

Editor comments

Comment: Please carefully check the reference to the figures. Figure 2 is not referred to in the text. Probably where Figure 3 is referred to for the first time, this should be Figure 2. Also other references to figures may be incorrect. Please check.

Reply and action: We have checked carefully the reference to figures and made corrections where necessary.

Comment: Please be certain to have all geographic names used in the text are also shown on the map of figure

Reply and action: We added all the names mentioned in the text to figure 1.

Comment: L35-36 „determine vertical fluxes between the surface and sub-thermocline layer.” Please add what kind of vertical fluxes. Of water, particles, organic matter, etc.?

Reply: We removed the previous sentence and added, what we mean.

Action: It reads now “Characteristics of the seasonal pycnocline (e.g. strength) determine vertical physical (e.g. heat and salt), biogeochemical (e.g. oxygen, nutrients), biological (e.g. plankton) or pollution (e.g. microplastics) fluxes between the surface and sub-thermocline layer.”

Comment: L36-37 “Moreover, the vertical structure of currents is strongly linked to pycnoclines (Suhhova et al., 2018).” This is not clear to me. Please expand and/or explain.

Reply: We made the sentence more specific.

Action: “Moreover, the current shear maximum is strongly linked to the vertical location of a seasonal pycnocline (Suhhova et al., 2018).”

Comment: L46 “approximately” instead of “virtually”

Reply and action: done.

Comment: L49-50 Please rearrange the references. Double parentheses are not necessary here.

Reply and action: done.

Comment: L133 Please define OSTIA

Reply and action: done.

Comment: L136 Insert year for the reference

Reply and action: Since we have added the most up to date reference related to OSTIA (Good et al 2020) during revision, this sentence and reference are not needed anymore in the manuscript.

Comment: L206 m-2 and delete: d

Reply and action: We fixed m-2, but d (day) should stay there. The unit is $N\ m^{-2}\ d$.

Comment: L303-304 “Thus, large scale atmospheric forcing alters the restratification.” This is not correct, I think. The large-scale forcing provides conditions that are beneficial for restratification.

Reply: Yes that is a good point, it was not well expressed.

Action: We changed to “Thus, large scale atmospheric forcing provides conditions for the restratification process.”

Comment: L307 4. Discussion (correct numbering).

Reply and action: done.

Comment: L330 phenomena (as the sentence is in plural)

Reply: We talk about process here (singular). According to our understanding, it should stay the same, as in the title.

Action: No action.

Comment: L336-337 “thus, winter stratification phenomenon occurred even when most of the Gulf of Finland was not covered by ice.” Exactly this has been written some lines above, so can be deleted here.

Reply and action: done.

Comment: L342 Please refer to Figure 1 here

Reply and action: done.

Comment: L347 I think “accounts” should be deleted here.

Reply and action: done.

Comment: L384 5. Conclusions (change numbering)

Reply and action: done.

Comment: L425 I think this means anonymous, right? Please use that term.

Reply and action: Yes and we changed it to anonymous.

Comment: L432-434 This reference is incomplete (no journal etc.), and with double terms. http and doi is the same. Please correct

Reply and action: done.

Comment: L436-438 No journal etc., and double link

Reply and action: done.

Comment: L447 Oceans not: Ocean.

Reply and action: done.

Comment: L448 Oceans not: Ocean

Reply and action: done.

Comment: L455-456 What kind of publication is this? This link is not valid. Please give more info and correct.

Reply: It is Fennel, K.: Convection and the timing of phytoplankton spring blooms in the western Baltic sea, *Estuar. Coast. Shelf Sci.*, 49(1), 113–128, doi:10.1006/ecss.1999.0487, 1999.

Action: We fixed the text.

Comment: L461 *Hydrobiologia*, 554, 57–65, 2006. (change format)

Reply and action: Done.

Comment: L484 idem dito, change format

Reply and action: Done.

Comment: L488-490 Please provide more info on this publication. The link does not lead to this paper.

Reply and action: Done.

Comment: L516-517 Provide editor of book

Reply: they are both authors of the chapter and the editors of the book.

Action: We provided.

Comment: L528 Page numbers missing

Reply and action: we added.

Comment: L573-574 Please provide more info on this reference

Reply and action: we provided.

Comment: L603-605 Please provide more info on this reference, delete: n.d.

Reply: since we have a provided more up to date reference (Good et al. 2020) during revision, this reference is not needed anymore.

Action: we removed this reference.

Comment: L618 Change date format 1 November etc.

Reply and action: done.

Comment: L627 caption Figure 4: These are not profiles but sections. What is called profile should be a transect.

Reply and action: We fixed.

Comment: Figure 4: It is strange to have the color scale in one of the panels. Please place it outside.

Reply and action: We fixed.

Comment: Figure 5 idem ditto

Reply and action: We fixed, except temperature. Because the color scale is not same in all panels.

Reviewer comments

General comments

Comment: The authors did a decent job in addressing my comments, and I am glad to see that the manuscript improved since my first read. However, I still have some concern regarding the quality of the writing and the figures. Some parts of the text, particularly the paragraphs introduced after the revision, contain some repetitive sentences and feel a bit jumbled. I also have a pseudo-major comment that I missed in the first round. I have the feeling that one of the main points of the manuscript is that wintertime haline stratification resulted in enhanced chlorophyll-a concentrations. You show this very nicely with the cruise data. Then you make a thorough effort to assess the generality and the spatial coverage of the haline stratification with different datasets, but there is no equivalent assessment for phytoplankton bloom or chlorophyll dynamics. The biological implications of your results is thus much weaker than the description of the physical rationale. Would it be possible to use a satellite product to expand the spatio-temporal coverage of chlorophyll observations? Below, I list a series of specific comments concerning mainly writing and presentation issues, but I may be missing a significant number of them. I suggest a careful inspection of these aspects before publication.

Reply: Thank you for your time and great suggestions again!

Action: We have addressed all the specific comments below. However, we are not able to perform an equivalent assessment for the chlorophyll-a dynamics. The main reason is unreliable remotely sensed Chl *a* data in this area. The standard products that are available in the CMEMS for instance are not accurate enough for the gulf. The Gulf of Finland is a special area and needs dedicated algorithms. Regional algorithms for spring and summer conditions have been developed here (e.g. <https://www.sciencedirect.com/science/article/pii/S0078323414500449?via%3Dihub>). To get specific algorithms for winter conditions is too big work to include in the present paper. Likely this work needs a separate paper itself. We think it is a good idea to include the satellite observations and we considered it already before submission, but we prefer to leave this work for the next publications.

Specific comments

Comment: Abstract. Please revise the abstract language. It feels patchy and contains repetitive sentences. For example the "relaxation of westerly winds" is mentioned twice to give a very similar message.

Reply: Yes, we agree.

Action: We revised the abstract according to your critics.

Comment: Line 12 "In this study, we demonstrate that wintertime UML stratification is common in the Gulf of Finland." This sentence is contradictory, if it is a mixed layer is not stratified by definition. I recommend formulating it differently.

Reply: Yes, we agree.

Action: It reads now: "In this study, we demonstrate that wintertime shallow stratification is common in the Gulf of Finland."

Comment: Line 15 "Fresher water and haline stratification occurs". That sounds a bit weird to me. Reformulate.

Reply: Yes, we agree.

Action: It reads now: "Haline stratification emerges"

Comment: Line 154 Add space after "simulations".

Reply and action: fixed

Comment: Line 206 m^{-02} to m^{-2}

Reply and action: fixed.

Comment: Lines 256-258 I think this sentence about the mechanism driving the spreading of haline stratification belongs more to the discussion. You need to support it with references. There is another interesting point that emerges from Figure 11b. There are a number of eddy-like frontal instabilities that seem spread shallow mixed layers towards the south. It may be worth mentioning this in the discussion. See for example: <https://science.sciencemag.org/content/337/6090/54.full?rss=1>

Reply: Yes, we agree, it rather belongs to the discussion. We think it is very important point you have made about eddies. Thank you"

Action: We removed that part from the results and merged it with the discussion. We mention the eddy-like features now in discussion. Moreover we added another panel (middle panel b) to the fig to discuss a bit more on that topic. The panel a shows the situation, when westerly winds dominate (as in previous version of the manuscript). Panel b (new) shows the situation after the dominance of easterly winds: advection along the northern coast. Panel c shows the development after short westerly wind

impulse. Thus, panel c explains how shallow mixed layer spreads to south, the precondition for the situation c is the „b“, i.e. fresher water along the northern coast. This temporal development well agrees with our Ferrybox observations (Fig. 6): fresher water first appears to the northern coast and after westerly wind impulse it spreads to the south.

Comment: Line 287 \Restratification phenomenon were". Phenomenon is singular, so \was".

Reply and action: fixed.

Comment: Lines 291-305 This part is a bit dense and hard to follow sometimes. Consider rephrasing a bit.

Reply and action: We rephrased some sentences here and hope it is better now.

Comment: Section numbering is wrong for Discussion and Conclusions

Reply and action: fixed.

Comment: Line 327 \Deepen the mixed layer depth". I would remove \depth".

Reply and action: fixed.

Comment: Lines 341-357 This paragraph is also a bit jumbled and contains typos like \accounts contributes". In line 344, it is not clear to me what you mean by \topography".

Reply: Yes, we agree.

Action: We have fixed the error and specified what we meant by tropography. We also made some other small changes to make it better to read.

Comment: Line 359 The meaning of \occasionally" here is blurry. Please try to be more precise.

Reply and action: We agree and found the word „occasionally“ indeed is not necessary here.

Comment: Lines 390-393 This sentence is weirdly constructed.

Reply and action: We changed it. We believe it is now better to read.

Comment: Lines 395 \We can assume" doesn't sound very convincing to me, maybe \Therefore, our results suggest/indicate"

Reply: We agree

Action: We changed as you suggested.

Comment: Figure 4, caption There is a double \.." after 2911/12. Also 2911 is wrong.

Reply and action: We fixed.

Comment: Figure 6 The tick labels of the colorbar overlap with the ticklabels on the y-axis.

Reply: We fixed.

Comment: Figure 10a It is extremely difficult to extract information from this new panel, too many super-imposed lines. Please consider improving this.

Reply: We made it easier for a reader.

Action: We kept only two highest NAO years and two lowest NAO years to illustrate the impact on the time-series of the UML in the Gulf of Finland. We also mention the selected years in the text (end of the results chapter). We kept all years for the Gotland Deep, but the same color.

Comment: Panel labelling. The labelling of the different panels (a, b, c, etc) is located in different places for the different figures, sometimes it is inside the figure, sometimes in the panel title, others in the y-axis label. It would be better for the reader to homogenise this.

Reply and action: We homogenized.

Winter stratification phenomenon and its consequences in the Gulf of Finland, Baltic Sea

Taavi Liblik, Germo Väli, Inga Lips, Madis-Jaak Lilover, Villu Kikas, Jaan Laanemets

5 Department of Marine Systems at Tallinn University of Technology, Tallinn 12616, Estonia

Correspondence to: Taavi Liblik (Taavi.liblik@taltech.ee)

Abstract. Stratification plays an essential role in the marine ecosystem, with a shallow mixed layer being one of the preconditions for enhanced primary production in the ocean. In the Baltic Sea, the general understanding is that the upper mixed layer (UML) is well below the euphotic zone in winter. In this study, we demonstrate that wintertime UML-shallow stratification is common in the Gulf of Finland. Shallow haline stratification and it forms at a depth comparable to the euphotic zone in late January–early February. The onset of restratification is likely associated with the annual cycle of westerly winds, which ease off in late January–early February. Stratification is first invoked along the northern coast by the westward advection of riverine water forced by easterly winds and is expanded to the south when the prevailing wind direction changes from easterly to a westerly direction of the gulf after the relaxation of westerly winds. Fresher water and high haline stratification occurs-emerges approximately one month later in the southern part of the gulf. Winter restratification can occur in the whole gulf and also in the absence of ice, thus, it is a regular seasonal feature in the area. Interannual variations in the wintertime UML correspond with variations in the North Atlantic Oscillation. Chlorophyll *a* concentrations in winter can be comparable to mid-summer; the limiting factor for phytoplankton bloom in winter is likely insufficient solar radiation.

1. Introduction

25 Upper layer stratification is an important characteristic in the dynamics of the pelagic ecosystem. However, to our knowledge, the formation of wintertime haline stratification in the upper layer of the whole Gulf of Finland has not been investigated; the present study focuses on the formation of wintertime haline stratification caused by freshwater inflow and wind forced circulation, and the observed haline stratification explains early phytoplankton dynamics. The Baltic Sea is shallow and brackish, has limited water exchange with the North Sea and is characterized by strong seasonality and gradients of oceanographic parameters (e.g. Leppäranta and Myrberg, 2009). The upper mixed layer (UML), with a typical depth of 10–20 m, forms in spring and is separated from the rest of the water column by a seasonal thermocline. The mixed layer warms up to 15–24 °C (e.g. Stramska and Bialogrodzka, 2015; Tronin, 2017) and thermal stratification strengthens until August. The thermocline is eroded by thermal convection, wind stirring and current shear induced mixing, and the mixed layer deepens down to the sea bottom or the halocline at 40–80 m depth in autumn–winter (e.g. Lass et al., 2003; Liblik and Lips, 2017; Väli et al., 2013). This annual stratification cycle has substantial implications for physical, biogeochemical and biological processes in the sea. Characteristics of the seasonal pycnocline (e.g. strength) determine vertical physical (e.g. heat and salt), biogeochemical (e.g. oxygen, nutrients), biological (e.g. plankton) or pollution (e.g.

40 [microplastics](#)) fluxes between the surface and sub-thermocline layer. Moreover, the [current shear](#)
45 [maximum](#) ~~vertical structure of currents~~ is strongly linked to [the vertical location of the seasonal](#) pycnoclines
(Suhhova et al., 2018). The annual cycle in stratification, together with solar radiation, mainly determines
seasonality in primary production and nutrient consumption. Vertical mixing from the deeper layers, and low
production in winter, allows nutrients to accumulate in the upper layer (e.g. Lilover and Stips, 2008; Nehring and
Matthäus, 1991). The water column becomes stable in spring and the mixed layer is shallower than the euphotic
zone, so that the spring bloom is triggered when solar radiation is sufficiently strong (Fleming and Kaitala, 2006;
Jaanus et al., 2006; Lips et al., 2014; Wasmund et al., 1998).

Stratification in the northeastern Baltic Sea is particularly strong and variable. The largest river in the
Baltic Sea catchment area, the Neva, discharges into the eastern end of the Gulf of Finland with a mean runoff of
3700 m³ s⁻¹ (Johansson, 2016). Since river discharge is concentrated in the east, and the gulf is connected to the
50 Baltic Proper in the west, there is a mean longitudinal salinity gradient in the upper layer from [virtually](#)
[approximately](#) 0 g kg⁻¹ at the easternmost end to 6 g kg⁻¹ in the west (Alenius et al., 1998). Also, mean salinity in
the upper layer is lower on the northern coast than the southern [\(e.g. Kikas and Lips, 2016\)](#) due to the mean
cyclonic circulation in the upper layer and prevailing westward current along the northern coast (Palmen, 1930;
Rasmus et al., 2015; Stipa, 2004), ~~(e.g. Kikas and Lips, 2016)~~. Free water exchange between the gulf and the Baltic
55 Proper means that there is a quasi-permanent halocline and saltier deep layer in the gulf. This lateral and vertical
structure can be strongly modified by wind forcing; westerly winds drive accumulation of saltier upper layer water,
deepen the UML (Liblik and Lips, 2017) and cause weakening of the halocline (Elken et al., 2003). This process
can lead to the complete mixing of the water column in the gulf in the winter (Elken et al., 2014; Liblik et al.,
2013; Lips et al., 2017). In contrast, easterly winds encourage westward transport of riverine water and strengthen
60 haline stratification in the whole water column (Liblik and Lips, 2017). Wind-driven processes also generate
considerable across-gulf inclination of the pycnoclines (Liblik and Lips, 2017) and upwelling and downwelling
events along the southern and northern coasts (Kikas and Lips, 2016; Lehmann et al., 2012; Lips et al., 2009).

The northeastern part of the Baltic Sea is ice covered every winter (e.g. Uotila et al., 2015), although ice
extent has high interannual variability. The brackish nature of Baltic Sea water means that the maximum density
65 temperature T_{md} (2.2–3.3 °C) is higher than the freezing temperature (from –0.4 to –0.1 °C), unlike most of the
world ocean. Thus, when the temperature of the surface layer is below T_{md} , warming increases water density and
causes convection and vertical mixing, while cooling stabilizes the water column. Water temperature typically
exceeds the T_{md} in northern and eastern parts of the Baltic Sea during winter (Karlson et al., 2016; Liblik et al.,
2013), but it is not always the case in offshore areas in the southern Baltic Sea (e.g. Stepanova et al., 2015). Lateral
70 haline buoyancy flux can compensate the thermal convection and stabilization of the shallow upper layer in spring
and can occur at temperatures already below T_{md} (Eilola, 1997; Eilola and Stigebrandt, 1998; Stipa et al., 1999).
One reason for the latter is the relatively low thermal expansion at temperatures around T_{md} , i.e. the impact of
temperature on density is relatively small compared to the impact of salinity. Thus, onset of the seasonal pycnocline
is not necessarily initiated by thermal buoyancy but could be related to haline buoyancy. Temperature below T_{md}
75 in the cold intermediate layer after establishment of the seasonal pycnocline provides direct evidence of the latter
(Chubarenko et al., 2017; Eilola, 1997; Liblik and Lips, 2017). Haline stratification creates favourable conditions
for spring phytoplankton bloom (Kahru and Nömmann, 1990; Lips et al., 2014); without haline stratification,
warming would cause mixing until T_{md} is reached.

Haline stratification under ice has been observed in a number of locations including in the vicinity of
80 River Siikajoki mouth in Bothnian Bay (Granskog et al., 2005), at Tvärminne in the northwestern Gulf of Finland
(Merkouriadi and Leppäranta, 2015) and Himmerfjärden bay in the western Baltic Proper (Kari et al., 2018). Ice
coverage prevents wind mixing so that even relatively low river runoff can form a plume of fresher water and
stratification that can reach 10–20 km from the river mouth. A number of studies (Granskog et al., 2005; Kari et
al., 2018; Merkouriadi and Leppäranta, 2015) have investigated winter and early spring haline stratification locally
85 in nearshore regions and near relatively small freshwater sources.

The Gulf of Finland has favorable preconditions for haline stratification in the upper layer in winter. The
gulf receives large amounts of fresh water, and it is at least partly covered by ice during winter. The present study
hypothesizes that haline stratification occurs at a depth comparable to the euphotic zone in the Gulf of Finland,
and potentially in the northeastern Baltic Proper, during wintertime. This means that the general understanding
90 that the water column is mixed down to the halocline in the open Baltic Sea in winter (Leppäranta and Myrberg,
2009) might not be valid in the northeastern Baltic Sea. To test this hypothesis, we analyzed data from research
vessel measurement campaigns, autonomously acquired Ferrybox data and historical sources, along with model
simulation data.

95 2. Data and methods

In situ and remote sensing data

We arranged two measurement campaigns in winters 2011/12 and 2013/14 aboard RV *Salme* to investigate
100 estuarine circulation reversals in the Gulf of Finland (Fig. 1); six along the gulf [thalweg](#) surveys were conducted
in each winter, with full details of survey and data processing in Liblik et al. (2013) and Lips et al. (2017). In the
present study, we utilized temperature, salinity and chlorophyll *a* (Chl *a*) data from cruises in 2011 (21 December),
2012 (24–25 January, 7–8 February, 29 February, 15–16 March) and 2014 (9–10 January, 3–4 February, 4–5
March). Vertical profiles of temperature, salinity and Chl *a* fluorescence were recorded using an Ocean Seven
105 320plus CTD probe (Idronaut S.r.l.) equipped with a Seapoint Chl *a* fluorometer. The salinity data were calibrated
against water sample analyses using a high precision salinometer 8410A Portasal (Guildline). The mean difference
and standard deviation of salinity measured by CTD and salinometer was -0.022 ± 0.014 g kg⁻¹ in 2011/2012 and
 -0.009 ± 0.009 in 2013/2014. Thus, after removal of offsets, the accuracy of salinity data was 0.02 g kg⁻¹.
Temperature sensors were calibrated before and after surveys in the Idronaut factory and the differences with the
110 calibration device were smaller than the initial accuracy (0.001 °C) of the Ocean Seven 320plus temperature sensor.

Chl *a* fluorescence data was compared and calibrated against water samples on the selected cruises. The
linear regression between Chl *a* fluorescence sensor values and Chl *a* acquired from water samples was: Chl *a* =
Fl × 1.42 (r² = 0.90, n = 33), where Fl is the Chl *a* fluorescence recorded by the Seapoint Chl *a* fluorometer. The
Chl *a* concentration in the water samples was determined using Whatman GF/F glass fibre filters following
115 extraction at room temperature in the dark with 96% ethanol for 24 h. The Chl *a* content from the extract was
measured spectrophotometrically (Thermo Helios g) in the laboratory (HELCOM, 1988). Phytoplankton biomass
was determined from water samples from a selection of stations in winter 2014 (Fig. 1). Sub-samples (100 ml)

were preserved and analyzed following HELCOM recommendations and EVS-EN 15972:2011 standard. Phytoplankton carbon (C) content was calculated using the C: biovolume factors method of Menden-Deuer and Lessard (2000) and for photosynthetic naked ciliate *Mesodinium rubrum* according to the method of Putt and Stoecker (1989).

Wind data were recorded at Tallinnamadal and Kalbådagrund lighthouses (Fig. 1) at heights of 36 m and 32 m above sea level and 1-h and 3-h intervals, respectively. A height correction coefficient of 0.91 (neutral atmospheric stratification) was applied to convert wind speed measurements to 10 m height equivalent (Launiainen and Saarinen, 1984). Wind measurements from Tallinnamadal for winters 2011/12, 2013/14 and 2015/16 were used in the oceanographic data analysis. The Kalbådagrund dataset for the period 1981–2015 was used to illustrate the annual cycle of the along-gulf component of wind stress.

Ferrybox measurements of temperature and salinity between Tallinn–Helsinki for January–March 2012, 2014 and 2016 were also used in the study. Details of the Ferrybox system and data processing methods are given in Kikas and Lips (2016). Analyses have shown that a correction of 0.08 g kg^{-1} (the value has been stable over the years) must be added to the recorded salinity (Kikas and Lips, 2016). The standard deviation of the difference in salinity measured by Ferrybox and a high precision Portasal salinometer was 0.01 g kg^{-1} after bias correction. The accuracy of the Ferrybox temperature sensor is $0.04 \text{ }^\circ\text{C}$ (Kikas and Lips, 2016).

Historical data collected by the Department of Marine Systems at Tallinn University of Technology and the ICES HELCOM dataset (<https://ocean.ices.dk/helcom/>) were used to determine past stratification conditions. Quality assurance and data processing were in accordance with the HELCOM Monitoring Manual (Anonymous, 2017).

OSTIA ([The Operational Sea Surface Temperature and Ice Analysis](#), Donlon et al., 2012; Good et al., 2020) daily mean sea surface temperature (SST) data for the period 2010–2019 were obtained from the Copernicus Marine Environment Monitoring Service. ~~The mean difference between the OSTIA SST product and in situ measurements is $0.01\text{--}0.03 \text{ }^\circ\text{C}$ and the standard deviation is $0.4\text{--}0.5 \text{ }^\circ\text{C}$.~~ Daily mean SST along the thalweg in the Gulf of Finland (Thalweg GoF in Fig. 1) and in the [Eastern Gotland Deep Basin](#) (box in Fig. 1) was calculated to determine if and when SST was above or below T_{md} . Salinities of 6 g kg^{-1} and 7 g kg^{-1} were used in T_{md} estimation for the Gulf of Finland and [Eastern Gotland Deep Basin](#), respectively.

Time series of the large-scale North Atlantic Oscillation (NAO) index was used to explain the interannual variability of wintertime upper layer stratification in the Gulf of Finland. Long-term observations of the sea level pressure differences between Reykjavik (Iceland) and Gibraltar (Spain) constitute the NAO index, which is available from the Climatic Research Unit, University of East Anglia (Jones et al., 1997; <https://crudata.uea.ac.uk/cru/data/nao/nao.dat>).

Density is given as a potential density anomaly (σ_θ) to a reference pressure of 0 dbar (Association for the Physical Sciences of the Sea, 2010). The UML depth was defined as the minimum depth where $\rho_z \geq \rho_3 + 0.15 \text{ kg m}^{-3}$ was satisfied. The density at 3 m depth is ρ_3 and ρ_z is the density at depth z .

Modeling

The study used the General Estuarine Transport Model (GETM, Burchard and Bolding (2002)) to obtain UML parameters in the Gulf of Finland and the Eastern Baltic Sea. GETM is a primitive equation 3-dimensional, free surface hydrostatic model with a built-in vertically adaptive coordinate scheme (Hofmeister et al., 2010). The latter has been shown to significantly reduce numerical mixing in the simulations (Gräwe et al., 2015).

Vertical mixing in the GETM is calculated using a General Ocean Turbulence Model (GOTM, Umlauf and Burchard (2005)). For the current study, the eddy diffusivity and eddy viscosity parameters were found using a two-equation $k-\epsilon$ model coupled with an algebraic second-moment closure (Burchard et al., 2001; Canuto et al., 2001).

A horizontal grid spacing of 0.5 nautical miles (approximately 926 m) was established for the setup domain of the whole Baltic Sea (Fig. 1), with 60 vertically adaptive layers. Parameters controlling the vertical resolution of the model during simulations were taken from Hofmeister et al. (2010) and Gräwe et al. (2015). The digital topography of the Baltic Sea was taken from the Baltic Sea Bathymetry Database (<http://data.bshc.pro/>, last accessed 1 April 2020), with additional data for the Gulf of Finland from Andrejev et al. (2010). Surface boundary conditions (wind stress and surface heat flux components) were calculated using bulk formulae from data generated by the operational forecast model HIRLAM (High-Resolution Limited Area Model). HIRLAM is used and maintained by the Estonian Weather Service and has a spatial resolution of 11 km and a daily forecast interval of 1 h for a total forecast length of 54 h (Männik and Merilain, 2007). All meteorological parameters were interpolated to the model grid. Model simulation was performed from 1 April 2010 to 31 December 2019.

Open boundary conditions were used in the Danish Straits. Inflow and outflow from the model is barotropically controlled using sea surface height measurements from Gothenburg station and, more specifically, Flather (1994) radiation. In terms of temperature and salinity, the model is relaxed towards climatological profiles along the open boundary using sponge layer factors according to the method of Martinsen and Engedahl (1987). The simulation used freshwater input from the 54 largest Baltic Sea rivers, together with their interannual variability as reported in HELCOM (Johansson, 2016). The riverine input is treated as a rise in the sea surface height and each river has a prescribed constant salinity of 0.5 g/kg that is diluted in the corresponding grid cell. River water temperature is assumed to be the same as that in the target cell.

The initial thermohaline field was taken from the Copernicus reanalysis of the Baltic Sea for the period 1989–2014. As the product provides a horizontal resolution of 3 nautical miles (approximately 5.56 km), and a vertical resolution from 5 m at the surface up to 50 m in the near-bottom layers, it was interpolated to the target grid. Model simulations started from a motionless state, that is with initial sea surface height and current velocity set to zero. Previous studies (e.g. Lips et al., 2016) have shown that wind-driven circulation in the Baltic Sea adjusts to forcing within 5 days.

Model validation used available Ferrybox data (2011–2016) along the Tallinn to Helsinki transect (see Fig. 1 for location). The model captures the observed variability of temperature and salinity reasonably well (Fig. 2). Standard deviations of simulated temperature and salinity for the overall (1 November 2011–1 June 2016) and wintertime (December to March 2011–2016) periods are close to observations. The standard deviation of simulated salinity is smaller than the observed for winter 2016 (January–March) and larger for 2012, while for 2014 it is close to the observed. The variability of temperature is captured well – standard deviations from the simulations

195 are at least 0.8 of the observed for all time periods, although the model slightly overestimated temperature variability for the winter of 2012.

The overall correlation coefficient for salinity is 0.62, while it is over 0.74 for both the whole wintertime period and single years as well. There is a higher correlation for temperature (as expected); overall correlation, which includes seasonal variability, is 0.99, and for wintertime it is 0.95. Very high correlation (>0.94) for temperature is also shown for individual winters. Root mean squared differences between model and observed
200 values are slightly larger for salinity but do not exceed the observed variability. In general, the model captures wintertime changes in the surface layers of the Gulf of Finland well. More details about model setup and validation in the Baltic Proper are given in Zhurbas et al. (2018).

205 3. Results

3.1. Onset of stratification and its link to wind forcing

To demonstrate the link between wind forcing, the onset of stratification and increase in Chl *a*, we analyzed temperature, salinity, density and Chl *a* distributions along the gulf thalweg together with wind data for
210 winters 2011/12 and 2013/14. Prior to the survey of 21 December 2011, there was a strong westerly wind with a maximum along gulf wind stress of 1.3 N m^{-2} (Fig. 3a). Cumulative wind stress increased by $6 \text{ N m}^{-2} \text{ d}$ from 1 November to 21 December, resulting in a warm ($>5 \text{ }^\circ\text{C}$, Fig. 4a), relatively salty ($>6.3 \text{ g kg}^{-1}$, Fig. 4b) and well-mixed water column in the gulf (Fig. 4c). Chl *a* concentrations were very low, below 1 mg m^{-3} (Fig. 4d). Prior to the survey on 24–25 January 2012, weaker easterly winds had prevailed since mid January (Fig. 3a). Lower
215 temperature ($3\text{--}4 \text{ }^\circ\text{C}$, Fig. 4e) in the upper 20 m coincided with slightly fresher water on 24–25 January 2012 (Fig. 4f). A salinity minimum (down to 5.8 g kg^{-1}) caused stratification in the upper layer (Fig. 4g) at a distance of 80–110 km in the section; this location was also characterized by slightly higher Chl *a* concentration (up to 1.5 mg m^{-3}) (Fig. 4h). Variable and relatively weak winds prevailed in late January and early February (Fig. 3a). On 7–8
220 February 2012, temperature of the upper layer was below T_{md} ($2.7 \text{ }^\circ\text{C}$) (Fig. 4i), salinity was low ($4.8\text{--}6.0 \text{ g kg}^{-1}$, Fig. 4j) and there was a marked stratification and shallow UML (Fig. 4k). Higher Chl *a* concentration, occasionally $>2 \text{ mg m}^{-3}$, was seen in the fresher and colder water along the section (Fig. 4l). Lateral Chl *a* extent was closely linked to the salinity (density) structure, with higher Chl *a* concentration associated with lower salinity and vice versa. Westerly winds prevailed in the period before the next survey at the end of February (Fig. 3a), resulting in well mixed conditions and relatively high salinity ($6.0\text{--}6.7 \text{ g kg}^{-1}$) in the western part of the section on 29 February
225 (Fig. 4m and n). Lower salinity, stronger stratification and slightly higher Chl *a* in the upper layer were observed in the central part of the section (Fig. 4n–p). The eastern part of the section was not visited on 29 February due to ice conditions. In the middle of March (15–16 March) the water temperature was still well below T_{md} and strong haline stratification was observed along the whole transect (Fig. 4r–t). Chl *a* concentrations in the upper layer were within the range $2\text{--}4 \text{ mg m}^{-3}$ (Fig. 4u).

230 Similar trends in wind forcing and spatiotemporal patterns of temperature, salinity, density and Chl *a* were observed in winter 2013/14. Strong westerly winds dominated until early January 2014, with an increase in cumulative wind stress of $10 \text{ N m}^{-2} \text{ d}$ from 1 November 2013 (Fig. 3b). The 9–10 January 2014 survey shows a

well-mixed water column and low Chl *a* (Fig. 5a–d). Fresher and colder water was found in the upper layer on 3–4 February (Fig. 5e and f). Lower temperature and salinity caused stratification in the upper layer (Fig. 5g) and slightly higher Chl *a* concentration (Fig. 5h), but only slightly higher Chl *a*, was found in the upper layer on 3–4 February (Fig. 5e–h). By 4–5 March, the area of fresher (salinity <6 g kg⁻¹) and colder water had expanded (Fig. 5i and j). The shallow UML extended over most of the section (Fig. 5j, k). The cold and fresher upper layer showed higher Chl *a* concentrations, up to 3 mg m⁻³ especially in the eastern part of the section (Fig. 5i, j, l).

Thus, haline stratification and elevated Chl *a* concentration was observed in both winters (2011/12 and 2013/14) from the beginning of February. A shallow UML (<20 m) was absent after prevailing westerly winds and when SST was >T_{md}. Stratification formed as fresher water occupied the upper layer.

To examine temporal trends in haline stratification in more detail, we analyzed across the gulf changes in temperature and salinity using measurements acquired by the Ferrybox system along the Tallinn–Helsinki transect for January–March 2012, 2014 and 2016 (Fig. 6). Generally, temporal changes in salinity and temperature along the transect were quite similar for each of the study years, as was wind forcing (Fig. 3). Strong westerly winds dominated until early or mid-mid-January, and after the relaxation of wind forcing, fresher water was recorded in the transect.

Based on observations at the longitudinal sections (Figs. 4 and 5), the highest sea surface salinity at which stratification and relatively shallow UML can form was assumed as 6 g kg⁻¹. Similar to the along-gulf observations (Fig. 4a, b), salty and warm water occupied the transect at the beginning of January 2012 (Fig. 6a, b). The northern part of the transect was covered in fresher water (< 6 g kg⁻¹) by the end of January, although salinity slightly increased in the southern part of the section at this time. Since the main sources of freshwater are in the east, water must have flown westward along the northern coast. The area covered by fresher water widened to almost the entire section by mid February. Water temperature declined below T_{md} in the northern part in the first half of January, while in the central and southern part of the section temperature dropped below T_{md} by the end of January. A similar spatiotemporal pattern in sea surface salinity was observed in 2014 and 2016 (Fig. 6c and g–f). Fresher water first appeared in the northern part in the first half of January in both 2014 and 2016 (Fig. 6c and g). The onset of haline stratification occurred slightly earlier in 2016 due to wind forcing – the westerlies had eased off by the end of December 2015 (Fig. 3c). The segment covered by fresher water widened during January and most of the transect was occupied by water with salinity <6 g kg⁻¹ at the end of January 2016 and in mid-mid-February 2014. A pulse of strong westerly wind occurred at the end of January–beginning of February 2016 (Fig. 3e). We suggest that the lighter, less saline water that originates in the east flowed westwards along the northern coast and was later transported to the southern coast in the central and western part of the gulf. The latter is likely related to the Ekman transport induced by the westerly wind impulse (Fig. 3). Thus, stratification related to the spreading of fresher water forms about one month earlier in the northern part of the gulf than in the southern part.

3.2. Spatiotemporal patterns of restratification

Here, we examine the spatiotemporal pattern of the restratification process using model simulation data and statistics of historical observations. As noted from the in situ observations, haline stratification forms after the

relaxation of westerly winds. The annual cycle of the along-gulf component of wind stress shows higher monthly mean values ($>0.04 \text{ N m}^{-2}$) and higher variability from October–January (Fig. 7); this means that strong westerly winds are more frequent and storminess is higher in these months. As a consequence, UML depth $<20 \text{ m}$ was infrequent and mean UML depth varied between 40–60 m in the western and central gulf in November, December and January 2010–2019 (Fig. 8). As an exception, the probability of UML depth $<20 \text{ m}$ was 30–40% in the northern part of the eastern area in January. Winds from the west are weaker and storms are less frequent in February and March (Fig. 8). In February, the occurrence of UML depth $<20 \text{ m}$ increased to 50–60% (Fig. 8), although in the southern and western parts of the gulf, mean UML depth was 30–40 m. The statistics from model simulation data agree well with our observations of westward advection of fresher water from the northern coast (Fig. 6a, c and g). Mean UML depth was 20 m or lower in the central part of the gulf in March, and thicker at the gulf entrance (Fig. 8); the occurrence of UML depth $<20 \text{ m}$ was $>60\%$ in the central part, around 50% at the gulf entrance and much lower to the west of longitude 22° E (Fig. 8). A similar pattern is shown in the mean occurrence of the density difference between 40 m depth and the sea surface of $>0.5 \text{ kg m}^{-3}$, based on in situ measurements for the period 1904–2020 (Fig. 9): occurrence was 40–75% in the central part of the gulf, 30–50% in the entrance of the gulf and $<5\%$ further to the west. Thus, wintertime upper layer stratification extends to 23° E in the western gulf.

Model simulation data (2010–2019) were used to examine the development of UML depth from November to March in the Gulf of Finland, Eastern Gotland Basin (Fig. 10a and b) and along a transect from the northern Baltic Proper to the central Gulf of Finland (Fig. 10c) and in the Eastern Gotland Deep Basin. The time series of mean UML depth for transects in the gulf (Thalweg GoF, Fig. 1) and Eastern Gotland Basin (box, Fig. 1) showed considerable synoptic and interannual variability, especially in the gulf (Fig. 10a–c and b). The maximum mean UML depth in the gulf mostly occurred in December–the beginning of January, well mostly before SST decreased to T_{md} (Fig. 10a and b). The onset of restratification occurred at temperatures below $-T_{\text{md}}$ (Fig. 10b). The temperature dropped below T_{md} later and rose above T_{md} earlier in the Eastern Gotland Basin compared to the gulf. In five winters out of ten SST did not fall below T_{md} in the Eastern Gotland Basin (Fig. 10b). However, whether the temperature was below T_{md} or not, restratification phenomenon were absent from the upper layer in the Eastern Gotland Basin in January–March; this means that buoyancy, created by slight thermal stratification at $<T_{\text{md}}$, is overshadowed by vertical mixing in the Eastern Gotland Basin. Vertical mixing also dominated in the Gulf of Finland in November–December. Still, from late January or early February, the advection of fresher water (Fig. 6a, c and g) creates a shallow mixed layer (Fig. 10a and b–e).

Time series of simulated UML depth along the transect from the northern Baltic Proper to the central Gulf of Finland from October to March in 2010–2019 showed considerable synoptic and interannual variability (Fig. 10e). The deepest UML occurred in the gulf in winters 2011/12 and 2013/14 (Fig. 10a and b), i.e. precisely the years when measurements along the thalweg also showed deep UML in the gulf (Figs. 4 and 5). The deeper UML is associated with the estuarine circulation reversal caused by strong westerly winds gave rise to a deep UML, while restratification occurred after prevailing easterly winds (Figs. 3–5). The frequency of westerly (easterly) winds over the Gulf of Finland in winter is positively (negatively) correlated to the NAO index (Jaagus and Kull, 2011). The strong reversal event and deep UML in winter 2011/12 were accompanied by an anomalously high positive NAO index (Liblik et al., 2013). The mean December to February NAO index in 2011/12 was 2.18.

Likewise, the mean NAO index in the other three winters (2013/14, 2014/15, 2015/2016) when mean UML depth in the gulf reached 60 m or deeper was > 2 in ~~December–February~~ (Fig. 10b). Winters 2010/11 and 2012/13, which stand out in the time series with ~~early-onset~~ restratification (shallow UML) onset in early January, had the lowest December–February averaged NAO indices during the period 2010–2019: -1.06 and 0.47 , respectively (Fig. 10-a and -b). Thus, large scale atmospheric forcing ~~alters~~ influences provides conditions for the restratification process. Low NAO index and easterly winds support restratification while high NAO index and westerly winds have the opposite effect.

2. 4. Discussion

Positive net buoyancy flux is required for the onset of stratification in the upper layer. Processes causing negative buoyancy fluxes include vertical mixing caused by wind stirring, current shear and convection. Positive buoyancy fluxes result from advection (arrival) of lighter water to the sea surface or of denser water to the subsurface. Likewise, warming of the surface layer at temperatures above T_{md} or cooling below $-T_{md}$ strengthens stratification. The magnitude of positive buoyancy imparted from the cooling of water below $-T_{md}$ is rather small. If we consider salinity of 6 g kg^{-1} , the density difference between waters at T_{md} ($2.8 \text{ }^\circ\text{C}$) and freezing temperature ($-0.3 \text{ }^\circ\text{C}$) is 0.07 kg m^{-3} . This is the maximum density change if the water temperature is below T_{md} and salinity is 6 g kg^{-1} . We get the same density difference if we keep temperature constant ($1 \text{ }^\circ\text{C}$) and vary salinity by 0.09 g kg^{-1} . Our data show that changes in sea surface salinity in winter are of the order of $1\text{--}2 \text{ g kg}^{-1}$ (Fig. 6a, c and g), so the effect of salinity change to the density and buoyancy flux is about 10–20-fold higher than the effect of temperature change in the gulf. We can conclude that fresher water advection from the east is the primary source of buoyancy for the development of the stratification.

Freshwater transport is controlled by wind forcing; easterly winds support advection of fresher water to the west while westerly winds impede it (Liblik and Lips, 2012). However, if fresher water is already present along the north coast, westerly winds spread it to the south due to Ekman transport and create stratification there (Figs. 3 and 6), as noted in summer also by Pavelson et al. (1997). To exemplify the processes, three snapshots from the Gulf of Finland in 2011/2012 are illustrated in Fig. 11. When strong westerly winds dominated in November–beginning of January (Fig. 3a), estuarine circulation reversal led to the vanishing of stratification (Fig. 4c), the deep UML formed, and riverine water transport to the west was blocked (Fig. 11a). Easterly winds dominated from 14 January to 5 February, and as a result, westward advection of fresher water along the northern coast of the gulf and formation of shallow UML were observed (Fig. 11b). Westerly wind impulse on 5–8 February caused Ekman transport of surface layer fresher water to the south expanding so the area of shallow UML (Fig. 11c) and forming preconditions for phytoplankton growth. Due to the instability of baroclinic jets at the density fronts, the filaments formed and transport the saltier water to the north (Fig. 11b) and fresher water to the south (Fig. 11c). The widening of shallow UML and elevated Chl a concentration was also observed from measurements along the gulf thalweg (Fig. 4k and l). The stratification and phytoplankton bloom initiated by eddy-driven stratification has also drawn attention in other areas in the recent decade (Mahadevan et al., 2012; Mikaelyan et al., 2020).

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350 Wintertime stratification phenomenon in nearshore regions, extending 10–20 km from the coast, have
been reported in several locations in the Baltic Sea (Granskog et al., 2005; Kari et al., 2018; Merkouriadi and
Leppäranta, 2015). However, these studies were concerned with stratification under the ice, whereas in our study
of the Gulf of Finland, we have shown that wintertime stratification may also occur at the basin-scale (along-gulf
extent 400 km) and in the absence of considerable ice coverage. During the onset of restratification in late January
355 2012, the Gulf of Finland was virtually ice-free. In both winters (2011/12 and 2013/14), only the eastern part of
the Gulf of Finland and the adjacent northern shore of the gulf were ~~ice-ice~~ covered at the end of January, ~~thus,~~
~~winter stratification phenomenon occurred even when most of the Gulf of Finland was not covered by ice.~~ It should
be noted that, along with the frequency of easterly winds, low NAO index is also associated with ~~increased~~ ice
coverage (Jaagus, 2006). The landfast ice zone would be expected to prevent vertical mixing and therefore supports
360 lateral advection of riverine fresher water (Granskog et al., 2005).

The western border of the observed stratification phenomenon is around 23° E, i.e. at the entrance area to
the gulf between Hiiumaa Island and the Finnish coast (Fig. 1). ~~This means vertical mixing dominates over lateral
buoyancy fluxes in the Baltic Proper and shallow stratification is not a common feature.~~ The absence of the
phenomenon in the Baltic Proper can be explained by the long distance from rivers, ~~and due to~~ its larger size and
365 ~~topographywide shape~~ (Fig. 1). Riverine input per unit area in the Gulf of Finland is 7–8 times larger than in the
Baltic Proper (Leppäranta and Myrberg, 2009). As the wintertime stratification phenomenon vanishes at the wider
entrance area to the Gulf of Finland, it is likely that the elongated, ~~and~~ narrow shape of the gulf ~~accounts also~~
contributes to the formation of stratification in addition to ~~as well as~~ high freshwater input. In the northern part of
the Gulf of Finland, ~~the~~ occurrence of the shallow (<20 m) ~~UML halocline~~ reached over 50% in February, and in
370 the southern part, it reached over 50% in March. The ~~high synoptic scale and~~ interannual variability of UML depth
can be related to ~~the the wind regime and~~ NAO index (Janssen et al., 2004), ~~respectively~~. High positive NAO index
is associated with high wind stress, low ice cover, strong upwelling/downwelling (Janssen et al., 2004) and extreme
estuarine circulation reversal events (Liblik et al., 2013; Lilover et al., 2017; Lips et al., 2017; Suhhova et al.,
2018). Enhanced vertical transport by upwelling/downwelling, wind stirring, and reversal events cause vertical
375 mixing, deepening of the UML, and upward transport of nutrients from the deeper layers (Janssen et al., 2004;
Lilover and Stips, 2008; Lips et al., 2017). Conversely, a low NAO index supports the restratification and
consumption of riverine nutrients in the Gulf of Finland while the vertical mixing of nutrients from the deeper
layer is modest.

We observed Chl *a* ~~concentrations~~ up to 3.0 and 4.5 mg m⁻³ from February to the first half of March, respectively
380 in 2012 and 2014, i.e. ~~occasionally~~ comparable with the mean Chl *a* concentrations values in summer in the Gulf
of Finland (Kononen et al., 1998; Suikkanen et al., 2007). The higher Chl *a* concentration coincided with a cold
and fresher upper layer and stronger stratification. The distribution of phytoplankton biomass concentration (Fig.
12) generally follows Chl *a* structure (Fig. 5) in winter 2014. The observed winter biomass concentrations were
much lower compared to summer values in the Gulf of Finland (Kononen et al., 1998, 1999). This discrepancy is
385 probably related to the biomass/ Chl *a* ratio being low in winter (about 20) and higher in summer (about 60), as
shown for instance in the southern Baltic (Jakobsen and Markager, 2016). They explained the seasonal course of
the biomass/ Chl *a* ratio as follows: the acclimatization of pigments occurs in the cells at low light conditions and
the accumulation of excess carbon at high light and low nutrient conditions. (Lyngsgaard et al., 2017). High
summer biomass/ Chl *a* ratio (64) was also estimated in the Gulf of Finland (Kononen et al. 1998). The dominant

390 species in the phytoplankton community in more elevated biomass patches in February was the photosynthetic
ciliate *Mesodinium rubrum*, which is often the dominant primary producer in the post-spring bloom period (Lips
and Lips, 2017). In March, *M. rubrum* dominated in the western part of the study area, whereas at other stations
the spring bloom dinoflagellates were equally abundant as the photosynthetic ciliate.

395 Spring bloom is instigated when phytoplankton growth exceeds losses in the upper layer due to grazing
or vertical mixing downwards (Smetacek and Passow, 1990). Necessary conditions for spring bloom are a
stabilized upper layer that is thinner than the depth of the euphotic zone, available nutrients, and strong enough
solar radiation (Fennel, 1999). UML depth was 10–20 m in most of the Gulf of Finland in early March 2012 and
2014. Euphotic layer depth, estimated according to Luhtala and Tolvanen (2013) from our Secchi depth
400 measurements, was 15–19 m in both winters, i.e. comparable with the UML depth. Also, there were sufficient
nutrients available in the upper layer in February and March 2014 (Lips et al., 2017). We do not have a reference
for the nutrients data in 2012. Thus, the limiting factor for phytoplankton growth is likely insufficient solar
radiation. The mean downward shortwave radiation doubles in the area from February (40–50 Wm⁻²) to March
(90–100 Wm⁻²) and quadruples in April (160–200 W m⁻²) (Rozwadowska and Isemer, 1998; Zapadka et al., 2020).
405 The onset of spring bloom typically occurs in April in the Gulf of Finland (Groetsch et al., 2016; Lips et al., 2014;
Lips and Lips, 2017).

3.5. Conclusions

410 Using in situ measurements and model simulation [data](#), we have demonstrated wintertime occurrence of
haline stratification at a depth comparable to that of the euphotic zone ~~in~~ in the Gulf of Finland, well before the
onset of thermal stratification in spring. Stratification forms in late January–early February as a result of the
westwards advection of riverine water ~~along the northern coast of the gulf~~. Stratification is maintained by the
positive buoyancy flux created by the advection, which is stronger than the negative flux resulting from vertical
mixing. The advection of riverine water occurs after ~~the easing of westerly winds~~; relaxation of westerly winds,
415 ~~which~~ which is a part of the annual cycle of the local wind regime ~~and, thus~~. Thus, the ~~mid~~ mid-winter restratification is
a regular seasonal feature in the area. [Easterly winds support westward advection of fresher water](#) and shallow
stratification formation [along the northern coast](#). Expansion of the area covered by the shallow UML occurred
when the prevailing wind direction changed from easterly to a westerly direction. Haline stratification occurred
420 approximately one month later along the southern coast of the gulf.

[Earlier observations of a local stratification phenomenon in the Baltic Sea nearshore regions in winter
were under conditions of ice coverage.](#) Our observations show that haline stratification can occur in the whole
Gulf of Finland and in the absence of ice cover. Therefore, ~~our results suggest we can assume~~ that wintertime
stratification is a common phenomenon in the Gulf of Finland and its western boundary is at the entrance area to
425 the gulf, between Hiiumaa Island and the Finnish coast.

Elevated Chl *a* and phytoplankton biomass was registered in the UML in the Gulf of Finland before the
spring bloom. The limiting factor for phytoplankton growth in winter is likely insufficient light radiation. The

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exact role of wintertime stratification in the nutrient cycle and phytoplankton dynamics in the Gulf of Finland needs further investigation.

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Code availability. Scripts to analyze the results are available upon request. Please contact TL.

Author contributions. TL led the analyses of the data and writing of the manuscript with contributions from GV, JL, M-JL and IL. TL was responsible for the measurements and GV for the modelling activities. VK was responsible for gathering and processing of the Ferrybox data. IL arranged phytoplankton biomass measurements.

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Competing interests. We declare that no competing interests are present.

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4. References

450

Alenius, P., Myrberg, K. and Nekrasov, A.: The physical oceanography of the Gulf of Finland: a review, *Boreal Env. Res.*, 3, 97–125 [online] Available from: <http://www.borenav.net/BER/pdfs/ber3/ber3-097-125.pdf> (Accessed 3 February 2018), 1998.

455

Andrejev, O., Sokolov, A., Soomere, T., Värvi, R. and Viikmäe, B.: The use of high-resolution bathymetry for circulation modelling in the Gulf of Finland, *Est. J. Eng.*, 16(3), 187–210, 2010.

Anonymous: Manual for Marine Monitoring in the COMBINE Programme of HELCOM, [online] Available from: [http://www.helcom.fi/Documents/Action areas/Monitoring and assessment/Manuals and Guidelines/Manual for Marine Monitoring in the COMBINE Programme of HELCOM.pdf](http://www.helcom.fi/Documents/Action%20areas/Monitoring%20and%20assessment/Manuals%20and%20Guidelines/Manual%20for%20Marine%20Monitoring%20in%20the%20COMBINE%20Programme%20of%20HELCOM.pdf) (Accessed 19 December 2017), 2017.

460

Association for the Physical Sciences of the Sea, I.: The international thermodynamic equation of seawater-2010: Calculation and use of thermodynamic properties Intergovernmental Oceanographic Commission., 2010.

Burchard, H. and Bolding, K.: GETM – a general estuarine transport model. Scientific Documentation. Technical report EUR 20253 en. In: Tech. Rep. European Commission, Ispra, Italy., 2002.

465

Burchard, H., Bolding, K., Burchard, H. and Bolding, K.: Comparative Analysis of Four Second-Moment Turbulence Closure Models for the Oceanic Mixed Layer, *J. Phys. Oceanogr.*, 31(8), 1943–1968, doi:10.1175/1520-0485(2001)031<1943:CAOFSM>2.0.CO;2, 2001.

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- Canuto, V. M., Howard, A., Cheng, Y. and Dubovikov, M. S.: Ocean turbulence. Part I: One-point closure model-momentum and heat vertical diffusivities, *J. Phys. Oceanogr.*, 31(6), 1413–1426, doi:10.1175/1520-0485(2001)031<1413:OTPIOP>2.0.CO;2, 2001.
- 470 Chubarenko, I. P., Demchenko, N. Y., Esiukova, E. E., Lobchuk, O. I., Karmanov, K. V., Pilipchuk, V. A., Isachenko, I. A., Kuleshov, A. F., Chugaevich, V. Y., Stepanova, N. B., Krechik, V. A. and Bagaev, A. V.: Spring thermocline formation in the coastal zone of the southeastern Baltic Sea based on field data in 2010–2013, *Oceanology*, 57(5), 632–638, doi:10.1134/S000143701705006X, 2017.
- 475 Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E. and Wimmer, W.: The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, *Remote Sens. Environ.*, 116, 140–158, doi:10.1016/J.RSE.2010.10.017, 2012.
- Eilola, K.: Development of a spring thermocline at temperatures below the temperature of maximum density with application to the Baltic Sea, *J. Geophys. Res. Oceans*, 102(C4), 8657–8662, doi:10.1029/97JC00295, 1997.
- Eilola, K. and Stigebrandt, A.: Spreading of juvenile freshwater in the Baltic proper, *J. Geophys. Res. Oceans.*, 103(C12), 27795–27807, doi:10.1029/98JC02369, 1998.
- 480 Elken, J., Raudsepp, U. and Lips, U.: On the estuarine transport reversal in deep layers of the Gulf of Finland, *J. Sea Res.*, 49(4), 267–274, doi:10.1016/S1385-1101(03)00018-2, 2003.
- Elken, J., Raudsepp, U., Laanemets, J., Passenko, J., Maljutenko, I., Pärn, O. and Keevallik, S.: Increased frequency of wintertime stratification collapse events in the Gulf of Finland since the 1990s, *J. Mar. Syst.*, 129, 47–55, doi:10.1016/j.jmarsys.2013.04.015, 2014.
- 485 Fennel, K.: Convection and the timing of phytoplankton spring blooms in the western Baltic sea, *Estuar. Coast. Shelf Sci.*, 49(1), 113–128, doi:10.1006/ecss.1999.0487, 1999.
- Flather, R. A.: A storm surge prediction model for the northern Bay of Bengal with application to the cyclone disaster in April 1991, *J. Phys. Oceanogr.*, 24(1), 172–190, doi:10.1175/1520-0485(1994)024<0172:ASSPMF>2.0.CO;2, 1994.
- 490 Fleming, V. and Kaitala, S.: Phytoplankton spring bloom intensity index for the Baltic Sea estimated for the years 1992 to 2004, in *Hydrobiologia*, 554, 57–65, 2006.
- Good, S., Fiedler, E., Mao, C., Martin, M. J., Maycock, A., Reid, R., Roberts-Jones, J., Searle, T., Waters, J., While, J. and Worsfold, M.: The Current Configuration of the OSTIA System for Operational Production of Foundation Sea Surface Temperature and Ice Concentration Analyses, *Remote Sens.*, 12(4), 720, doi:10.3390/rs12040720, 2020.
- 495 Granskog, M. A., Ehn, J. and Niemelä, M.: Characteristics and potential impacts of under-ice river plumes in the seasonally ice-covered Bothnian Bay (Baltic Sea), *J. Mar. Syst.*, 53(1–4), 187–196, doi:10.1016/j.jmarsys.2004.06.005, 2005.
- 500 Gräwe, U., Holtermann, P., Klingbeil, K. and Burchard, H.: Advantages of vertically adaptive coordinates in numerical models of stratified shelf seas, *Ocean Model.*, 92, 56–68, doi:10.1016/j.ocemod.2015.05.008, 2015.
- Groetsch, P. M. M., Simis, S. G. H., Eleveld, M. A. and Peters, S. W. M.: Spring blooms in the Baltic Sea have weakened but lengthened from 2000 to 2014, *Biogeosciences*, 13, 4959–4973, doi:10.5194/bg-13-4959-2016, 2016.
- HELCOM: Guidelines for the Baltic monitoring programme for the third stage., *Balt. Sea Environ. Proc.*, 27D, 1–161, 1988.
- 505 Hofmeister, R., Burchard, H. and Beckers, J.-M.: Non-uniform adaptive vertical grids for 3D numerical ocean models, *Ocean Model.*, 33(1–2), 70–86, doi:10.1016/j.ocemod.2009.12.003, 2010.

- Jaagus, J.: Trends in sea ice conditions in the Baltic Sea near the Estonian coast during the period 1949/1950-2003/2004 and their relationships to large-scale atmospheric circulation, *Boreal Env. Res.*, 11, 169–183, 2006.
- 510 Jaagus, J. and Kull, A.: Changes in surface wind directions in Estonia during 1966–2008 and their relationships with large-scale atmospheric circulation, *Est. J. Earth Sci.*, 60, 220–231, doi:10.3176/earth.2011.4.03, 2011.
- Jaanus, A., Hajdu, S., Kaitala, S., Andersson, A., Kaljurand, K., Ledaine, I., Lips, I. and Olenina, I.: Distribution patterns of isomorphic cold-water dinoflagellates (*Scrippsiella/Woloszynskia* complex) causing “red tides” in the Baltic Sea, in *Hydrobiologia*, 554, 137–146, 2006.
- 515 Jakobsen, H. H. and Markager, S.: Carbon-to-chlorophyll ratio for phytoplankton in temperate coastal waters: Seasonal patterns and relationship to nutrients, *Limnol. Oceanogr.*, 61(5), 1853–1868, doi:10.1002/lno.10338, 2016.
- Janssen, F., Neumann, T. and Schmidt, M.: Inter-annual variability in cyanobacteria blooms in the Baltic Sea controlled by wintertime hydrographic conditions, *Mar. Ecol. Prog. Ser.*, 275, 59–68, doi:10.3354/meps275059, 2004.
- 520 Johansson, J.: Total and regional runoff to the Baltic Sea, HELCOM Balt. Sea Environ. Fact Sheets. Online [online] Available from: https://helcom.fi/media/documents/BSEFS_Total-and-regional-runoff-to-the-Baltic-Sea-in-2015.pdf (Accessed 3 January 2020), 2016.
- Jones, P. D., Jonsson, T. and Wheeler, D.: Extension to the North Atlantic oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland, *Int. J. Climatol.*, 17(13), 1433–1450, doi:10.1002/(SICI)1097-0088(19971115)17:13<1433::AID-JOC203>3.0.CO;2-P, 1997.
- Kahru, M. and Nömmann, S.: The phytoplankton spring bloom in the Baltic Sea in 1985, 1986: multitude of spatio-temporal scales, *Cont. Shelf Res.*, 10(4), 329–354, doi:10.1016/0278-4343(90)90055-Q, 1990.
- Kari, E., Merkouriadi, I., Walve, J., Leppäranta, M. and Kratzer, S.: Development of under-ice stratification in Himmerfjärden bay, North-Western Baltic proper, and their effect on the phytoplankton spring bloom, *J. Mar. Syst.*, 186, 85–95, doi:10.1016/j.jmarsys.2018.06.004, 2018.
- 530 Karlson, B., Andersson, L. S., Kaitala, S., Kronsell, J., Mohlin, M., Seppälä, J. and Willstrand Wranne, A.: A comparison of FerryBox data vs. monitoring data from research vessels for near surface waters of the Baltic Sea and the Kattegat, *J. Mar. Syst.*, 162, 98–111, doi:10.1016/j.jmarsys.2016.05.002, 2016.
- 535 Kikas, V. and Lips, U.: Upwelling characteristics in the Gulf of Finland (Baltic Sea) as revealed by Ferrybox measurements in 2007–2013, *Ocean Sci.*, 12(3), 843–859, doi:10.5194/os-12-843-2016, 2016.
- Kononen, K., Hällfors, S., Kokkonen, M., Kuosa, H., Laanemets, J., Pavelson, J. and Autio, R.: Development of a subsurface chlorophyll maximum at the entrance to the Gulf of Finland, Baltic Sea, *Limnol. Oceanogr.*, 43(6), 1089–1106, doi:10.4319/lno.1998.43.6.1089, 1998.
- 540 Kononen, K., Huttunen, M., Kanoshina, I., Laanemets, J., Moisander, P. and Pavelson, J.: Spatial and temporal variability of a dinoflagellate-cyanobacterium community under a complex hydrodynamical influence: a case study at the entrance to the Gulf of Finland, *Mar. Ecol. Prog. Ser.*, 186, 43–57, doi:10.3354/meps186043, 1999.
- Lass, H. U., Prandke, H. and Liljebladh, B.: Dissipation in the Baltic proper during winter stratification, *J. Geophys. Res.*, 108(C6), 3187, doi:10.1029/2002JC001401, 2003.
- 545 Launiainen, J. and Saarinen, J.: Marine wind characteristics in the northern Baltic Sea, Finnish, *Mar. Res.*, 250, 52–86, 1984.
- Lehmann, A., Myrberg, K. and Höflich, K.: A statistical approach to coastal upwelling in the Baltic Sea based on the analysis of satellite data for 1990–2009, *Oceanologia*, 54(3), 369–393, doi:10.5697/OC.54-3.369, 2012.

- 550 Leppäranta, M. and Myrberg, K.: Topography and hydrography of the Baltic Sea, in *Physical Oceanography of the Baltic Sea*, edited by M. Leppäranta and K. Myrberg, pp. 41–88, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009.
- Liblik, T. and Lips, U.: Variability of synoptic-scale quasi-stationary thermohaline stratification patterns in the Gulf of Finland in summer 2009, *Ocean Sci.*, 8(4), 603–614, doi:10.5194/os-8-603-2012, 2012.
- 555 Liblik, T. and Lips, U.: Variability of pycnoclines in a three-layer, large estuary: the Gulf of Finland, *Boreal Environ. Res.*, 22, 27–47, 2017.
- Liblik, T., Laanemets, J., Raudsepp, U., Elken, J. and Suhhova, I.: Estuarine circulation reversals and related rapid changes in winter near-bottom oxygen conditions in the Gulf of Finland, Baltic Sea, *Ocean Sci.*, 9(5), 917–930, doi:10.5194/os-9-917-2013, 2013.
- 560 Lilover, M.-J., Elken, J., Suhhova, I. and Liblik, T.: Observed flow variability along the thalweg, and on the coastal slopes of the Gulf of Finland, *Baltic Sea, Estuar. Coast. Shelf Sci.*, doi:10.1016/j.ecss.2016.11.002, 2017, S108-S115.
- Lilover, M. J. and Stips, A.: The variability of parameters controlling the cyanobacteria bloom biomass in the Baltic Sea, *J. Mar. Syst.*, 74(SUPPL.), 108–115, doi:10.1016/j.jmarsys.2008.03.029, 2008.
- 565 Lips, I. and Lips, U.: The Importance of *Mesodinium rubrum* at Post-Spring Bloom Nutrient and Phytoplankton Dynamics in the Vertically Stratified Baltic Sea, *Front. Mar. Sci.*, 4(DEC), 407, doi:10.3389/fmars.2017.00407, 2017.
- Lips, I., Lips, U. and Liblik, T.: Consequences of coastal upwelling events on physical and chemical patterns in the central Gulf of Finland (Baltic Sea), *Cont. Shelf Res.*, 29(15), 1836–1847, doi:10.1016/j.csr.2009.06.010, 2009.
- 570 Lips, I., Rünk, N., Kikas, V., Meerits, A. and Lips, U.: High-resolution dynamics of the spring bloom in the Gulf of Finland of the Baltic Sea, *J. Mar. Syst.*, 129, 135–149, doi:10.1016/J.JMARSYS.2013.06.002, 2014.
- Lips, U., Zhurbas, V., Skudra, M. and Väli, G.: A numerical study of circulation in the Gulf of Riga, Baltic Sea. Part I: Whole-basin gyres and mean currents, *Cont. Shelf Res.*, 112, 1–13, doi:10.1016/J.CSR.2015.11.008, 2016.
- 575 Lips, U., Laanemets, J., Lips, I., Liblik, T., Suhhova, I. and Suursaar, Ü.: Wind-driven residual circulation and related oxygen and nutrient dynamics in the Gulf of Finland (Baltic Sea) in winter, *Estuar. Coast. Shelf Sci.*, 195, 4–15, doi:10.1016/J.ECSS.2016.10.006, 2017.
- Luhtala, H. and Tolvanen, H.: Optimizing the Use of Secchi Depth as a Proxy for Euphotic Depth in Coastal Waters: An Empirical Study from the Baltic Sea, *ISPRS Int. J. Geo-Information*, 2(4), 1153–1168, doi:10.3390/ijgi2041153, 2013.
- 580 Mahadevan, A., D’Asaro, E., Lee, C. and Perry, M. J.: Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms, *Science* (80-.), 336(6090), 54–58, doi:10.1126/science.1218740, 2012.
- Männik, A. and Merilain, M.: Verification of different precipitation forecasts during extended winter-season in Estonia, *HIRLAM Newsl.* (65–70). Swedish Meteorol. Hydrol. Institute., 2007.
- Martinsen, E. A. and Engedahl, H.: Implementation and testing of a lateral boundary scheme as an open boundary condition in a barotropic ocean model, *Coast. Eng.*, 11(5–6), 603–627, doi:10.1016/0378-3839(87)90028-7, 1987.
- 585 Menden-Deuer, S. and Lessard, E. J.: Carbon to volume relationships for dinoflagellates, diatoms, and other protist plankton, *Limnol. Oceanogr.*, 45(3), 569–579, doi:10.4319/lo.2000.45.3.0569, 2000.
- Merkouriadi, I. and Leppäranta, M.: Influence of sea ice on the seasonal variability of hydrography and heat content in Tvärminne, Gulf of Finland, *Ann. Glaciol.*, 56(69), 274–284, doi:10.3189/2015AoG69A003, 2015.

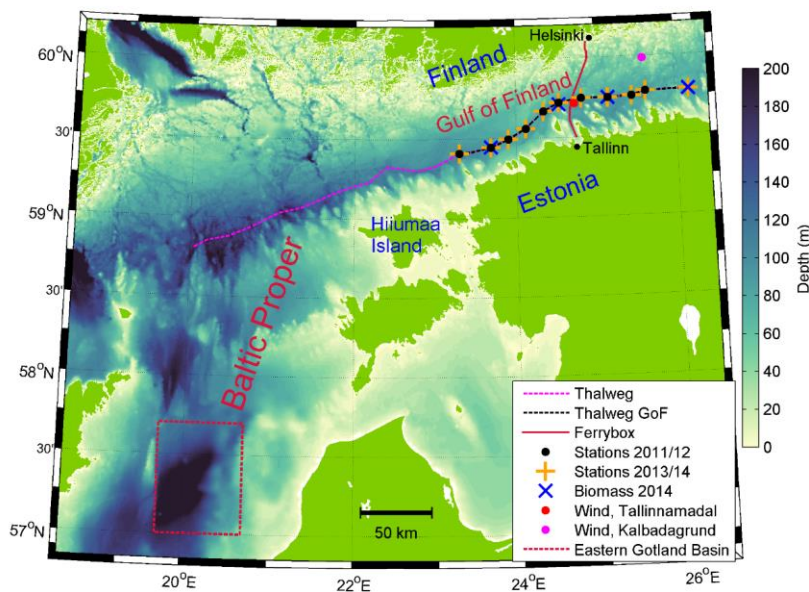
- 590 Mikaelyan, A. S., Mosharov, S. A., Kubryakov, A. A., Pautova, L. A., Fedorov, A. and Chasovnikov, V. K.: The impact of physical processes on taxonomic composition, distribution and growth of phytoplankton in the open Black Sea, *J. Mar. Syst.*, 208, 103368, doi:10.1016/j.jmarsys.2020.103368, 2020.
- Nehring, D. and Matthäus, W.: Current Trends in Hydrographic and Chemical Parameters and Eutrophication in the Baltic Sea, *Int. Rev. der gesamten Hydrobiol. und Hydrogr.*, 76(3), 297–316, doi:10.1002/iroh.19910760303, 1991.
- 595 Palmén, E.: Untersuchungen über die Strömungen in den Finnland umgebenden Meeren, *Meeren. Soc. Sci. Fenn., Comm. Phys.-Math.*, 5(12), 1–94, 1930.
- Pavelson, J., Laanemets, J., Kononen, K. and Nömmann, S.: Quasi-permanent density front at the entrance to the Gulf of Finland: response to wind forcing, *Cont. Shelf Res.*, 17(3), 253–265, doi:10.1016/S0278-4343(96)00028-3, 1997.
- 600 Putt, M. and Stoecker, D. K.: An experimentally determined carbon : volume ratio for marine “oligotrichous” ciliates from estuarine and coastal waters, *Limnol. Oceanogr.*, 34(6), 1097–1103, doi:10.4319/lo.1989.34.6.1097, 1989.
- Rasmus, K., Kiirikki, M. and Lindfors, A.: Long-term field measurements of turbidity and current speed in the Gulf of Finland leading to an estimate of natural resuspension of bottom sediment, *Boreal Environ. Res.*, 20, 735–747 [online] Available from: <http://www.borenv.net/BER/pdfs/ber20/ber20-735.pdf> (Accessed 11 June 2019), 2015.
- 605 Rozwadowska, A. and Isemer, H.-J.: Solar radiation fluxes at the surface of the Baltic Proper. Part 1. Mean annual cycle and influencing factors, *OCEANOLOGIA*, 40(4), 307–330, 1998.
- 610 Smetacek, V. and Passow, U.: Spring bloom initiation and Sverdrup’s critical-depth model, *Limnol. Oceanogr.*, 35(1), 228–234, doi:10.4319/lo.1990.35.1.0228, 1990.
- Stepanova, N. B., Chubarenko, I. P. and Shchuka, S. A.: Structure and evolution of the cold intermediate layer in the southeastern part of the Baltic Sea by the field measurement data of 2004–2008, *Oceanology*, 55(1), 25–35, doi:10.1134/S0001437015010154, 2015.
- 615 Stipa, T.: Baroclinic adjustment in the Finnish coastal current, *Tellus A*, 56(1), 79–87, doi:10.1111/j.1600-0870.2004.00041.x, 2004.
- Stipa, T., Tamminen, T. and Seppälä, J.: On the creation and maintenance of stratification in the Gulf of Riga, *J. Mar. Syst.*, 23(1–3), 27–49, doi:10.1016/S0924-7963(99)00049-4, 1999.
- 620 Stramska, M. and Biatogrodzka, J.: Spatial and temporal variability of sea surface temperature in the Baltic Sea based on 32-years (1982–2013) of satellite data, *Oceanologia*, 57(3), 223–235, doi:10.1016/J.OCEANO.2015.04.004, 2015.
- Suhhova, I., Liblik, T., Lilover, M.-J. and Lips, U.: A descriptive analysis of the linkage between the vertical stratification and current oscillations in the Gulf of Finland, *Boreal Environ. Res.*, 23, 83–103, 2018.
- 625 Suikkanen, S., Laamanen, M. and Huttunen, M.: Long-term changes in summer phytoplankton communities of the open northern Baltic Sea, *Estuar. Coast. Shelf Sci.*, 71(3–4), 580–592, doi:10.1016/j.ecss.2006.09.004, 2007.
- Tronin, A.: The satellite-measured sea surface temperature change in the Gulf of Finland, *Int. J. Remote Sens.*, 38(6), 1541–1550, doi:10.1080/01431161.2017.1286057, 2017.
- Umlauf, L. and Burchard, H.: Second-order turbulence closure models for geophysical boundary layers. A review of recent work, *Cont. Shelf Res.*, 25(7–8), 795–827, doi:10.1016/j.csr.2004.08.004, 2005.
- 630 Uotila, P., Vihma, T. and Haapala, J.: Atmospheric and oceanic conditions and the extremely low Bothnian Bay sea ice extent in 2014/2015, *Geophys. Res. Lett.*, 42(18), 7740–7749, doi:10.1002/2015GL064901, 2015.

Väli, G., Meier, H. E. M. and Elken, J.: Simulated halocline variability in the Baltic Sea and its impact on hypoxia during 1961-2007, *J. Geophys. Res. Ocean.*, 118(12), 6982–7000, doi:10.1002/2013JC009192, 2013.

635 Wasmund, N., Nausch, G. and Matthäus, W.: Phytoplankton spring blooms in the southern Baltic Sea—spatio-temporal development and long-term trends, *J. Plankton Res.*, 20(6), 1099–1117, doi:10.1093/plankt/20.6.1099, 1998.

Zapadka, T., Ostrowska, M., Stoltmann, D. and Krężel, A.: A satellite system for monitoring the radiation budget at the Baltic Sea surface, *Remote Sens. Environ.*, 240, doi:10.1016/j.rse.2020.111683, 2020.

640 Zhurbas, V., Väli, G., Golenko, M. and Paka, V.: Variability of bottom friction velocity along the inflow water pathway in the Baltic Sea, *J. Mar. Syst.*, 184, 50–58, doi:10.1016/J.JMARSYS.2018.04.008, 2018.



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650 **Fig. 1. Bathymetric map of the Baltic Proper and the Gulf of Finland. The locations of the Thalweg from the Central Gulf of Finland, CTD stations along the gulf (Thalweg GoF) visited in 2011/12 -and 2013/14, phytoplankton biomass sampling stations along the gulf in 2014, transect from the northern Baltic Proper to the central Gulf of Finland (Thalweg + Thalweg GoF), Tallinn–Helsinki Ferrybox line, Tallinnamadal and Kalbadagrund wind measurements locations and Eastern Gotland Basin (box) Gotland Deep area are shown.**

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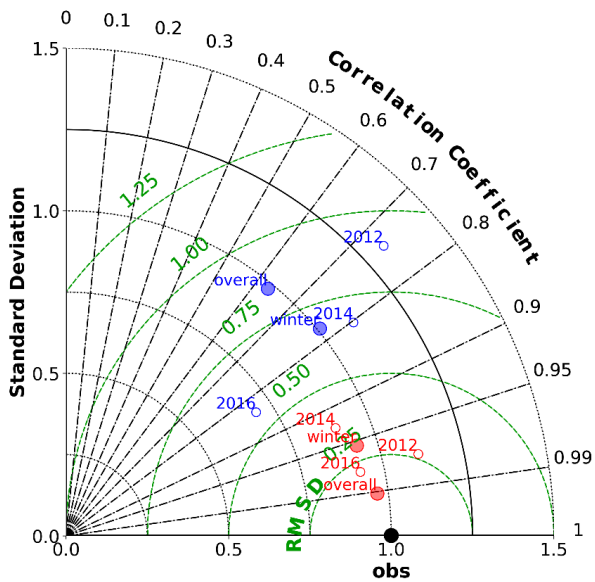


Fig. 2. Taylor diagram of simulated and measured temperature (red) and salinity (blue) along the Ferrybox transect from Tallinn to Helsinki. Overall – all available observations from 1_11_November 2011 to 11_06_June 2016 (filled circles); winter – all available observations from December to the end of March, 2011–2016 (filled circles) and winter observations from January–March in 2012, 2014 and 2016 (open circles).

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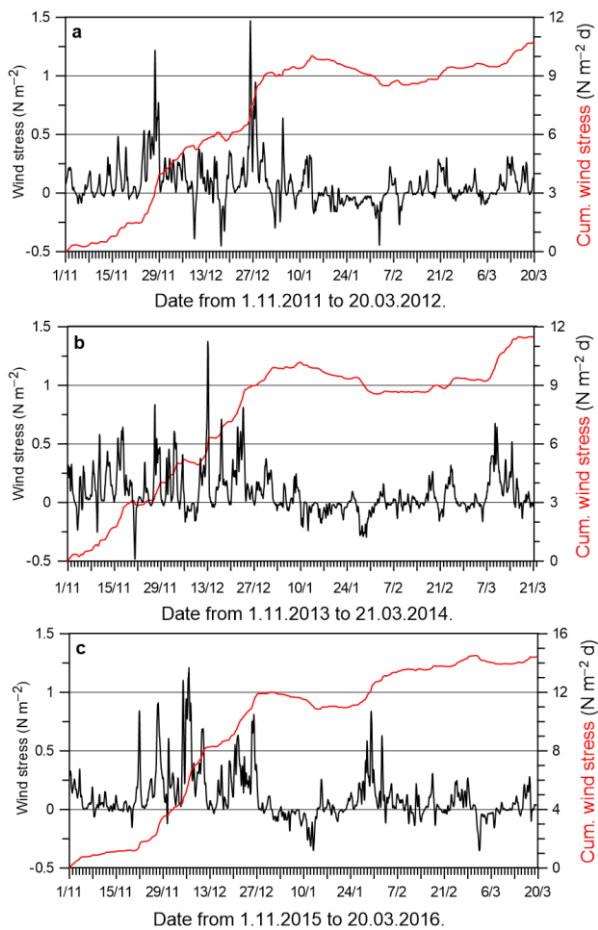


Fig. 3. Time series of an along-gulf component of wind stress (black curve, positive eastward) and cumulative along-gulf wind stress (red curve), based on wind data measured at Tallinnamadal Lighthouse in the Gulf of Finland. (a) 1 November 2011 to 20 March 2012; (b) 1 November 2013 to 21 March 2014; (c) 1 November 2011 to 20 March 2016.

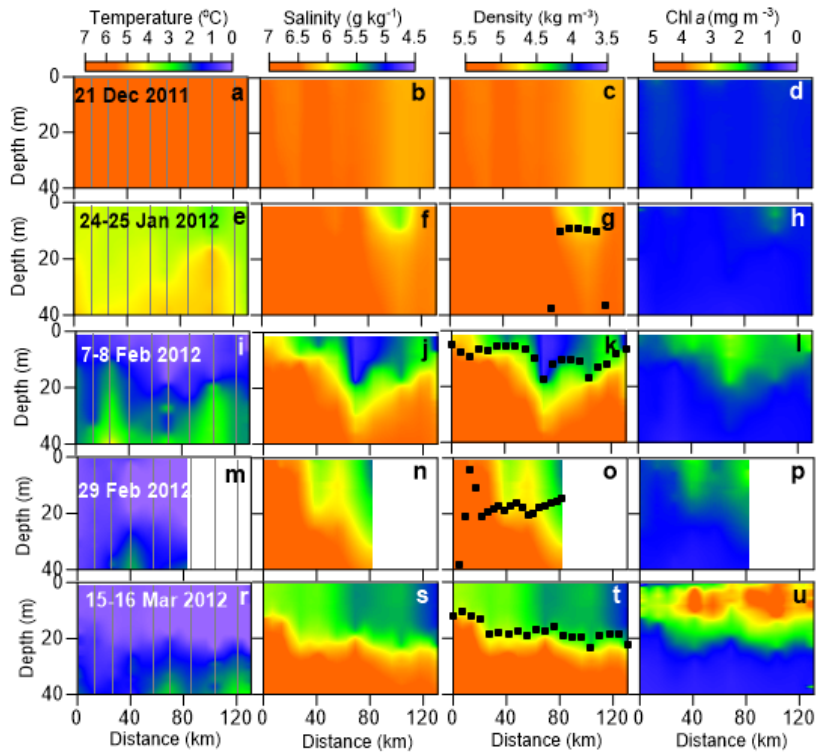
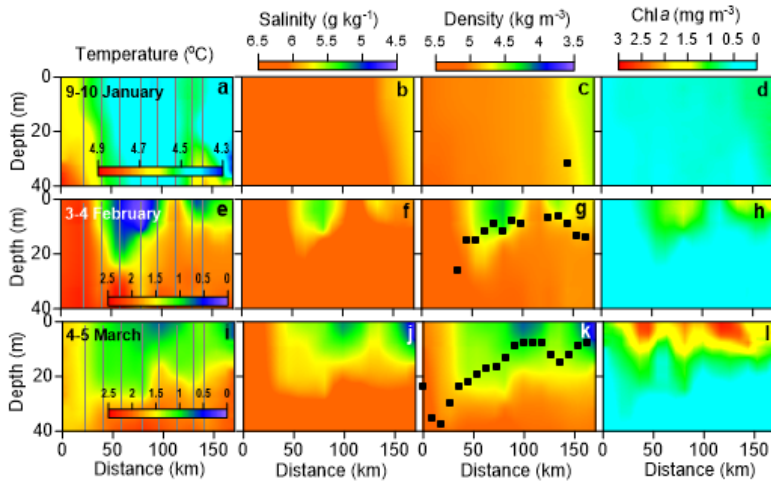


Fig. 4. Vertical sections of temperature, salinity, density anomaly and Chl *a* along a west to east profile transect in the Gulf of Finland (black dots in Fig. 1) in winter 2011/12. Vertical gray lines mark the location of CTD-casts. Black dots on density anomaly panels mark the depth of the upper mixed layer.

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Fig. 5. Vertical sections of temperature, salinity, density anomaly and Chl *a* along a west to east profile in the Gulf of Finland (orange crosses in Fig. 1) in winter 2013/14. Vertical gray lines mark the location of CTD-casts. Black dots on density anomaly panels mark the depth of the upper mixed layer. Separate colour scale for temperature on 9–10 January was used.

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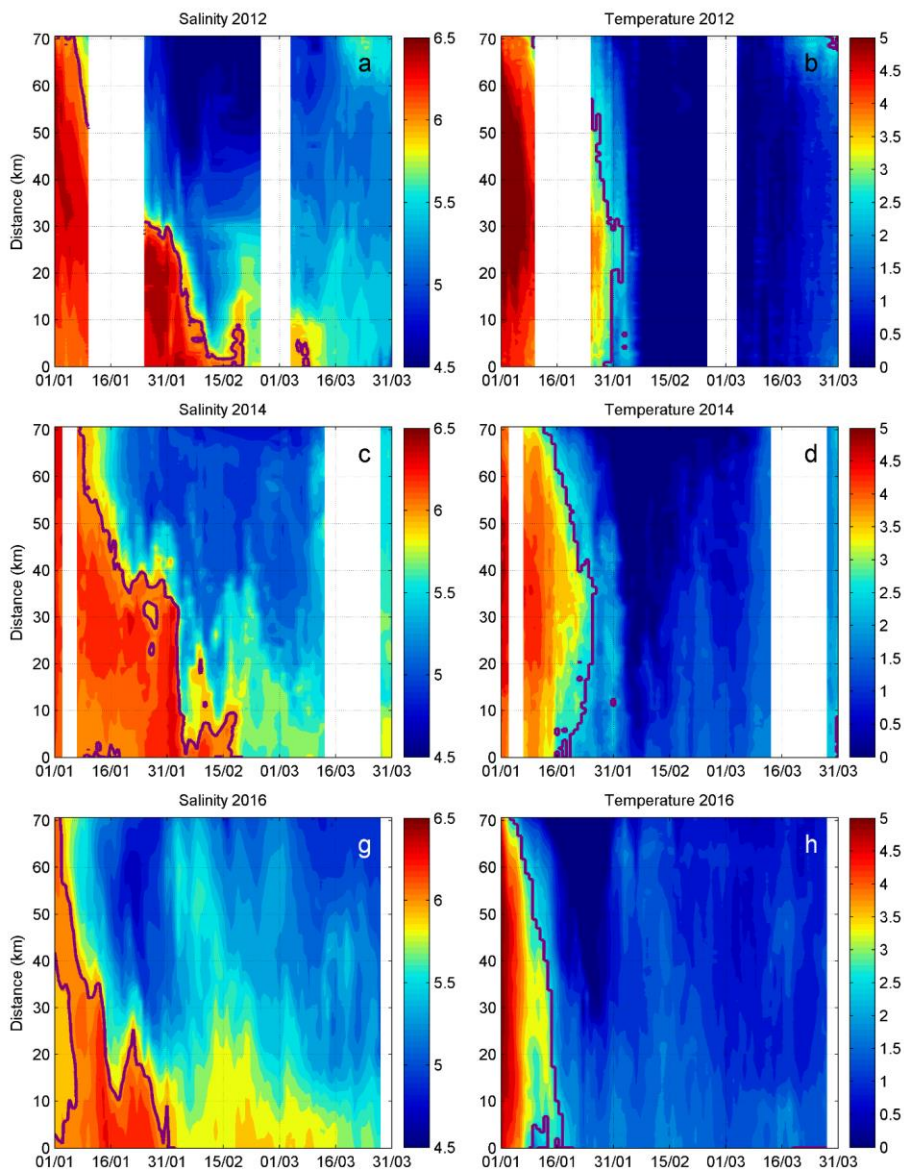


Fig. 6. Salinity (g kg^{-1}) and temperature ($^{\circ}\text{C}$) of the upper layer along a transect from Tallinn to Helsinki (red line in Fig. 1) in January–March 2012, 2014 and 2016. The isoline 6 g kg^{-1} is marked on the salinity plots and the maximum density temperature T_{md} on the temperature plots. The starting point of the transect ($x = 0 \text{ km}$) is in the Bay of Tallinn at 59.500° N and 24.752° E .

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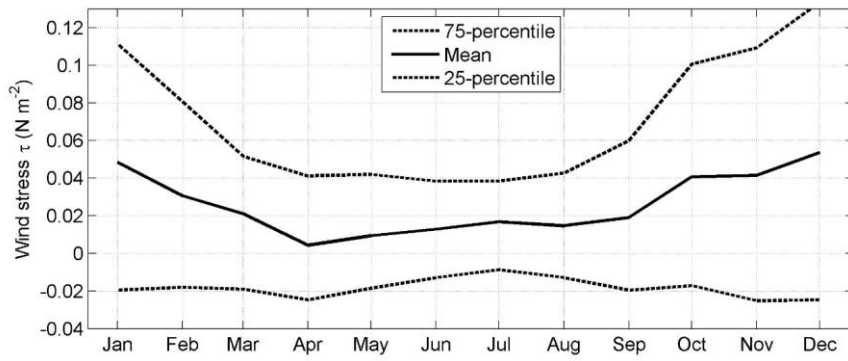


Fig. 7. Annual cycle of an along-gulf component of wind stress. Mean (solid black curve, positive eastward), 75- and 25-percentiles (dashed lines) are based on data from 1981-2015, measured at Kalbådagrund Lighthouse, Gulf of Finland.

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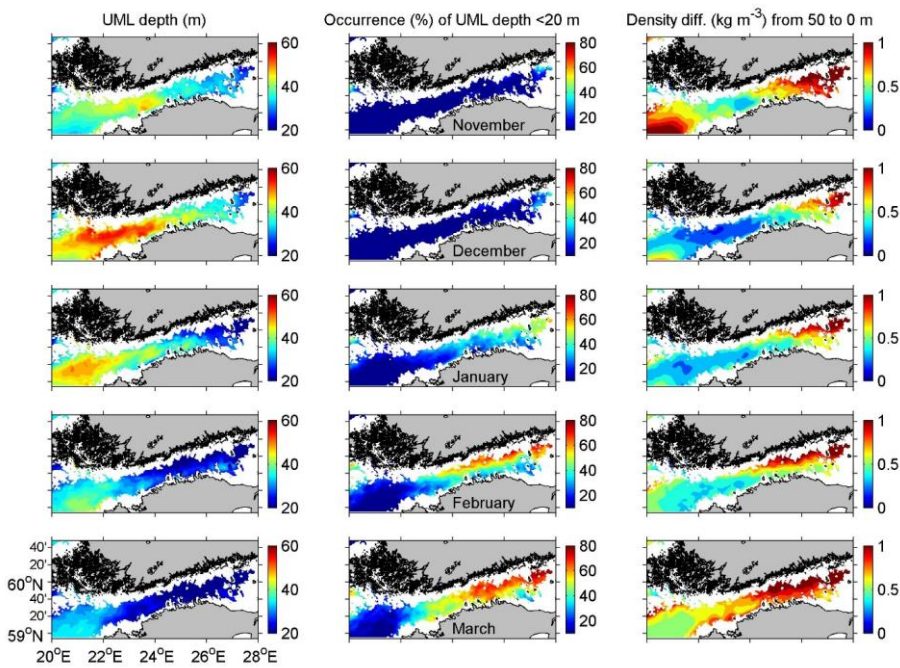
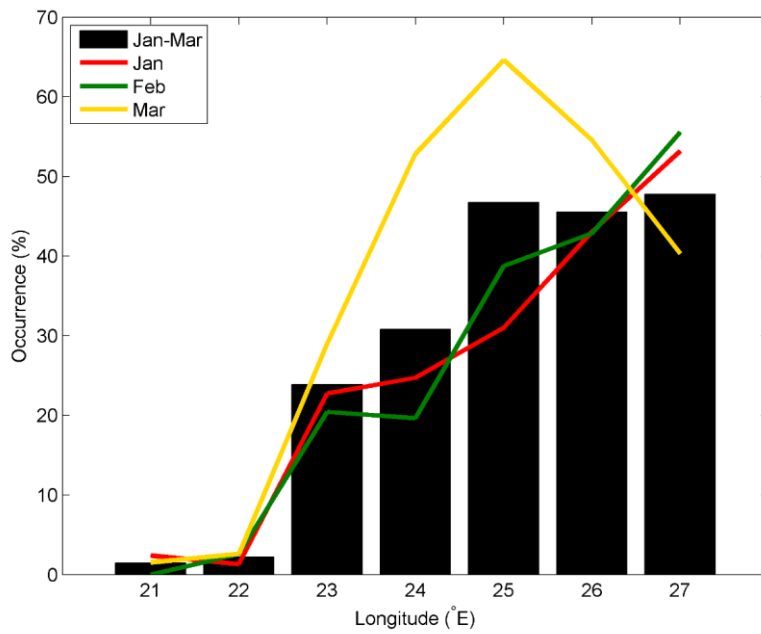
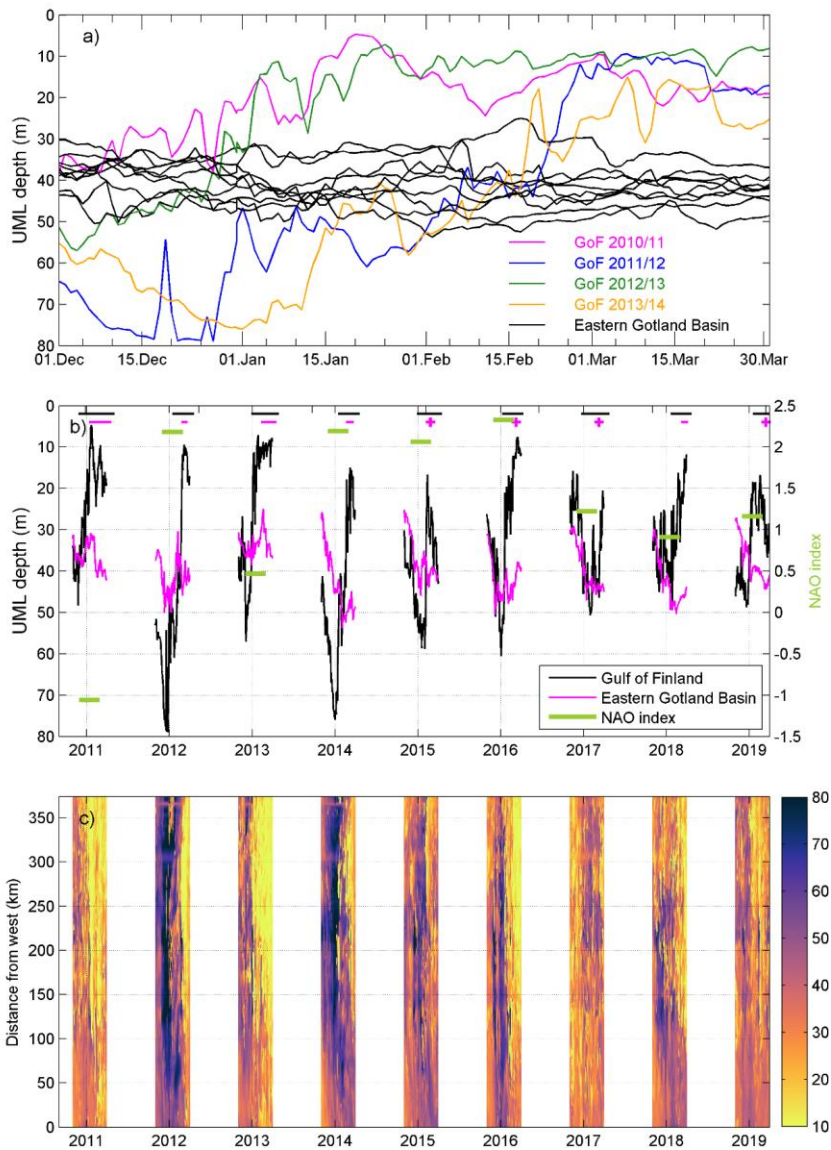


Fig. 8. Mean simulated upper mixed layer (UML) depth, percent occurrence of UML depth <20 m and density difference between 50 and 0 m depth from November to March, 2010 to 2019.



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Fig. 9. Occurrence. The occurrence of $>0.5 \text{ kg m}^{-3}$ density difference between 40 m depth and the sea surface in the Gulf of Finland from January to March 1904–2020. A total of 2560 temperature-salinity data pairs for the surface layer and 40 m depth are included.

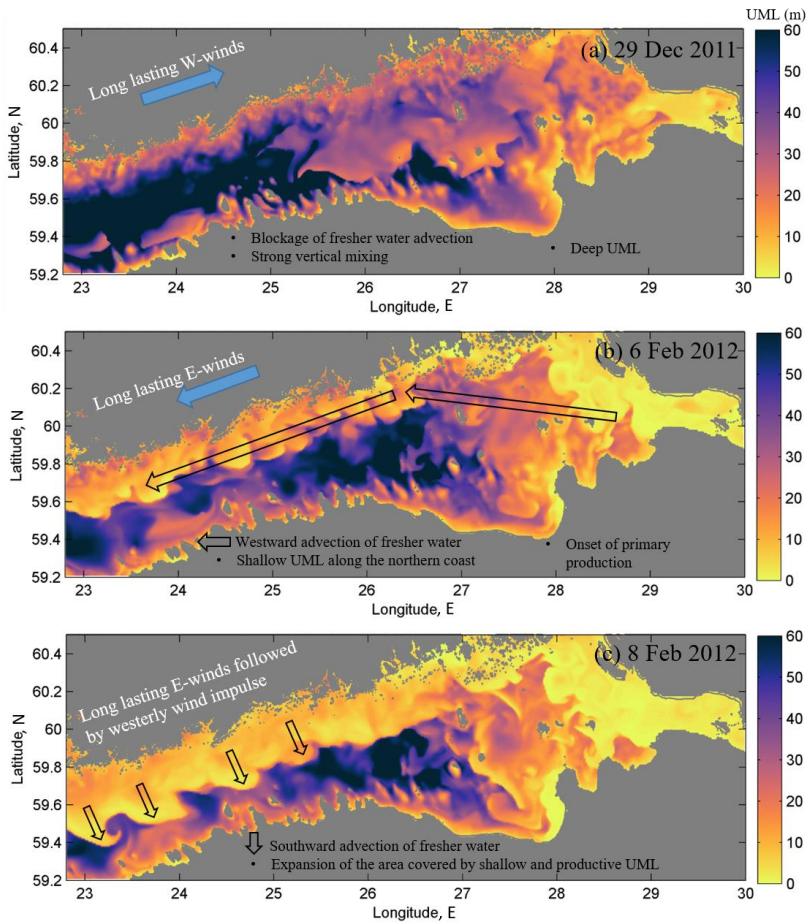


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 Fig. 10. (a-b) Time series of mean upper mixed layer depth in the Gulf of Finland and [Eastern Gotland Deep-Basin](#) based on model simulation data [from November to March, 2010 to 2019](#). The areal mean in (a) is calculated for the [selected transects](#) in the Gulf of Finland (Thalweg GoF, Fig. 1) and [for](#) the box in the [Eastern Gotland Deep-Basin](#) (Fig. 1). [Only selected four winters are shown for the Gulf of Finland to illustrate the difference between years with high positive NAO index \(2011/2012, 2013/2014\) and low NAO](#)

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index (2010/2011, 2011/2012/2013), but all winters 2010-2019 are shown for the Eastern Gotland Basin in (a). In (b), green horizontal lines mark the mean December–February NAO index (from Jones et al., 1997); black and pink horizontal lines mark where the OSTIA SST is below T_{md} and pink crosses indicate where the minimum winter temperature did not fall below T_{md} in the Eastern Gotland Deep Basin. (c) Depth of the upper mixed layer along the transect from the northern Baltic Proper to the central Gulf of Finland (Thalweg in Fig. 1) for ~~November~~ October to March, 2010 to 2019.



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Fig. 11. Upper mixed layer depth (m) based on model simulation data in the Gulf of Finland on (a) 29 December 2011, and (b) 8-6 February 2012 and (c) 8 February 2012. Strong westerly winds dominated before the 29 December 2011 survey. Easterly winds dominated prevailing before 6 February 2012 was followed by westerly wind impulse (see Fig. 3a). while variable and weaker wind occurred before the 8 February survey.

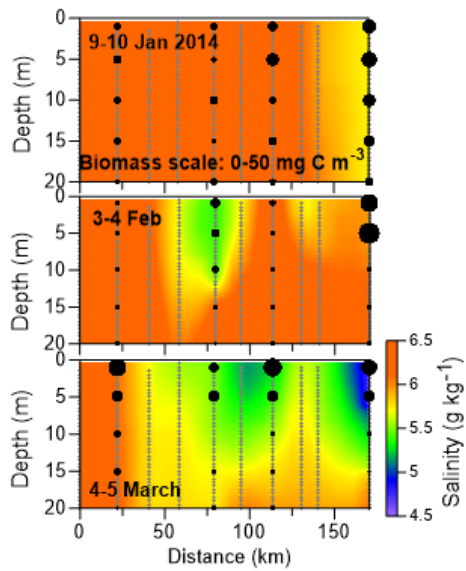


Fig. 12. Vertical distributions of salinity (color scale) and phytoplankton biomass (black dots) along the Gulf of Finland in winter 2014. Phytoplankton biomass (mg C m^{-3}) scale is shown in the upper panel. Biomass sampling locations are shown in Fig. 1 (blue crosses). Vertical gray lines mark the location of CTD-casts.

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