Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Dynamics of the Baltic Sea Straits via Numerical Simulation of Exchange Flows

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(OMOD, 2018+recent developments with V. Haid, J. Staneva and W. Chen)

COMMODORE Conference
Hamburg
28-31 January 2020

Research questions:

- *Primary and secondary circulation*
- *Large-scale and eddy circulation*
- *Role of bathymetry*

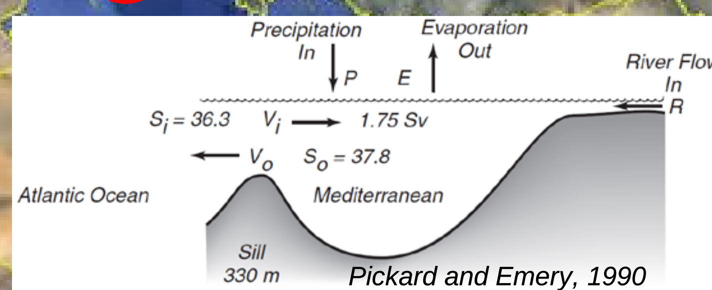
- *Where do we need high resolution?*
- *The impact of narrow straits on the dynamics of interconnected basins (water and salt cycles).*
- *Are the straits dynamics similar to estuarine circulation?*
- *Data needed*

Motivation:

*- Use unstructured-grid models to accurately resolve processes in the narrow straits and exchange between the inter-connected basins at the same time (**in one model**).*

From Marsigli (1681) to (Knudsen (1900) and beyond)

Water cycle and the challenge of basin inter-connections



$$Q1 + R = Q2$$

$$Q1S1 = Q2S2$$

$$Q1 = R/(S1/S2 - 1)$$

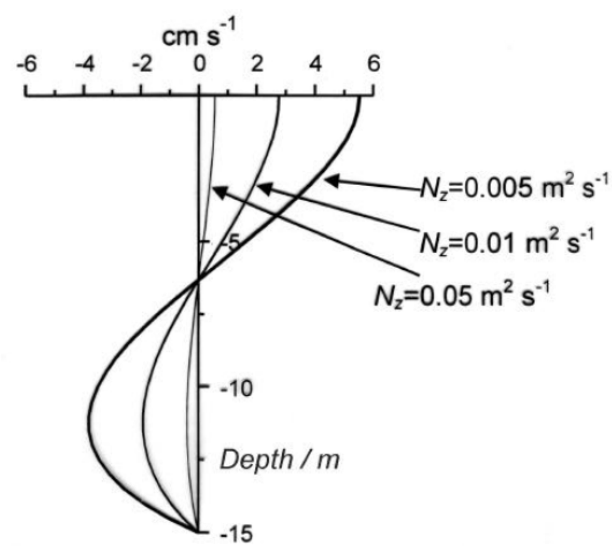
$$Q2 = R/(1 - S2/S1)$$

Estuarine classification

Geyer and MacCready
(Annu. Rev. Fluid Mech. 2014. 46:175–97)

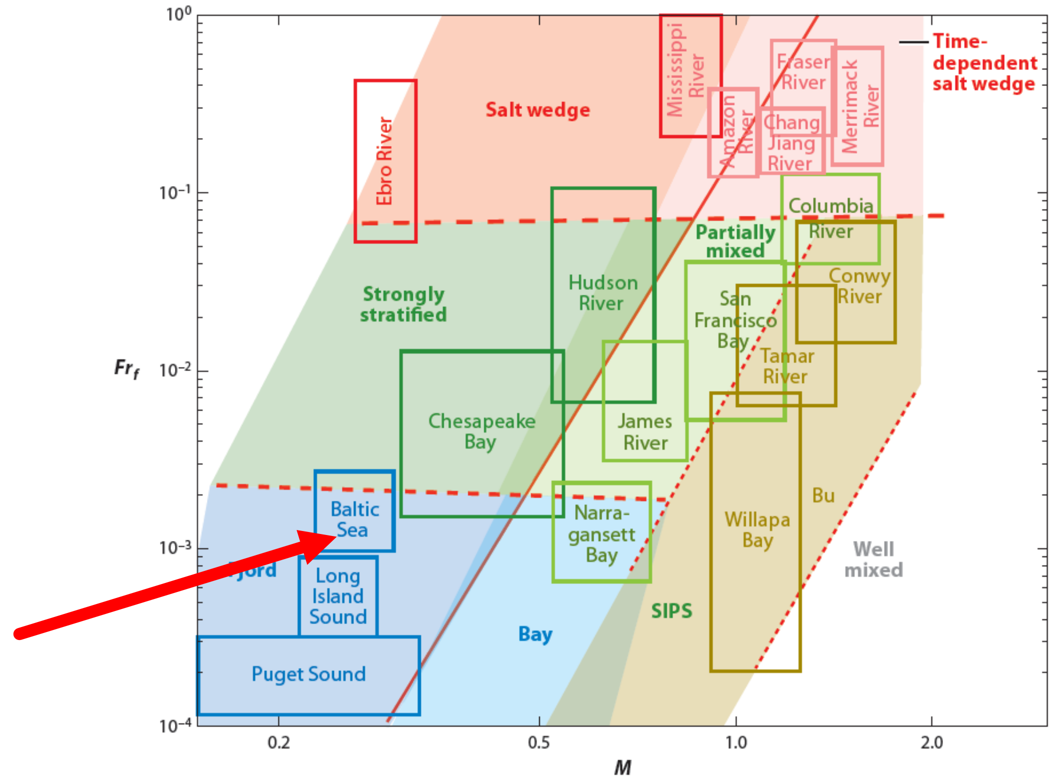
$Fr_f = U_R/(\beta g s_{ocean} H)^{1/2}$, freshwater Froude number measuring the ratio between the net velocity due to river flow and the maximum frontal propagation speed No H.

Hansen-Rattray profile of estuarine circulation:



$$u(z) = \frac{1}{48}\frac{1}{\rho}\frac{\partial \rho}{\partial x}\frac{gh^3}{N_z}\left(1-8\frac{z^3}{h^3}-9\frac{z^2}{h^2}\right)$$

*Hansen & Rattray, (J. Marine Research, **23**, 104-122; 1965)*



$M^2 = C_D U_T^{\,2}/(\omega No\, H^2)$

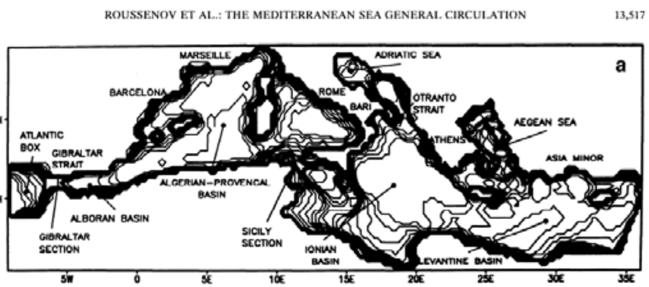
$M^2 = C_D U_T^{\,2}/(\omega No\, H^2)$ quantifies the effectiveness of tidal mixing measuring the ratio of the tidal timescale to the vertical mixing timescale.

C_D is the friction parameter,
U_T is the amplitude of the depth-averaged tidal velocity,
ω is the tidal frequency,
$No = (\beta g_{socean}/H)^{1/2}$ is the buoyancy frequency,
H is the depth,
U_R is the velocity of river flow,
$\beta = 7.7 \times 10^{-4}$ is the coefficient of salinity contraction,
and g is the gravitational acceleration.

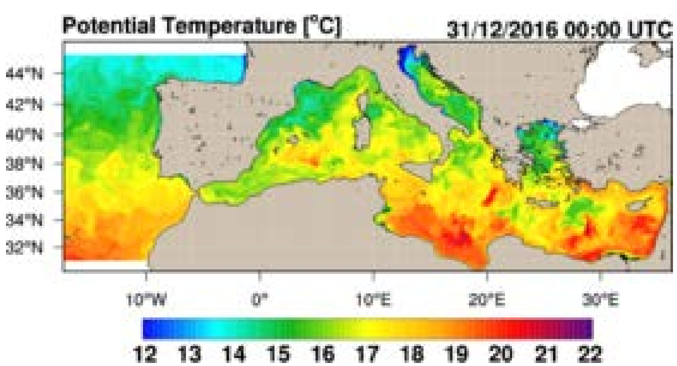
Well-known (ocean) cases

Denmark Strait (deep part <100 km wide)

Strait of Gibraltar (~300-900 m deep and ~15 km wide)

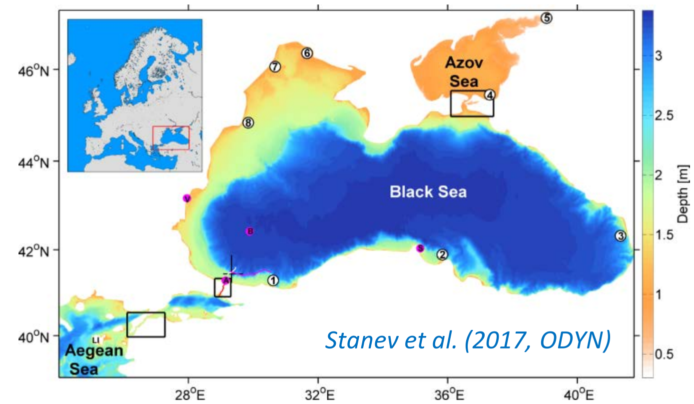


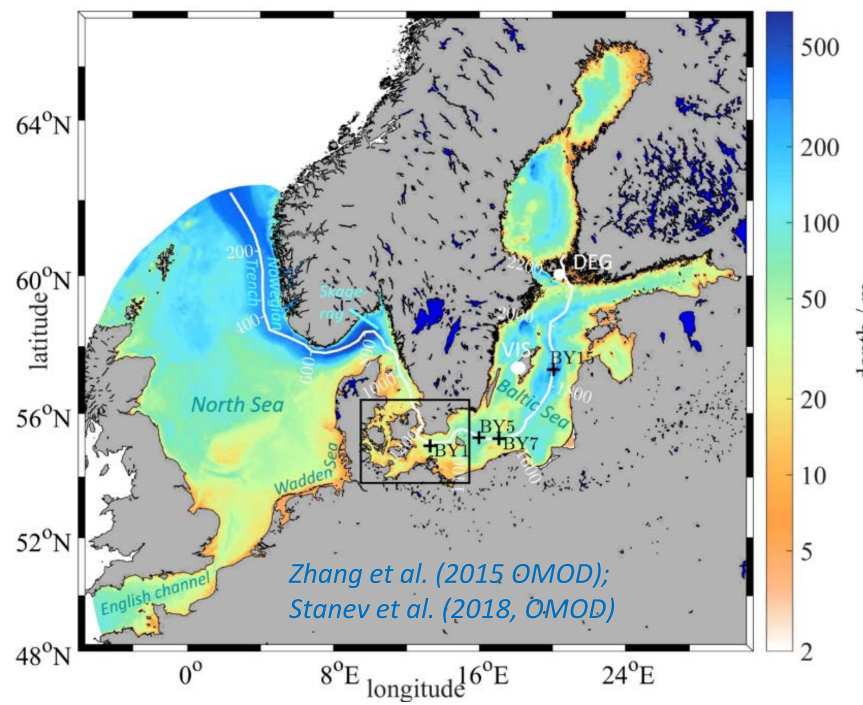
1995: ~30 km grid



Now CMEMS ~4-5 km

Less well-known cases of inland estuarine basins
- Large salinity contrasts (different frontal dynamics)





The model

Semi-implicit Cross-scale Hydroscience Integrated System Model; www.schism.wiki

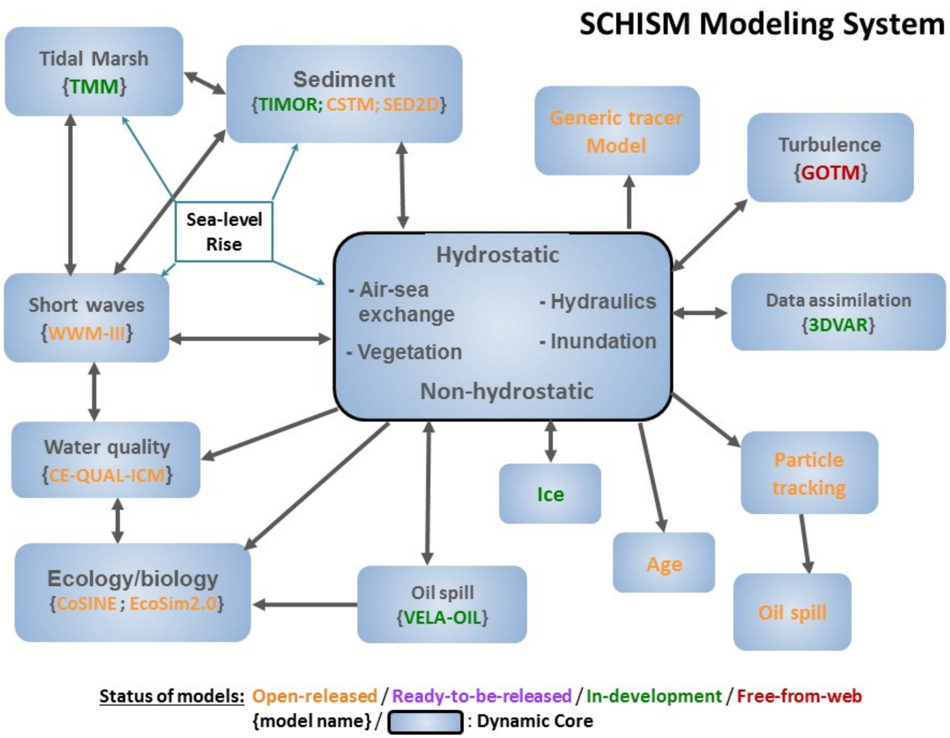
SCHISM

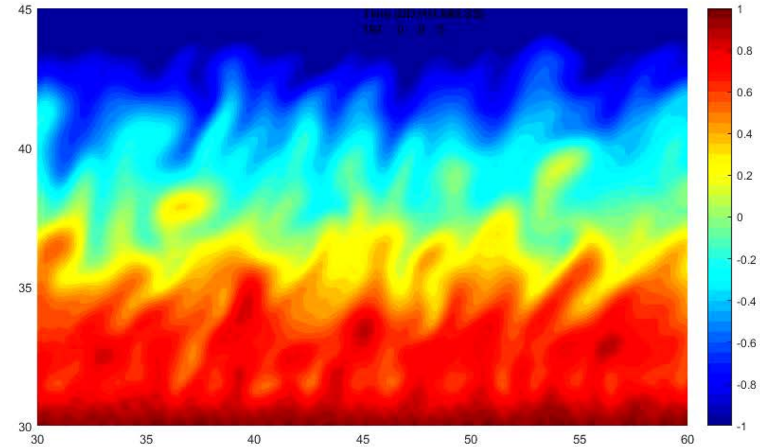
3D, primitive equations, unstructured-grid.

- Upgrade from an existing model (SELFE, A Semi-implicit Eulerian-Lagrangian Finite Element model for cross-scale ocean circulation).

- Uses hybrid finite element and finite volume approach.

- New viscosity formulation (effectively filters out spurious modes without introducing excessive dissipation).





- New higher-order implicit advection scheme for transport (TVD^2) is proposed to effectively handle a wide range of Courant numbers

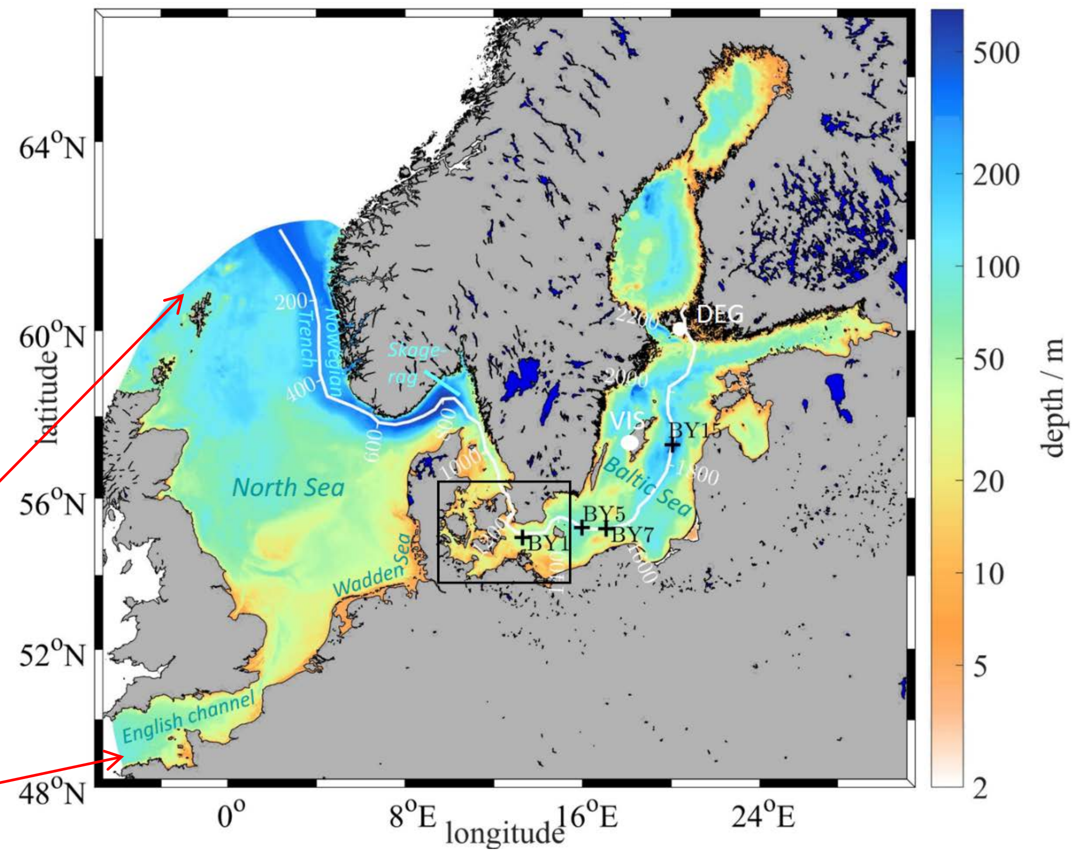
- Addition of quadrangular elements into the model

- Flexible vertical grid system (Zhang et al. 2015, OM)

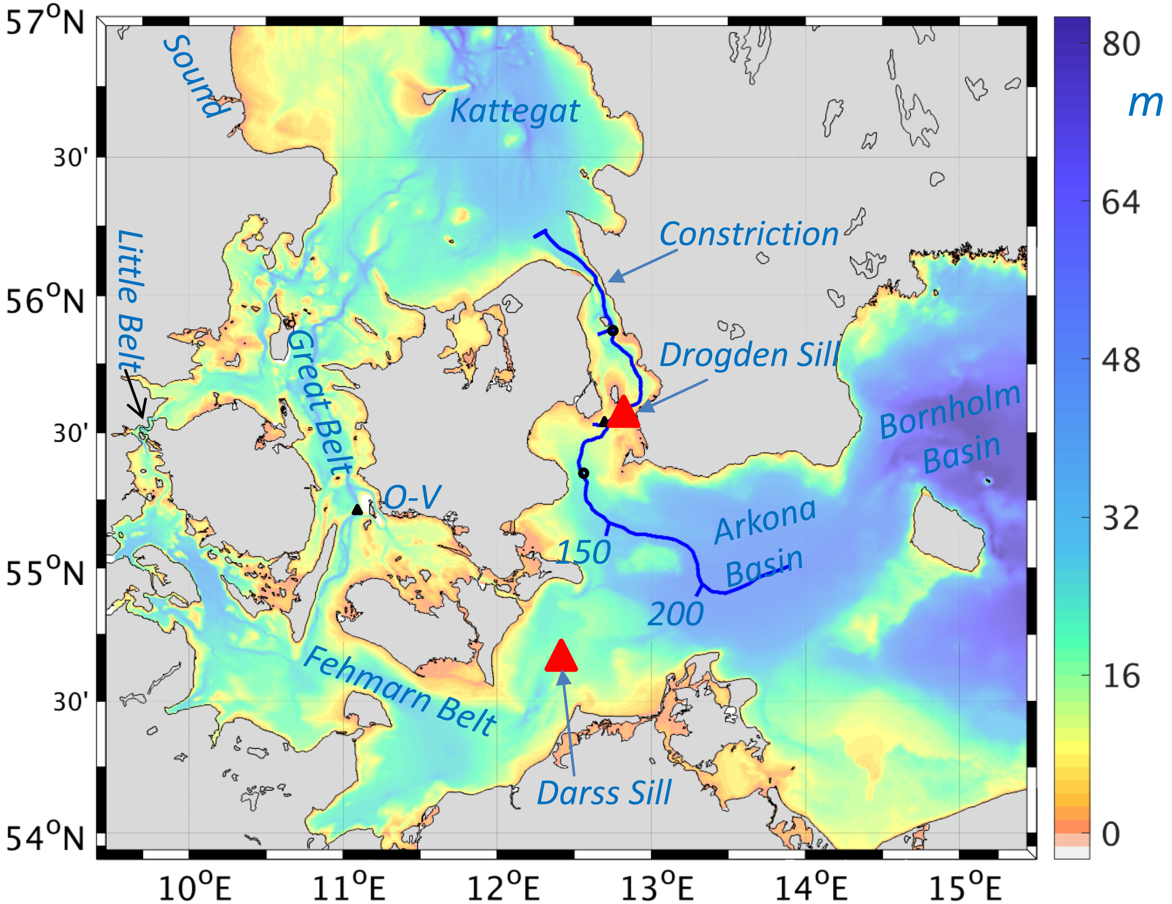
- Model polymorphism that unifies 1D/2DH/2DV/3D cells in a single model grid.

Zhang Y.J., F. Ye, E. V. Stanev, and S. Grashorn (2016): Ocean Modelling.

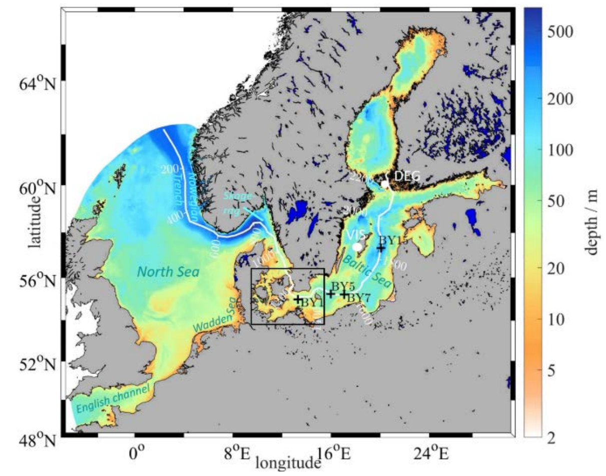
The North Sea - Baltic Sea model



- Open boundary forcing: Copernicus AMM7 (7km)
- Atmospherical forcing: DWD Cosmo EU (7km)
- River forcing: SMHI EHYPE from 34 rivers (North Sea and Baltic Sea)
- *~400 K nodes with a minimum grid side length of ~80m (in the narrow areas of the Little Belt), elsewhere almost uniform resolution of ~3 km.*



57°N
30'
56°N
30'
55°N
30'
54°N
10°E
11°E
12°E
13°E
14°E
15°E
Sound
Kattegat
Little Belt
Great Belt
Constriction
Drogden Sill
Bornholm Basin
O-V
Arkona Basin
150
200
Fehmarn Belt
Darss Sill
80
64
48
32
16
0
m

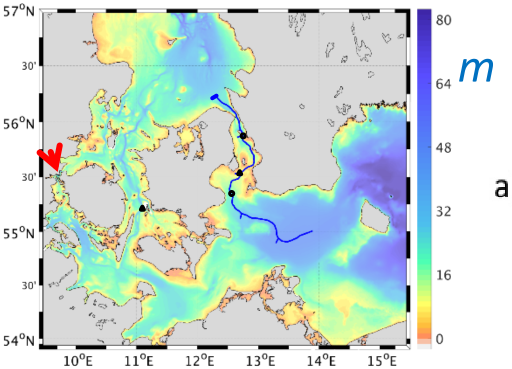


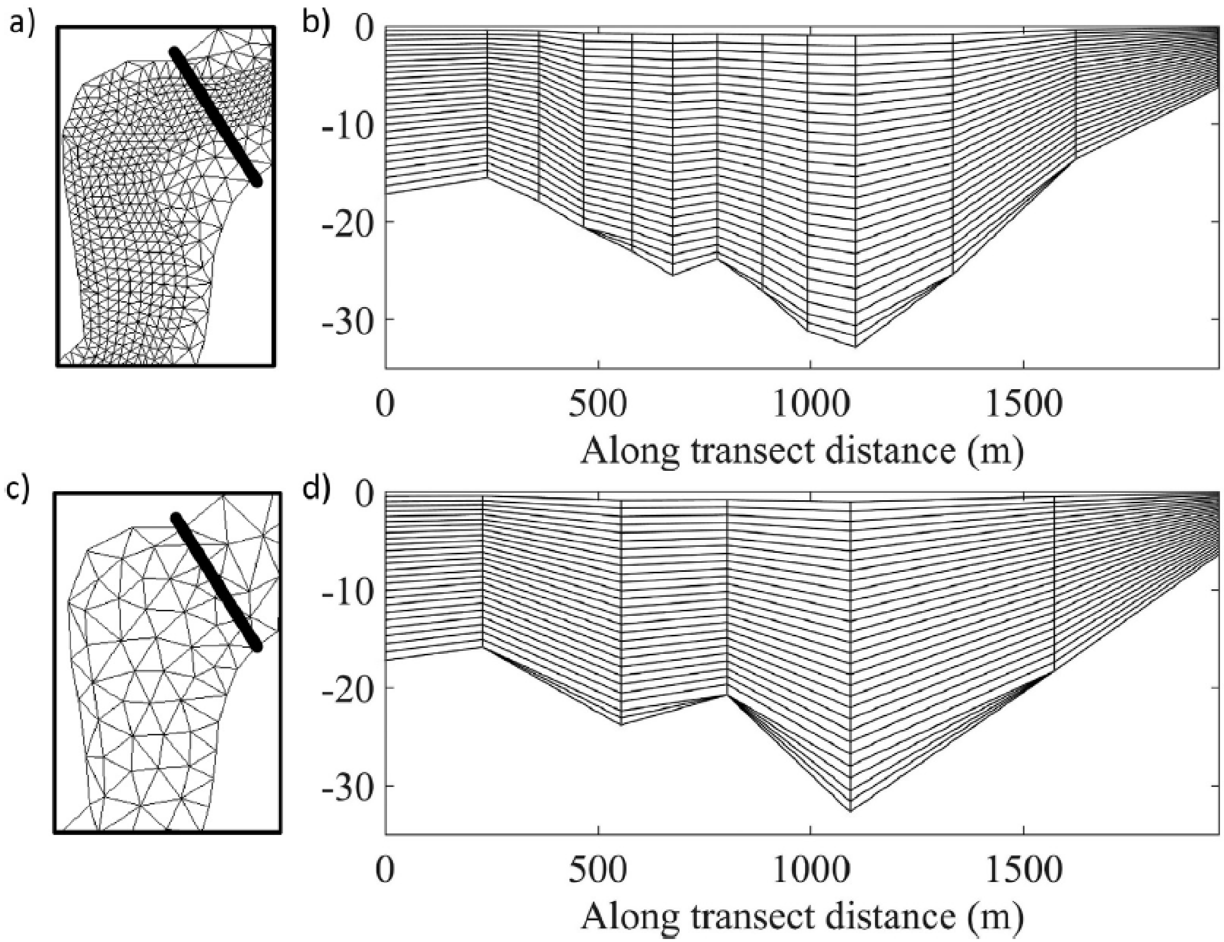
64°N
60°N
56°N
52°N
48°N
0°
8°E
16°E
24°E
latitude
longitude
North Sea
Baltic Sea
Wadden Sea
English channel
BY1
BY5
BY7
500
200
100
50
20
10
5
2
depth / m

Mesh details, Little Belt

Two experiments:

COARSE, FINE

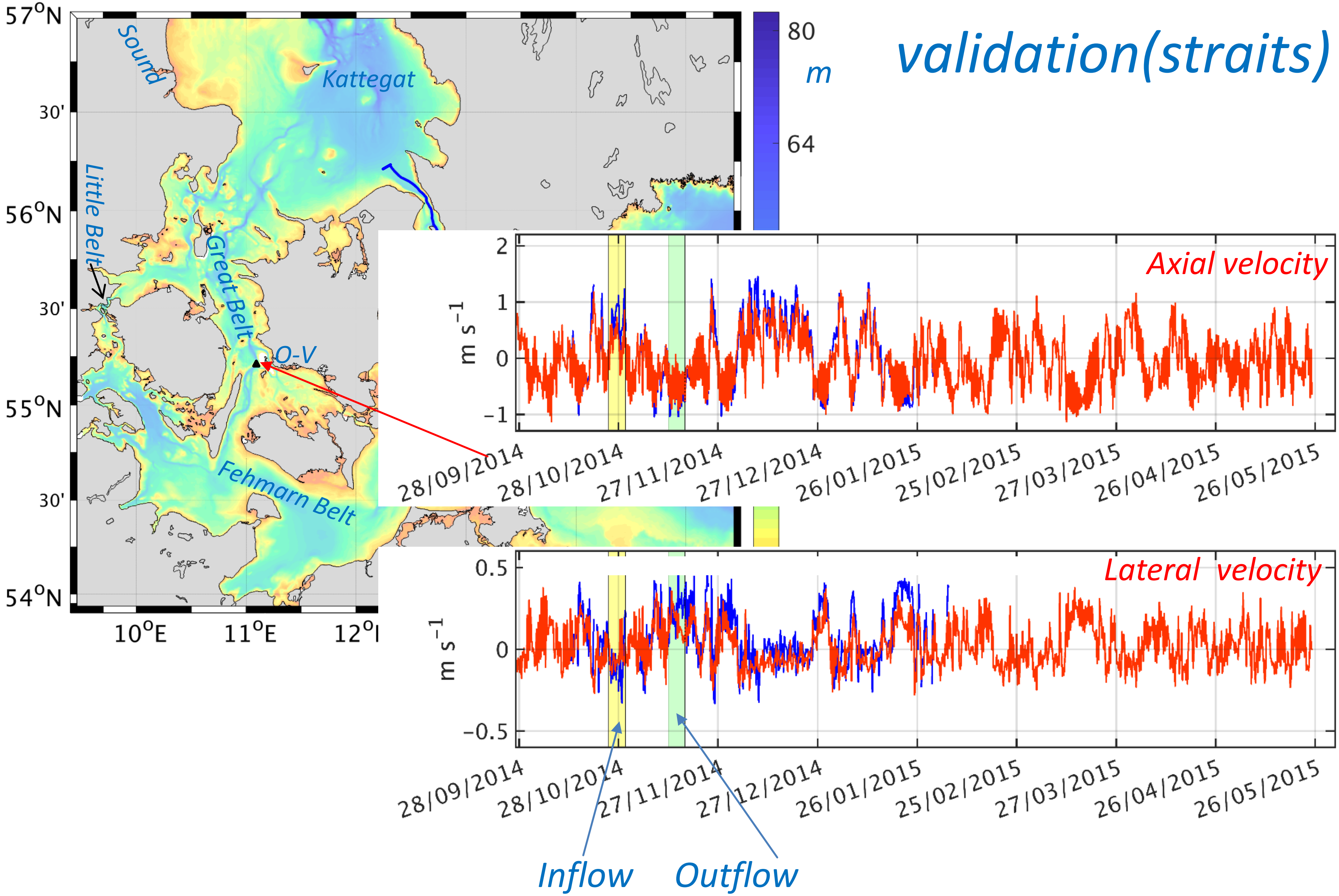




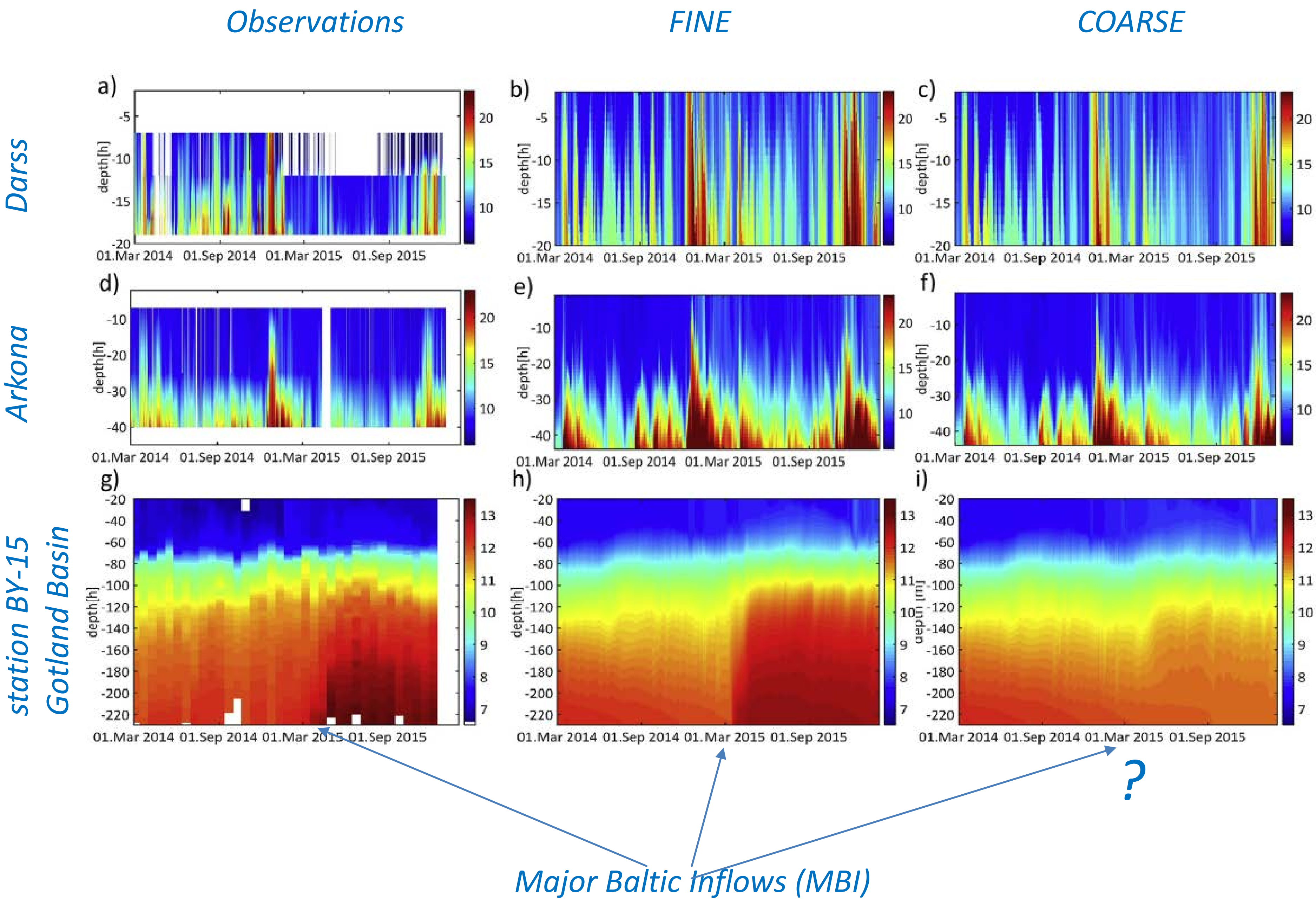
FINE

COARSE

Model validation(straits)

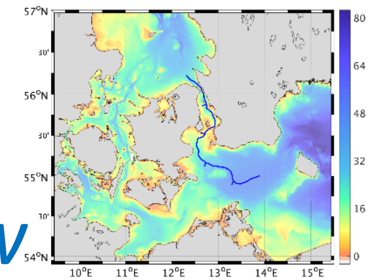


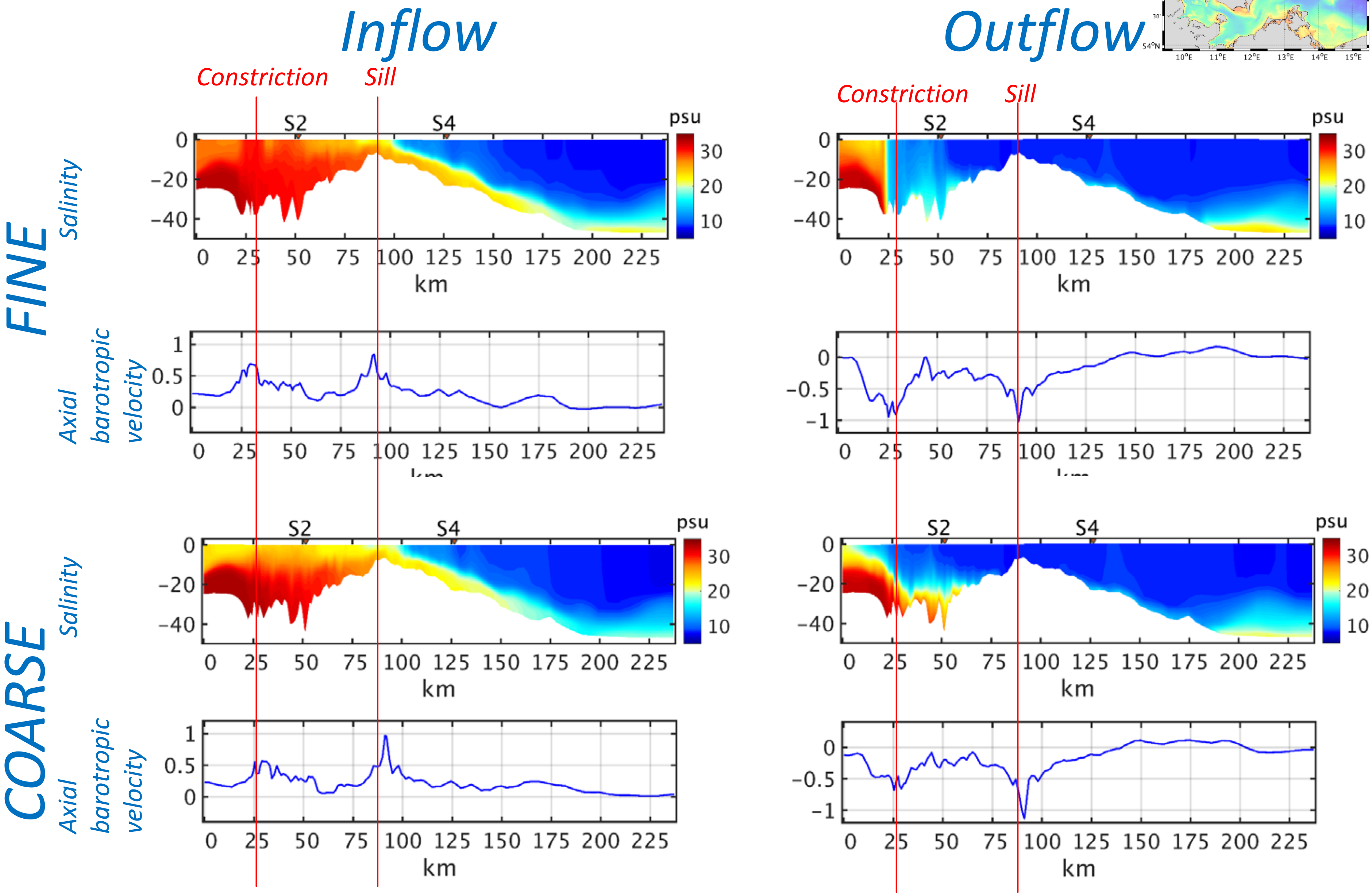
Model validation(saninity, MBI)



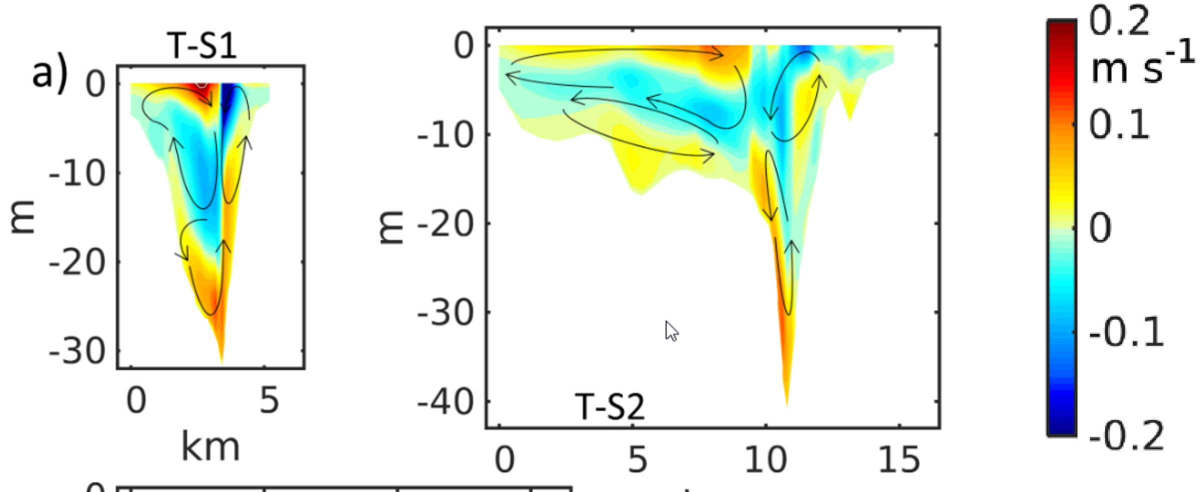
Axial properties (COARSE versus FINE)

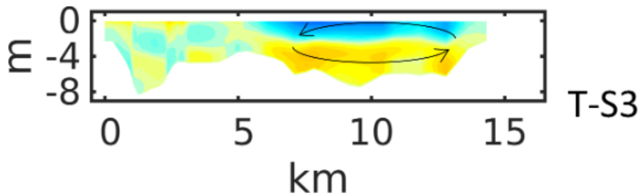
Similarities and differences with the estuarine circulation



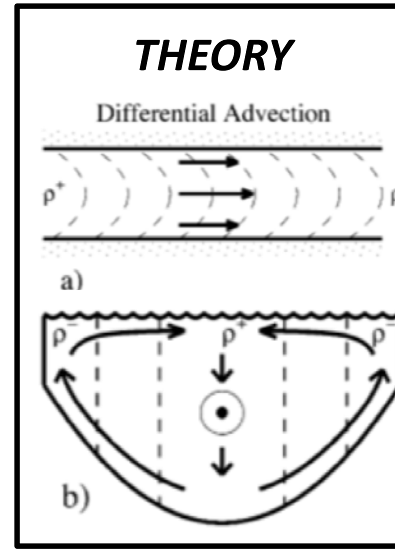


inflow (25-30 October 2014)

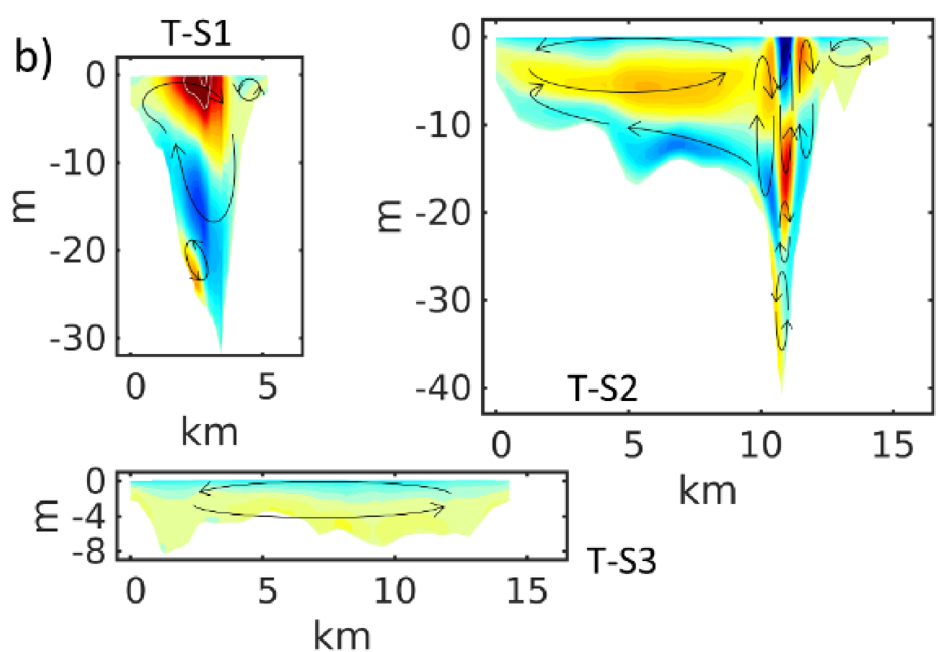


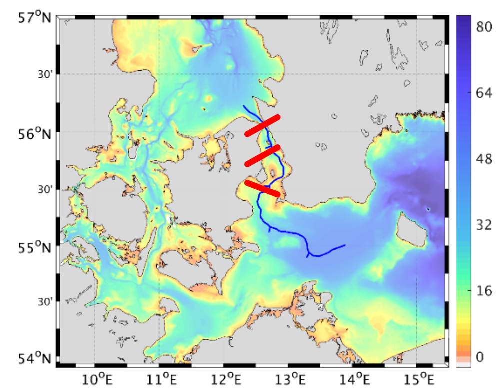


Notice the scales of the secondary circulation



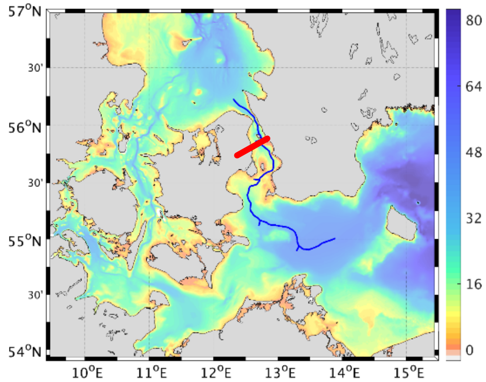
outflow (12-17 November 2014)





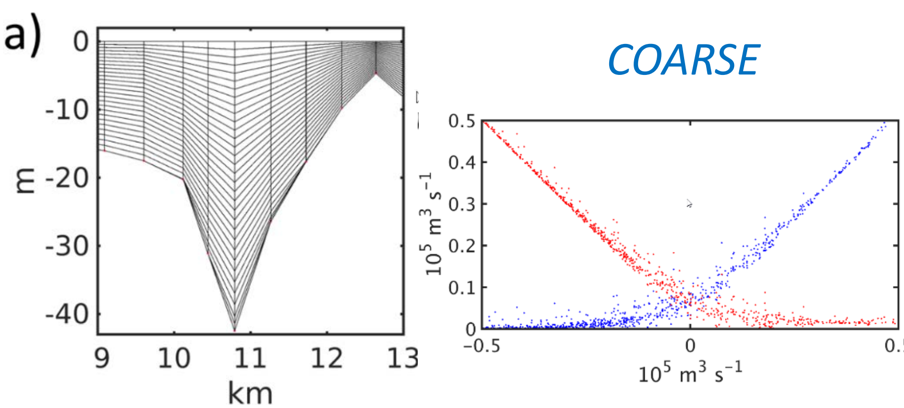
Different appearance of lateral flows

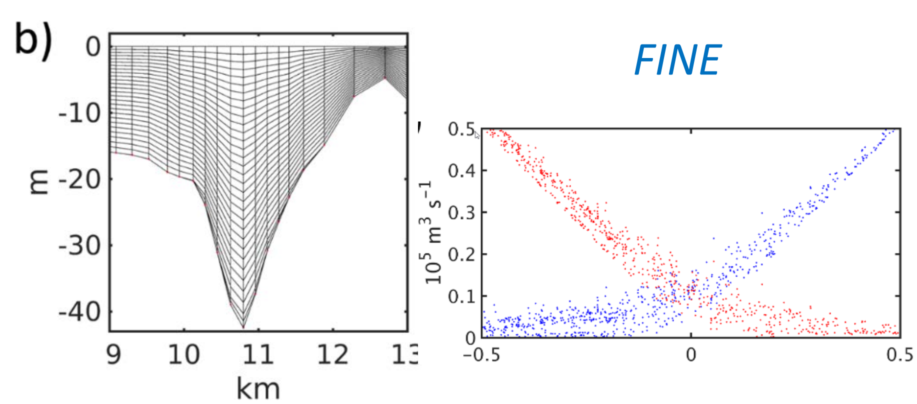
Lateral flows in COARSE and FINE

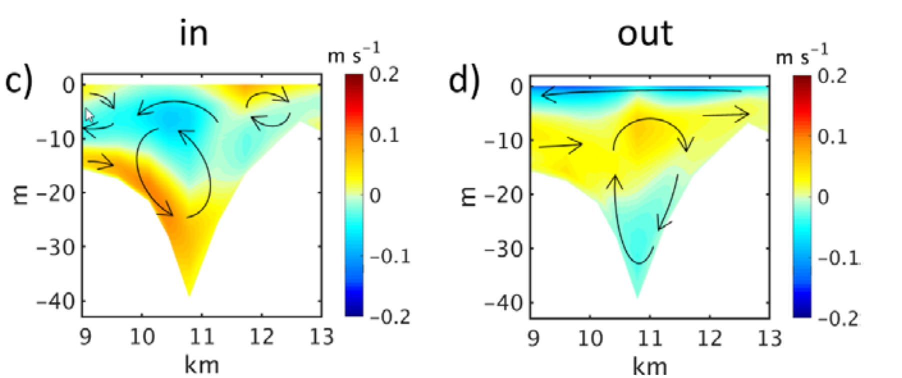


Impact on the axial circulation

The axial transport through the Sound in COARSE is 12% smaller.
The ratio between transports in the Great Belt and the Sound changes from 2.7 (in FINE) to 3 (in COARSE).
These "small" differences (lateral velocity ~0.1 x axial velocity) are important for the overall salt balances.

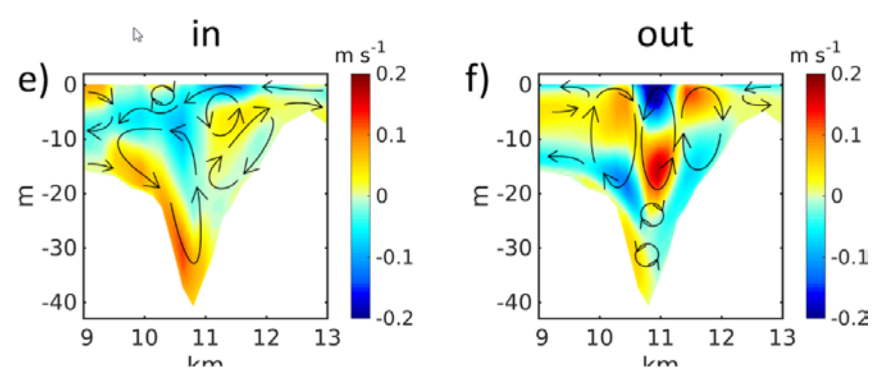






Inflow (25-30/10/2014)

Outflow (12-17/11/2014)



Inflow (25-30/10/2014)

Outflow (12-17/11/2014)

Conclusions:

1. *The role of horizontal resolution is crucial (missing physics in COARSE, analogy eddy-resolving models and non-eddy-resolving models).*
2. *Various appearance of secondary circulatiuon (theory and real situations; straits and estuaries).*
3. *Seamless modelling of interbasin exchange*

is promissing for process studies.

4. Seamless modelling has also a great potential for operational use, for instance developing interfaces for coupled regional coastal and estuarine predictions.

Stanev, E. V., J. Pein, S. Grashorn, Y. Zhang, and C. Schrum (2018). Dynamics of the Baltic Sea Straits via Numerical Simulation of Exchange Flows. Ocean Modelling, 131, 40-58.

Haid, V., E. V. Stanev, J. Pein, J. Staneva, W. Chen (2020). Secondary circulation in shallow ocean straits: Observations and numerical modeling of the Danish Straits. Ocean Modelling, Volume 148, April 2020, 101585