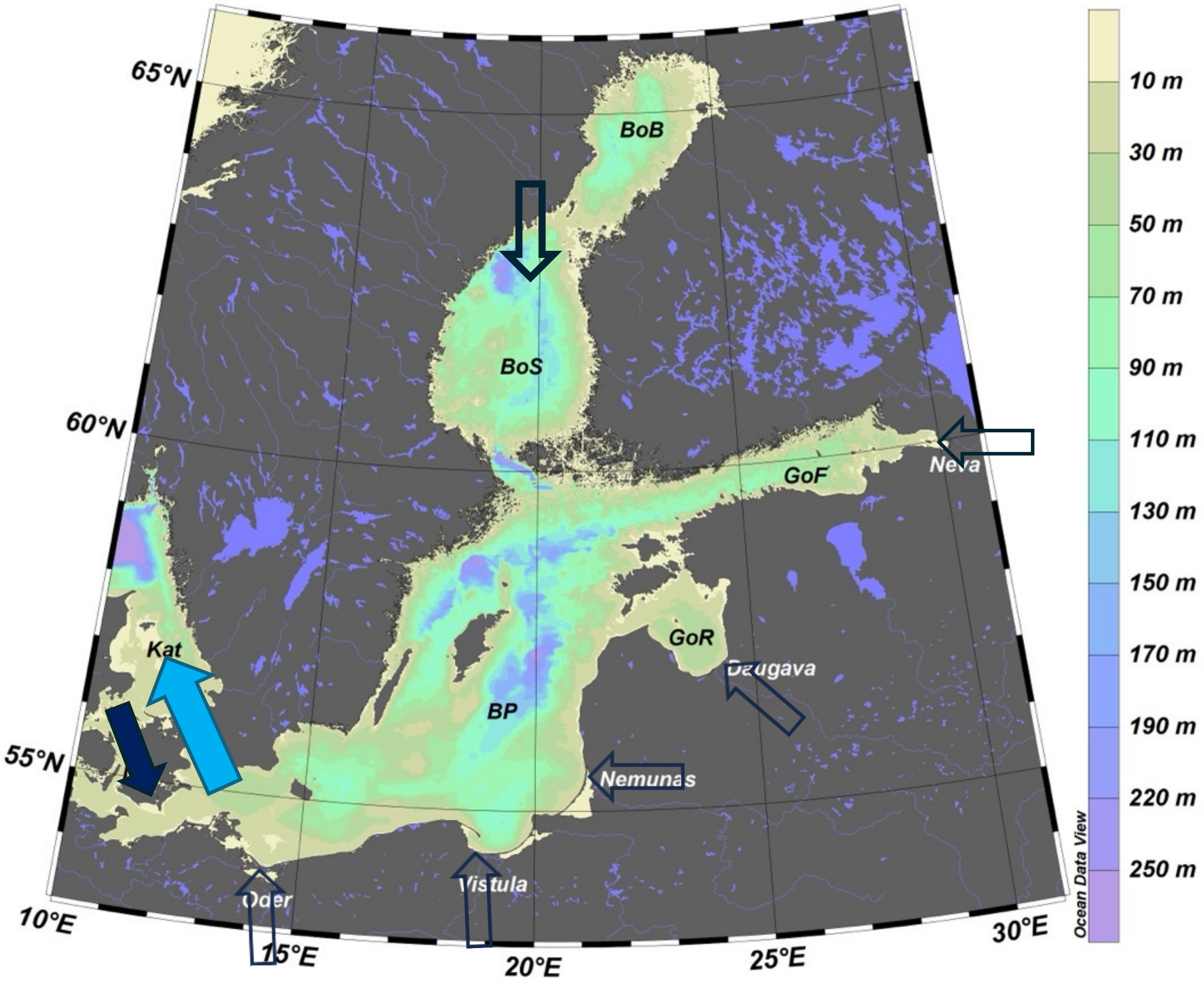
Submesoscale features associated with mesoscale dynamics in a stratified estuary

Urmas Lips[1], Kai Salm[1], Taavi Liblik[1], Germo Väli[1], Nelli Rünk[1], Inga Lips[1,2]
[1]Tallinn University of Technology, Department of Marine Systems, Estonia
[2]EuroGOOS AISBL, Belgium

IUGC2024

Baltic Sea – geography and forcing



Parameters of the Baltic Sea (without Kattegat):

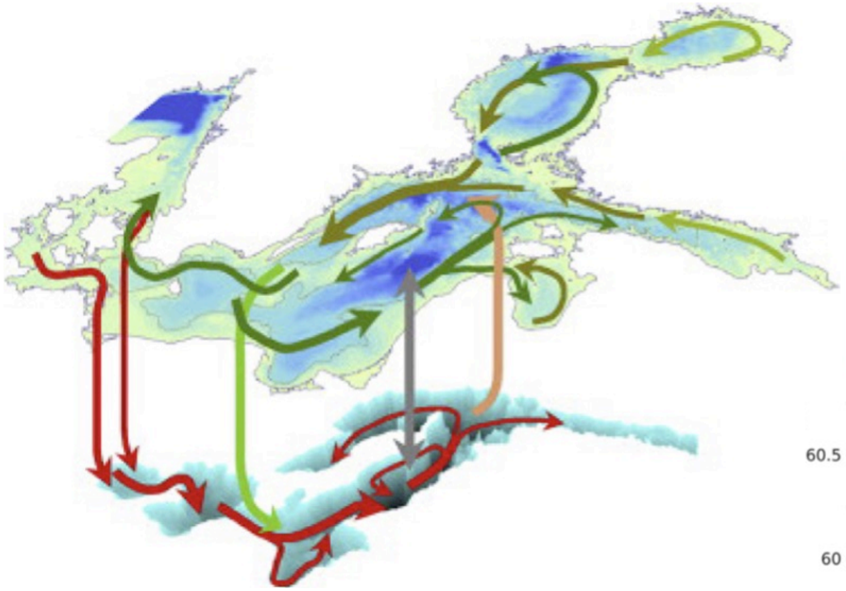
- area – 393 000 km^2
- volume – 21 205 km^3
- average depth – 54 m
- maximum depth – 459 m
- river discharge (BACC I, II) – 14 119 $m^3 s^{-1}$ or 445 $km^3 year^{-1}$
- P-E – 40-60 $km^3 year^{-1}$
- water residence time 25-30 years

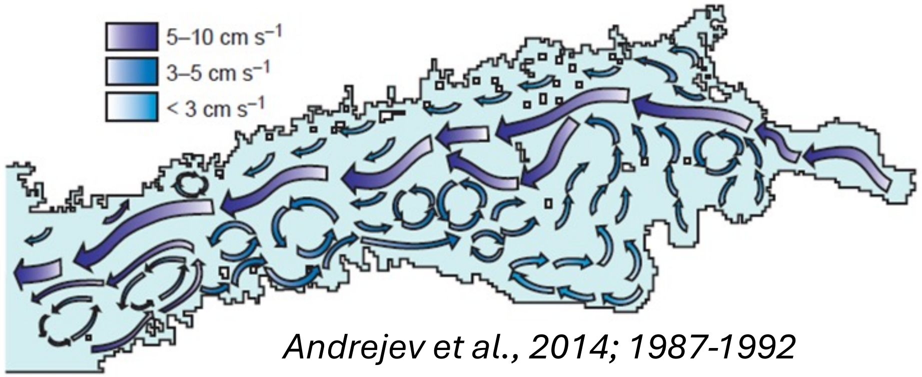
The main physical forcing components for the Baltic Sea system are the **atmospheric forcing**, **exchange** of heat energy and freshwater **through the sea surface**, and input of **freshwater from rivers** and **saltier water through the Danish Straits**.

Note: freshwater and saltier water inputs are geographically localized, **creating horizontal buoyancy and sea level gradients** (like global buoyancy gradients due to global heat flux differences).

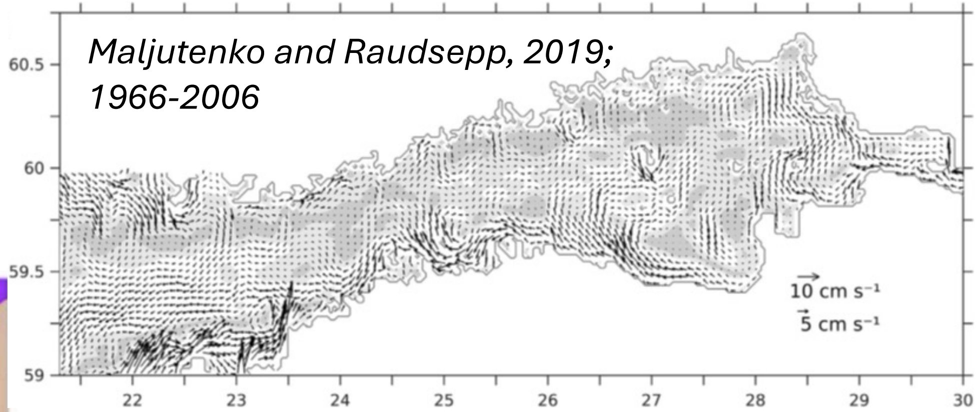
Baltic Sea – general circulation and gradients

General circulation in the surface (green) and bottom (red) layer. The light green and beige arrows show **entrainment**, and the grey arrow shows **diffusion** (*from Omstedt et al., 2014; scheme by Elken and Matthäus, 2008*).

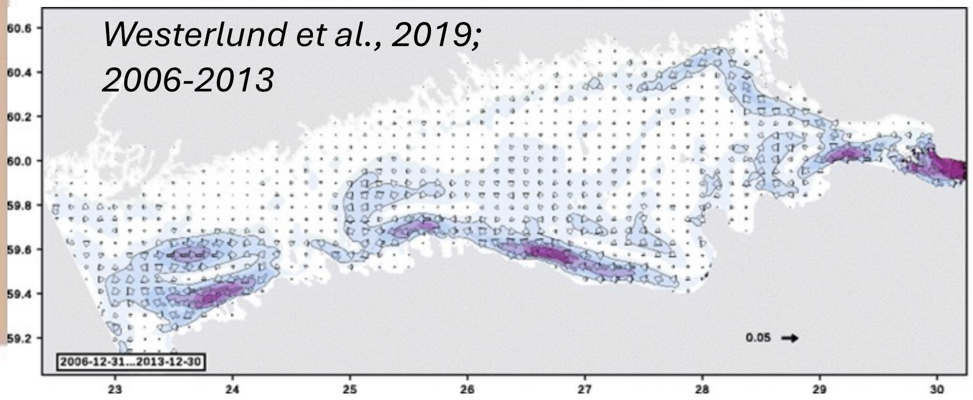




Andrejev et al., 2014; 1987-1992

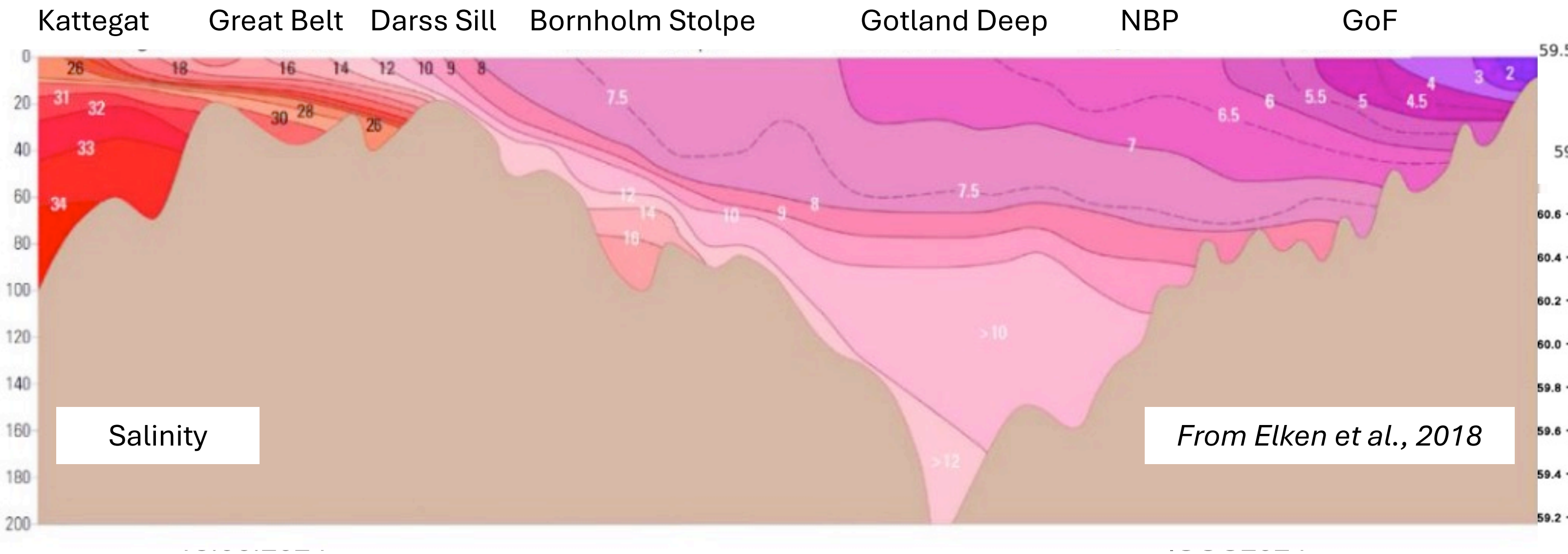


Maljutenko and Raudsepp, 2019; 1966-2006



Westerlund et al., 2019; 2006-2013

Salinity section from Kattegat to the Gulf of Finland



From Elken et al., 2018

Baltic Sea – mixing processes

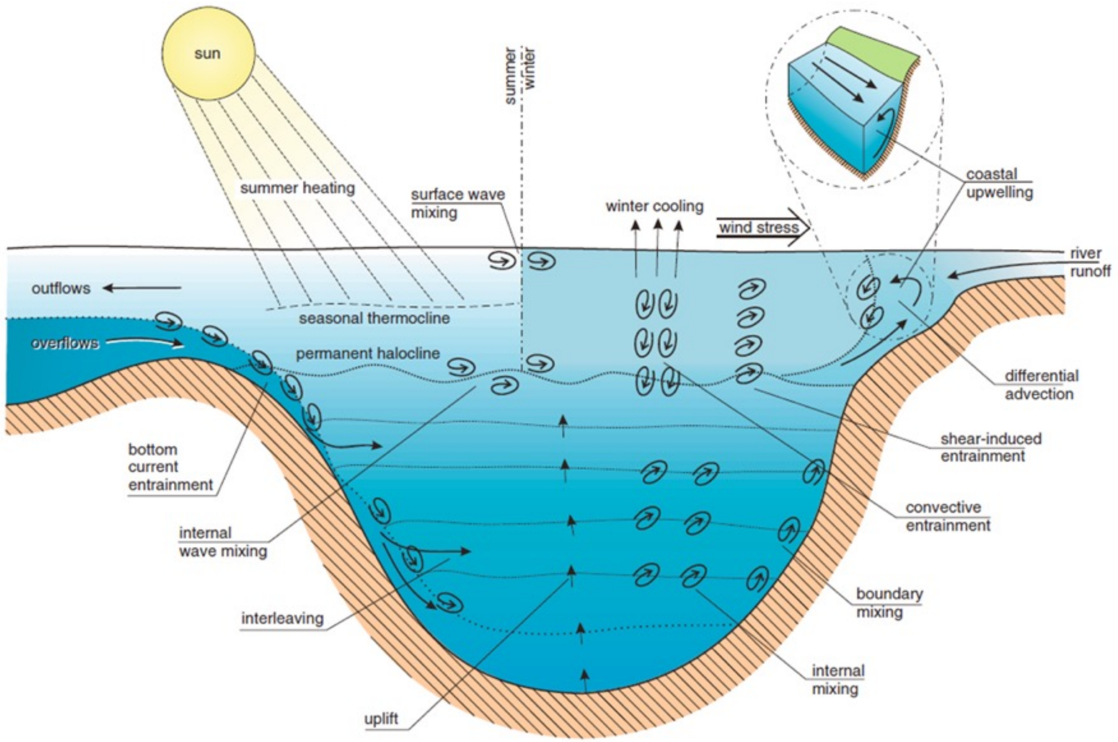
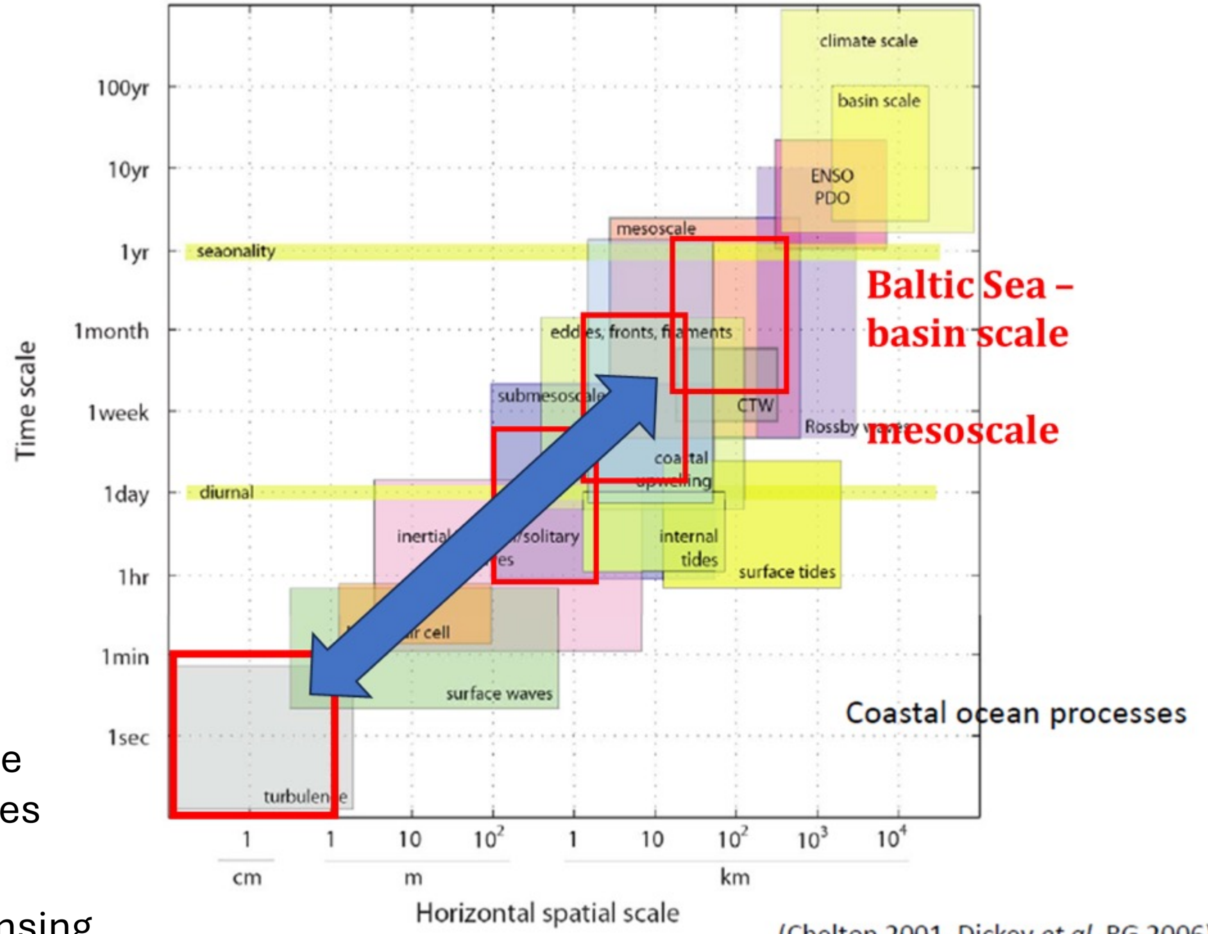


Fig. 2. Scheme of vertical mixing and transport processes in the Baltic Sea.

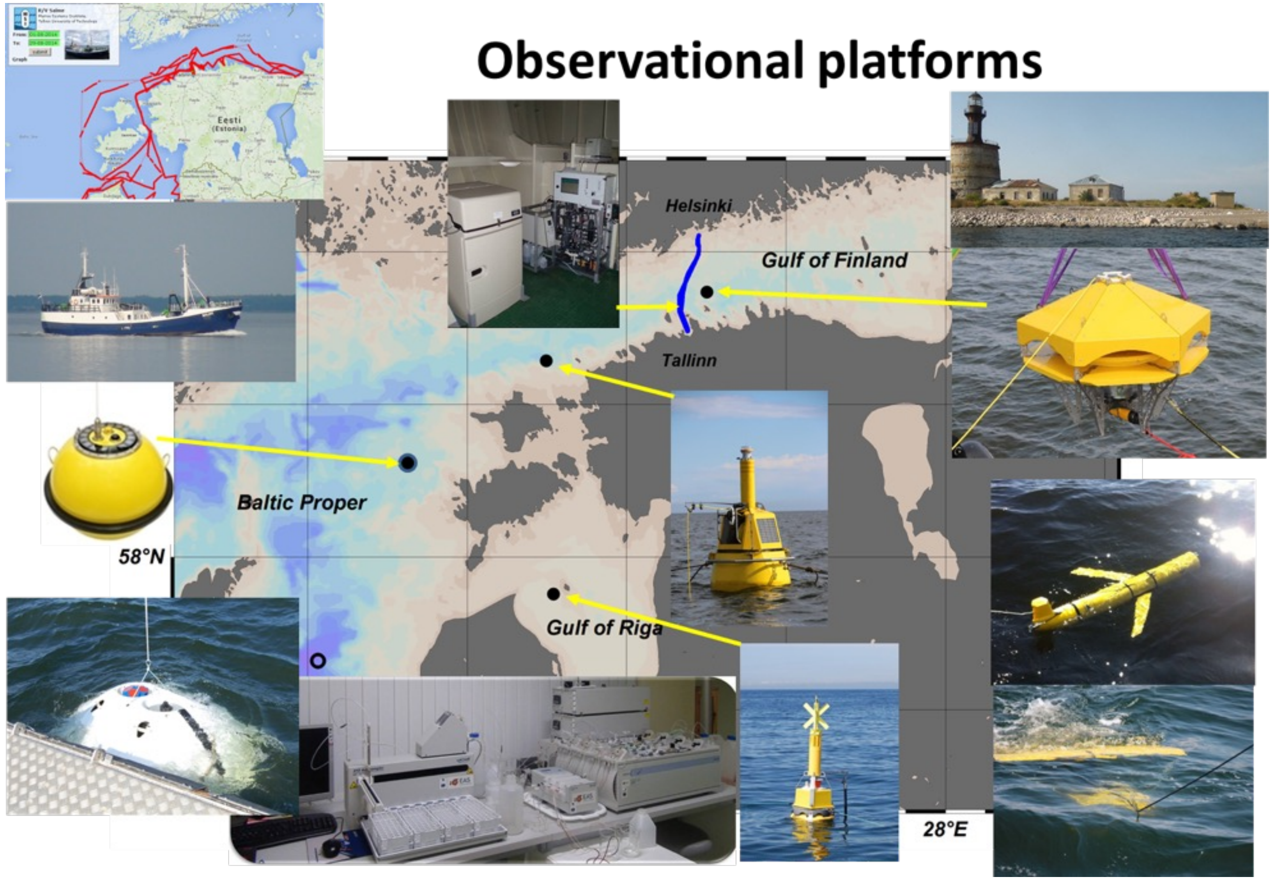


(Chelton 2001, Dickey *et al*, RG 2006)

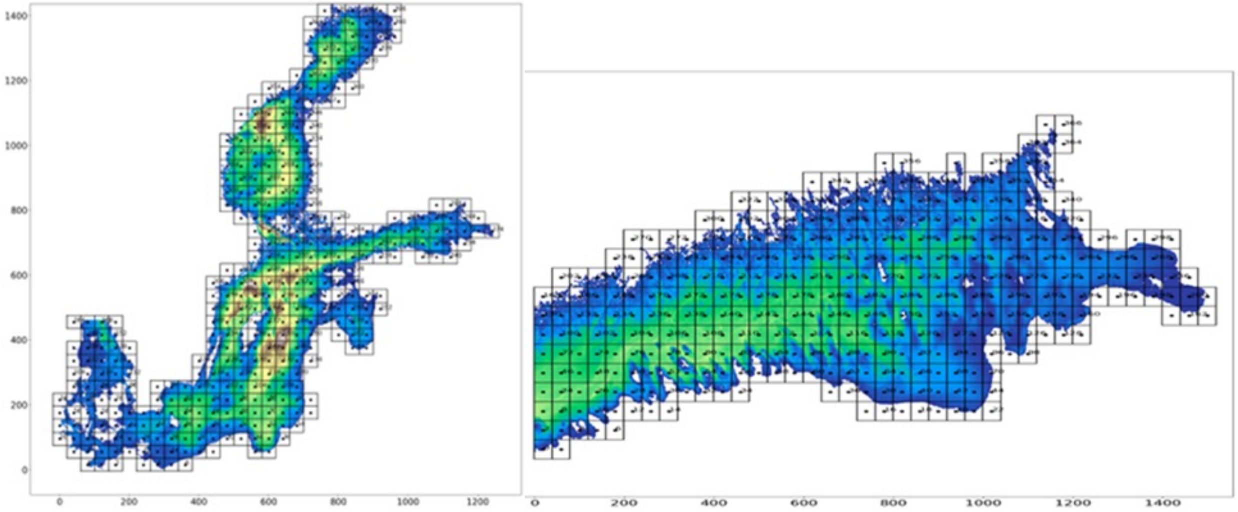
All known relevant mixing and transport processes in the Baltic Sea were listed in (Reissmann et al., 2009). For that time, submesoscale processes contributing to vertical mixing and restratification were not in the list.

During last 10-15 years a considerable amount of modelling, remote sensing and observational evidence have been published on the presence and role of submesoscale processes.

Methods of studying submesoscale processes

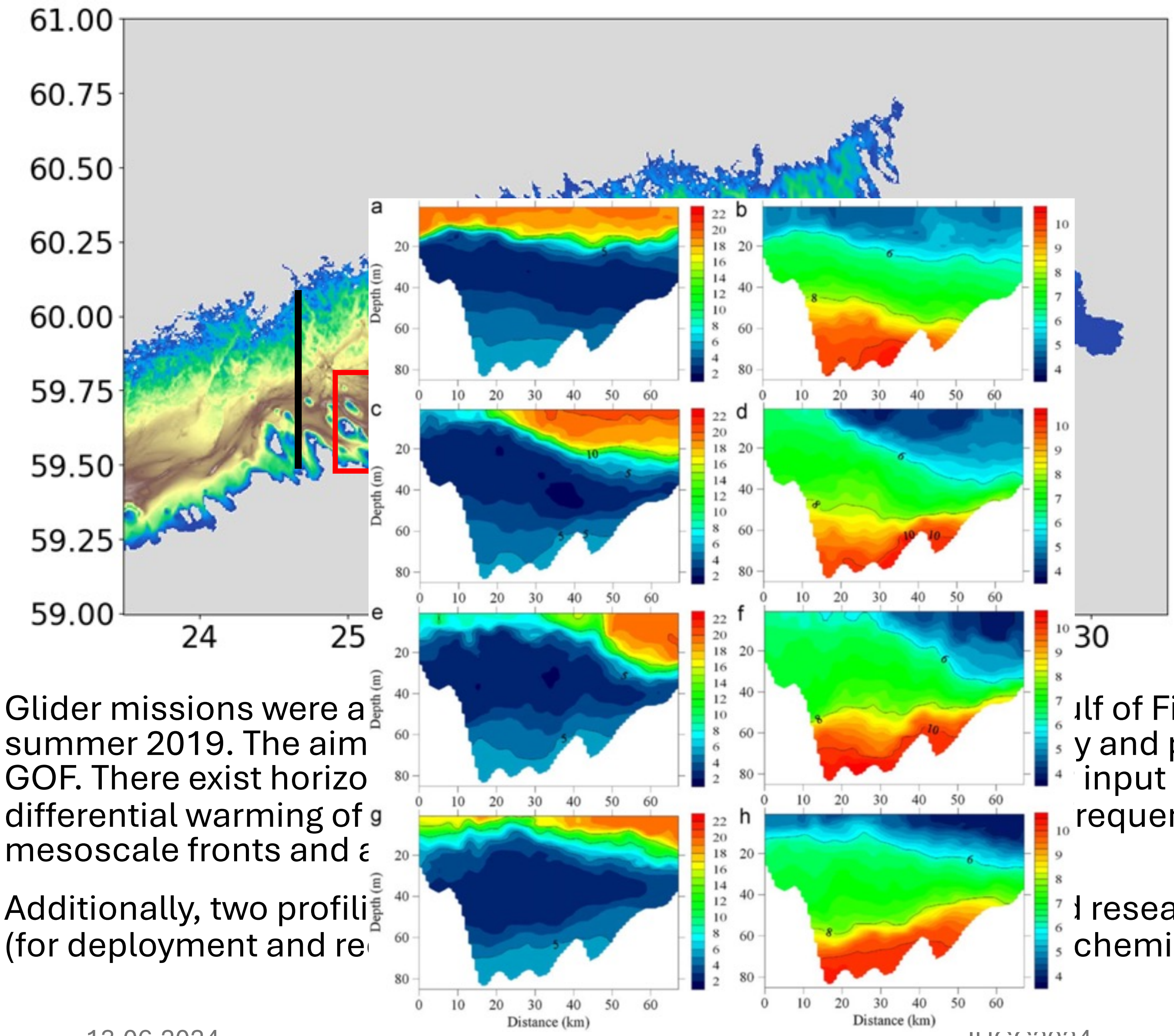


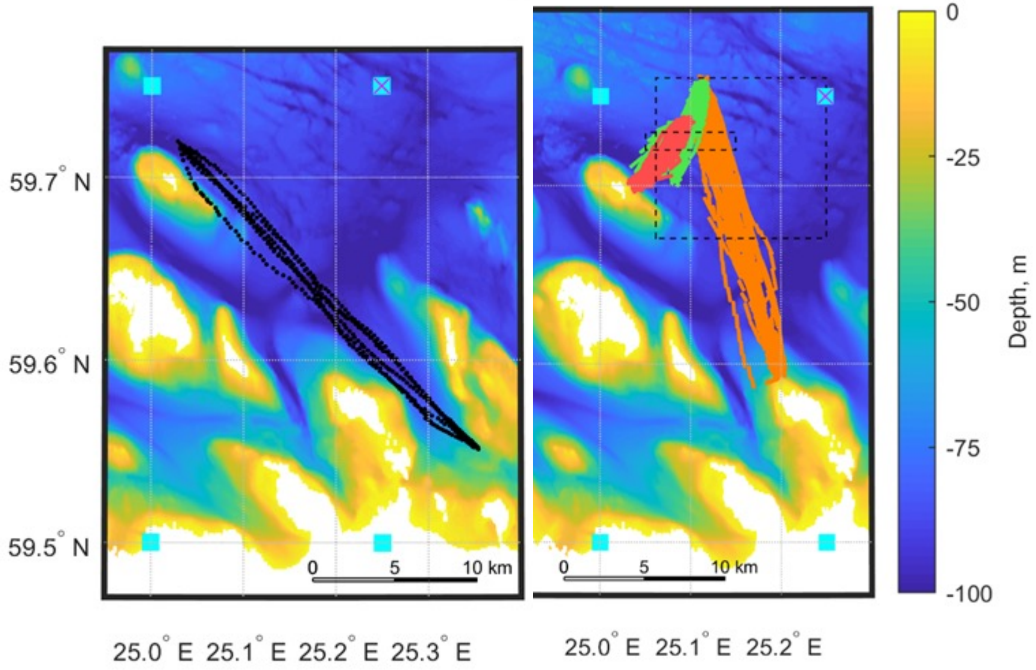
Observational platforms include the research vessel (with a flow-through system), ferryboxes, ADCPs, profiling buoys and a bottom-mounted station, Scanfish, wave buoys, a glider (since 2014), etc.



- **GETM** (General Estuarine Transport Model, IOW version)
- **k-*e*** turbulence (vertical); horizontal **Smagorinsky** (1963) **viscosity** and diffusion
- Nested model simulations – **1 n.m.** Baltic Sea, **1 km** Baltic Proper, **250 m** Gulf of Finland
- **ERA5** (ECMWF) atmospheric forcing
- Rivers based on **E-HYPE** (SMHI)
- Modelling period **2018-2021**
- Submesoscale permitting model
- Model outputs: 3D fields with a time step of 30 minutes
- Coupled biogechemical model ERGOM is used for some applications

Glider missions in the GOF in 2016, 2018, and 2019

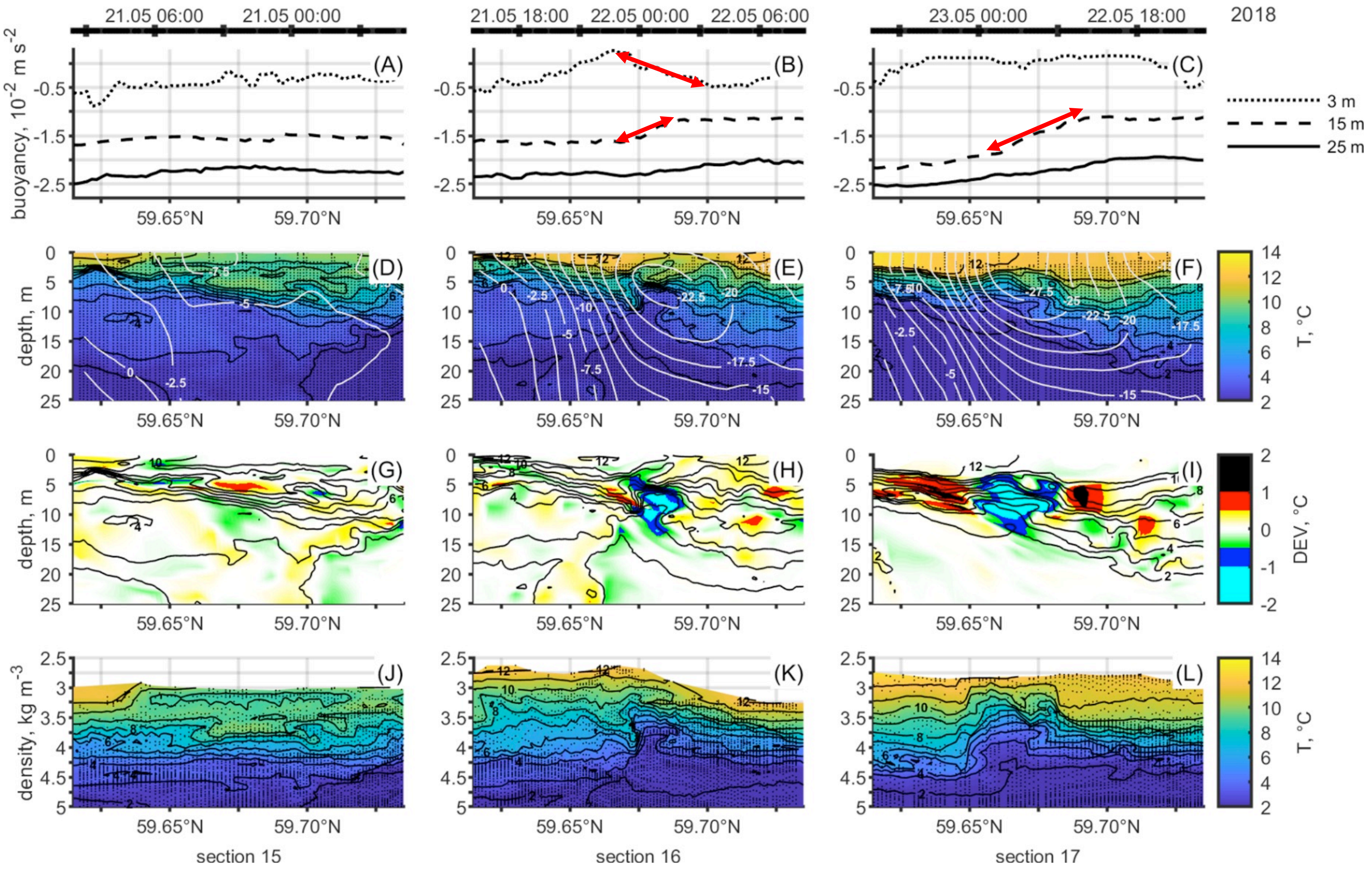




Glider missions were a … ulf of Finland in spring 2016, spring 2018 and spring and summer 2019. The aim … y and processes in this relatively dynamic area of the GOF. There exist horizo … input in the east and saltier water input in the west, differential warming of g … requent upwelling (downwelling) events creating mesoscale fronts and a …

Additionally, two profili … d research vessel visits with sampling were conducted (for deployment and re … chemical/biological analyses).

Submesoscale features at mesoscale fronts

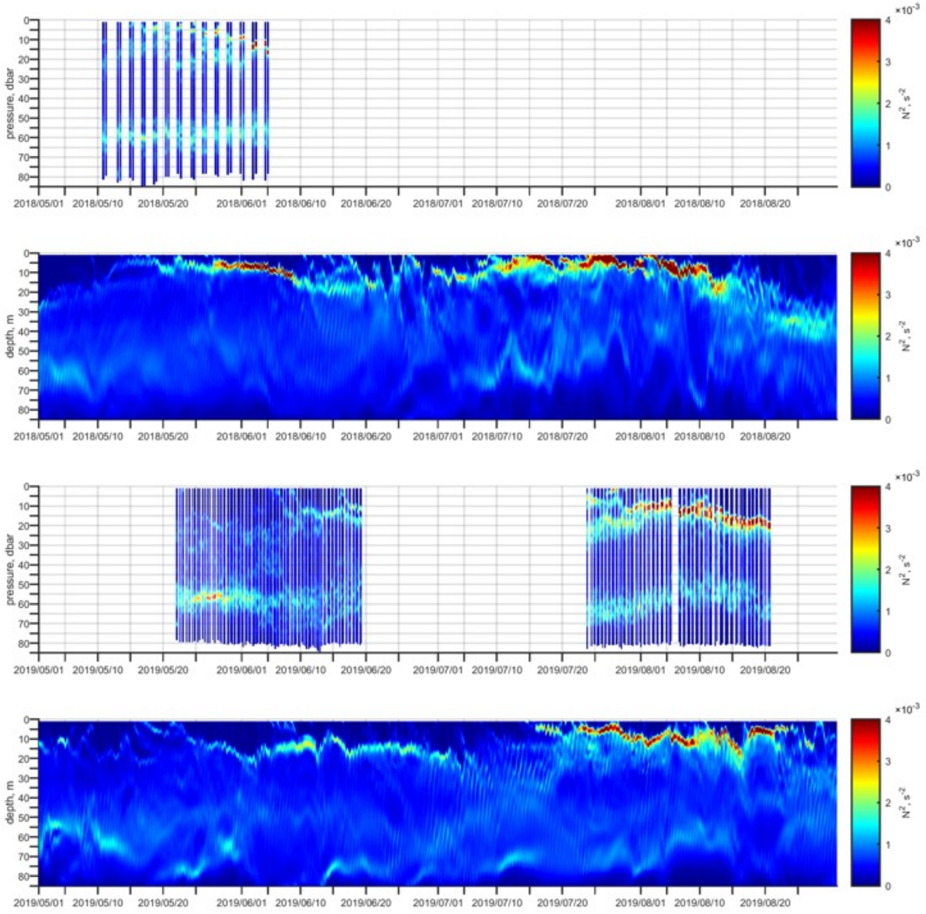


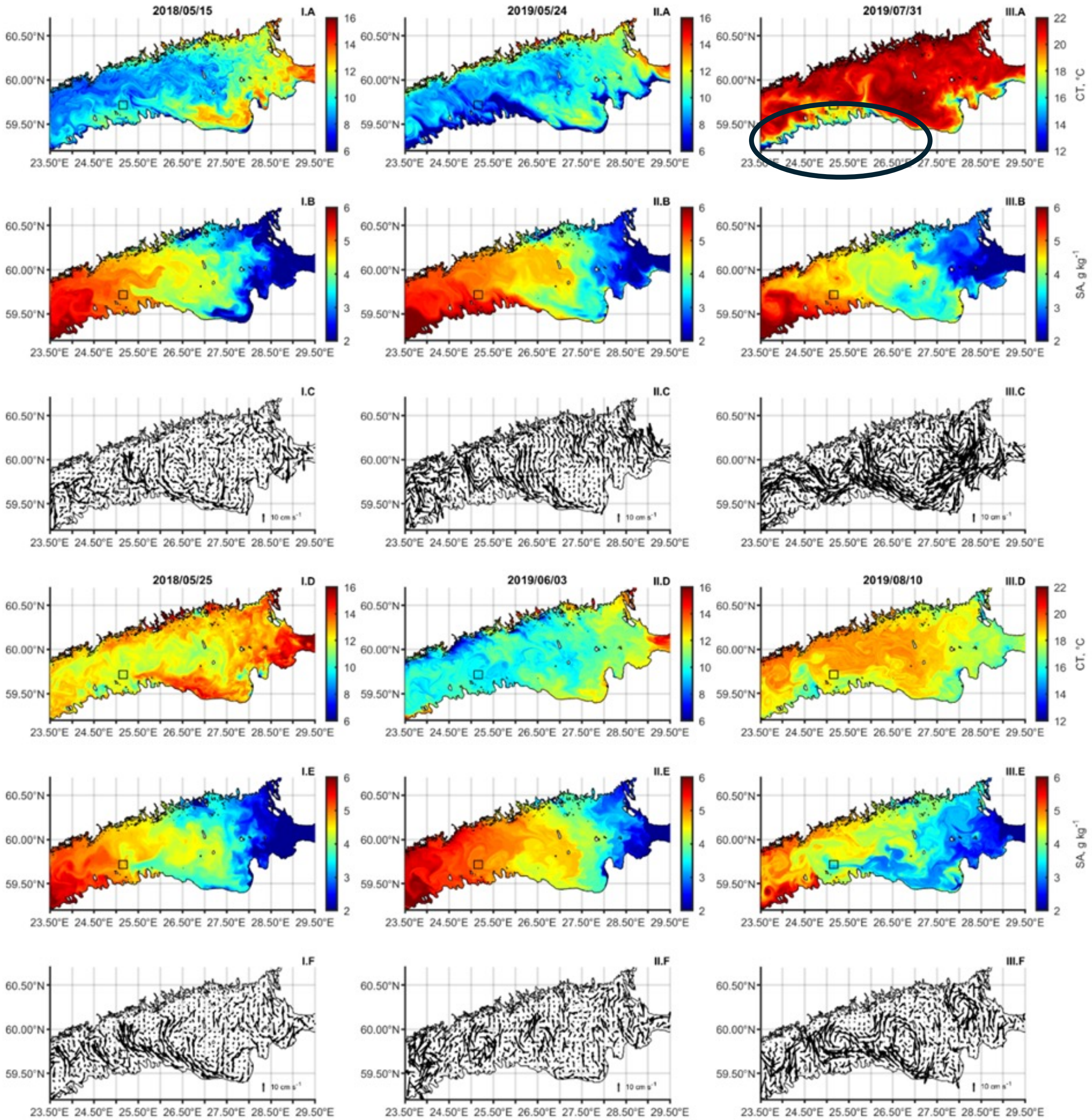
Examples of distributions of buoyancy and vertical sections of temperature, along-isopycnal temperature deviation and temperature against density along the glider track in the GOF in spring 2018.

Submesoscale intrusions emerged at mesoscale fronts (buoyancy gradients) in the conditions of changing forcing – in this case, when wind forcing that created upwelling front weakened.

We propose that they were traces of the frontal submesoscale circulations due to the baroclinic (wind-induced) instability. The frontal submesoscale acted against the persistence of the front.

Larger-scale background



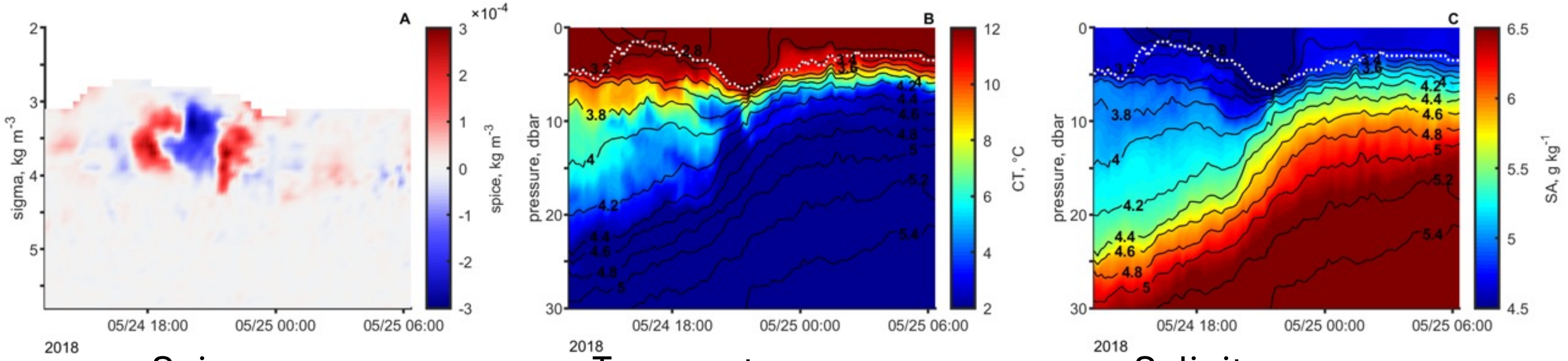


The observed and simulated squared Brunt-Väisälä frequency (N^2) from May to August in 2018 and 2019.

Examples of temperature, salinity and current fields during three glider missions in 2018-2019.

Upwellings and strong horizontal gradients were present.

Distribution of submesoscale spice

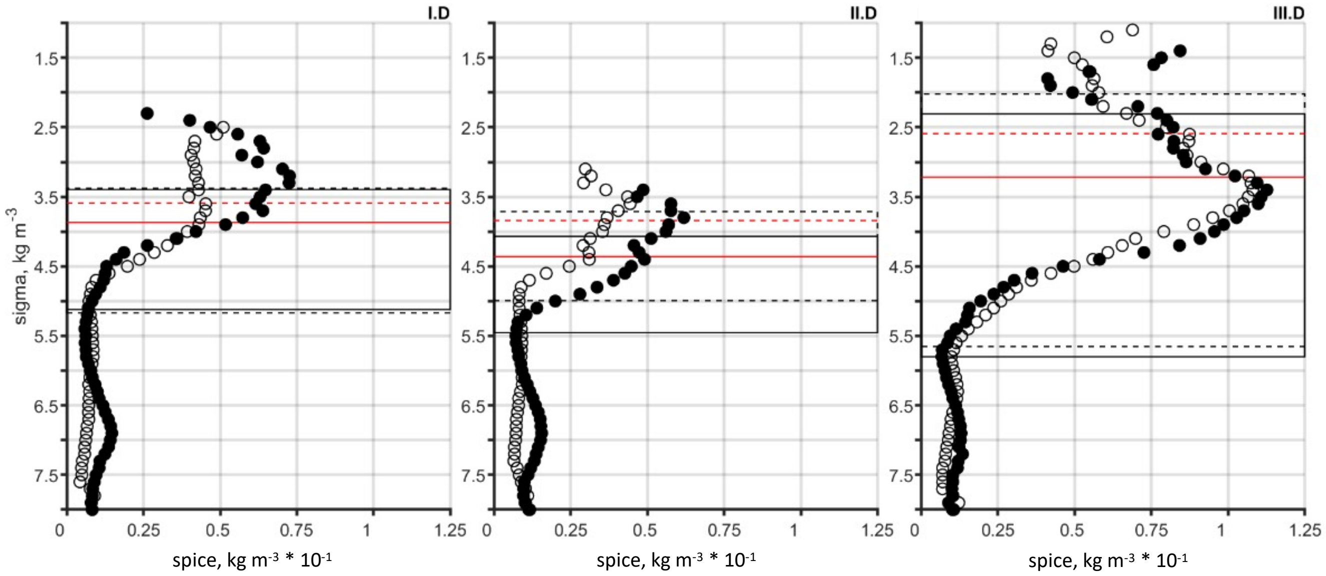


Spice Temperature Salinity

An example of temperature, salinity and spice sections from spring 2018.

Spice is defined as the sum of the temperature anomalies (relative to the surrounding 4 km averages) scaled by the thermal expansion coefficient and the salinity anomalies scaled by the haline contraction coefficient

$$spice = \alpha\Delta T + \beta\Delta S$$



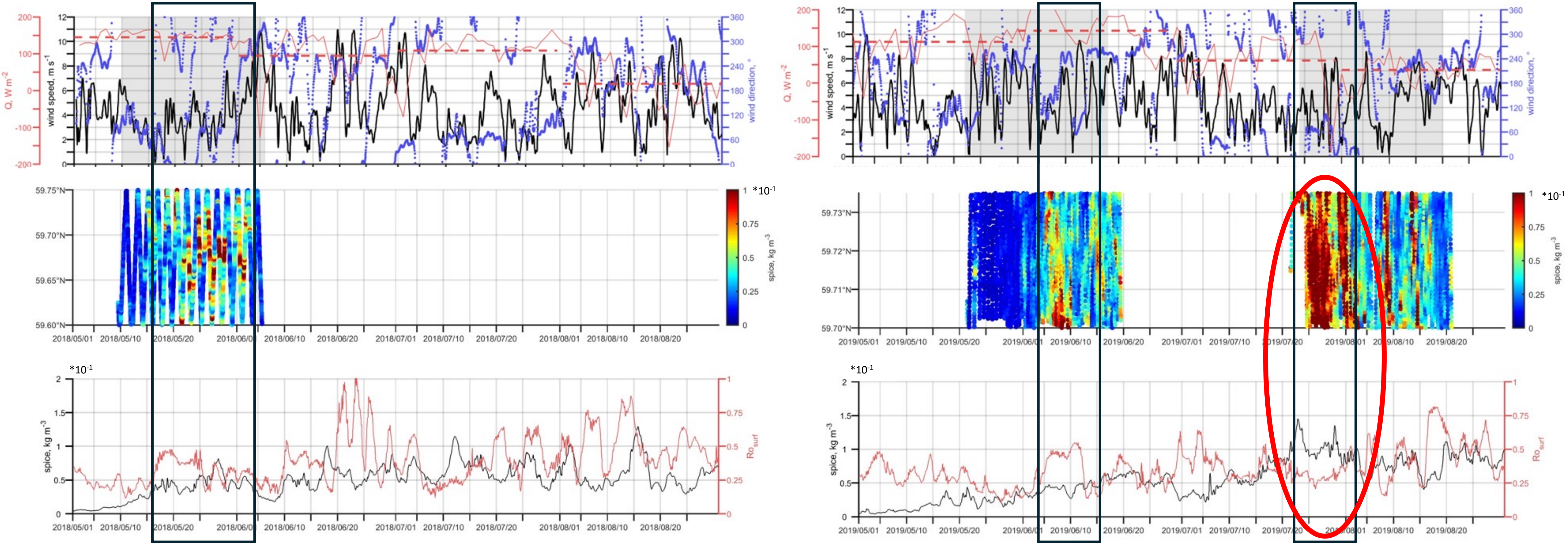
Spring 2018 Spring 2019 Summer 2019

Average vertical spice distributions calculated from the measurements (black dots) and the modelled data (white circles) in each mission. The black lines (solid, measurements; dashed, model) highlight the average upper mixed layer depth and the depth of minimum temperature. The red lines (solid, measurements; dashed, model) exhibit the average depth of the maximum density gradient.

During both spring missions, spice was the highest around the depth of the UML and at shallower depths (lower densities) than the depth (density) of the maximum vertical density gradient. However, in July–August 2019, the spice peak was moved to the depths beneath the UML and was located immediately below the maximum density gradient.

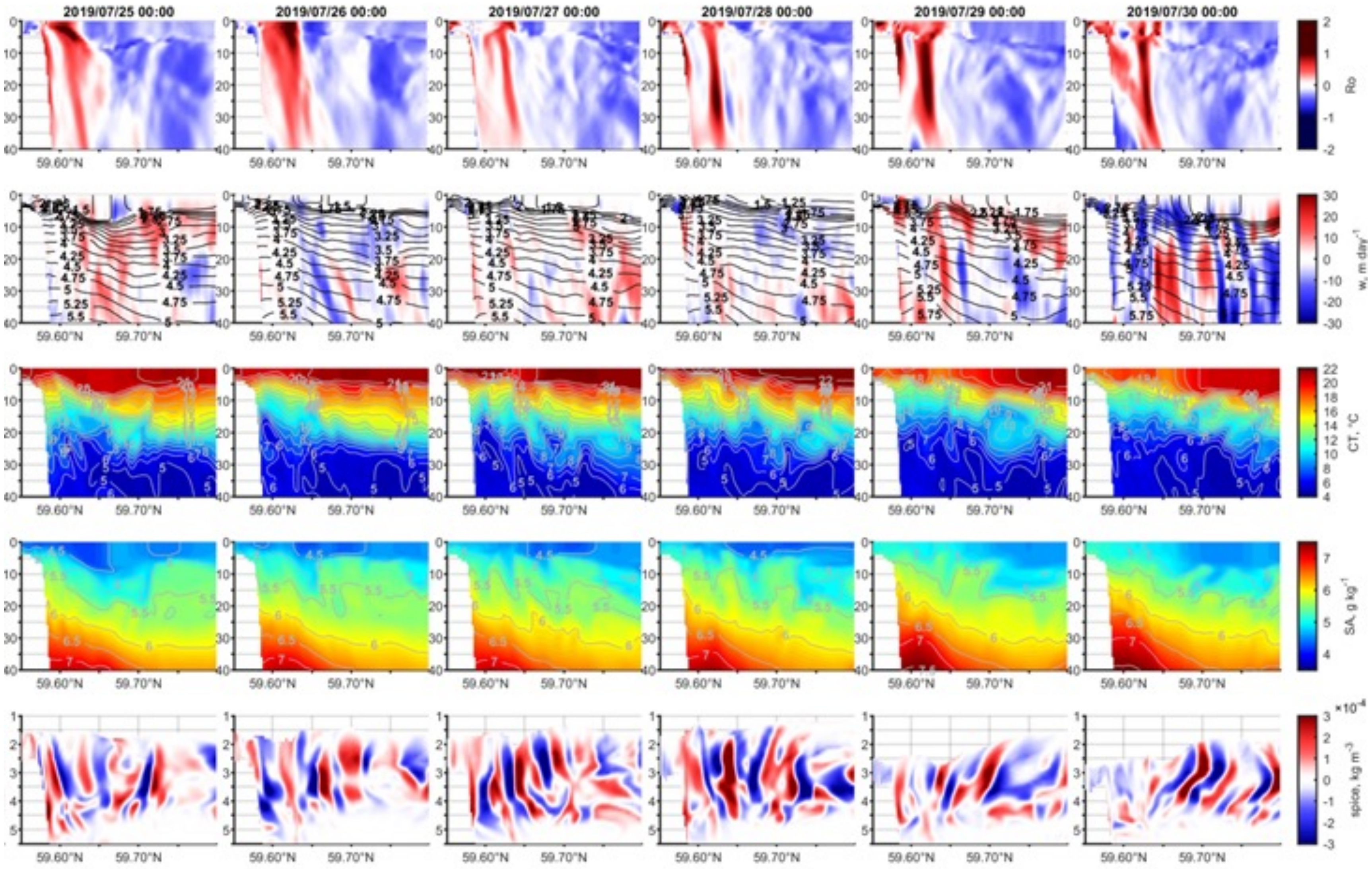
Forcing, spice and vorticity

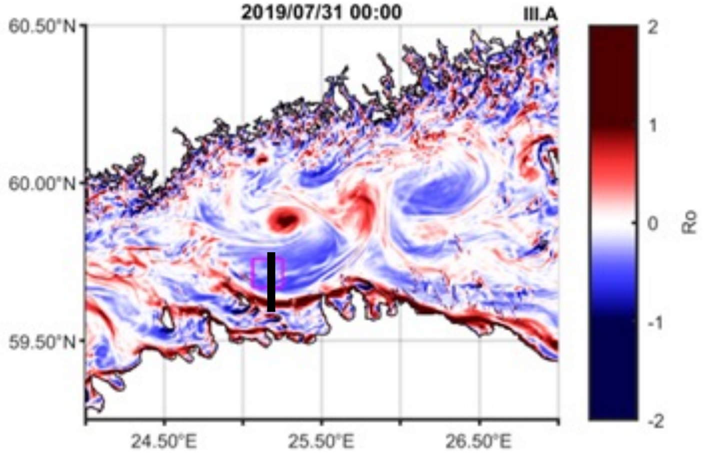
$$Ro = \frac{\zeta}{f}\text{, where}\quad \zeta = v_x - u_y$$



The daily average net surface heat flux, Q, (red, dashed line showing the monthly average), wind speed (black) and direction (blue) – upper panels; the root mean square spice in the density range limited by the depth of minimum temperature along the glider trajectory (middle panels) and from the model, which were calculated in a 10×10 km study window; black line shows the spice and red line the root mean square Rossby number on the surface (lower panels).

Conditions for elevated spice below the pycnocline

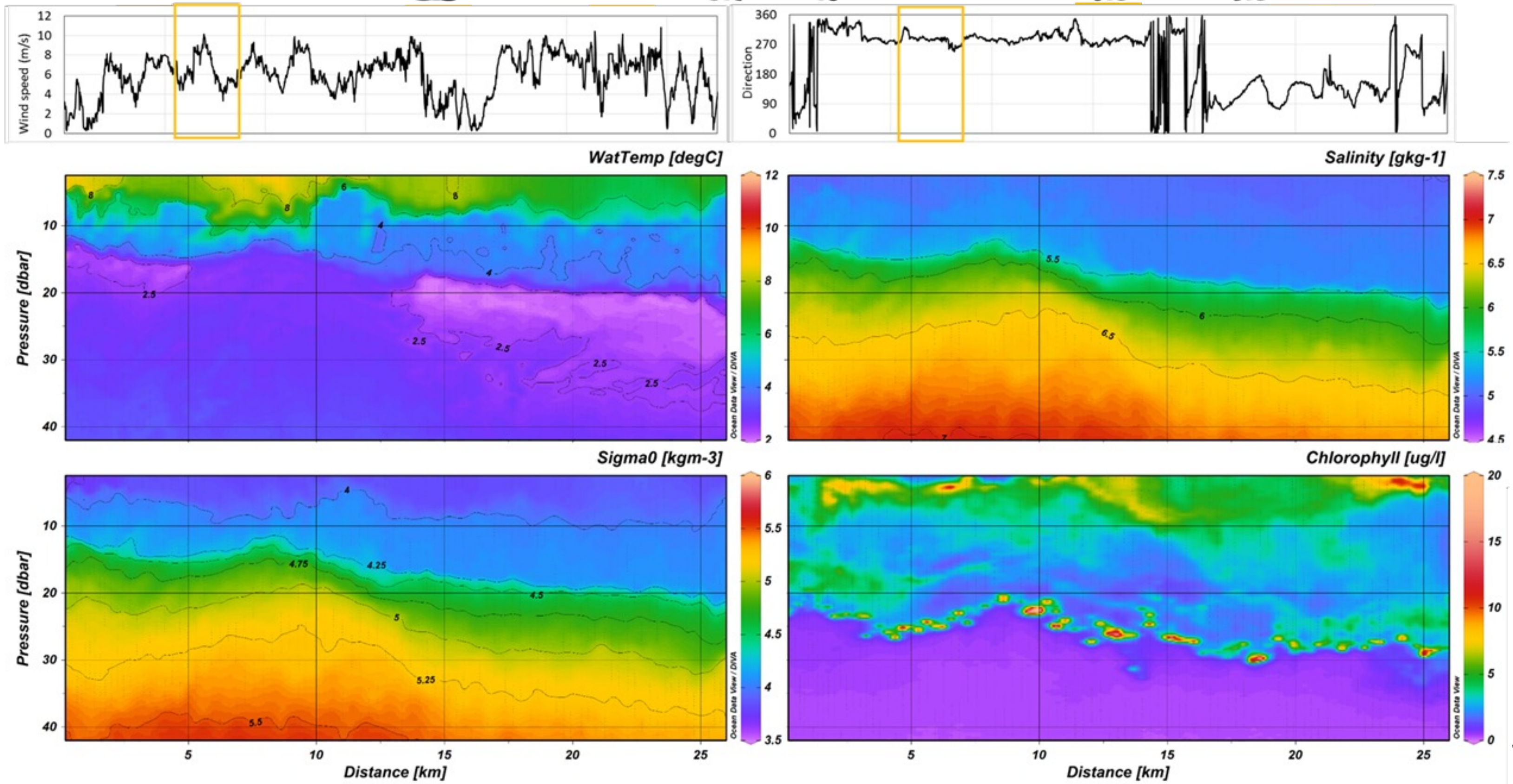


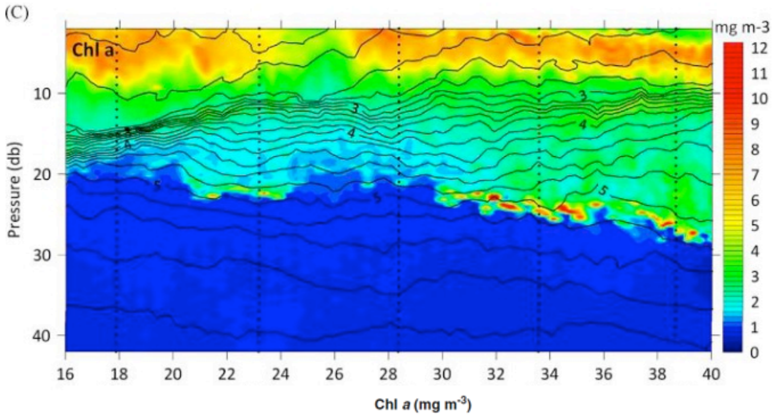


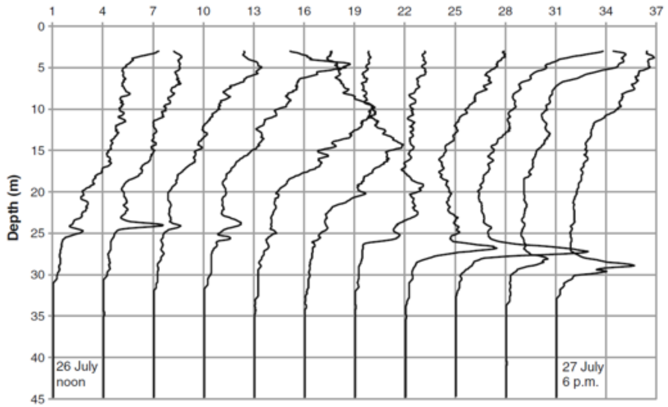
A prolongation of the study section towards the shore (coastal upwelling jet) reveals a high Ro number region there and high submesoscale variability along the inclined isopycnals (in the thermocline) over the entire section.

It suggests that submesoscale flows are associated with the instability of the jet and cause subduction of near-surface waters below the thermocline

Occurrence and decay of sub-surface Chl-a maxima







Submesoscale patches of high chlorophyll signal were abundant in downwelling-favorable conditions while they disappeared and fueled the near-surface bloom when the wind turned (causing convergence near the shore).
We suggest that the same mechanism (subduction by submesoscale flows) contributes to their maintenance.

Similar patches have also been recorded earlier in summer with the main species *Heterocapsa triquetra*, which is capable of vertical migration In spring, the fastest migrating species is *Mesodinium rubrum ;* in our case, dinoflaggelates dominated (*Peridiniella catenata*)

Conclusions

- Gliders are able to catch submesoscale variability and features
- Submesoscale intrusions are associated with mesoscale buoyancy fronts, including upwellings
- Changes in forcing (wind and buoyancy flux) create favorable conditions for the submesoscale to emerge
- The location of the spice maximum depends on forcing conditions (e.g. positive or negative buoyancy flux)
- High spice levels below the maximum vertical buoyancy gradient can be attributed to the subduction at the upwelling fronts
- Phytoplankton can benefit from submesoscale subduction and associated (slower) upward movement of sub-surface waters

Thank you for your attention!

Urmas Lips, urmas.lips@taltech.ee

Tallinn University of Technology, Department of Marine Systems

https://www.facebook.com/taltechmerefys/videos/718141386304230