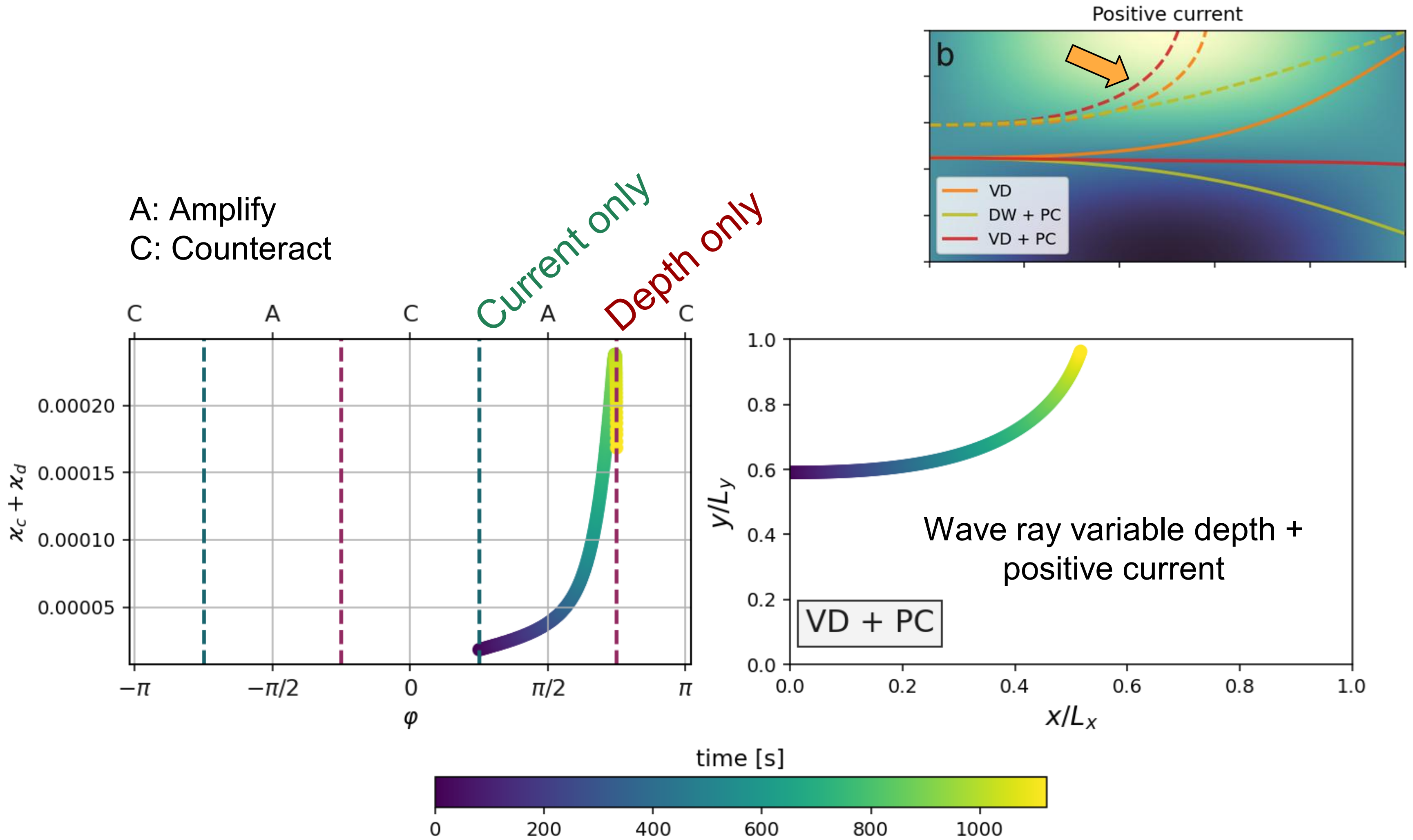
x–y view



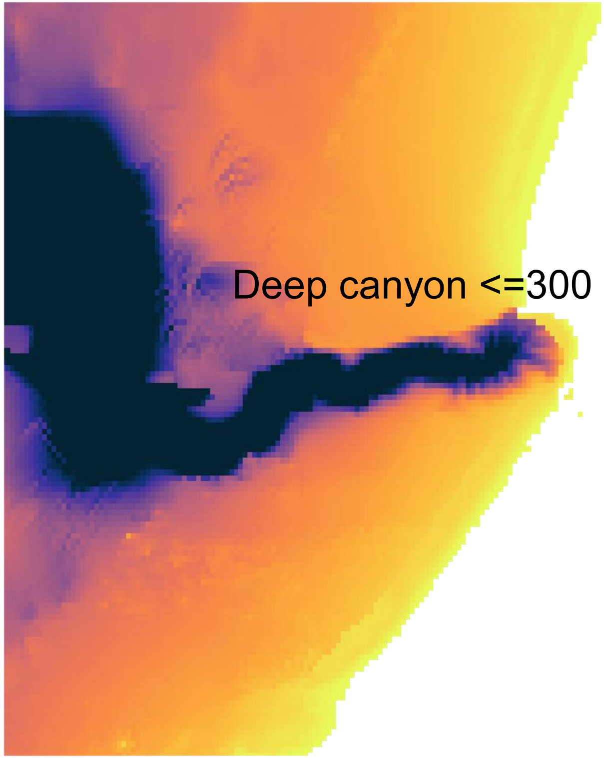
Polar coordinate view

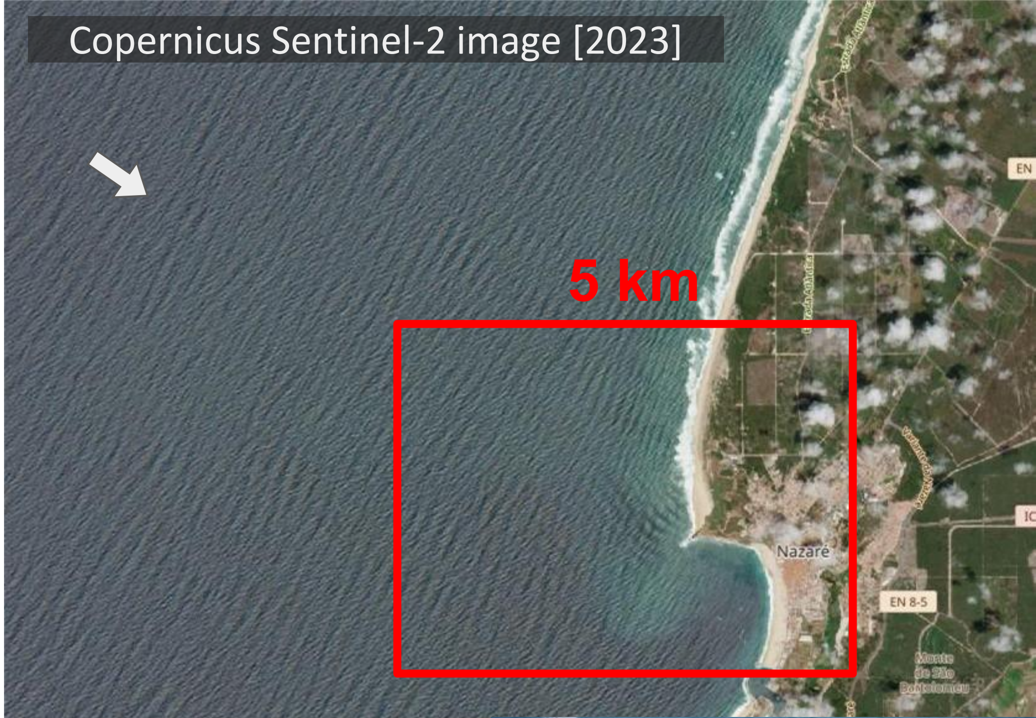


A: Amplify C:


Positive current
b
VD
DW + PC
VD + PC
A: Amplify
C: Counteract
Current only
Depth only
C A C A C
0.00020
0.00015
0.00010
0.00005
$\varkappa_c + \varkappa_d$
$-\pi$ $-\pi/2$ 0 $\pi/2$ π
φ
1.0 0.8 0.6 0.4 0.2 0.0
y/L_y
0.0 0.2 0.4 0.6 0.8 1.0
x/L_x
Wave ray variable depth + positive current
VD + PC
time [s]
0 200 400 600 800 1000

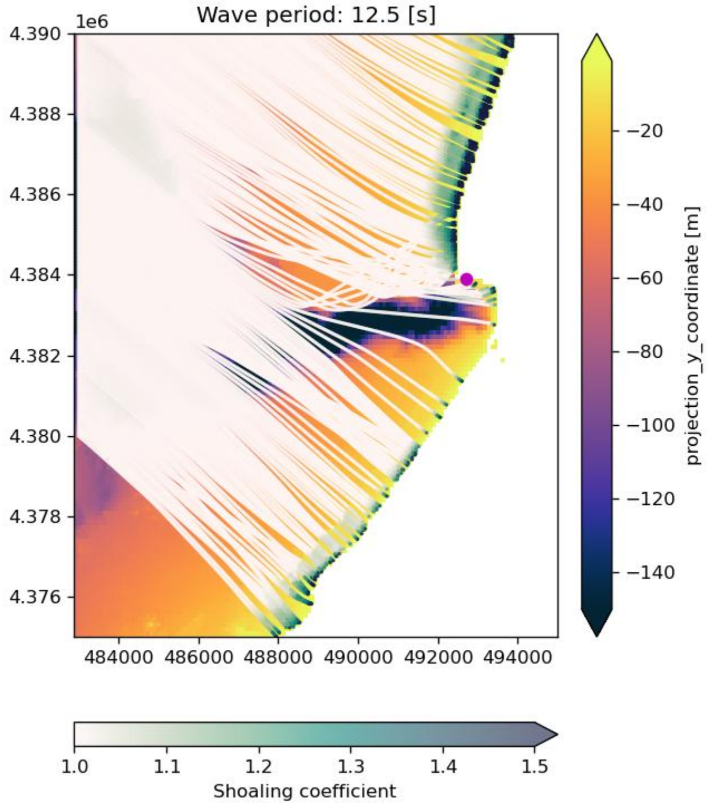
Wave refraction at Nazaré

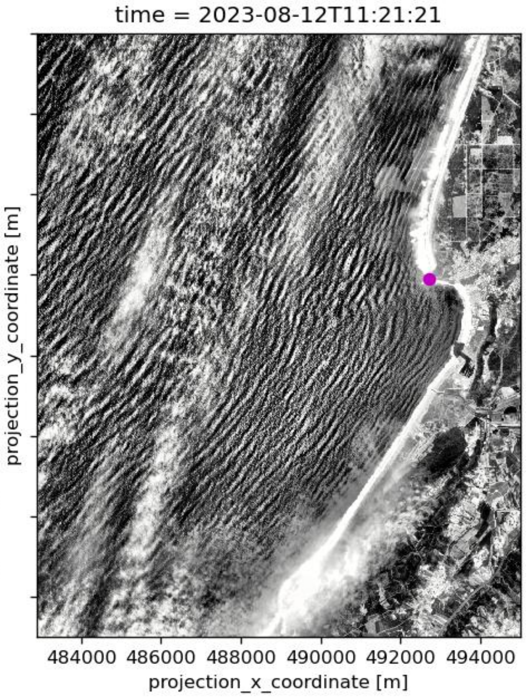




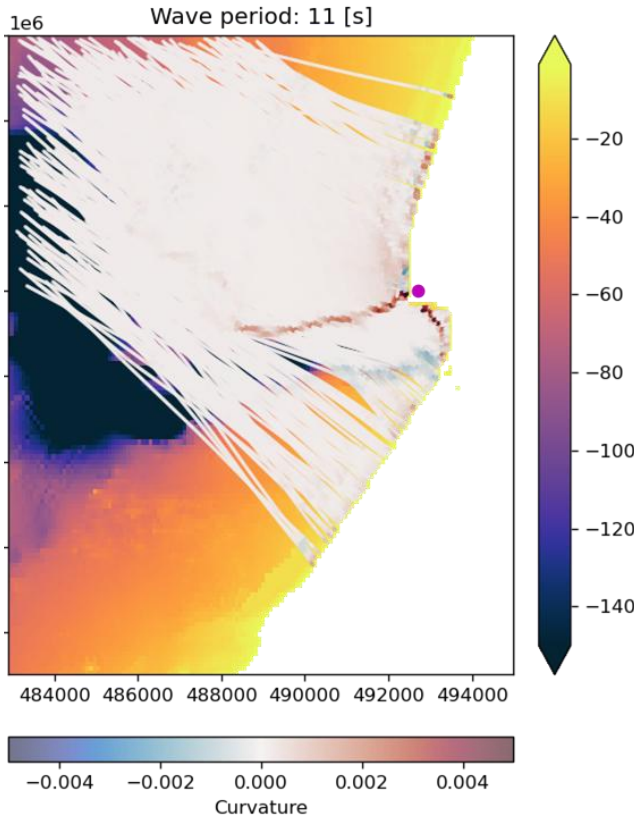

From surf-escape.com

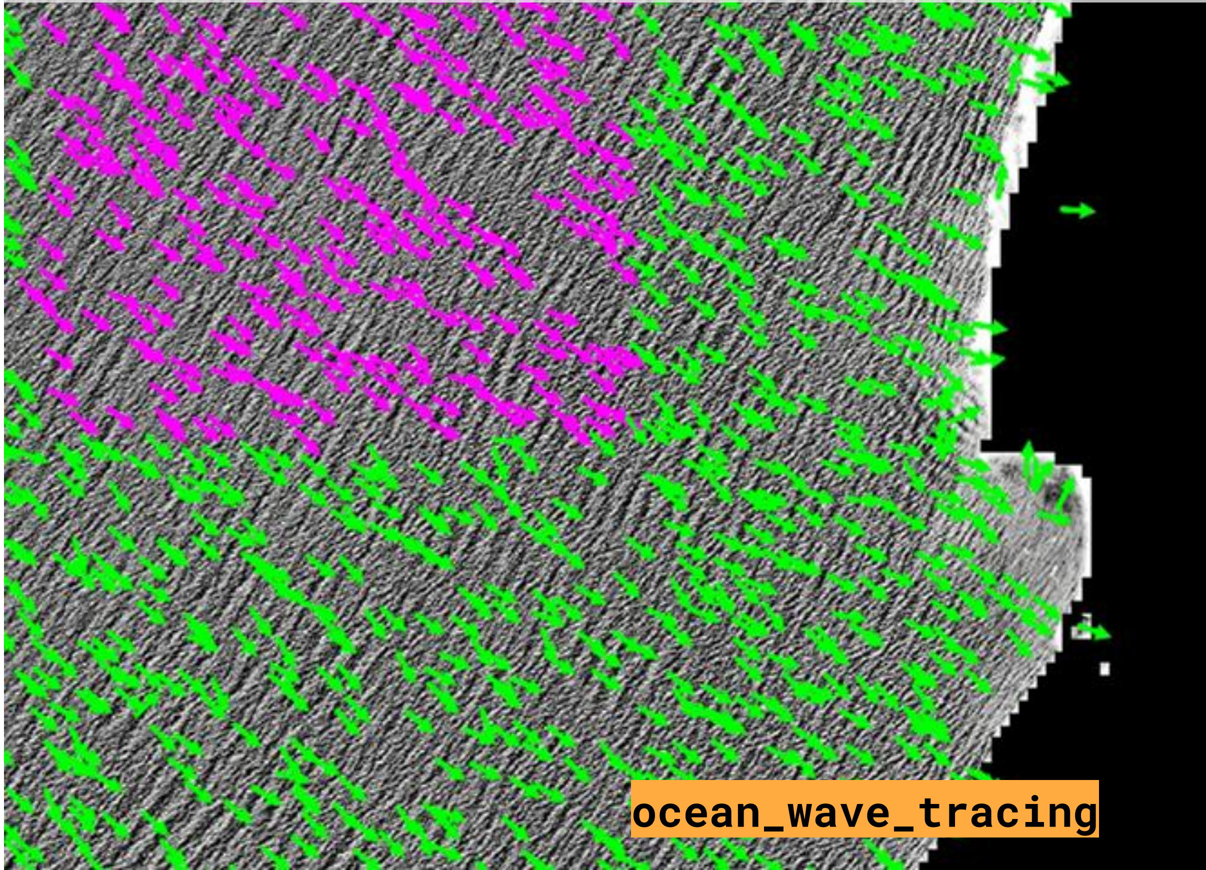
Other examples from Nazaré



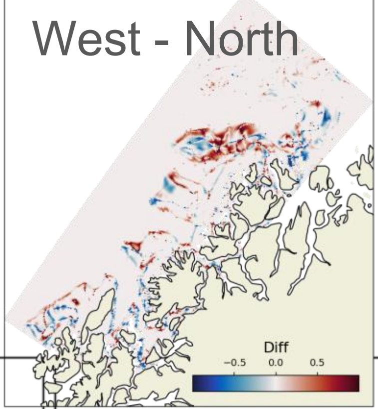


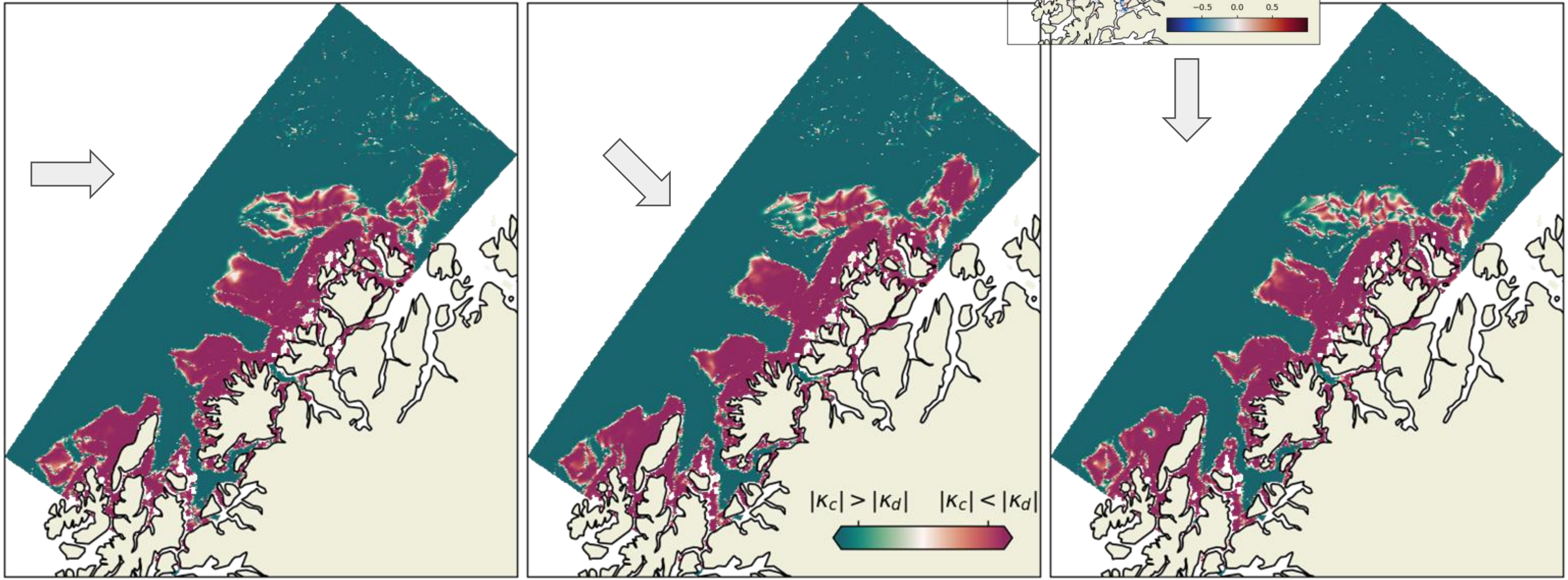
Propagating rays with location and initial direction from Sentinel-2 image



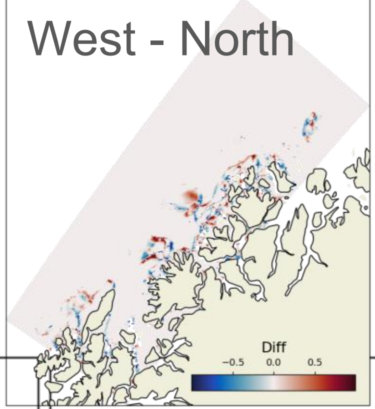


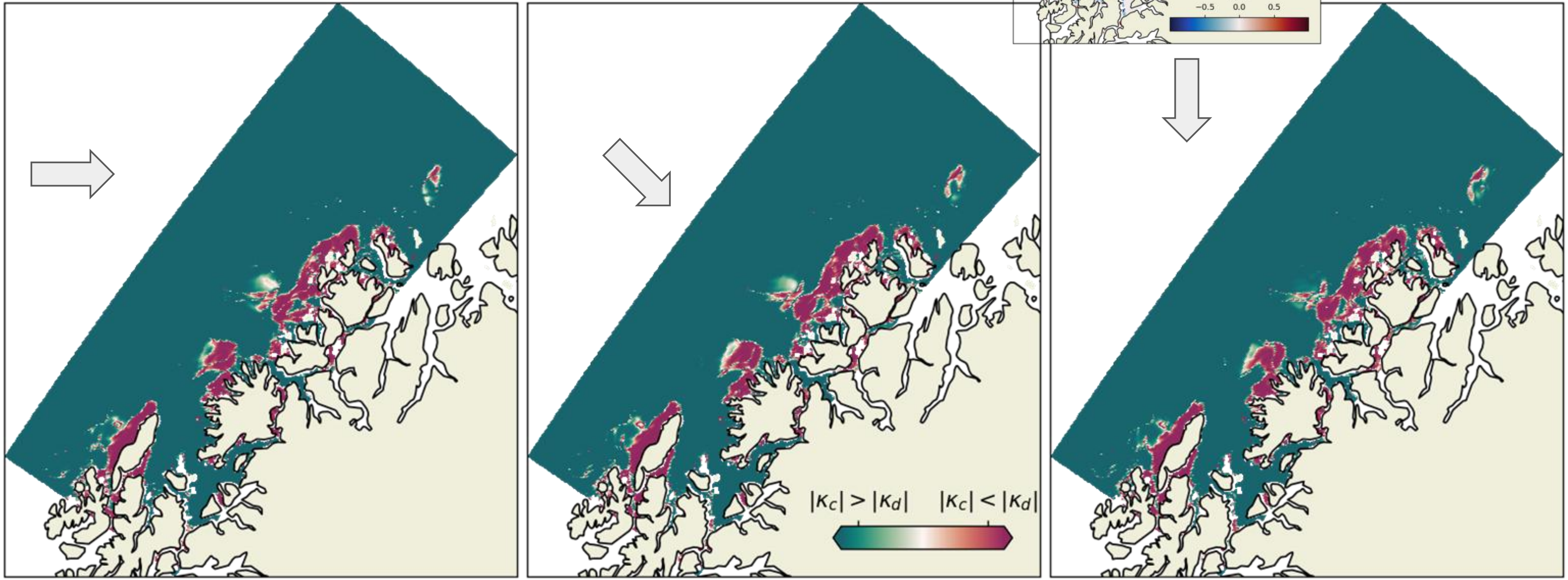
Simulating some directions (12s)

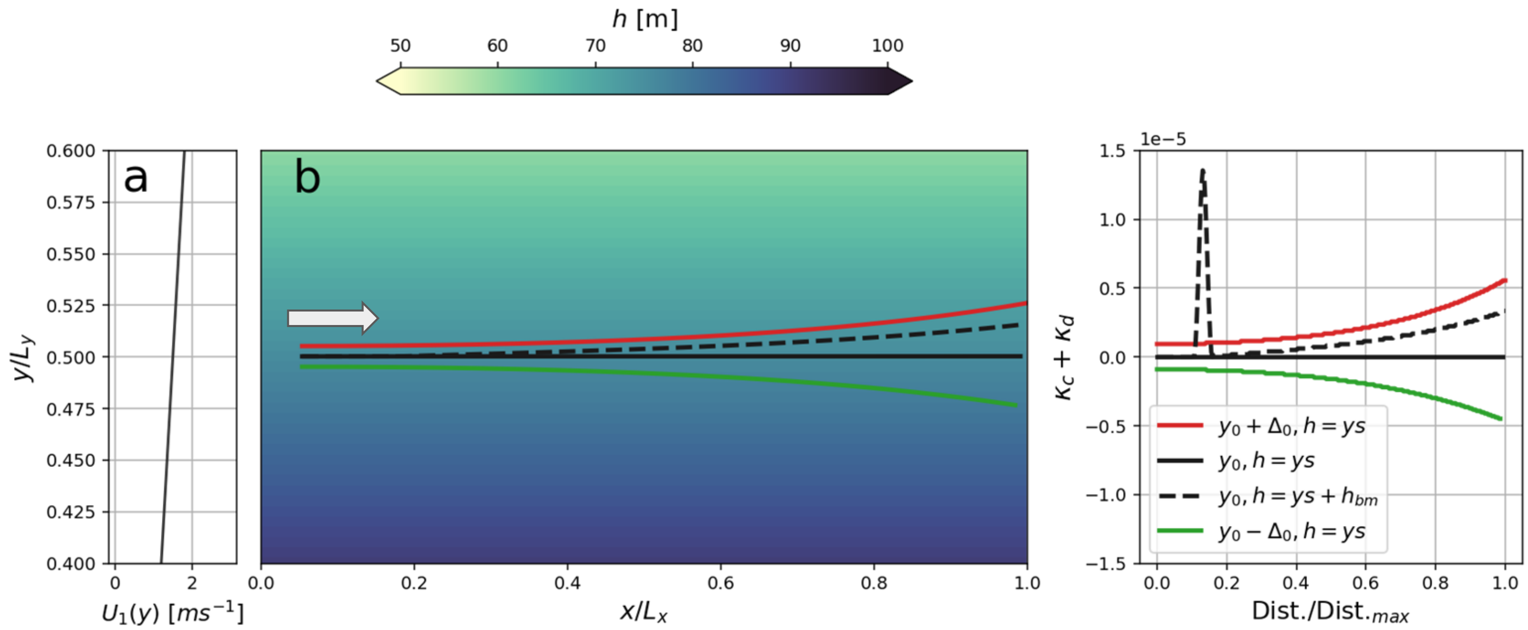




Simulating some directions (8 s)







Sensitivity to initial position and bathymetry variations

- Current with constant shear + bathymetry with constant slope
- Small bump in bathymetry change both *kh* and *k* (dashed line)

Halsne and Li (**2025**)