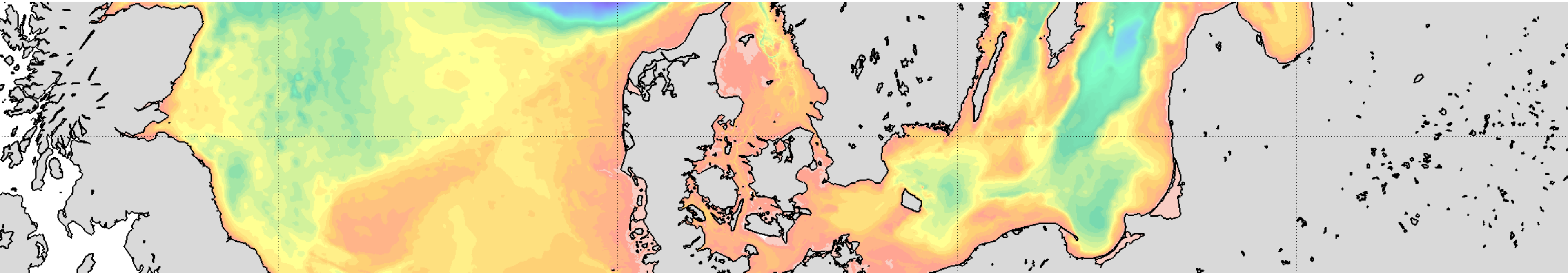
SECONDARY CIRCULATION IN OCEAN STRAITS:

OBSERVATIONS AND NUMERICAL MODELING OF THE DANISH STRAITS

SCHISM



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EGU General Assembly

Vienna, May 6, 2020

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Welcome and thank you for your interest!

We all know that these are extraordinary times and while this presentation was planned to be an oral presentation, I tried to add all the necessary information. However, should you find something missing or are interested in more detail, please know that our publication

Haid et al., 2020, Secondary circulation in shallow ocean straits: Observations and numerical modeling of the Danish Straits. Ocean Modelling 148, 101585. https://www.sciencedirect.com/science/article/pii/S1463500319303099?via%3Dihub

will provide you with further facts.

INTRODUCTION

The Danish straits

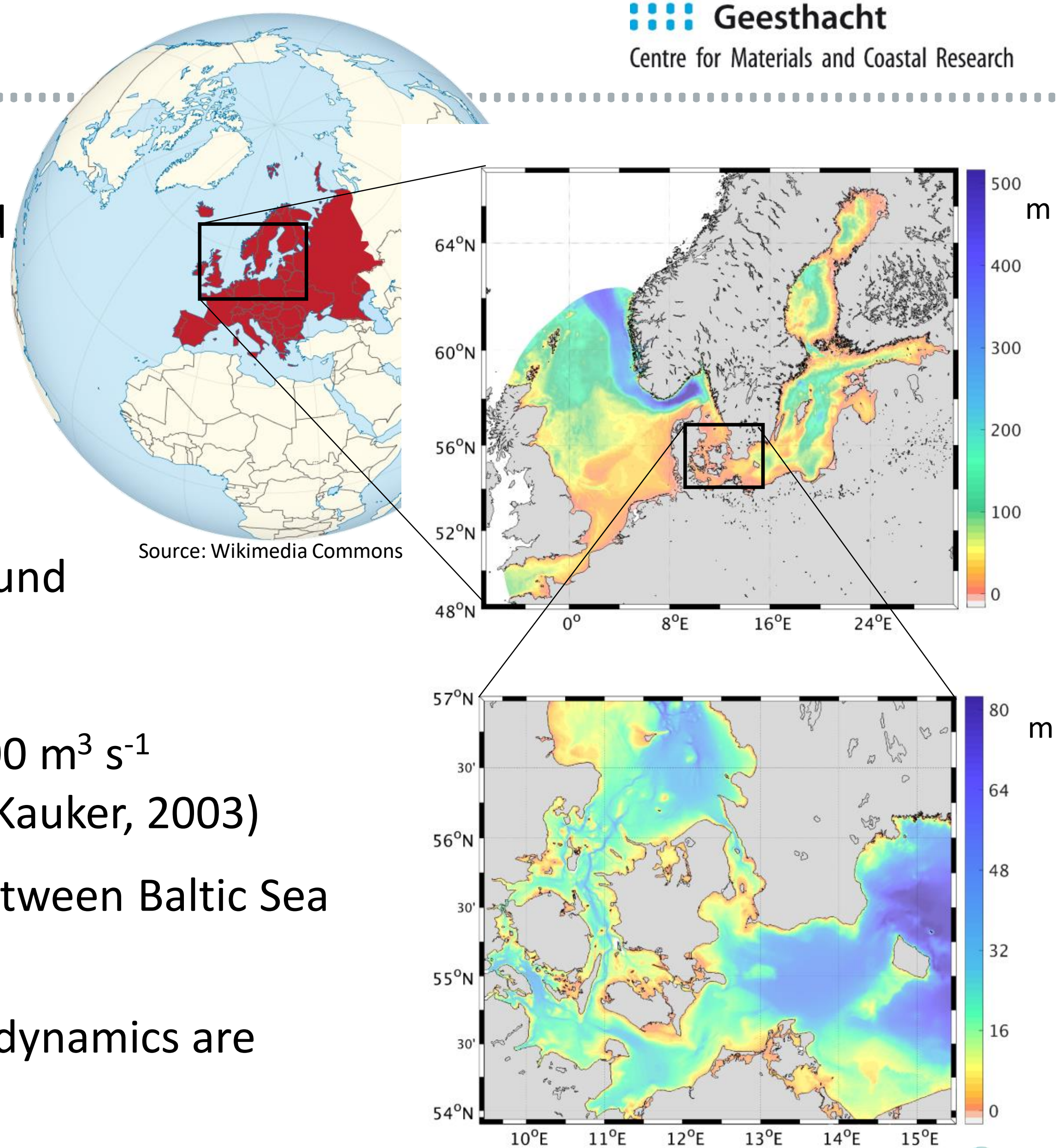
- The Danish Straits are located in the North Sea – Baltic Sea Transition Zone

- There are three connecting, narrow and shallow straits: Little Belt, Great Belt, and Sound (west to east)

- The Baltic Sea receives ~16000 m^3 s^{-1} freshwater input (Meier and Kauker, 2003)

  → strong salinity gradient between Baltic Sea and North Sea

  → in many aspects the strait dynamics are comparable to estuaries

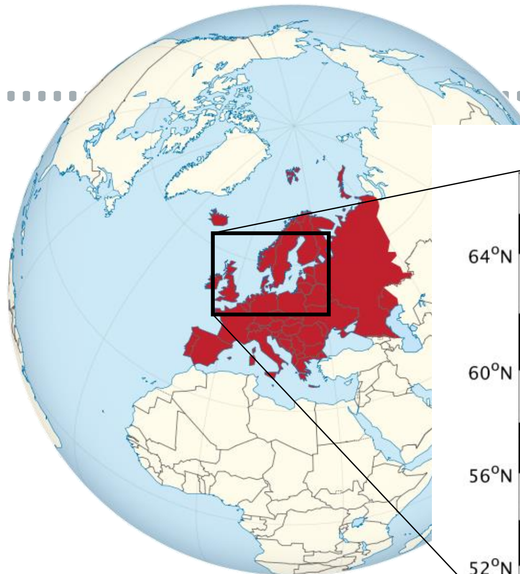


Source: Wikimedia Commons

INTRODUCTION

Secondary circulation

We applied the analysis of primary (axial) and secondary (lateral) circulation typically used for estuaries.



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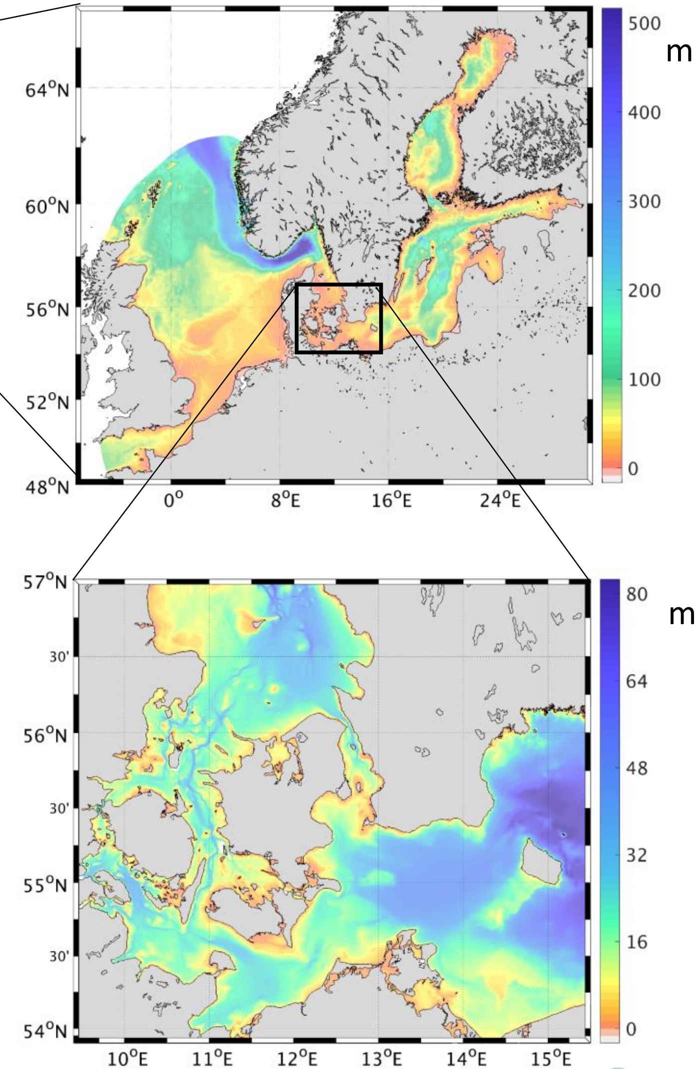


However, the straits are under a strong atmospheric influence:

inflow/outflow is controlled by air pressure and winds,
leading to irregular events on scales of several days,

in contrast to a strong tidal influence typical in estuaries.

METHODS

Model, grid, data sets etc.

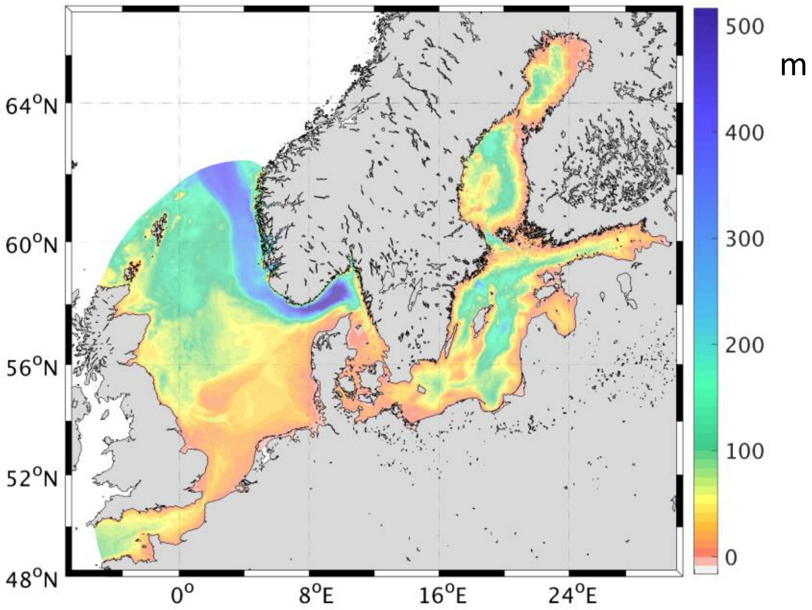
- SCHISM (Semi-implicit Cross-Scale Hydroscience Integrated System Model; Zhang et al. 2016)

- Regional North Sea - Baltic Sea grid (Stanev et al. 2018)
  - horizontal resolution 3 km to 100 m
  - variable # (max. 59) sigma layers with shaved cell technique (LSC^2; Zhang et al. 2015)

- Initialisation:
  monthly climatological temperature and salinity data (Janssen et al. 1999)

- Surface forcing:
  - hourly 7-km COSMO EU data from DWD
  - river runoff from EHYPE (SMHI)

- Open boundary forcing:
  hourly Copernicus product



VALIDATION

Comparison with current meter data

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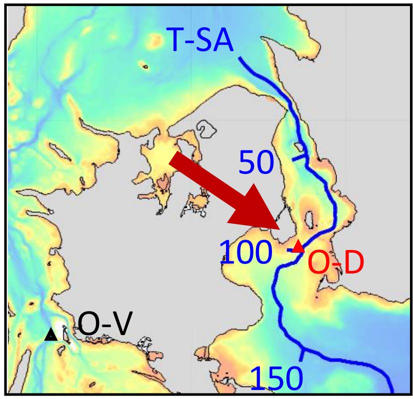
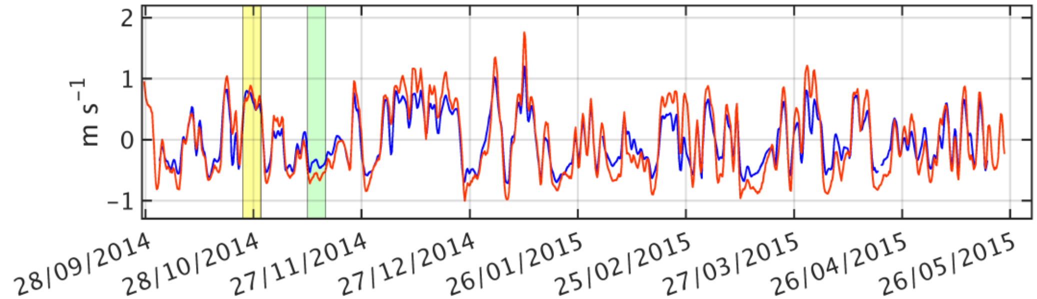
Correlation coefficient

Drogden Fyr, 5m Velocities

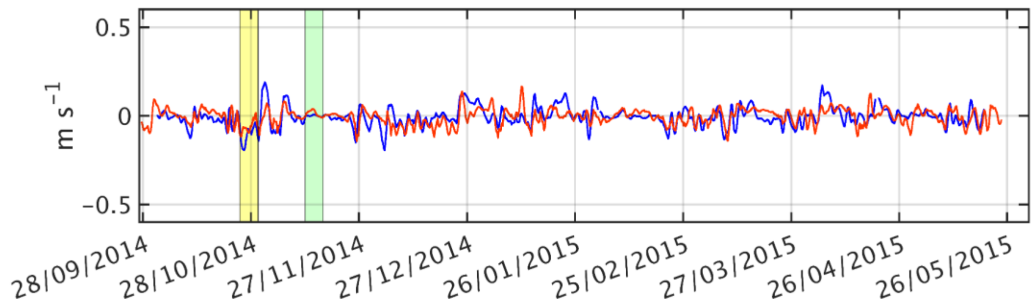


axial



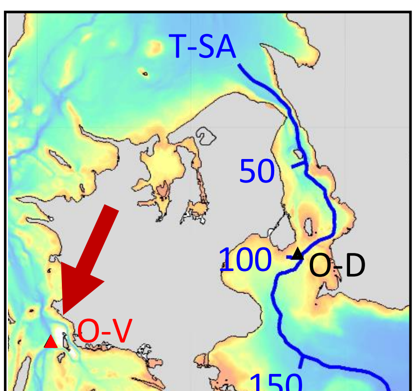
0.91

lateral

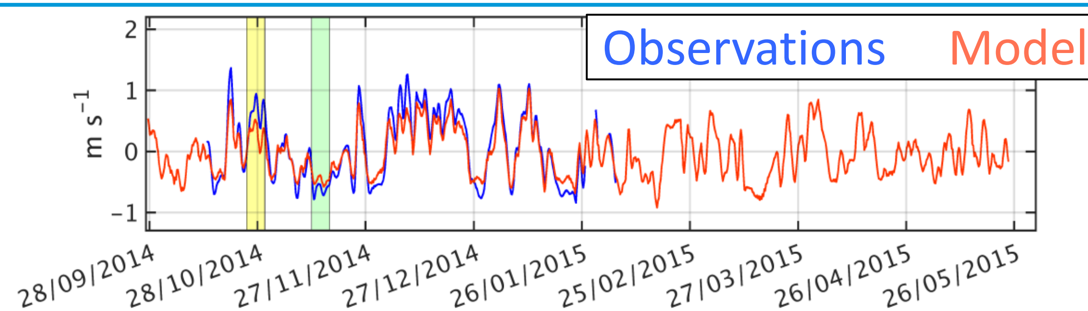


0.35

Vengeancegrund, 5m Velocities

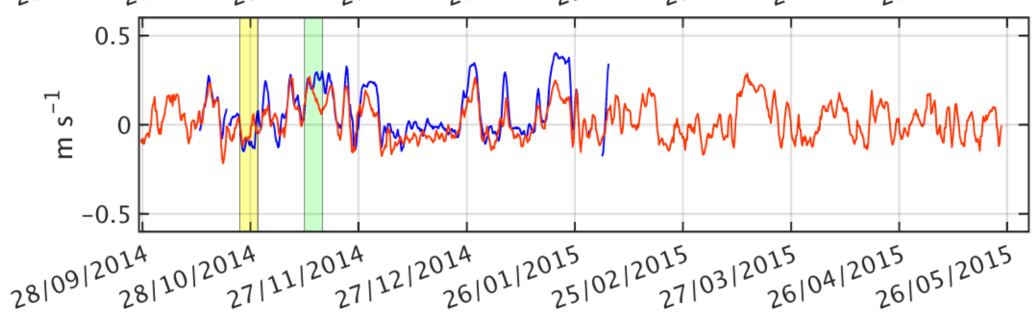


axial



0.89

lateral



0.68

VALIDATION

Comparison with current meter data

Current observations of the necessary duration are sparse and we are lucky to have two stations to compare with.

At both stations, the model shows very good agreement for the axial flow with a correlation coefficient close to 0.9.

For the lateral flow, the station in the Great Belt (Vengeancegrund) shows a good performance with a correlation coefficient of 0.68.

The comparatively low correlation for lateral flow in the Sound is due to the station‘s location in a very shallow area (Drogden Sill, 8 m depth), where the water is well mixed and thus secondary circulation is weak. The signal-to-noise ratio at this station (Drogden Fyr) is very high.

In the following, we will examine the secondary circulation in the Sound at different locations.

LATERAL VELOCITY

on four cross sections through the Sound

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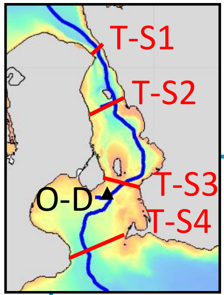
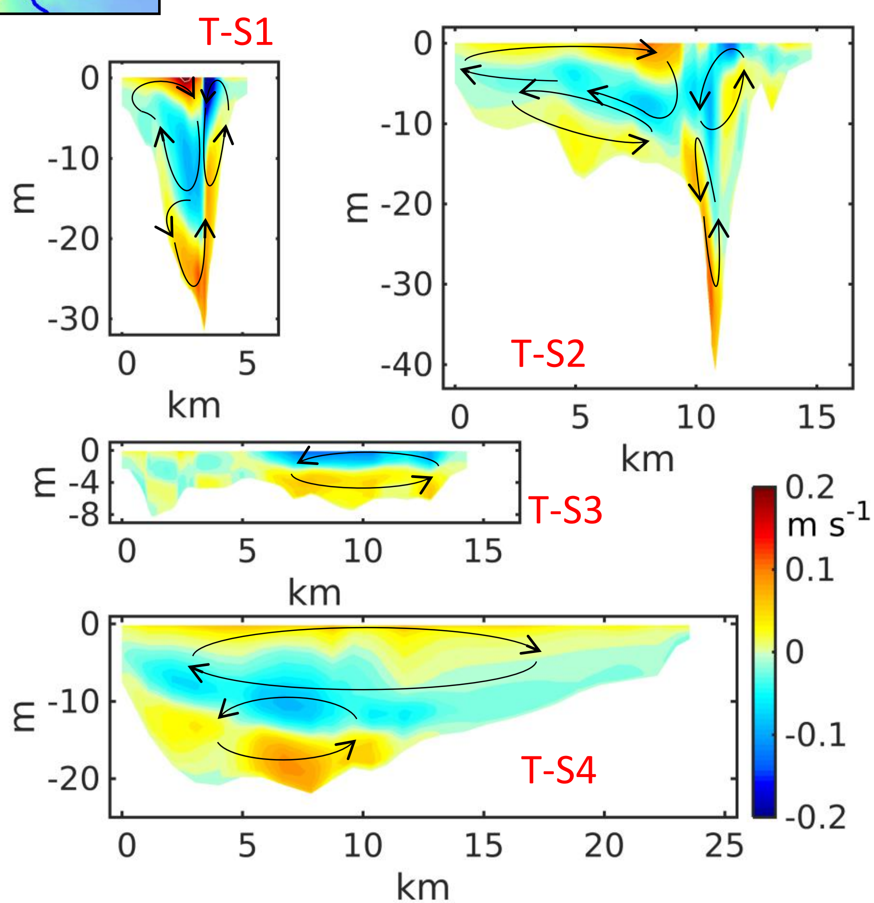


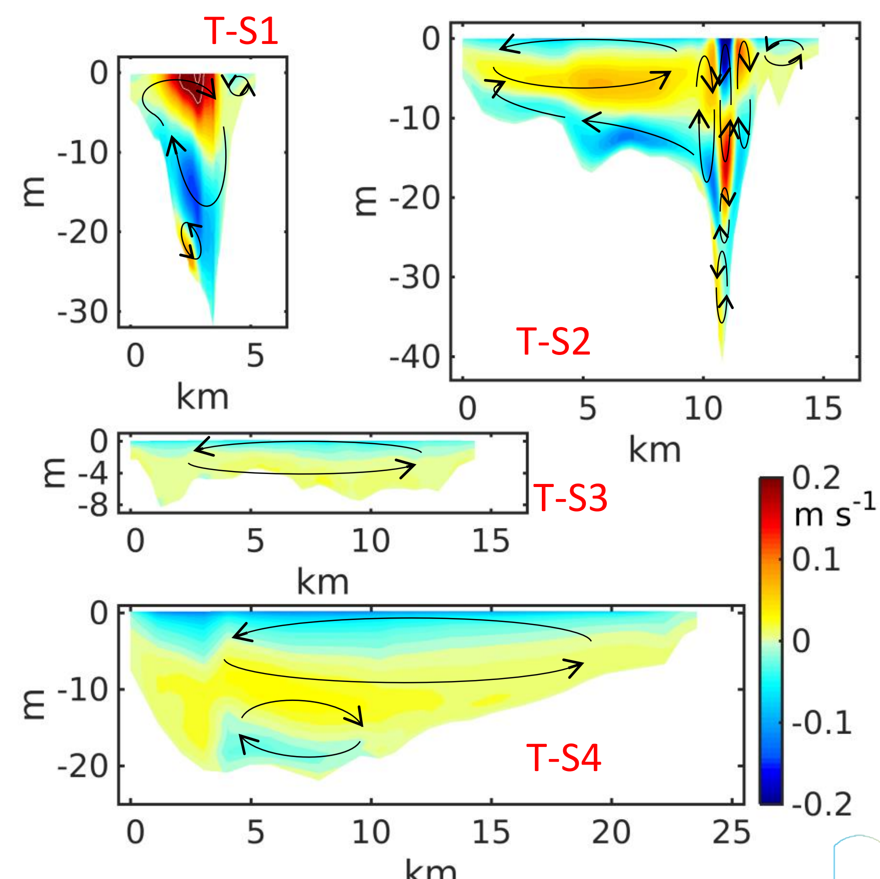
Inflow phase

25-30 October 2014



Outflow phase

12-17 November 2014



LATERAL VELOCITY

on four cross sections through the Sound

The patterns of the secondary circulation are strongly determined by topography and position in the strait. Also, inflow and outflow will not necessarily generate opposing circulation patterns.

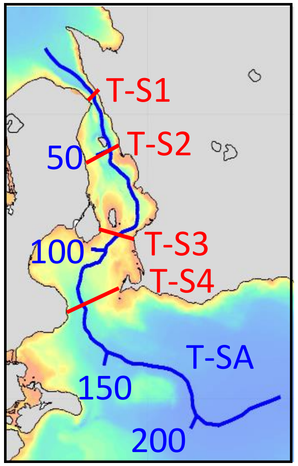
On the northern end of the Sound, the influence of the high salinity North Sea water makes itself known during the inflow phase. T-S1 and TS-2 show features reminiscent of the textbook case of differential advection in an estuary during flood.

However, the interplay with other influences (Coriolis force, streamline curvature, advected lateral momentum) complicates the apparent patterns of the secondary circulation.

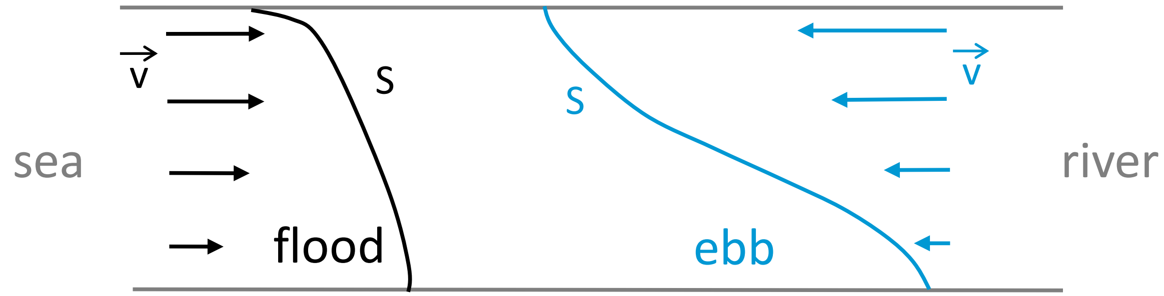
T-S1 and T-S2 also feature the highest lateral velocities. At the shallow T-S3 transect they are lowest. This is in keeping with the missing ‚signal' at the observation station Drogden Fyr.

DIFFERENCES TO ESTUARINE CIRCULATION

Along-channel transect T-SA



Tidal straining in estuaries (Simpson et al., 1990):

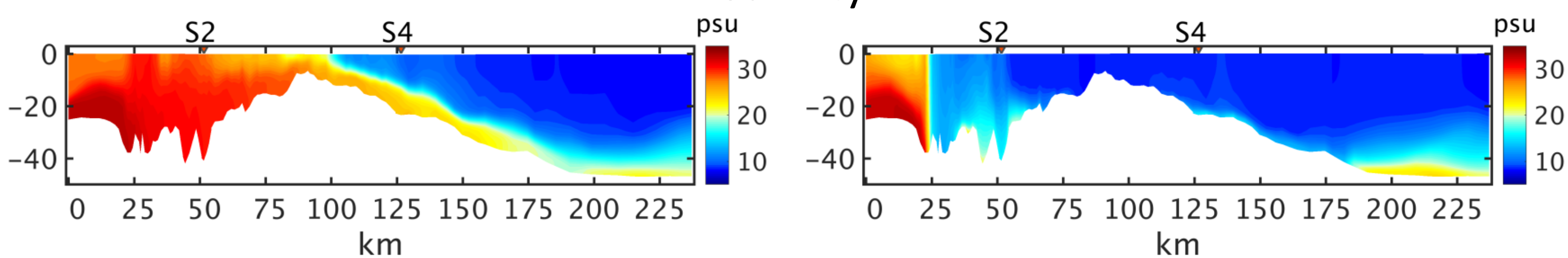


In the Sound:

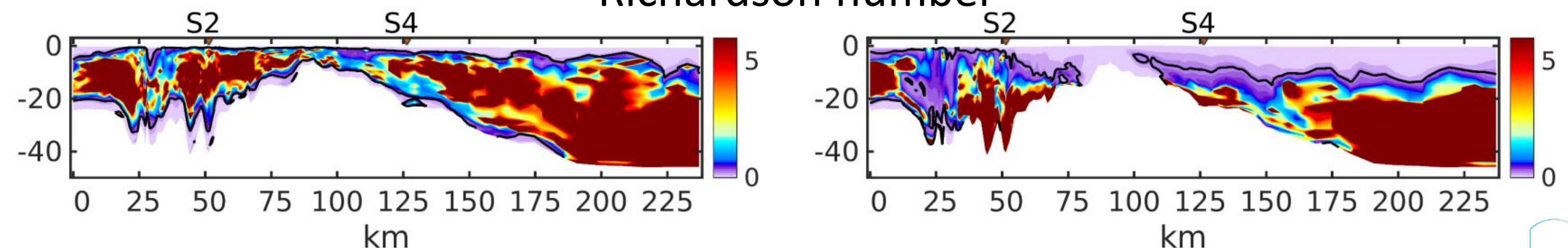
inflow

outflow

Salinity



Richardson number



DIFFERENCES TO ESTUARINE CIRCULATION

Along-channel transect T-SA

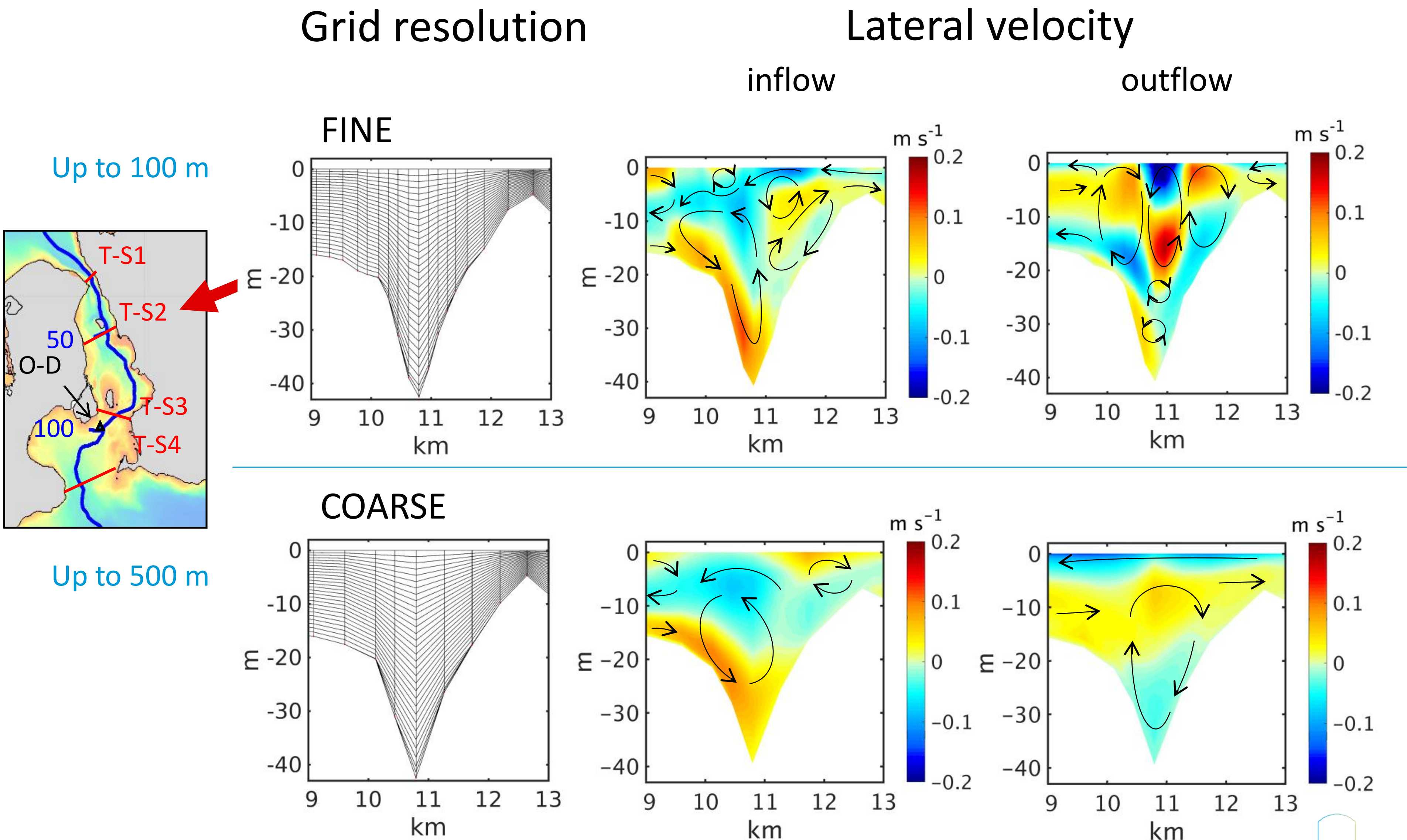
In a transect along the strait, we find interesting features unknown from estuaries.
In contradiction to tidal straining in estuaries, (where the flood tends to weaken the water column stability and during ebb the surface flow of fresh water has a stabilizing effect,) in the Sound the water column appears well mixed during the outflow phase and gradient Richardson numbers are lower than during the inflow phase.

There are several reasons why the behaviour differs from estuaries:

- Inflow and outflow phases are of irregular duration and intensity. In the presented case e.g. the outflow velocities are twice as fast, secondary circulation and mixing is therefore enhanced.
- The phases last for several days (the figure shows a 6-day mean). Time enough to flush a large portion of the strait and move the salinity front by 75 km.
- The geometry of a strait typically features one or more narrow and/or shallow constricting areas in the middle and widen toward both ends, while an estuary typically widens toward the sea.

INFLUENCE OF MODEL RESOLUTION

Transect T-S2, lateral velocity



INFLUENCE OF MODEL RESOLUTION

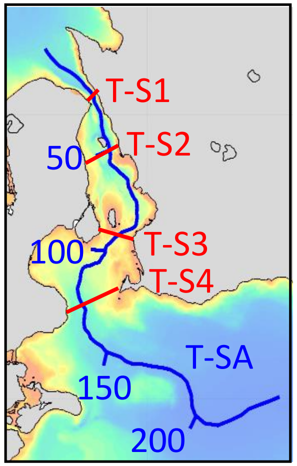
Transect T-S2, lateral velocity

How important is it to adequately resolve the secondary circulation in straits (and what is an adequate resolution)?

Comparing the previously presented experiment (FINE, up to 100 m horizontal resolution) with an experiment with a minimum resolution of 500 m (COARSE), we find that in COARSE the complexity of the secondary circulation is much reduced as smaller circulation cells cannot be resolved. This entails an underestimation of lateral (and vertical) velocities and therefore mixing.

INFLUENCE OF MODEL RESOLUTION

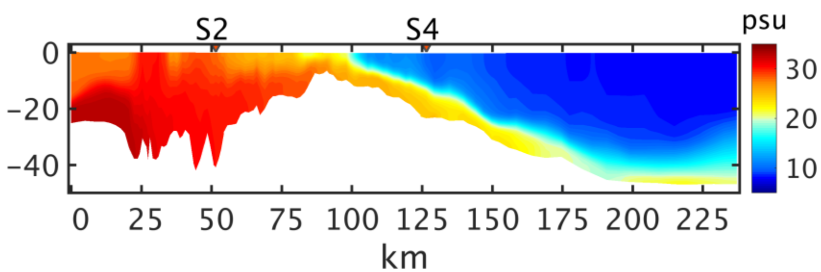
Transect T-SA, along-channel characteristics

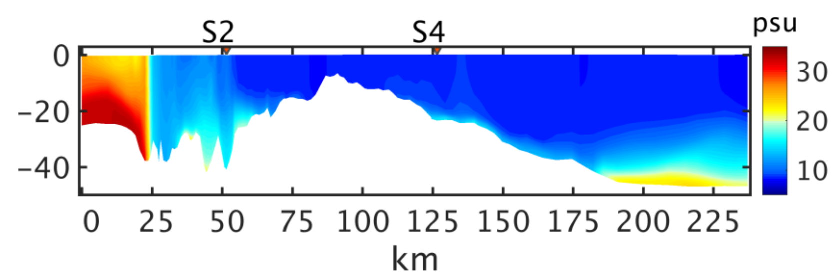


Salinity

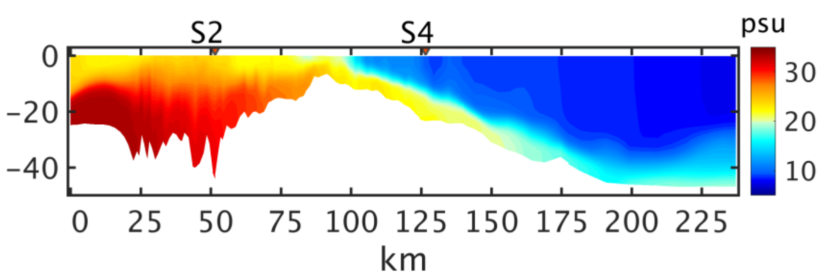
inflow | outflow

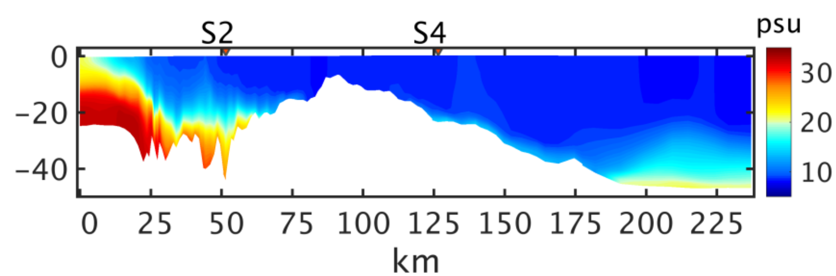
FINE





COARSE





The effect is clearly visible in the transect along the strait:

- In COARSE the water column north of the sill (km 0-90) is more stratified during both inflow and outflow.
- The stronger mixing in FINE allows more saline water to reach the depth of the sill and allows for a gravity current of denser water to flow along the bottom slope into the Baltic Sea during the inflow phase.
- During the outflow phase, FINE features a salinity front near the narrowest part of the strait and the strong mixing prevents the flow of very low-salinity surface water into the North Sea (as seen in COARSE).

INFLUENCE OF MODEL RESOLUTION

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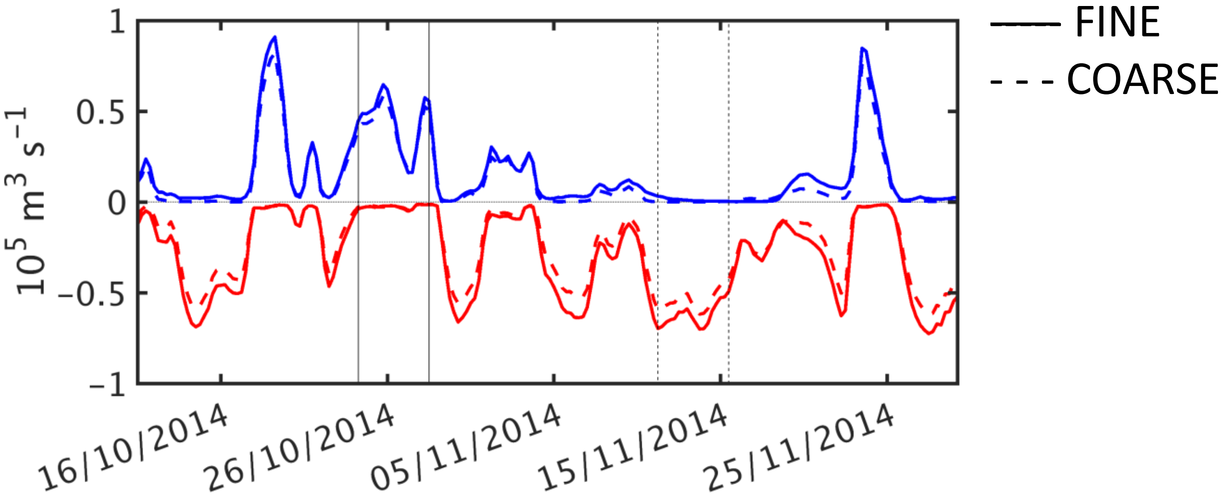
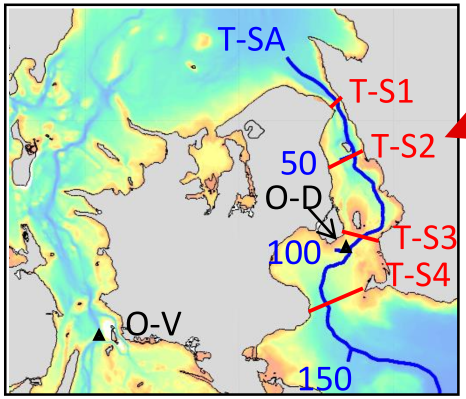
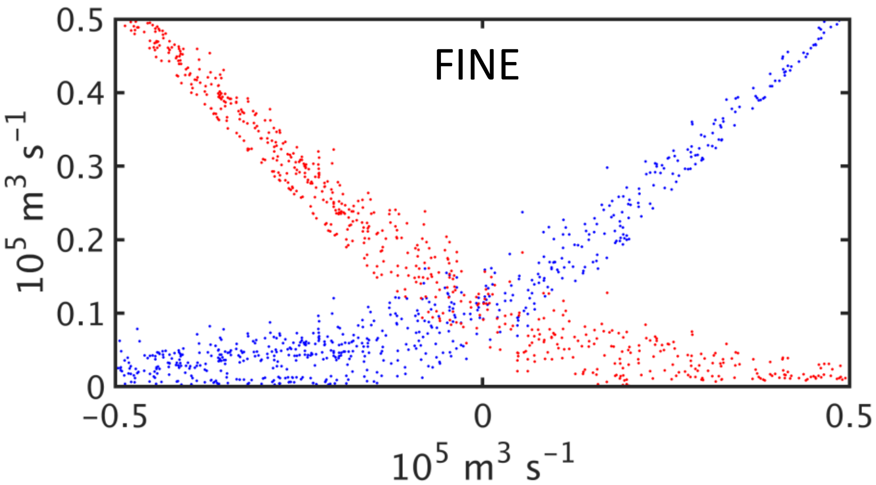
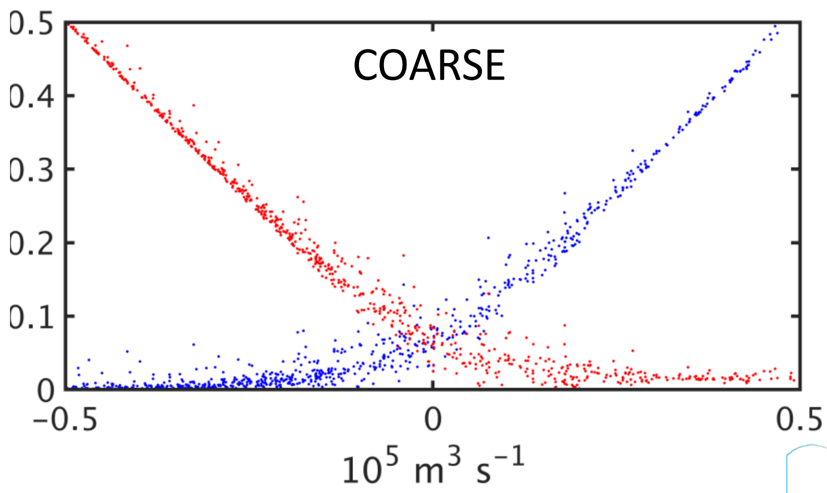
Transect T-S2, two-directional transport

Two-directional transport









INFLUENCE OF MODEL RESOLUTION

Transect T-S2, two-directional transport

These changes also affect the axial flow through the strait.

Volume transport is higher in FINE since a fully developed secondary circulation allows for an easier momentum transfer from axial to lateral direction, and back, when the flow navigates the complex geometry of the strait (Pein et al., 2018).

Not only peak transports are higher in FINE, also the two-directional transports are strengthened at T-S2. The inflow of saline water is higher, which is compensated with an increased counter-flow of fresher water (and vice versa for the outflow phase).

SUMMARY AND CONCLUSIONS

Secondary circulation in ocean straits

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- Position and topography exert a strong influence on the appearance of the secondary circulation, which differs strongly with location
- Circulation differs from estuarine circulation due to
  - Irregularity of forcing
  - Net inflow of comparable magnitude as two-way exchange flow
  - Different geometry (two-way funnel)
  - Longer time scales
- Inadequate resolution leads to
  -> misrepresentation of secondary circulation cells
  -> underestimation of vertical and horizontal mixing
  -> biased axial flow, water characteristics and transports

For further details:
Haid et al., 2020, Secondary circulation in shallow ocean straits: Observations and numerical modeling of the Danish Straits. Ocean Modelling 148, 101585.
DOI: 10.1016/j.ocemod.2020.101585

Thank you for reading!